National Toxicology Program
U.S. Department of Health and Human Services

Center For The Evaluation Of Risks To Human Reproduction

NTP-CERHR Monograph on the Potential Human Reproductive and Developmental Effects of Acrylamide

February 2005 *NIH Publication No. 05-4472*

Table of Contents

[This page intentionally left blank]

Preface

The National Toxicology Program (NTP) established the NTP Center for the Evaluation of Risks to Human Reproduction (CERHR) in 1998. The CERHR is a publicly accessible resource for information about adverse reproductive and/or developmental health effects associated with exposure to environmental and/or occupational chemicals. The CERHR is located at the National Institute of Environmental Health Sciences (NIEHS) of the National Institutes of Health and Dr. Michael Shelby is the director.[1]

The CERHR broadly solicits nominations of chemicals for evaluation from the public and private sectors. The CERHR follows a formal process for review and evaluation of nominated chemicals that includes multiple opportunities for public comment. Chemicals are selected for evaluation based upon several factors including the following:

- potential for human exposure from use and occurrence in the environment
- extent of public concern
- production volume
- extent of data from reproductive and developmental toxicity studies

The CERHR convenes a scientific expert panel that meets in a public forum to review, discuss, and evaluate the scientific literature on the selected chemical. Public comment is invited prior to and during the meeting. The expert panel produces a report on the chemical's reproductive and developmental toxicities and provides its opinion of the degree to which exposure to the chemical is hazardous to humans. The panel also identifies areas of uncertainty and where additional data are needed. The CERHR expert panels use explicit guidelines to evaluate the scientific literature and prepare the expert panel reports. Expert panel reports are made public and comments are solicited.

Next, the CERHR prepares the NTP-CERHR monograph. The NTP-CERHR monograph includes the NTP brief on the chemical evaluated, the expert panel report, and public comments on that report. The goal of the NTP brief is to provide the public, as well as government health, regulatory, and research agencies, with the NTP's interpretation of the potential for the chemical to adversely affect human reproductive health or children's health. The NTP-CERHR monograph is made publicly available electronically on the CERHR web site and in hard copy or CD-ROM from the CERHR.

---

[1]Information about the CERHR is available on the web at <*http://cerhr.niehs.nih.gov*> or by contacting the director:

NIEHS, P.O. Box 12233, MD EC-32,
Research Triangle Park, NC 27709
919-541-3455 [phone]
919-316-4511 [fax]
shelby@niehs.nih.gov [email]

Information about the NTP is available on the web at <*http://ntp-server.niehs.nih.gov*> or by contacting the NTP Liaison and Scientific Review Office at the NIEHS:

liaison@starbase.niehs.nih.gov [email]
919-541-0530 [phone]

Introduction

Acrylamide was nominated for CERHR evaluation in 2002. The reason for nomination was that acrylamide, a chemical with known toxic properties, had recently been reported to be present in some foods. Acrylamide was selected for expert panel evaluation because of (a) recent public concern for human exposures through its presence in some starchy foods cooked at high temperatures, *e.g.*, French fries and potato chips, and (b) the availability of new data on human exposure, bioavailability, and reproductive toxicity.

Acrylamide is used in the production of polyacrylamide, which is used in water treatment, pulp and paper production, mineral processing, and scientific research. Polyacrylamide is used in the synthesis of dyes, adhesives, contact lenses, soil conditioners, cosmetics and skin creams, food packaging materials, and permanent press fabrics. Acrylamide has been shown to induce neurotoxicity in highly exposed workers and in cases of acute poisoning. In animal studies, exposure to acrylamide has been shown to cause cancer and adverse effects on reproduction and fetal development.

As part of the evaluation of acrylamide, the CERHR convened a panel of scientific experts (Appendix I) to review, discuss, and evaluate the scientific evidence on the potential reproductive and developmental toxicities of the chemical. The expert panel did not evaluate the evidence for the carcinogenicity or neurotoxicity of acrylamide. There was a public meeting of the CERHR Acrylamide Expert Panel on May 17 – 19, 2004 in Alexandria, VA. The CERHR received numerous public comments throughout the evaluation process.

The NTP-CERHR monograph on acrylamide includes the NTP brief on acrylamide, a list of the expert panel members (Appendix I), the expert panel's report on acrylamide (Appendix II), and all public comments received on the expert panel's report on acrylamide (Appendix III). The NTP-CERHR monograph serves as a single, collective source of information on the potential for acrylamide to adversely affect human reproduction or development. Those interested in reading this monograph may include individuals, members of public interest groups, and staff of health and regulatory agencies.

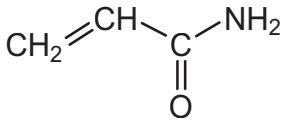
The NTP brief included within this monograph presents the NTP's interpretation of the potential for exposure to acrylamide to cause adverse reproductive or developmental effects in people. The NTP brief is intended to provide clear, balanced, scientifically sound information. It is based on information provided in the expert panel report, public comments on that report, and additional scientific information published following the public meeting of the expert panel.

NTP Brief on Acrylamide

What is Acrylamide?

Acrylamide is a crystalline white powder with a molecular formula of C_3H_5NO and the structure shown in Figure 1.

Figure 1.
Chemical structure of Acrylamide



Acrylamide is principally used in the production of polymers and gels, in scientific research, and as a cement binder. Polyacrylamide, the polymerized form of acrylamide, has a variety of uses. It is used in water treatment, pulp and paper production, mineral processing, and scientific research. Polyacrylamide is used in the synthesis of dyes, adhesives, contact lenses, soil conditioners, cosmetics and skin creams, food packaging materials, and permanent press fabrics. Low exposures to acrylamide can occur from contact with polyacrylamide-containing products.

Acrylamide is produced commercially in three ways: from acrylonitrile by a catalytic method, using a sulfuric acid method, or by enzymatic hydration by micro-organisms. The catalytic method is the preferred industrial process, due to the increased purity of the product. In this method, acrylonitrile is hydrated with a fixed copper catalyst. Unreacted acrylonitrile is recycled over the catalyst in a continuous process. Acrylonitrile is removed by evaporation and the catalyst is removed by filtration.

The demand for acrylamide was reported at 170 million pounds in 1999 and 205 million pounds in 2003. In 1997, the total output of acrylamide in the United States was 217 million pounds.

In April 2002, the presence of acrylamide in foods was reported by the Swedish National Food Administration and researchers from Stockholm University. They found that acrylamide was formed in some foods cooked at high temperatures (120–170°C or 248–338°F) by the reaction of the amino acid asparagine with a reducing sugar such as glucose.

Acrylamide can be released into the environment directly or as a result of applications using polyacrylamide such as water purification, soil conditioning, and depolymerization of polyacrylamide products. Federal regulations require that acrylamide levels not exceed 0.05% (weight/weight) when polyacrylamide is added to drinking water at a concentration of 1 ppm (1 mg/L) to remove particulate contaminants. According to the Toxics Release Inventory database, 8.7 million pounds of acrylamide were released into the environment from United States manufacturing and processing facilities in 2000.

Are People Exposed to Acrylamide?*

Yes. The general public is exposed to acrylamide by ingesting food or drink, by inhaling acrylamide in cigarette smoke, or through dermal contact with acrylamide-containing materials, such as cosmetics or other personal care products. However, data on human exposure by most of these routes are very limited. The recent (2002) finding of acrylamide in foods prompted the U.S. Food and Drug Administration to conduct a survey of foods for acrylamide content. It was found that acrylamide is formed in starchy foods such as potatoes or grains when they are heated to high temperatures. Cooked foods of animal origin, such as beef, poultry, and fish,

* Answers to this and subsequent questions may be: *Yes, Probably, Possibly, Probably Not, No or Unknown*

had lower or undetectable levels of acrylamide. In general, the survey reported levels of acrylamide in prepared foods in the parts per billion (ppb or μg/kg food) range. Among the foods tested, French fries (117 – 1325 ppb) and potato chips (117 – 2762 ppb) had some of the highest acrylamide levels. Average dietary exposure of the general U.S. population is estimated to be 0.43 μg/kg bw/day (micrograms per kilogram body weight per day). Average dietary exposures of children in the 2 – 5 year age group are estimated to be 1.06 μg/kg bw/day. Acrylamide is also found in cigarette smoke; it is reported that mainstream smoke from a single cigarette contains 1.1 – 2.34 μg acrylamide.

Human exposures to acrylamide can also be estimated by measuring the amount of acrylamide bound to proteins in the blood. Using this method, the total acrylamide exposure in non-smokers with no occupational exposure is estimated at 0.85 μg/kg bw/day. Exposure of smokers with no occupational exposure to acrylamide is estimated to be 3.4 μg/kg bw/day, approximately 4-fold higher than the general non-smoking population.

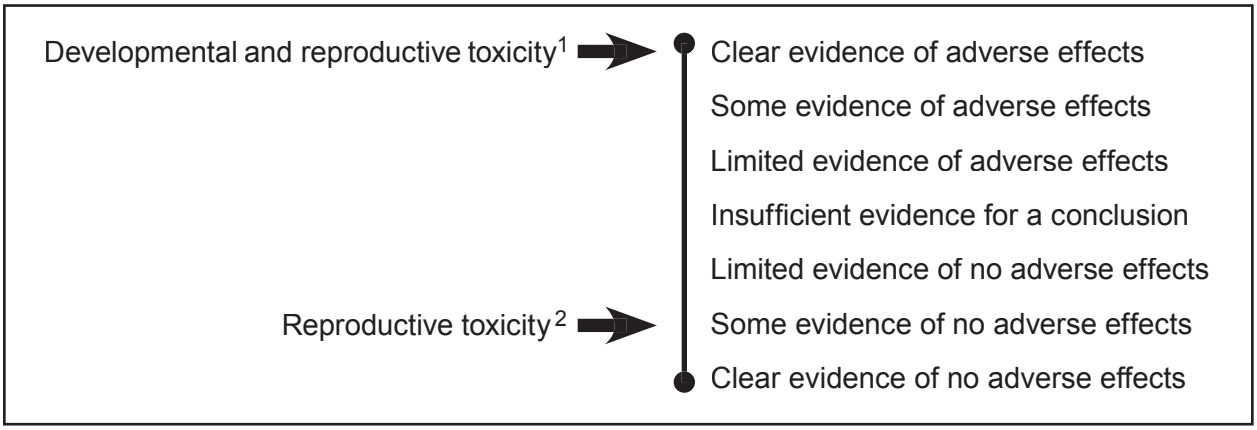
Occupational exposure to acrylamide can occur by inhalation and skin contact. Airborne exposures may result during the production of acrylamide, polyacrylamide, or in the use of acrylamide grout. Based on available data, the expert panel calculated mean and upper boundary workplace acrylamide inhalation exposures at 1.4 – 18.6 μg/kg bw/day and 43 μg/kg bw/day, respectively. Data were not available for occupational exposures by skin contact. Comments submitted by the North American Polyelectrolyte Producers Association (see Appendix III) state that, under current industrial hygiene practices, occupational exposures to acrylamide are substantially lower than those estimated by the expert panel.

Can Acrylamide Affect Human Development or Reproduction?

*Possibly***.** There is no direct evidence that exposure of the general population to acrylamide adversely affects reproduction or development. However, studies reviewed by the expert panel show that oral exposure of laboratory animals to high amounts of acrylamide can adversely affect reproduction and development (Figure 2).

Scientific decisions concerning health risks are generally based on what is known as "weight-of-evidence" approach. In this case, recognizing the absence of human data and clear evidence

Figure 2. *The weight of evidence that acrylamide causes adverse developmental or reproductive effects in animals*



[1] reproductive effects in male mice and rats
[2] for female mice and rats

of adverse effects in laboratory animals (Figure 2), the NTP judges the scientific evidence sufficient to conclude that acrylamide may adversely affect human development and/or reproduction if exposures are sufficiently high.

Supporting Evidence

As presented in the expert panel report (see Appendix II for details and literature citations), the panel concluded that acrylamide induces developmental and reproductive toxicity in experimental animals. The critical developmental toxicity studies in rodents show that oral exposure of pregnant dams to acrylamide at doses at or greater than 45 mg/kg bw/day (1 milligram, or mg, equals 1000 μg so this dose equals 45,000 μg/kg bw/day) results in marginally reduced fetal body weights in mice and at doses of approximately 4–5 mg/kg bw/day (4,000-5,000 μg/kg bw/day) results in reduced pup weights in rats. Furthermore, the expert panel concluded that acrylamide produces developmental neurotoxicity in rat pups at maternal doses of 15 mg/kg bw/day (15,000 μg/kg bw/day). However, at doses of 10 mg/kg bw/day (10,000 μg/kg bw/day) or higher, it was not possible for the expert panel to determine if the adverse effects observed in offspring were the direct effect of fetal exposure or were secondary to maternal toxicity.

Studies show that acrylamide induces reproductive toxicity in rats and mice, as evidenced by reduced litter sizes and increased deaths of embryos and fetuses. When male rats or mice are exposed to acrylamide in drinking water and then mated to unexposed females, litter sizes are decreased at doses of 5–8 mg/kg bw/day (5,000–8,000 μg/kg bw/day) in rats and at 7–8 mg/kg bw/day (7,000–8,000 μg/kg bw/day) in mice. However, when females are exposed by drinking water to doses up to 10–14 mg/kg bw/day (10,000–14,000 μg/kg bw/day for rats and 7–8 mg/kg bw/day (7,000–8,000 μg/kg bw/day) for mice, there is no indication of reproductive toxicity. The panel concluded that the reproductive toxicity of acrylamide observed in male rodents at these doses is due to multiple effects, including impairment of mating ability and genetic damage in sperm that results in death of the embryo or fetus, i.e., post-implantation loss. Other studies show that acrylamide can adversely affect cells in the testis that develop into sperm. At higher doses (40 mg/kg bw/day (40,000 μg/kg bw/day) for 5 days), tests for genetic damage in sperm of male mice are positive. The types of genetic damage induced in male mouse germ cells include dominant lethal mutations that result in death of the embryo or fetus, rearrangements of broken chromsosomes known as reciprocal translocations, and mutations in individual genes known as specific locus mutations. These effects are induced in post-meiotic germ cells, primarily in late spermatids and early spermatozoa. However, one publication reports the induction of specific locus mutations in spermatogonia. Routes of acrylamide exposure shown to cause genetic damage in male mouse germ cells include drinking water, intraperitoneal injection, and dermal application. In a more recent study (Adler et al., 2004), acrylamide applied to the skin of male mice was shown to induce reciprocal translocations. This study also confirmed earlier findings that application of acrylamide to the skin of male mice induced dominant lethal mutations.

It is not clear if these genetic effects in germ cells are induced directly by acrylamide or by its mutagenic metabolite, glycidamide, which has also been shown to induce dominant lethal mutations and reciprocal translocations. However, in a recent study by Ghanayem et al. (2004), the induction of dominant lethal mutations in male mouse germ cells by acrylamide was compared in 2 strains of mice, wild-type mice and mice lacking the gene for cytochrome P4502E1 (CYP2E1). The latter strain does not produce detectable levels of glycidamide fol-

lowing exposure to acrylamide. Using doses of 12.5, 25, and 50 mg/kg bw/day for 5 consecutive days, a dose-dependent increase in dominant lethal mutations was observed in wild-type males. No evidence of dominant lethal mutations was observed at any dose level in males lacking the gene for CYP2E1. Thus, it appears that glycidamide, the metabolite of acrylamide, is responsible for the male mouse germ cell mutations resulting from acrylamide exposure.

Because these germ cell mutagenicity studies were conducted using only relatively high doses of acrylamide, the shape of the dose-response curve at exposure levels nearer to those experienced by humans is not known. However, due to the magnitude of the effects observed at the doses tested, it seems likely that similar effects will occur at lower doses. The panel noted that there was sufficient information from genetic toxicity tests to conclude that acrylamide induces transmissible genetic damage in the germ cells of male mice. Such genetic damage may lead to infertility or genetic disorders in subsequent generations.

No data are available on the reproductive or developmental effects of acrylamide in humans. However, based on toxicokinetic, absorption, distribution, metabolism, and excretion data from rats, mice, and humans the observed adverse effects in rodents are assumed to be relevant to humans.

Should Exposures to Acrylamide Cause Concern?

Probably Not. The limited data available on acrylamide exposure in the general U.S. population indicates that exposure levels are far below those that induce reproductive and developmental toxicity in laboratory rodents. More data are needed to better define human acrylamide exposure levels, the relationship of exposures to blood adduct levels, and variations in acrylamide metabolism across the population.

Are Current U.S. Occupational Exposures to Acrylamide High Enough to Cause Concern?

Possibly. While major improvements in controlling worker exposures have occurred in the United States, occupational exposures appear to be considerably higher than exposures of the general population. Clear evidence that acrylamide induces reproductive toxicity in rodents and the absence of dose-response data for genetic damage in male germ cells at low doses leave open the possibility of adverse effects if workers are exposed to high levels of acrylamide.

Based on estimates of general population exposure, information on occupational exposures, and studies in laboratory animals, the NTP offers the following conclusions (Figure 3):

The NTP concurs with the CERHR Acrylamide Expert Panel that there is negligible concern for adverse developmental and reproductive effects from acrylamide exposure to the general population.

This conclusion is based on the low levels of estimated exposures to acrylamide in the general population. Further, developmental effects in experimental animals occur at comparatively high doses and are often associated with maternal toxicity.

The NTP concurs with the CERHR Acrylamide Expert Panel that there is minimal concern for acrylamide-induced heritable effects in the general population.

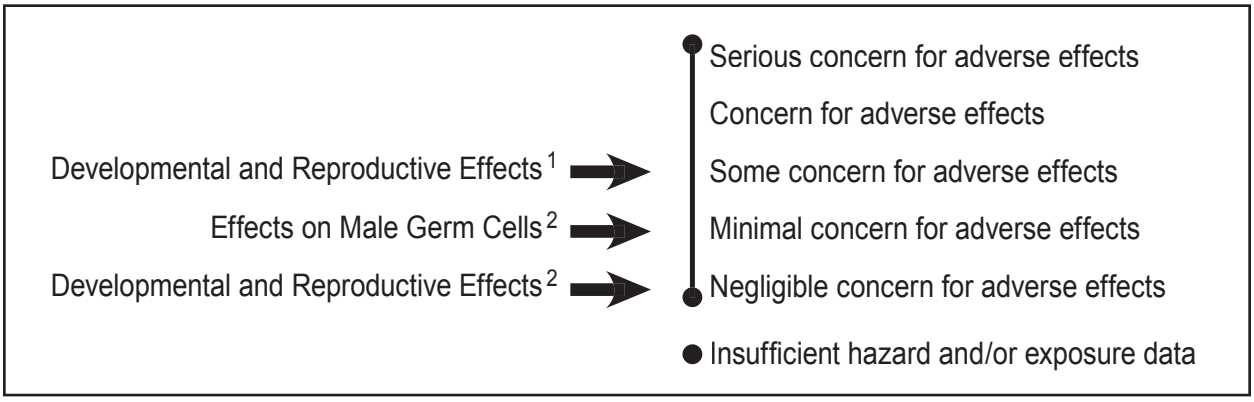
This conclusion is based on evidence that exposure of male laboratory rodents to high doses of acrylamide causes genetic damage in sperm. While the exposure levels at which these effects are observed far exceed exposures in the general population, the nature and potential consequences of genetic damage in germ cells lead to a level of concern higher than negligible.

The NTP concurs with the CERHR Acrylamide Expert Panel that there is some concern for adverse reproductive and developmental effects from occupational acrylamide exposures.

This conclusion is based on studies in laboratory animals showing acrylamide exposure levels that induce neurotoxicity sometimes induce reproductive or developmental toxicity. Because neurotoxicity has been reported in people as a result of high acrylamide exposures in some occupational settings, there is a possibility that adverse reproductive or developmental effects might result from these neurotoxic exposures. However, according to comments from NAPPA (see Appendix III), "…there have been no reported cases of neurotoxicity due to workplace exposure to acrylamide in the United States in the past two decades."

These conclusions are based on the information available at the time this brief was prepared. As new information on toxicity and exposure accumulate, it may form the basis for either lowering or raising the levels of concern expressed in the conclusions.

Figure 3. *NTP conclusions regarding the possibilities that human development or reproduction might be adversely affected by exposure to acrylamide*



[1] for occupational exposures (includes mutagenic effects on male germ cells)
[2] for the general population

References

Adler ID, Gonda H, Hrabe de Angelis M, Jentsch I, Otten IS, Speicher MR. (2004) Heritable translocations induced by dermal exposure of male mice to acrylamide. Cytogenet. Genome Res. 104:271-276

Ghanayem BI, Witt KL, El-Hadri L, Hoffler U, Kissling GE, Shelby MD, Bishop JB. (2005) Comparison of germ cell mutagenicity in male CYP2E1-null and wild-type mice treated with acrylamide: evidence supporting a glycidamide-mediated effect. Biology of Reproduction. 72:157-163.

Appendix I. NTP-CERHR Acrylamide Expert Panel

A 14-member panel of scientists covering disciplines such as toxicology, occupational exposure, and epidemiology, was recommended by the Core Committee and approved by the Associate Director of the National Toxicology Program. The panel critically reviewed documents and identified key studies and issues for plenary discussions. At a public meeting held May 17-19, 2004, the expert panel discussed these studies, the adequacy of available data, and identified data needed to improve future assessments. The expert panel reached conclusions on whether estimated exposures may result in adverse effects on human reproduction or development. Panel assessments were based on the scientific evidence available at the time of the final meeting. The expert panel report was made available for public comment on June 30, 2004, and the deadline for public comments was August 16, 2004 (*Federal Register* Vol. 69 No. 118, 34382–34383, June, 2004). The Expert Panel Report on Acrylamide is provided in Appendix II and the public comments received on the report are in Appendix III. Input from the public and interested groups throughout the panel's deliberations was invaluable in helping to assure completeness and accuracy of the reports. The Expert Panel Report on Acrylamide is also available on the CERHR website <*http://cerhr.niehs.nih.gov*>.

Appendix I. NTP-CERHR Acrylamide Expert Panel

Jeanne M. Manson, Ph.D., M.S.C.E. (Chair)
University of Pennsylvania
Philadelphia, PA

Michael J. Brabec, Ph.D.
Eastern Michigan University
Ypsilanti, MI

Judy Buelke-Sam, M.A.
Toxicology Services
Greenfield, IN

Gary P. Carlson, Ph.D.
Purdue University
West Lafayette, IN

Robert Elliot Chapin, Ph.D.
Pfizer Inc.
Groton, CT

John Bruce Favor, Ph.D.
GSF
Neuherberg, Germany

Lawrence J. Fischer, Ph.D.
Michigan State University
East Lansing, MI

Dale Hattis, Ph.D.
Clark University
Worcester, MA

Peter S. J. Lees, Ph.D.
The Johns Hopkins University
Baltimore, MD

Sally Perrault-Darney, Ph.D.
U.S. Environmental Protection Agency
Research Triangle Park, NC

Joe C. Rutledge, M.D.
Children's Hospital and Regional Medical Center
Seattle, WA

Thomas J. Smith, Ph.D., CIH
Harvard School of Public Health
Boston, MA

Raymond R. Tice, Ph.D.
Integrated Laboratory Systems, Inc.
Research Triangle Park, NC

Peter K. Working, Ph.D.
Cell Genesys, Inc.
South San Francisco, CA

National Toxicology Program
U.S. Department of Health and Human Services

Center For The Evaluation Of Risks To Human Reproduction

Appendix II

NTP-CERHR EXPERT PANEL REPORT ON THE REPRODUCTIVE AND DEVELOPMENTAL TOXICITY OF ACRYLAMIDE

June 2004 *NTP-CERHR-Acrylamide-04*

TABLE OF CONTENTS

Appendix II

ABBREVIATIONS

ACGIH .....American Conference of Governmental Industrial Hygienists
ABT.....1-aminobenzotriazole
ANOVA .....analysis of variance
AUC .....area under the concentration versus time curve
BMD10 .....“benchmark dose, 10% effect level”
BMDL .....benchmark dose 95th percentile lower confidence limit
bw.....body weight
^{14}C.....carbon-14
C.....Celsius
CAS RN .....Chemical Abstracts Service Registry Number
CERHR .....Center for the Evaluation of Risks to Human Reproduction
CFR.....Code of Federal Regulations
CIIT.....Chemical Industry Institute of Toxicology
CIR.....Cosmetic Ingredient Review
cm^2 .....centimeter(s) squared
CNS.....central nervous system
CYP.....cytochrome P450
DAPI .....4’,6-diamidino-2-phenylindole
dB.....decibel(s)
DNA .....deoxyribonucleic acid
DPM.....disintegrations per minute
DOE .....Department of Energy
EASE.....estimation and assessment of substance exposure
EPA .....Environmental Protection Agency
f.....female
F_0.....parental generation
F_1.....first filial generation
F_2.....second filial generation
FAO .....Food and Agricultural Organization of the United Nations
FDA.....Food and Drug Administration
FISH.....fluorescence in situ hybridization
g.....gram(s)
G_2 .....second gap phase of meiosis
GD.....gestation day(s)
GLP.....Good Laboratory Practice
GSH.....glutathione
GST.....glutathione-S-transferase
h.....hour(s)
HBSS .....Hanks’ balanced salt solution
hCG.....human chorionic gonadotropin
Hg.....mercury
HPLC .....high performance liquid chromatography
HSDB.....Hazardous Substances Data Bank

IARC .....International Agency for Research on Cancer
i.p. .....intraperitoneal
IPCS .....International Programme on Chemical Safety
IRIS .....Integrated Risk Information System
i.v. .....intravenous
JIFSAN .....Joint Institute for Food Safety and Applied Nutrition
KD.....receptor affinity
kg.....kilogram(s)
K_{ow} .....octanol-water partition coefficient
L .....liter(s)
LC .....liquid chromatography
LD_{50} .....lethal dose, 50% mortality
LOAEL.....low observed adverse effect level
m .....male
M.....molar
m^3.....meter(s) cubed
mg .....milligram(s)
min .....minute(s)
mL.....milliliter(s)
mm .....millimeter(s)
mM.....millimolar
mmol .....millmole(s)
MS.....mass spectrometry
n or no. .....number
NCFST .....National Center for Food Safety and Technology
ng.....nanogram(s)
NICHD.....National Institute of Child Health and Human Development
NIEHS.....National Institute of Environmental Health Sciences
NIH .....National Institutes of Health
NIOSH .....National Institute of Occupational Safety and Health
nmol .....nanomole(s)
NOAEL .....no observed adverse effect level
NOEL.....no observed effect level
NS .....non-significant
NTP.....National Toxicology Program
OECD.....Organization for Economic Co-operation and Development
OSHA.....Occupational Safety and Health Administration
PBPK .....physiologically-based pharmacokinetic model
PBS .....phosphate-buffered saline
PEL .....permissible exposure limit
pmol .....picomole(s)
p.o.....peroral
ppb.....parts per billion
PND.....postnatal day(s)
ppm .....parts per million

RACB.....reproductive assessment by continuous breeding
REL.....relative exposure limit
SD .....standard deviation
SEM .....standard error of the mean
SOCMA .....Synthetic Organic Chemical Manufacturers Association
TLV .....threshold limit value
TWA.....time weighted average
UDS.....unscheduled DNA synthesis
WHO .....World Health Organization
Δ .....change
µg.....microgram(s)
µm .....micrometer(s)
µmol .....micromole(s)

LIST OF TABLES

LIST OF FIGURES

PREFACE

The National Toxicology Program (NTP) and the National Institute of Environmental Health Sciences (NIEHS) established the NTP Center for the Evaluation of Risks to Human Reproduction (CERHR) in June 1998. The purpose of the Center is to provide timely, unbiased, scientifically sound evaluations of human and experimental evidence for adverse effects on reproduction, to include development, caused by agents to which humans may be exposed.

Acrylamide was selected for expert panel evaluation because of recent public concern for human exposures through its presence in some prepared foods, especially starchy foods cooked at high temperatures, such as French fries and potato chips. Acrylamide is used in the production of polyacrylamide, which is used in water treatment, pulp and paper production, and mineral processing. Polyacrylamide is also used in the synthesis of dyes, adhesives, contact lenses, soil conditioners, cosmetics and skin creams, food packaging materials, and permanent press fabrics. Acrylamide is a known health hazard. It has been shown to induce neurotoxicity in highly exposed workers and in cases of acute poisoning. In animal studies, exposure to acrylamide has been shown to cause cancer and adverse effects on reproduction and fetal development.

To obtain information about acrylamide for the CERHR evaluation, the PubMed (Medline) and Toxline databases were searched with CAS RNs for acrylamide (79-06-1), its metabolite glycidamide (5694-00-8), and relevant keywords. Since recent reviews were available, the search was limited to studies published in English between 1991 and 2004. References were also identified from databases such as REPROTOX®, HSDB, IRIS, and DART and from report bibliographies.

This evaluation results from the effort of a fourteen-member panel of government and non-government scientists that culminated in a public expert panel meeting held May 17 – 19, 2004. This report is a product of the Expert Panel and is intended to (1) interpret the strength of scientific evidence that acrylamide is a reproductive or developmental toxicant based on data from *in vitro*, animal, or human studies, (2) assess the extent of human exposures to include the general public, occupational groups, and other subpopulations, (3) provide objective and scientifically thorough assessments of the scientific evidence that adverse reproductive/developmental health effects may be associated with such exposures, and (4) identify knowledge gaps to help establish research and testing priorities to reduce uncertainties and increase confidence in future assessments of risk. This report has been reviewed by CERHR staff scientists, and by members of the Acrylamide Expert Panel. Copies have been provided to the CERHR Core Committee, which is made up of representatives of NTP-participating agencies.

The NTP-CERHR is headquartered at NIEHS, Research Triangle Park, NC and is staffed and administered by scientists and support personnel at NIEHS and at Sciences International, Inc., Alexandria, Virginia.

Reports can be obtained from the website <*http://cerhr.niehs.nih.gov/*> or from:

Michael D. Shelby, Ph.D.
NIEHS EC-32
PO Box 12233
Research Triangle Park, NC 27709
919-541-3455
shelby@niehs.nih.gov

A REPORT OF THE CERHR ACRYLAMIDE EXPERT PANEL:

Jeanne Manson, Ph.D., M.S.C.E., Chair	University of Pennsylvania, Philadelphia PA
Michael J. Brabec, Ph.D.	Eastern Michigan University, Ypsilanti MI
Judy Buelke-Sam, M.A.	Toxicology Services, Greenfield IN
Gary P. Carlson, Ph.D.	Purdue University, West Lafayette IN
Robert E. Chapin, Ph.D.	Pfizer Inc., Groton CT
John B. Favor, Ph.D.	GSF-National Research Center for Environment and Health, Neuherberg Germany
Lawrence J. Fischer, Ph.D.	Michigan State University, Lansing MI
Dale Hattis, Ph.D.	Clark University, Worcester MA
Peter S. J. Lees, Ph.D.	Johns Hopkins University, Baltimore MD
Sally Perreault-Darney, Ph.D.	US EPA, Research Triangle Park NC
Joe Rutledge, M.D.	Children's Hospital, Seattle WA
Thomas J. Smith, Ph.D., C.I.H.	Harvard School of Public Health, Boston MA
Raymond R. Tice, Ph.D.	Integrated Laboratory Systems, Inc., Research Triangle Park NC
Peter Working, Ph.D.	Cell Genesys, Inc., South San Francisco CA

With the Support of CERHR Staff:

NTP/NIEHS

Michael Shelby, Ph.D.	Director, CERHR
Christopher Portier, Ph.D.	Associate Director, National Toxicology Program

Sciences International, Inc.

Anthony Scialli, M.D.	Principal Scientist
Annette Iannucci, M.S.	Toxicologist
Gloria Jahnke, D.V.M.	Toxicologist

Note to Reader:

This report is prepared according to the Guidelines for CERHR Panel Members established by NTP/NIEHS. The guidelines are available from the CERHR web site <*http://cerhr.niehs.nih.gov/*>. The format for Expert Panel Reports includes synopses of studies reviewed, followed by an evaluation of the Strengths/Weaknesses and Utility (Adequacy) of the study for a CERHR evaluation. Statements and conclusions made under Strengths/Weaknesses and Utility evaluations are those of the Expert Panel and are prepared according to the NTP/NIEHS guidelines. In addition, the Panel often makes comments or notes limitations in the synopses of the study. **Bold, square brackets** are used to enclose such statements. As discussed in the guidelines, square brackets are used to enclose key items of information not provided in a publication, limitations noted in the study, conclusions that differ from authors, and conversions or analyses of data conducted by the panel.

1.0 CHEMISTRY, USAGE, AND EXPOSURE

As noted in the CERHR Expert Panel Guidelines, Section 1 is initially based on secondary review sources. Primary study reports are addressed by the Expert Panel if they contain information that is highly relevant to a CERHR evaluation of developmental or reproductive toxicity or if the studies were released subsequent to the reviews. For primary study reports that the Expert Panel reviewed in detail, statements are included about the strengths, weaknesses, and adequacy of the studies for the CERHR review process.

1.1 Chemistry

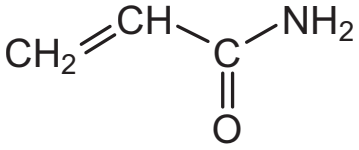
1.1.1 Nomenclature

The CAS RN for acrylamide is 79-06-1. Synonyms for acrylamide include *(1)*:
2-propenamide; 2-propeneamide; acrylic amide; ethylene carboxamide; ethylenecarboxamide; propenamide; propenoic acid, amide; vinyl amide.

1.1.2 Formula and Molecular Weight

Acrylamide has a molecular mass of 71.08; its molecular formula is C_3H_5NO *(2)*. The structure for acrylamide is shown in Figure 1.

Figure 1: *Chemical Structure of Acrylamide*



1.1.3 Chemical and Physical Properties

Acrylamide is available as an odorless, white crystalline solid or as an aqueous solution *(3)*. Physicochemical properties are listed in Table 1. In air, 1 ppm acrylamide = 2.9 mg/m^3 at 25ºC *(4)*.

Table 1. Physicochemical Properties of Acrylamide

Property	*Value*
Boiling point	125ºC @ 25 mm Hg
Melting point	84.5ºC
Flammability	Non-flammable[a]
Specific gravity	1.122 g/mL
Solubility in water	2,215 g/L @ 30ºC
Vapor pressure	6.75×10^{-3} mm Hg
Stability	May polymerize violently at temperatures above melting point
Reactivity	Reacts with acids, bases, and oxidizing agents[a]
Log K_{ow}	From -1.65 to -0.67

HSDB *(2)*, EU *(5)*
[a]Mallinckrodt *(6)*

1.1.4 Technical Products and Impurities

The solid form of acrylamide is available as a technical grade that is 97% pure and an ultra-pure grade that is 99% pure *(2)*. Concentrations of aqueous solutions range from 40 to 50%. Copper is often added at concentrations less than 100 ppm to inhibit polymerization. Trace impurities depend on the method of manufacture and can include water, iron, butanol, sodium sulfate, acrylic acid, sulfuric acid, acrylonitrile, 3-hydroxypropionitrile, 3-hydroxypropionamide, and tris-nitrilopropionamide *(2, 5)*.

Trade names for acrylamide include: AAM, Optimum, Amresco Acryl-40, and Acrylage1 *(7)*.

1.2 Use and Human Exposure

1.2.1 Production Information

The two main methods of manufacturing acrylamide include the sulfuric acid method or catalytic hydration of acrylonitrile *(2, 3)*. In the sulfuric acid method, acrylamide monomer is separated from its sulfate salt using a base neutralization or an ion exchange column *(2)*. With the catalytic hydration method, acrylonitrile solution is passed over a fixed copper catalyst bed at 70 – 120ºC to produce a 48 – 52% solution *(3)*. Unreacted acrylonitrile is recycled over the catalyst bed in a continuous process. Acrylonitrile is removed by evaporation and catalyst is removed by filtration. The catalytic method has been the preferred process since the 1970s because it yields purity, no undesirable by-products, and greater conversion efficiency, and it eliminates a costly purification step. An enzymatic hydration process using micro-organisms to convert acrylonitrile to acrylamide can also be used to manufacture acrylamide *(8)*.

Past or current manufacturers of acrylamide include: Ciba Specialty Chemicals Corp., Cytec Industries Inc., Dow Chemical USA., and Nalco Chemical Co. *(2)*. Additional manufacturers or importers may include American Cyanamid Company, BF Goodrich Co., and Cosan Chemical Corp *(7)*. According to the North American Polyelectronic Producers Association, there are currently 4 manufacturers of acrylamide in the US: Cipa Specialty Chemicals Corp., Cytec Industries, Inc., Nalco Chemical Co., and Flocryl, Inc. (part of SNF, Inc.)

The demand for acrylamide was reported at 170 million pounds in 1999 and 205 million pounds in 2003 *(2)*. In 1997, the total output of acrylamide in the US was 217 million pounds *(9)*. One hundred million pounds of acrylamide were produced in and 15 million pounds were imported into the US in 1992 *(10)*.

1.2.2 Use

Acrylamide is used in scientific research, as a cement binder, and in the production of polymers and gels *(11)*. The majority of acrylamide (>90%) is used in the manufacture of polymers such as polyacrylamide. Such polymers can contain trace concentrations of monomer *(2, 5)*. In 1999, 60% of polyacrylamide was used in water treatment, 20% in pulp and paper production, and 10% in mineral processing *(2)*. Polyacrylamide polymers are also used in certain cosmetics, some food packaging materials such as paperboard, soil conditioning agents, plastics, and specialized grouting agents *(9, 12)*. A search of the NLM Household Products Database *(13)* revealed polyacrylamide as an ingredient in several skin lotions or creams. Acrylamide polymers or co-polymers are also used in textile industries, in electrophoretic gels, as a medium for hydroponically-grown crops, in sugar refining, and in bone

cement *(11*). Polyacrylamide is also used in crude oil production; coatings used in home appliances, building materials, and automotive parts; explosives; adhesives; printing inks; adhesive tapes; latex; herbicidal gels; and as a clarifier in food manufacturing *(5, 9*). Polyacrylamide is also used in gelatin capsules, in the manufacture of dyes, and in co-polymers used in contact lenses *(9*).

1.2.3 Occurrence

Acrylamide could potentially be present in food, drinking water, indoor air, or the environment, as a result of anthropogenic or natural processes.

The presence of acrylamide in some types of food cooked at high temperatures was reported by the Swedish National Food Administration and researchers from Stockholm University in April, 2002 *(14*). In a limited survey of various food types, acrylamide concentrations were found to be highest in starchy foods cooked by methods such as frying, grilling, and baking. There is evidence that acrylamide concentrations increase with higher temperature and longer cooking duration. The survey found no acrylamide in foods cooked at temperatures below 120ºC. In most surveys, acrylamide was not detected or present at low concentrations in unheated or boiled foods *(11, 15*). Table 2 lists acrylamide concentrations detected in various food types. It was noted that the types of food analyzed included staple foodstuffs representing more than one third of consumer caloric intake in the US *(16*).

Table 2. Acrylamide Concentrations in Foods, as Reported in Friedman (11)

Food	***Acrylamide Concentration (µg/kg=ppb)***
Almonds, roasted	260
Asparagus, roasted	143
Baked products: bagels, breads, cakes, cookies, pretzels	70–430
Beer, malt, and whey drinks	30–70
Biscuits, crackers	30–3,200
Cereals, breakfast	30–1,346
Chocolate powder	15–90
Coffee powder	170–351
Corn chips, crisps	34–416
Crispbread	800–1,200
Fish products	30–39
Gingerbread	90–1,660
Meat and poultry products	30–64
Onion soup and dip mix	1,184
Nuts and nut butter	64–457
Peanuts, coated	140
Potato boiled	48
Potato chips, crisps	170–3,700
Potato, French fried	200–12,000
Potato puffs, deep-fried	1,270
Snacks, other than potato	30–1,915
Soybeans, roasted	25
Sunflower seeds, roasted	66
Taco shells, cooked	559

Acrylamide concentrations measured in recent FDA surveys of US foods are listed in Table 3 (FDA *(17, 18*). Acrylamide concentrations were found to vary widely among food categories.

***Table 3. Acrylamide Concentrations Measured in US Foods by FDA surveys** (17, 18)*

Food Type	***Acrylamide Concentrations (ppb)***
Infant fruit-, vegetable-, starch-, or meat-based foods and juices	ND – 118
Infant sweet potato foods	37 – 121
Infant cereals	ND – <10
Infant snacks (biscuits, cookies, toast, fruit wagon wheels)	20 – 267
Infant formulas (soy or milk-based)	ND – <10
French fries (fast food or cooked supermarket fries)	117 – 1325
Potato chips	117 – 2762
Potatoes (fresh, boiled, or mashed)	ND – <10
Potatoes (baked)	17 – 32
Potato snacks other than chips	1168 – 1243
Starchy snack foods other than potatoes	12 – 990
Cereals	11 – 1057
Untoasted breads or bakery products: (bagels, breadcrumbs, doughnuts, pizza, tortillas, pies, pastries, cake, muffins, pancakes, pastas)	ND – 130
Toasted, baked, or fried breads or bakery products (bagels, pizza, tortillas)	13 – 364
Crackers	26 – 647
Pastas or noodles	ND
Cookies	36 – 432
Rice (not fried)	ND
Rice (fried)	14 – 34
Fresh, frozen, or canned fruits, vegetables, and juices	ND – 83
Juice (prune)	53 – 267
Fruit spreads, jellies, or jams	ND – <10
Sweet potatoes	66 – 153
Olives	123 – 1925
Protein foods (meat, poultry, fish, and non-meat products)	ND – 116
Gravies and seasonings	ND – 151
Nuts, nut butters, beans, and seeds	ND – 457
Coffee (not brewed)	37 – 539
Coffee (brewed)	3 – 13
Dried food (soups, macaroni and cheese, sauces)	<10 – 1184
Dairy foods (milk, cheese, ice cream, milk shake, pudding, sour cream, yogurt, buttermilk)	ND – 43
Postum hot beverages (brewed)	93 – 3747
Eggs	ND
Instant breakfasts or food bars	70 – 398

Table 3. Acrylamide Concentrations Measured in US Foods (continued)

Food Type	*Acrylamide Concentrations (ppb)*
Chocolate products	ND – 909
Candy, sweets/sugars/syrups (non-chocolate)	ND
Gelatins	ND – <10
Fats/oils (butter, cream substitute, margarine, oils, salad dressings)	ND
Beverages (beer, bottled water, sodas, tea, wine)	ND
Mixtures (casseroles, sandwiches, soups, chili)	ND – 187

ND = not detected
General limit of quantitation is 1 ppb for brewed coffee and 10 ppb for other food products
Values that were below the limit of quantitation but above 0 were reported as <10 ppb

There are some data on mechanisms of acrylamide formation in foods. Data suggest that a large portion of acrylamide in baked or fried foods is derived from heat-based reactions between the amino group of the amino acid asparagine and the carbonyl group of reducing sugars such as glucose *(11)*. A Panel assembled by JIFSAN/NCFST *(19)*, "…felt generally confident that free asparagine and carbohydrates (especially free reducing sugars) accounted for the majority of acrylamide in fried potato products." Foods rich in both asparagine and reducing sugars originate from plant sources such as potatoes or cereal grains, but apparently not animal products such as beef, poultry, or fish *(11)*.

The presence of trace acrylamide concentrations in food could also result from the use of acrylamide polymers or co-polymers in food processing or food packaging materials. As noted in an IARC *(8)* review, FDA regulates the use of acrylamide polymers or co-polymers in food contact materials (21 CFR 175.105, 175.300, 177.1010, 176.180), limits residual acrylamide concentrations to 0.05% (w/w) in resins used in food treatment (21 CFR 173.5) or as boiler water additives (21 CFR 173.310), and limits residual acrylamide concentrations to 0.2% (w/w) in polymers added to water used to wash fruit and vegetables (21 CFR 173.315), in polymers or resins used in paper or paperboard intended for food contact (21 CFR 176.110, 176.170), or in modified starch (21 CFR 178.3520).

Trace concentrations of acrylamide could also occur in some drugs. The FDA requires that residual acrylamide concentrations not exceed 0.2% (w/w) in polymers used as film formers in gelatin capsules (21 CFR 172.255) *(8)*.

Acrylamide may be present in drinking water due to the use of polyacrylamide flocculants to remove particulate contaminants. Federal regulations require that residual acrylamide concentrations do not exceed 0.05% (w/w) when polyacrylamide is added to drinking water at 1 ppm **[1 mg/L]**; public water systems must annually certify (by third party or manufacturer certification) to the State that polymer and monomer concentrations are within acceptable limits *(20, 21)*. Due to this regulation, acrylamide concentrations in drinking water are not expected to exceed 0.5 ppb **[0.5 µg/L]**.

Acrylamide is a component of cigarette smoke *(12, 14)*; therefore, smoking could potentially be a source of acrylamide in indoor air. Mainstream cigarette smoke acrylamide content is 1.1 – 2.34 µg per cigarette (reviewed by Smith, et al. *(22)*). No data were found reporting acrylamide concentrations in indoor air from environmental tobacco smoke.

Acrylamide could be present in the environment as a result of direct releases or leaching of residual monomer during the use of polyacrylamide polymers in applications such as water purification or soil conditioning. During sludge conditioning processes, 92–100% of residual acrylamide was reported to leach from acrylamide polymers *(3)*. According to the TRI database, 8.7 million pounds of acrylamide were released to the environment from US manufacturing and processing facilities in 2000 *(23)*.

Acrylamide released into outdoor air can react with species such as hydroxyl radicals; the half-life for the reaction occurring at room temperature was reported at 8.3 h *(5)*. Because of its high water solubility, rain will likely remove acrylamide vapor from the atmosphere.

Acrylamide released to surface waters will not likely volatilize to air because of its high water solubility and low vapor pressure. Biodegradation appears to be the main process of removal from surface water. An OECD study found acrylamide to be readily biodegradable at concentrations lower than 2 mg/L *(5)*. Half-lives of 55–70 h were reported in fresh water under aerobic conditions *(3)*. IPCS *(3)* concluded that because acrylamide is readily biodegraded by microorganisms and because it has a high water solubility and low lipid solubility (log $K_{ow} = -1.65$), it is unlikely to bioconcentrate or biomagnify in food organisms.

Adsorption of acrylamide on soils or sediments is likely negligible and acrylamide is reported to be highly mobile in soils *(5)*. Acrylamide is degraded in soil with a rate dependent on soil type, pH, and temperature. Half-lives for degradation in soil were reported at 20–45 h at 25 mg/kg at 22ºC and 95 h at 500 mg/kg at 20ºC *(3, 5)*.

Information on acrylamide concentrations in environmental samples is limited to reports published in the 1970s and 1980s *(5)*. In those reports acrylamide concentrations were generally low in surface or sea waters in the US or UK (<0.2–3.4 μg/L). The recent European Union (EU) *(5)* analysis of exposures to acrylamide in drinking water as a result of treatment with polyacrylamide resin estimated a worst-case concentration of 0.125 μg/L. Acrylamide concentrations were below the detection limit (0.1–25 μg/L) in 5 drinking water samples from the US. Concentrations in treated wastewaters from sewage and chemical plants can be much higher. Sealing waste water systems with acrylamide-containing grout can lead to water contamination; for example, 400 μg/L was measured in a sample from a treated drain in Japan. Acrylamide concentrations ranged from <0.2 to 1,100 μg/L in various waste or process water samples obtained primarily in the UK.

[The rapid biodegradation and lack of bioaccumulation of acrylamide do not eliminate the possibility of a local pollution problem, but no data were obtained to indicate an existing problem near any major source.]

Residual concentrations of acrylamide are present in some cosmetics and toiletries containing polyacrylamide. According to the Cosmetics Ingredient Review (CIR) *(24)*, concentrations of residual acrylamide in polyacrylamide have been reported to range from <0.01 to 0.1%. Table 4 lists polyacrylamide and estimated acrylamide concentrations in cosmetics and toiletries based on information submitted to the FDA and estimates conducted by the Cosmetics, Toiletries, and Fragrance Association (unpublished data reviewed in CIR 2003 *(24)*).

Table 4. Polyacrylamide and Estimated Acrylamide Concentrations in Cosmetics and Toiletries [modified from CIR 2003 (24)]

Product Category (total # in category in 2002)	*Total # Containing Polyacrylamide in 2002[a]*	*Polyacrylamide Concentration (%) (Reported in 2002)[b]*	*Estimated Acrylamide Concentration[b] (ppm[c])*
Eye lotion (NS)	NS	1.6–2.5	<0.1–<1.3
Eye makeup preparations (152)	2	0.05	0.003
Hair conditioners (651)	1	0.7–1	0.04–<0.05
Tonics, dressings, and other hair grooming aids (598)	4	2	0.08
Hair colors, rinses, conditioners	NS	NS	NS
Non-coloring hair preparations (NS)	NS	0.9–1.4	0.04–0.06
Foundations (324)	4	0.2–1.3	0.01–0.2
Other makeup preparations (201)	1	NS	NS
Nail and skin care cosmetics (NS)	NS	NS	NS
Nail creams and lotions (NS)	NS	0.6%	<0.03
Underarm deodorants (247)	1	NS	NS
Personal cleanliness products (247)	2	NS	NS
Aftershave lotion (231)	2	2	0.2
Skin cleansing products (775)	4	NS	NS
Face and neck lotions, powders, and creams (310)	17	0.3–1.6	0.02–1.2
Body and hand lotions, powders, and creams (840)	16	0.2–2.8	0.02–<1.2
Moisturizers (905)	24	0.3–1.5	0.01–<0.75
Night creams, lotions, powders, and sprays (200)	6	0.3–0.8	0.01–0.03
Paste masks/mud packs (271)	6	0.3–0.7	0.04
Skin fresheners (184)	1	NS	NS
Other skin preparations (725)	9	0.2–2.5	0.01–<0.1
Suntan gels, creams, and liquids (131)	2	0.5–1	0.06–0.1
Indoor tanning preparations (71)	8	NS	NS

NS = Not stated
[a] Based on information submitted to the FDA
[b] Based on information or estimates from the Cosmetics, Toiletries, and Perfumery Association
[c] 1 ppm = 0.0001%

1.2.4 Human Exposure

1.2.4.1 General population exposure

The general population can be exposed to acrylamide through oral, dermal, or inhalation routes.

As noted in Section 1.2.3, acrylamide is produced in some foods during high temperature cooking. A

Panel assembled by the FAO/WHO *(14)* estimated exposure to acrylamide through food intake using food consumption data from Australia, Norway, the Netherlands, Sweden, and the US. The lower bound estimate of typical acrylamide food exposures was 0.3 – 0.8 μg/kg bw/day; intakes in children were estimated to be 2 – 3 times the adult rate when expressed as a body weight ratio. Although based on limited data, the FAO/WHO Panel stated that the data do allow for uncertainty estimates for median food exposures for Western European, Australian, and North American diets. These estimates give no indication of the upper limit of reasonable intake levels. They also do not report the uptake levels in teenagers and young adults, who might be expected to have the highest consumption of the foods with the highest concentrations of acrylamide, such as French fried potatoes and potato chips.

Additional estimates of acrylamide intake through food were reported in a review by the European Commission *(25)*. The review reports acrylamide intakes ranging between 35 and 40 μg/day (~0.5 μg/kg bw/day based on a 70 kg bw) as estimated by a Swedish group. Intakes of 0.30 – 1.10 μg/kg bw/day in adults and 0.30 – 2.1 μg/kg bw/day in 13-year-old children were estimated by a Norwegian group.

Results of initial food testing conducted by the FDA are in basic agreement with reported concentrations of acrylamide in foods from other nations *(15, 17, 18)*.

A more systematic estimate of US population dietary exposures has recently been presented by scientists at the FDA.*(26)*. FDA workers have compiled a substantial, although not necessarily statistically representative, set of measurements of acrylamide in major types of foods consumed in the US. Utilizing these limited measurements and the results of broad population surveys of the consumption of different foods by large representative samples of the US population, DiNovi and Howard constructed a Monte Carlo simulation model to assess the likely population distribution of US dietary exposure to acrylamide. The dietary exposures of the general US population (age 2 and over) were estimated as a mean of 0.43 μg/kg bw/day, with a 90th percentile of 0.92 μg/kg bw/day. Children in the 2 – 5 year age group were estimated to have higher exposures (mean 1.06 μg/kg bw/day and 90th percentile 2.31 μg/kg bw/day). These findings correspond reasonably closely to similar types of estimates made in other countries. The FDA will continue to estimate and update exposure estimates as new data are obtained on acrylamide concentrations in foods.

Sorgel et al. *(27)* reported milk acrylamide concentrations of 10.6 – 18.8 ng/mL and 3.17 – 4.86 ng/mL in 2 women who consumed about 1 mg and 800 μg of acrylamide, respectively, by eating potato chips. Based on an assumed daily consumption of 500 mL milk, Sorgel et al. estimated acrylamide intake in infants at 2 – 10 μg/day. Intake in a 3-kg baby was estimated at 0.66 – 3.3 μg/kg bw/day.

Drinking water consumption was assumed by the EU *(5)* to be the only significant source of human environmental exposure to acrylamide. Such exposure can be estimated by assuming that drinking water contains the maximum concentration of acrylamide (0.5 μg/L in the US, see Section 1.2.3), an intake rate of 2 L/day, and a body weight of 70 kg *(5)*. Based on these assumptions, the estimated upper bound exposure for adults would be 0.014 μg/kg bw/day in the US. The EU *(5)* also estimated local human exposures that could potentially result following sewer repairs using acrylamide grouts. A value of 0.11 μg/kg bw/day was estimated for small-scale repairs. Using acrylamide concentrations measured in surface or ground water following an incident during tunnel construction in Sweden and assuming that the contaminated water would be used for drinking water, a worst case exposure

was estimated at 2,620 μg/kg bw/day. **[CERHR notes that the incident involved unintended leaking of a grouting agent into a nearby waterway by contamination of waste water, and that this event represents an unlikely exposure scenario because the use of acrylamide grouts has been phased out.]**

Strengths/Weaknesses: There are several sources of ingestion exposures. Industrial releases of acrylamide to surface waters are limited and unlikely to accumulate because of biodegradation. Water contamination with acrylamide will not result in bioaccumulation because the acrylamide is highly water soluble and not lipophilic. In the 1970s and 1980s, acrylamide was present in public water supplies as a result of water treatment with polyacrylamide to aid flocculation. Polyacrylamide/free acrylamide content in drinking water is expected to be well below 0.125 μg/L in Europe. Currently there are few data, but acrylamide concentrations in all drinking water samples were lower than the limits of detection. The current data for assessment of food, water, and general environmental exposures are limited and highly uneven spatially and temporally. The most data are available for major baked, roasted, and fried food sources, most of which show low acrylamide concentrations of approximately 15–350 μg/kg of food. However, baked and fried carbohydrates containing asparagine and reducing sugars, especially potatoes cooked at high temperatures for prolonged periods, can produce 120–12,000 μg/kg of acrylamide. There is the possibility of acrylamide uptake by food from container coatings, but limits on free acrylamide in the polyacrylamide used in coatings are likely to minimize the levels of food contamination. There are no data to show the extent of contamination. Exposures by ingestion of contaminated food have been extrapolated from the limited data on food content by making assumptions about the quantities of food items eaten by various population subgroups. These contamination estimates must be considered very rough and approximate. Uptake from cosmetics, consumer products, some gardening products, paper and pulp products, coatings, and textiles is possible because of contact with polyacrylamide containing free acrylamide, but such exposures have not been characterized. Uptake is unlikely to exceed trace levels because of limits on acrylamide content for individual products. Although acrylamide has been measured in cigarette smoke, there are no data on indoor exposures from environmental tobacco smoke. While the major routes of intake have been identified and indications of the ranges of exposure are available, there are insufficient statistical data to indicate the probability of exposure at various levels. For example, the highest concentrations appear to occur in some fried foods. Milk samples from only two nursing women have been tested after consumption of potato chips to obtain an indication of uptake by a nursing infant.

Utility/Adequacy for CERHR Evaluative Process: The data for general population ingestion exposures are too limited and anecdotal to provide more than indications of possible exposures of importance. Risk assessments to estimate dose have been conducted by several agencies using a range of assumptions. Given the limited data to guide these calculations, the accuracy of these estimates is uncertain.

CERHR is aware of four acrylamide dermal exposure estimates.

In estimating dermal exposure through contact with consumer products, the EU *(5)* considered exposure patterns of cosmetic use, soil-conditioning gardening product use, and contact with paper and pulp products, coatings, and textiles that contain polyacrylamide. It was concluded that the only relevant consumer exposures resulted from sporadic use of soil conditioners (5 μg/use) and potential daily exposure to cosmetics (67 μg/day). Using assumptions for residual acrylamide concentrations

(0.01%), 75% absorption, and 70-kg bw, a worst-case exposure level of 1 µg/kg bw/day was estimated. The EU noted that the Scientific Committee on Cosmetic Products and Non-Food Products Intended for Customers recommended reducing residual acrylamide concentrations in cosmetics. Based on those recommendations, the EU estimated that use of new cosmetics would result in exposure levels that are 200 – 1,000-fold lower.

In an unpublished review by Dybing and Sanner (1999, reviewed in CIR 2003 *(24)*), dermal exposure to acrylamide was estimated at 65 µg/day for "leave-on" cosmetics and 1.4 µg/day for rinse-off toiletries, for a total daily exposure level of 66.4 µg/day (1.1 µg/kg bw/day or 0.95 µg/kg bw/day based on a 60- or 70-kg body weight, respectively). Assumptions used in the exposure estimate were daily application of 38.8 g cream, containing 2% polyacrylamide with 0.01% acrylamide monomer, at 1 mg/cm^2 over an area of 19,400 cm^2. It appears that 100% skin absorption was assumed. Without equivalent analyses, it was estimated that use of a hair setting product would result in acrylamide exposure of 24 µg/day and nail polish would result in exposure to an additional 0.5 µg. Assumptions used to estimate exposure to rinse-off products such as shaving cream or soap were total daily use of 2 g and 4.8 g, respectively, with 10% residue left on skin. **[The Expert Panel used 1.1 µg/kg bw/day to represent a conservative estimate of upper bound dermal acrylamide exposures in women. Half that level (~0.5 µg/kg bw/day) was selected as a conservative estimate of mean dermal exposure from contact with personal care products.]**

The European Cosmetic Toiletry and Perfumery Association estimated a worst-case dermal acrylamide exposure of 0.33 µg/kg bw/day by assuming that >90% of polyacrylamide-containing products have acrylamide concentrations <1ppm and more than 75% have concentrations <0.4 ppm (unpublished study reviewed in CIR 2003 *(24)*). No additional details about the exposure estimate were provided.

An unpublished analysis by Shipp et al. (2000, reviewed in CIR 2003 *(24)*) estimated acrylamide lifetime average daily dose (LADD) from nine personal care and grooming products including deodorants, cleansing products, aftershave, special creams (e.g., face lotions), and shampoos. Factors considered in the estimate were percent polyacrylamide and acrylamide in product, amount of product used in 1 year, absorption and deposition factors, years of exposure, and body weight. Since each of these factors is best represented by a distribution, a Monte Carlo approach was used. As an example, a lognormal distribution was developed using mean, minimum, and maximum acrylamide concentrations of 0.03, 0.001, and 0.1%, respectively. Information on the amount of product used each year was collected from the Nielsen Household Panel market research survey, which was based on information from ~40,000 households. Data from the Sumner (1999 and 2001) studies were used to back calculate the percentage of dermal acrylamide absorption from an aqueous solution at 1.16 – 7.56%. **[From information presented earlier in the CIR report, it appears that dermal absorption was 2.4% over 24 hours in the Sumner (1999) study (calculated by CERHR based on a statement that a dermal dose of 137 mg/kg bw results in uptake of 3.3 mg/kg bw from skin), but the Sumner (2001) study stated that dermal absorption was 22% in 24 hours.]** A uniform distribution of 1 – 2% residue was estimated for rinse-off products. Deposition factor was unity for products applied to skin and was in direct proportion to surface area of hair, hands, and scalp for hair styling products. Based on a Monte Carlo analysis, the median, mean, and 90th percentile acrylamide LADD for females was estimated at 62×10^{-6}, 260×10^{-6}, and 430×10^{-6} µg/kg bw/day, respectively. The respective values in males were 50×10^{-6}, 200×10^{-6}, and 340×10^{-6} µg/kg bw/day.

Cigarette smoke is another source of acrylamide exposure. The acrylamide content in mainstream cigarette smoke has been measured at 1.1 – 2.34 µg per cigarette *(22)*. **[Assuming that a 70 kg adult smokes 20 cigarettes per day, the average inhaled dose would be 0.67 µg/kg bw/day. The upper bound exposure was estimated at 1.3 µg/kg bw/day by assuming that the upperbound exposure is twice the average exposure.]** Levels of acrylamide-hemoglobin adducts in cigarette smokers are discussed in Section 1.2.4.3.

1.2.4.2 Occupational exposures

Occupational exposure to acrylamide could occur during the manufacture of acrylamide monomers or polymers, during polyacrylamide use, in the preparation of polyacrylamide gels, and during the use of polyacrylamide grouts *(5)*. Exposure is a function of the quantity of free acrylamide present. Historically, under uncontrolled manufacturing conditions, exposures have been very high, such as 1 – 3 mg/m^3 in China *(28)*. During the use of polyacrylamide, where the exposure comes from the residual acrylamide in the solid polymer, exposure levels are low. Exposure to acrylamide is possible for workers in a wide range of industries that use polyacrylamide: paper and pulp, construction, foundry, oil drilling, textiles, cosmetics, food processing, plastics, mining, and agricultural occupations. However, the amount of free acrylamide is limited to 0.1% in the polymer, which sharply limits the level of exposure to the monomer in situations where there is contact. Workers could be exposed by inhaling dusts or vapors and through dermal contact with monomers or polymers. In the National Occupational Exposure Survey, the National Institute of Occupational Safety and Health (NIOSH) estimated that 10,651 workers, 721 of them female, were exposed to acrylamide in 1981 – 1983 *(29)*. Researchers or technicians who prepare polyacrylamide gels may also experience variable and intermittent exposures to acrylamide.

The American Conference of Governmental Industrial Hygienists (ACGIH) established a time weighted average (TWA) threshold limit value (TLV) of 0.03 mg/m^3 for acrylamide based on central nervous system (CNS) effects, dermatitis, and carcinogenicity (observed only in experimental animal studies) *(30, 31)*. A skin notation was included because limited data demonstrated toxicity following absorption of acrylamide through intact skin of humans and animals. NIOSH *(32)* also established a TWA recommended exposure limit (REL) of 0.03 mg/m^3, with a notation for dermal absorption for acrylamide. The Occupational Safety and Health Administration (OSHA) permissible exposure level (PEL) for acrylamide is 0.3 mg/m^3 *(33)*. **[The documentation for these standards may be useful to estimate exposures, but the limits themselves are not.]**

The EU *(5)* summarized workplace exposures to acrylamide; these values are listed in Table 5. Acrylamide exposures were highest during monomer production, with geometric means ranging from 0.09 to 0.13 mg/m^3. Polyacrylamide production had lower exposures, with geometric means from 0.01 to 0.02 mg/m^3. Later stages of polymer production represent less risk for exposure because the excess acrylamide monomer becomes trapped in the polymer matrix. Use of acrylamide grout for sewer sealing applications offers more opportunity for exposure because the free monomer as a powder may be used to make the grout on-site (use of water solution of monomer produces less exposure opportunity). In addition, the EU review noted that some of the values were obtained for production work processes that have since been automated, which would reduce exposure. Some of the measurements were taken during accidents or prior to installation of engineering controls. In addition, respiratory protection was used in some cases and actual inhaled respiratory exposures would be lower.

The only US data reported in Table 5 were for use of acrylamide grout in small-scale sewer repair operations. Those data were collected in two surveys conducted in 1986 and 1987 *(5)*.

[The Expert Panel estimated occupational acrylamide inhalation exposures using the Table 5 values reported for European workplaces. Based on geometric means of 0.01 – 0.13 mg/m^3 and assumptions of an 8-hour work day, an inhalation volume of 10 m^3 air/work day, and a 70-kg body weight, mean workplace inhalation exposures were estimated at 1.4 – 18.6 µg/kg bw/day. Assuming that the PEL (0.3 mg/m^3) represents the upper bound exposure, high-end worker exposure was estimated at 43 µg/kg bw/work day. Data from skin exposure and uptake are unknown and difficult to measure.]

Table 5. Workplace Inhalation Exposures to Acrylamide, European Union (5)[c]

Industry	*Country*	*Number of Samples*	*Arithmetic Mean (mg/m^3)*	*Geometric Mean (mg/m^3)*	*Range (mg/m^3)*
Acrylamide manufacture	UK	11	0.18	0.09	0.05 – 0.34
	Germany[a]	44	0.01	No data	<0.001 – 0.022
	Netherlands[a]	87	0.17	0.13	<0.05 – 1.3
Polyacrylamide manufacture	UK[a]	422	0.05	No data	0.01 – 0.77
	UK[a]	10	0.03	0.02	0.001 – 0.08
	UK[a]	4	0.01	0.01	0.01
	Germany[a]	No data	No data	No data	all <0.03
	Germany[a]	23	0.03	0.02	<0.001 – 0.099
Electrophoresis gels	UK[b] (manufacture)	4	0.03	0.006	0.002 – 0.012
	UK (use)	2	0.04	NA	<0.005 – 0.067
Polyacrylamide use	EASE model	NA	NA	NA	0.0001 – 0.003
	UK[a]	No data	No data	No data	All <0.015
	Netherlands	NA	NA	NA	<0.001 – 0.012
Large-scale acrylamide grout use (i.e., tunnel work)	Sweden	9	0.018	0.01	0.005 – 0.076
Small-scale acrylamide grout use (i.e., sewer repair)	US	5	0.047	0.029	0.008 – 0.12

[a] Personal samples.
[b] Values measured within an air-fed pressure suit.
[c] Information was obtained from Table 4.16 in the European Union report. Much of the information in this table is historical. See text for explanation.
NA=Non-applicable.
EASE=estimation and assessment of substance exposure.

Some US occupational exposure data were reported by IARC *(8)* and values for personal exposures are summarized in Table 6.

Table 6. Workplace Inhalation Exposures to Acrylamide in the US, IARC (8)

Operation/ Job Description	*Sample Type*	*Number of Samples*	*Air Concentrations (mg/m^3)*		*Year(s) Measured*
			Mean	*Range*	
Monomer production					
Reactor operator	Personal 4-h	1	0.48	NA	1971-1975
Dryer operator	Personal 4-h	1	0.52	NA	
Packing	Personal 4-h	2	0.64	0.52–0.76	
Control room	Personal 8-h	NR	NR	0.1–0.4	
Bagging room	Personal 8-h	NR	NR	0.1–0.9	
Processing	Personal 8-h	NR	NR	0.1–0.4	
Monomer and polymer production					
Monomer operators	Personal	19	0.065 GM	0.001–0.227	1984–1985
Polymer operators	Personal	27	0.031 GM	0.001–0.181	
Monomer material handlers	Personal	4	0.085 GM	0.017–0.260	
Polymer material handlers	Personal	4	0.023 GM	0.018–0.035	
Maintenance	Personal	14	0.013 GM	0.001–0.132	
Utility operators	Personal	4	0.116 GM	0.004–0.392	
Continuous monomer production	Personal TWA	NR	NR	0.1-0.6	1957-1970
Sewer line repair					
Grouting operation (2 sites)	Personal	12	0.010	0.003–0.02	1990
Grouting operation	Personal	2	0.005	0.002–0.007	1985
Grouting operation	Personal	6	0.10	0.008–0.36	1988
Coal plant					
Static thickening of coal waste	Personal	2	NR	<0.001	1992

NR=Not reported. NA=Non-applicable. GM=Geometric mean

All of the data are more than 10 years old. As seen in the European data, monomer production had the highest exposures, with geometric mean values ranging from 0.065 to 0.085 mg/m^3 in the 1980s. In the 1970s, concentrations were higher, approximately 0.1–0.9 mg/m^3. The overall trend in exposures in most US chemical production facilities has been downward since the 1970s because of improvements in engineering controls and personal protective equipment. Polymer production

concentrations in the 1980s had geometric mean values of 0.023 – 0.031 mg/m^3. Average exposures varied by job with utility workers having the highest geometric mean, 0.116 mg/m^3. It is not known if the monitored workers used personal protective equipment or if engineering controls were utilized. It is likely that the use of all types of controls has increased. Neither Table 5 nor Table 6 considers exposure that could occur through the dermal route. Since the addition of skin notations to the TLV for acrylamide, it is likely that protective equipment currently is used in large well controlled industrial operations where skin contact is possible. Skin protection may not be adequate in small businesses where there is frequently a lack of expertise and resources.

Dermal contact with acrylamide powder, solution, or vapor condensation may be a significant source of worker exposure. The EU *(5)* estimated dermal exposures to workers. Using an unvalidated method of measuring acrylamide levels on cotton liners worn within protective gloves, mean and high-end exposures were estimated, respectively, at 0.004 and 0.01 mg/cm^2 **[skin assumed]**/day during acrylamide manufacture and at 0.0004 – 0.01 and 0.08 mg/cm^2/day during polymer production. Dermal exposure during polymer use was predicted at from 1×10^{-5} to 1×10^{-4} mg/cm^2/day using the EASE model, which has large uncertainties for dermal exposures. For small-scale use of acrylamide grouts, the EU used a dermal exposure value of 5 mg/h in its risk characterization. The EU noted that additional dermal measurements included an acrylamide value of 2.49 mg/glove (4.98 mg/working shift total). However, it is clear neither how much of this acrylamide would have been absorbed, nor whether a worker could have tolerated this much acrylamide on his or her skin for 8 h. If all of the acrylamide were absorbed, the exposure would lead to very high internal doses. **[The very limited US data are consistent with the European data; because EASE estimates are not precise, the Expert Panel believes it appropriate to assume the European values apply to US workers.]**

In 2002, Pantusa et al. *(34)* measured air acrylamide exposures for personnel from biomedical research laboratories in Houston. Personal short-term air samples (15 minutes) were taken while subjects weighed crystalline acrylamide or poured liquid acrylamide for the preparation of polyacrylamide gels. Personal full-shift air exposures were measured during the entire period when exposure to acrylamide was possible and TWAs were calculated. Twenty subjects used crystalline acrylamide while nine subjects used solutions. Latex gloves were worn by all subjects and five individuals using crystalline acrylamide wore dust masks. Fifteen subjects working with crystalline acrylamide and six working with acrylamide solution wore lab coats. Short-term exposures exceeded the detection limit in all but three subjects using crystalline acrylamide and all but one subject using solution. Short-term exposures ranged from <0.00056 mg/m^3 to 0.022 mg/m^3 in users of crystalline acrylamide and from <0.0002 to 0.014 mg/m^3 in users of acrylamide solutions. TWA exposures ranged from 0.00007 to 0.020 mg/m^3 in subjects using crystalline acrylamide and from 0.00009 to 0.0028 mg/m^3 in subjects using solutions.

Strengths/Weaknesses: There are few current data for occupational exposures. In many of the historical situations, both inhalation and dermal routes of exposure were important. There are very few estimates of the degree of dermal contact; dermal exposure is difficult to estimate. The data from the Pantusa et al. study are somewhat useful for laboratory workers and show that these workers have very low exposures, although the number of observations is low. It is not clear how relevant the EU data on 1980s production worker exposures are for current exposure assessment.

Utility (Adequacy) for CERHR Evaluative Process: The exposure data are inadequate for estimating current exposures. There are too few observations and the data are generally not current. The dermal exposures and uptake are unknown, as is the effectiveness of protective gloves and clothing.

1.2.4.3 Exposures based on adduct formation

As discussed in Section 2.1.2, acrylamide and its metabolite, glycidamide, can both form covalent bonds with hemoglobin. The hemoglobin adduct products are being investigated as biomarkers of acrylamide exposure. Studies in rats have demonstrated dose-related increases in acrylamide adduct formation *(16*).

Calleman *(28*) published a study conducted to establish relationships between total exposures, diagnostic indicators, and toxic effects in Chinese workers. The study examined biomarkers of acrylamide exposure and neurologic effects in 41 workers employed at a plant that produced acrylamide monomers and co-polymers. Ten people from the same city were also examined and used to determine control values. Mean levels of biomarkers are summarized in Table 7, according to job categories.

Table 7. Biomarkers of Acrylamide Exposures in Chinese Workers, Calleman (28)[a]

Job category	*Plasma acrylamide (µmol/L)*	*S-(2-carboxyethyl)cysteine (µmol/24 h)*	*Acrylamide adduct (pmol/g globin)*	*Lifetime acrylamide AUC (mM*h)*
Controls	0.92	3.0±1.8	0	0
Packaging	2.2	93±72	3,900±2,500	8.9±9.1
Polymerization	1.3	58±75	7,700±3,400	10.0±5.8
Ambulatory	2.0	53±35	9,500±7,300	11.3±9.8
Synthesis	1.8±0.8	64±46[b]	13,400±9,800	19.2±10.6

[a]Values presented as means±SD; however, SD were not listed for some values
[b]This value was reported as 643 µmol in the text of the study

Concentrations of acrylamide valine adducts ranged from 300 to 34,000 pmol/g globin in exposed workers and were directly proportional to glycidamide adducts. Concentrations of acrylamide adducts and acrylamide area under the concentration versus time curve (AUC) over the active lifetime of workers correlated most highly with neurotoxicity. Correlation was also noted with urinary mercapturic acid S-(2-carboxyethyl)cysteine, but that biomarker is nonspecific because it also reflects acrylonitrile exposure. Plasma acrylamide concentrations correlated poorly with neurologic symptoms. Based on toxicokinetic parameters extrapolated from measurements in rats and adduct formation in a suicide victim, a first-order elimination rate of 0.15 h^{-1} was estimated for humans and used in a model to convert hemoglobin adduct concentrations to mg/kg bw/day concentrations.

A JIFSAN/NCFST *(16*) panel noted limitations regarding the estimation of human exposure levels to acrylamide based on adduct concentrations. First, the estimates represent exposures occurring over 120 days, the life of a human red blood cell. Second, adduct formation depends on numerous

personal factors, such as absorption of acrylamide and rate of metabolic removal. These factors limit the utility of adducts for predicting an individual's exposure. However, comparisons of adduct concentrations across exposure groups can give useful relative differences in exposure magnitude where the differences are large. Additionally, because toxicokinetics and metabolic factors vary among species, extrapolation of data from rodents may not result in an accurate description of acrylamide and glycidamide kinetics in humans.

Although estimation of exposure based on adduct formation is uncertain, some values are presented in this section for comparative purposes. Two recent original publications *(35, 36*) and values reported in a JIFSAN/NCFST *(16*) review are presented below.

In a study conducted at a German university, Schettgen et al. *(36*) measured hemoglobin adduct concentrations in 63 male and 9 female German subjects (ages 19 – 59 years) who were not exposed to acrylamide in the workplace. The subjects were first divided into groups of smokers and nonsmokers, based on the detection of N-cyanoethylvaline, an acrylonitrile adduct that is a specific and sensitive marker for cigarette smoke. Concentrations of N-2-carbamoylethylvaline, the acrylamide adduct, were reported separately for the 47 smokers and 25 nonsmokers, and those values are outlined in Table 8.

Table 8. Concentrations of Acrylamide Adduct, N-2-Carbamoylethylvaline, in Non-Occupationally Exposed German Subjects, Schettgen et al. (36)

Measurement	*N-2-Carbamoylethylvaline concentrations in pmol/g globin (µg/L blood)*	
	Nonsmokers	*Smokers*
Range	<12 – 50 (NE – 1.4)	13 – 294 (NE – 8.0)
Median	21 (0.6)	85 (2.3)
95th Percentile	46 (1.3)	159 (4.3)

NE=Not estimated

The study authors noted that their values for acrylamide adducts, <12 – 50 pmol/g globin in nonsmokers and 13 – 294 pmol/g globin in smokers, were within the ranges reported in other studies, which were 20 – 70 pmol/g in nonsmokers and 116 pmol/g in smokers. Based on adduct concentrations, considerations discussed by Calleman *(28*), and an elimination rate of 0.15 h^{-1}, Schettgen et al. *(36*) estimated a median acrylamide intake of 0.85 µg/kg bw/day in nonsmokers, and estimated that the value in smokers was about 4 times higher. **[The Expert Panel questions the estimate of 0.15 per hour, which does not make sense relative to the kinetics of the red cell if the adduct is stable because the kinetics are not first order.]**

In another publication, Schettgen et al. *(35*) measured concentrations of N-2-carbamoylethylvaline in workers exposed to ethylene and propylene oxide, but apparently not to acrylamide. The range of N-2-carbamoylethylvaline concentrations was <11 – 50 pmol/g globin in 24 nonsmokers and 16 – 294 pmol/g globin in 38 smokers. These investigators also examined the relationships between cigarettes smoked per day and acrylamide adducts; they estimated 6.1 pmol/g globin was formed

per cigarette/day, which compared well with the 8.5 pmol/g globin per cigarette observed by Fennel *(37*). Mainstream cigarette smoke has been measured for acrylamide content, which was 1.1–2.34 µg per cigarette *(22*). In combination with the estimates of adducts, there are approximately 3–8 pmol/g globin formed per µg of acrylamide in cigarette smoke. This adduct formation represents pure inhalation exposure and may be helpful for calibrating other inhalation exposure data.

Strengths/Weaknesses: The adduct data are relatively long-term measures that integrate all sources of exposure. Insofar as the exposures can be isolated, their relative magnitude can be estimated. Adduct concentrations in 2 groups of Germans *(35, 36*) and 1 group of Swedish unexposed workers *(38*) were 10–70 pmol/g globin. These adducts most likely come from dietary exposures, and possibly from environmental tobacco smoke exposures. Adduct concentrations in smokers were higher by about 4-fold in nearly all cases. Workers with occupational exposures measured by Calleman *(28*) had adduct concentrations that were orders of magnitude higher, as expected from their very high inhalation exposures. The toxicokinetics of acrylamide in subjects will not be identical, so some variability is expected. Additionally, the representativeness of the German and Swedish background concentrations and data from other locations are unknown, although the concentrations were of the same order of magnitude. More importantly, the Expert Panel cannot determine how much of the variation in adduct concentrations resulted from differences in exposures or differences in toxicokinetics, but the range in background concentrations can provide an indication of the range in acrylamide from water and dietary sources, and environmental tobacco smoke, if not the magnitude of intake.

Utility (Adequacy) for CERHR Evaluative Process: The hemoglobin adduct data from Schettgen, et al. *(35, 36*) provide an estimate of the background concentration of adducts from drinking water, cosmetics, dietary, and environmental tobacco smoke sources for nonsmokers. If the smoking rates of the smokers are known, then the rate of adduct formation by an inhalation exposure can be estimated. The occupational dermal exposures can be estimated if the inhalation exposures are known. Given that the adduct concentrations in smokers are much lower than those in occupationally exposed humans, the occupational inhalation exposures must be much higher than smoking exposures.

[A second estimate of smoker exposure to acrylamide was conducted by the Expert Panel using the adduct data (see estimate based on acrylamide concentration in cigarette smoke in Section 1.2.4.1). Based on the calculation by Schettgen et al. *(36*) that 21 pmol/g globin acrylamide adduct represents an intake of 0.85 µg/kg bw/day in nonsmokers, the median (85 pmol/g globin) and 95th percentile (159 pmol/g globin) adduct concentrations in smokers were estimated to represent acrylamide exposures of 3.4 and 6.4 µg/kg bw/day respectively.]

A JIFSAN/NCFST review *(16*) summarized some values of acrylamide adducts measured in occupationally and non-occupationally-exposed individuals and those values are outlined in Table 9. Although quantitation of acrylamide exposure is uncertain, the values suggest that acrylamide exposures in some workers greatly exceed general population exposures. Values also clearly show that cigarette smoking leads to a greater intake of acrylamide than dietary and other background sources.

Table 9. Acrylamide Adduct Concentrations Presented in Review by JIFSAN/NCFST (16)

Study Description	*Subjects*	*Acrylamide Adduct Concentrations (pmol/g globin)* [a]
Workers in a Chinese acrylamide and polyacrylamide manufacturing plant	Exposed workers	300 – 34,000
Comparison in smokers, nonsmokers, and lab workers using acrylamide to prepare polyacrylamide gels	Lab workers	54
	Smokers	116
	Nonsmoking controls	31
Comparison in workers with and without occupational exposure	Occupationally exposed	27 – 1,854
	Not occupationally exposed	30
Tunnel workers exposed to acrylamide and N-methyl-acrylamide through grouting material	"Normal background range" in workers	20 – 70
	Remaining workers	≤17,000

[a]Values were converted to pmol and the remaining units were reported as presented in the review. **[It is assumed that g globin was the denominator for all these values, although it was not specified in some cases.]**

1.3 Utility of Data

Overall there are limited data that address the magnitude of current population exposures. There are two types of exposure data, direct environmental measurements and hemoglobin adducts. The direct measurements require some assumptions about bioavailability to estimate dose, whereas hemoglobin adducts are indicators of total internal dose. Direct measurements include occupational and food item measurements. There are too few occupational data to adequately describe worker population exposures. Acrylamide has been measured in numerous foods over recent years and population estimates of dietary exposures have been derived. These estimates, however, are not yet based on fully representative sampling. There are increasing numbers of hemoglobin adduct measurements that will allow determination of relative acrylamide exposures from dietary (including drinking water), cosmetic, smoking, and occupational sources. Data on exposures are critical for understanding the health risks associated with acrylamide.

1.4 Summary of Human Exposure Data

Humans may be potentially exposed to acrylamide by ingesting food or drink, through dermal contact with acrylamide-containing materials, and by inhaling acrylamide vapors or particles. Data available to characterize each of these routes are very limited.

Most of the exposure data are for acrylamide present in food cooked at high temperatures. Starchy foods, especially potato preparations, fried, grilled, or baked, had the highest concentrations, ranging from ~10 to 12,000 μg/kg; concentrations in other foods were lower, ranging from <10 to 1,925 μg/kg. Estimates by several national and international groups indicated adult intakes in the range of 0.3 – 1.1 μg/kg bw/day and children's rates 2 – 3 times higher. A single study with 2 nursing women who ingested about 1 mg of acrylamide in potato chips showed breast milk to contain 3 – 19 ng/mL of acrylamide. Based on these data and a daily ingestion of 500 mL of breast milk, a 3-kg baby was

estimated to have an intake rate of 0.7 – 3 μg/kg bw/day.

A more systematic estimate of US population dietary exposures has recently been presented by scientists at the FDA *(26)*. FDA workers have compiled a substantial, though not necessarily statistically representative, set of measurements of acrylamide in major types of foods consumed in the US. Utilizing these measurements and the results of broad population surveys of the consumption of different foods by large representative samples of the US population, DiNovi and Howard constructed a Monte Carlo simulation model to assess the likely population distribution of US dietary exposure to acrylamide. The dietary exposures of the general US population (age 2 and over) were estimated as a mean of 0.43 μg/kg body weight/day, with a 90th percentile of 0.92 μg/kg bw/day. Children in the 2 – 5 year-old age group were estimated to have higher exposures (mean 1.06 μg/kg bw/day and 90th percentile 2.31 μg/kg bw/day). These findings correspond reasonably closely to similar types of estimates made in other countries.

Historically, occupational inhalation and dermal exposures have been substantial in the production and use of acrylamide. These airborne exposure scenarios include production of the acrylamide monomer (geometric mean = 0.09 – 0.13 mg/m^3) and polymer (geometric mean = 0.01 – 0.02 mg/m^3), and in the use of acrylamide grout as a waste-water system sealant (geometric mean = 0.01 – 0.029 mg/m^3). One investigator *(4)* has estimated that skin absorption predominated in monomer production exposures in China. The amount of exposure from skin contact and uptake is unknown and difficult to measure. Recent measurements of inhalation exposures during the laboratory preparation of polyacrylamide gels from acrylamide crystals or solutions reflect very low TWA air concentrations, 0.00007 – 0.03 mg/m^3. **[Based on geometric means of 0.01 – 0.13 mg/m^3 and an upper bound exposure of 0.3 mg/m^3 (PEL), the Expert Panel estimated mean and upper bound workplace acrylamide inhalation exposures at 1.4 – 18.6 μg/kg bw/day and 43 μg/kg bw/day, respectively (See Section 1.2.4.2). Data from skin exposure and uptake are unknown and difficult to measure]**

Mainstream cigarette smoke contains acrylamide at 1–2 μg/cigarette. Smokers have an exposure that measurably increases their hemoglobin adducts 3 – 4 fold higher than nonsmokers with no occupational exposure. **[Using concentrations of acrylamide measured in cigarette smoke, the Panel estimated mean and upperbound acrylamide exposures at 0.67 and 1.3 μg/kg bw/day, respectively, in smokers (see Section 1.2.4.1).]** Side-stream smoke has not been measured, but probably also contains acrylamide, which will lead to indoor environmental tobacco smoke exposures for nonsmokers. This source of acrylamide exposure has not been determined.

The relative intake of acrylamide from a variety of sources, including dietary, cigarette smoking, and occupational exposures can be estimated from measurements of acrylamide adducts on hemoglobin. Nonsmoking subjects without occupational exposures had a median adduct concentration of 21 pmol/g globin and smokers had a median 85 pmol/g globin. These values are consistent with values from two other studies. Based on the data from nonsmokers, Schettgen et al. *(36)* estimated an intake of 0.85 μg/kg bw/day. Given a median adduct concentration about four times higher in smokers, smoking appears to be a much more important source of acrylamide exposure than daily dietary intake. **[Total exposure in smokers based on adduct concentrations was estimated by the Panel. The median (85 pmol/g globin) and 95th percentile (159 pmol/g globin) adduct concentrations in smokers were estimated to represent acrylamide exposures of 3.4 and 6.4 μg/kg bw/day respectively**

(see Section 1.2.4.3)]. Historically, adduct concentrations from non-US occupational exposures have tended to cover a much wider range, going up to concentrations several orders of magnitude higher than in smokers, depending on job activities. However, similar data have not been obtained from a US occupational setting. While dermal exposures in occupational settings have been reported to be high enough to cause skin damage, the magnitude of human intake by skin absorption has not been measured and estimates are imprecise.

2.0 GENERAL TOXICOLOGY AND BIOLOGIC EFFECTS

As noted in the CERHR Expert Panel Guidelines, Section 2 of this report is initially based on secondary review sources. Primary studies are addressed by the Expert Panel if they contain information that is highly relevant to a CERHR evaluation of developmental or reproductive toxicity or if the studies were released subsequent to the reviews. For primary study reports that the Expert Panel reviewed in detail, statements are included about the strengths, weaknesses, and adequacy of the studies for the CERHR review process.

2.1 Toxicokinetics and Metabolism

2.1.1 Absorption

There are no known quantitative data on acrylamide absorption in humans. However, symptoms observed in poisoning cases or occupational exposures indicate that acrylamide is absorbed orally, dermally, and by inhalation *(3, 5*).

A pilot study conducted by a German group demonstrated that acrylamide is absorbed from food *(27*). Urinary acrylamide concentrations were measured in 9 healthy male volunteers (age 18–52 years) before and within 8 h after they ate up to 500 g of commercially available potato chips or crisp bread. A newly-developed liquid chromatography/tandem mass spectrometry (LC/MS/MS) method was used to quantitate acrylamide concentrations. Before eating, urinary acrylamide concentrations could only be estimated in 3 subjects and ranged from 0.659 to 2.04 ng/mL or from 0.338 to 1.084 µg excreted (minimal quantification concentration reported at 1 ng/mL). Within 8 h after eating potato chips or crisp bread, acrylamide was detected in the urine of 8 subjects at concentrations ranging from 1.97 to 6.31 ng/mL or from 0.48 to 5.70 µg excreted. **[There was no mention of dietary restrictions prior to the study, the amount of acrylamide in food samples was not reported, and acrylamide intake was not estimated.]** Acrylamide half-lives were measured using urinary excretion data in two subjects and those values are reported in Section 2.1.4. In addition, Sorgel et al. *(27*) measured acrylamide concentrations in human milk and conducted an *in vitro* placental transfer study, as discussed in Section 2.1.2.

Strengths/Weaknesses: The greatest strength of the study by Sorgel et al. *(27*) is the attempt to obtain toxicokinetic data in humans exposed to acrylamide in food. Qualitative data are presented indicating that ingestion of acrylamide-containing food results in increased concentrations of the chemical in urine and milk. This pilot study was limited by its small sample (nine men and two lactating women) and qualitative nature. The study also is hampered by the fact that intake was not determined and by the measurement of acrylamide in the urine rather than in blood plasma or serum. Excretion of acrylamide in urine accounts for only a small percentage of absorbed material and does not provide information on the large fraction of the chemical that is metabolized. The report suffers from inadequate, sketchy descriptions of the methodology used, which makes the validity of the reported data questionable.

Utility (Adequacy) for CERHR Evaluation Process: The data are not useful for a quantitative assessment of acrylamide absorption.

Rapid and complete uptake of acrylamide from the gastrointestinal tract of rats was evident by elimination rates that were similar following gavage and i.v. dosing *(4, 8*). Rapid absorption from the gastrointestinal tract was also demonstrated in studies with mice, dogs, and miniature pigs *(5, 39*).

Animal studies indicate absorption through the dermal route. In rats, 25% of 2 or 50 mg/kg bw doses were absorbed within 24 h; 26% of a 0.5% aqueous solution was absorbed within 24 h with 35% remaining in the skin *(4*). Another review reported 14–61% absorption of a dermally applied dose in rats *(39*). In studies comparing oral and dermal administration of ^{14}C-acrylamide in mice, less label was found in internal organs with dermal than with oral dosing *(2*); based on average ratios for crude binding to proteins, RNA, and DNA, Calleman *(28*) estimated that uptake through dermal exposure was about 35% of uptake through oral exposure. Studies in rabbits demonstrated that a 10–30% aqueous solution of acrylamide was rapidly absorbed through skin *(2, 3*). *In vitro* skin absorption studies demonstrated 42–93% absorption in rats, 94% absorption in pigs, and 27–33% absorption in humans *(39*). Variability of dermal absorption in rats was confirmed in 4 animals that when treated topically with 162 mg/kg acrylamide, absorbed 14, 15, 27, and 30% of the administered dose *(40*).

[The Expert Panel notes that information comparing *in vitro* dermal absorption in rats, pigs, and humans was obtained from three different studies. Direct comparison of the three studies, which may have been conducted by different methods, may not be appropriate.]

An unspecified amount of acrylamide was reported to be absorbed in mice and rats following a 6-h inhalation exposure to 3 ppm acrylamide *(39*).

Strengths/Weaknesses: The secondary sources disagree on whether acrylamide absorption is complete. Some, such as Calleman and the NIOH/NIOSH document *(4*), reach the conclusion that absorption is complete, but others, such as the JIFSAN/NCFST panel, suggest that such a conclusion cannot be reached on the basis of the Miller study, which itself does not come to such a conclusion. The workshop participants further pointed out that in another study by Barber et al. *(41*), there was a difference in absorption between oral and i.p. administration of acrylamide, suggesting that absorption from the gut is incomplete, although the different dose levels used, 20 and 50 mg/kg, might account for some of the discrepancy.

Utility (Adequacy) for CERHR Evaluation Process: The data indicate that absorption following oral administration in rats is rapid. Different studies showing differences in absorption following dermal applications cannot be directly compared. There may be more than a two-fold difference in dermal absorption among individual animals.

2.1.2 Distribution

Studies in rats, pigs, and dogs demonstrate that acrylamide absorbed through any exposure route is rapidly distributed throughout the body *(4*). Higher concentrations have been found in the liver and kidney of rats than in other tissues *(2*). Multiple dosing with 0.05 or 30 mg/kg bw for 13 days did not greatly alter distribution in most tissues, with the exception of red blood cells, plasma, and testis *(4*). Acrylamide and its metabolite glycidamide form adducts with sulfhydryl groups of hemoglobin and about 12% of the radiolabel is found in the red blood cells of rats dosed with radiolabeled acrylamide *(28*). These adducts persist in red blood cells with a half-life estimate of 10.5 days, reported in

several reviews *(2, 4, 39*). Calleman *(28*) noted that the half-life estimate of 10.5 days is most likely incorrect: the estimate mistakenly assumed first-order kinetics for elimination. In contrast to red blood cells, plasma concentrations of acrylamide or metabolites drop quickly *(2*). In testis, fat, liver, plasma, and kidney, there is a delay in reaching peak concentrations due to an initial absorption phase of ^{14}C-labeled chemical *(2, 4*). The high lipid content of the testis may account for the delay in distribution of hydrophilic acrylamide and its metabolites to that tissue *(42*). Acrylamide and its metabolites were not found to bioconcentrate in neural tissues *(4*). While the formation of acrylamide DNA adducts *in vivo* has not been detected, glycidamide was observed to form adducts with DNA in rats *(16, 28*).

One human study was reviewed in detail because it measured transfer of acrylamide across the placenta and into milk.

Sorgel et al. *(27*) measured the *in vitro* transfer of acrylamide in three isolated and perfused human placentas. Acrylamide was added to a tissue culture maternal perfusate at 1 μg/mL and concentrations of acrylamide were measured in maternal and fetal perfusate by LC/MS at 1, 3, 5, 9, 15, 25, and 30 minutes during perfusion. Average placental penetration of acrylamide was 18.2–23.2% during 5–30 minutes of perfusion. There was considerable variability with individual placental transfer percentages ranging from 8.9 to 49.6.

In the milk transfer part of the study conducted by Sorgel et al. *(27*), acrylamide concentrations in milk were measured in 2 mothers (ages 24 and 33 years) prior to and at 1, 3, 4, and 8 h after consuming food contaminated with acrylamide. The mothers did not consume food that could contain acrylamide for 10 h prior to the study. During the study, 1 mother ate 100 g of self-prepared potato chips, resulting in an estimated acrylamide intake of 1 mg. The second mother ate 100 g of commercially available potato chips, resulting in an estimated intake of 800 μg acrylamide. Prior to consuming the chips, milk-acrylamide concentrations were below the quantification concentration (5 ng/mL by LC/MS) in both mothers. In the first mother, acrylamide was detected in the milk at 3 and 4 h post-dosing at 10.6 and 18.8 ng/mL, respectively. Acrylamide concentrations in milk from the second mother were measured at 4.86 and 3.17 ng/mL at 4 and 8 h post-dosing, respectively. Acrylamide concentrations at all other time points were below the quantification limit. Sorgel et al. *(27*) estimated infant exposure levels based on acrylamide concentrations in milk and those estimates are discussed in Section 1.2.4.1.

Strengths/Weaknesses: The placental transfer studies of Sorgel et al. *(27*) used only three placentas, with considerable variability in the transfer results. While the authors attributed this variability to individual characteristics of the subjects, it is not possible from the paper to know whether there were technical problems in the placental perfusion preparations. The anatomic and functional condition of the perfused placentas was not ascertained before or after the study. The data on transfer in milk have the advantage of including estimates of acrylamide intake and milk measurements before and after ingestion of potato chips.

Utility (Adequacy) for CERHR Evaluation Process: The Panel has no confidence that the placental perfusion studies accurately represent *in vivo* placental transfer of acrylamide. The milk studies are useful in estimating potential exposure of nursing infants after maternal consumption of acrylamide-containing foods.

Another study evaluated the acrylamide-specific hemoglobin adduct *N*-2-carbamoylethylvaline and the acrylonitrile-specific hemoglobin adduct *N*-cyanoethylvaline in the blood of 10 nonsmoking women and 1 smoking woman a few hours prior to childbirth and in umbilical cord blood of their 11 neonates *(43*). The highest concentration of adducts were found in the blood of the smoking woman and her neonate, and these were the only samples with detectable *N*-cyanoethylvaline, which is specific for cigarette smoking. The maternal and neonatal concentrations of *N*-2-carbamoylethylvaline were correlated in the nonsmokers (Pearson r=0.859 **[*P*=0.0015]**). Based on the maternal adduct concentrations, the authors estimated an average daily intake of acrylamide for nonsmoking pregnant women at 0.85 μg/kg bw. Taking into consideration the relative lifespans of maternal and fetal erythrocytes, the authors estimated that fetal acrylamide internal dose on a weight-adjusted basis would be at least equal to that of the mother.

Strengths/Weaknesses: Schettgen et al. *(43*) clearly demonstrate a hemoglobin adduct of acrylamide, namely *N*-2-carbamoylethylvaline, in the cord blood of newborn humans. The study has strengths in the number of humans studied and a good statistical relationship between concentrations in the mothers and in the cord blood. The data indicate that there is a fair degree of parity between the concentrations observed in the mothers and the concentrations in their offspring. Although there was only one mother who smoked, her data support the conclusions of other studies with respect to higher concentrations of acrylamide adducts in smokers. Weaknesses include the lack of information on exposure and the reliance on another study for exposure estimates, but these estimates may not be too inaccurate. The extension of the calculations based on the size of the neonates and the half-life of fetal erythrocytes is difficult to understand without knowing the metabolic fate of acrylamide adducts upon turnover of erythrocytes.

Utility (Adequacy) for CERHR Evaluation Process: These data are very useful in estimating placental transfer of acrylamide to term human fetuses. The study provides confirmation of existing experimental animal data on placental transfer of acrylamide and its metabolic products. The experimental animal and human data make reasonable the estimate that exposure of the near-term fetus is similar to maternal exposure.

A number of original animal studies were reviewed in detail by CERHR because they examined maternal-fetal toxicokinetics or distribution within testes.

Edwards *(44*) gave a single 100 mg/kg i.v. dose of acrylamide **[purity unstated]** in water to pregnant Porton strain rats on gestation day (GD) 14 (n=4) or 21 (n=2) **[plug day not specified]**. One hour after dosing, rats were decapitated and fetuses removed. Fetuses were homogenized and extracted in 0.1% tris in methanol. Acrylamide in the extract was measured spectrophotometrically. Fetuses sampled on GD 14 gave mean acrylamide concentrations (± SEM) of 1.41 ± 0.03 μmol/g. Fetuses in 2 litters sampled on GD 21 gave acrylamide concentrations of 1.43 and 1.41 μmol/g. The authors cite a study showing that 1 h after male rats were given acrylamide 100 mg/kg i.v., mean blood-acrylamide concentration (± SEM) was 1.28 ± 0.04 μmol/mL. The author concludes that this finding "indicates that the placenta does not act as a barrier to acrylamide."

Strengths/Weaknesses: A strength of this study is its use of the Porton strain of rats, permitting evaluation of a different strain than is used by other investigators. It is a weakness, though, that this

study used only one acrylamide dose, which was extremely high compared to anticipated human exposures, and the number of litters sampled was very low. Adult values were obtained from a previous study in males, rather than from the dams in the current study. In addition, the spectrophotometric detection of acrylamide may lack the necessary specificity.

Utility (Adequacy) for CERHR Evaluation Process: These data are most useful in estimating comparable placental transfer of acrylamide in the Porton rat compared to other strains.

In an industry-funded study, Marlowe et al. *(45*) administered a single ^{14}C-acrylamide dose (116 – 121 mg/kg bw) **[purity unstated]** by gavage to male Swiss-Webster male or female mice on GD 0.5 or 17.5 (plug day considered GD 0.5 at noon) **[number of animals treated was not specified]**. Male mice were anesthetized and frozen at various time points between 0.33 and 9 h and 1, 3, and 9 days following treatment. Pregnant mice were anesthetized and frozen 3 or 4 h following treatment. The mice were later sectioned and exposed to x-ray film. Autoradiography results indicated that absorption was nearly complete within 3 h and radioactivity was widely distributed. Distribution was similar in the male and pregnant female mice. In male mice, radioactivity was detected in testis parenchyma at 1 h, in the seminiferous tubules and head of epididymis at 9 h, and only in tail of epididymis and crypts of glans penis epithelium at 9 days. The authors noted that the movement of acrylamide through the testis paralleled that of spermatids. Radioactivity in GD 13.5 fetuses was fairly evenly distributed with possibly higher concentrations in the CNS compared to concentrations in maternal mice. At 17.5 days, the fetal distribution pattern closely resembled that of adult rats; radioactivity in fetuses was concentrated in kidney, bladder, liver, intestinal contents, and forestomach mucosa. An intense accumulation of radioactivity was noted in fetal skin on GD 17.5.

Strengths/Weaknesses: A strength of this study is the tracking of distribution over time and the use of an alternative method for evaluating tissue distribution of a chemical. The semiquantitative nature of the results is a weakness of the study. In addition, the results shown as autoradiographs were claimed to be representative of all animals studied, but the number of animals studied was not given in the paper and remains unknown. The study used only a single acrylamide dose, which was high compared to anticipated human exposures. A limitation of the study is that it speaks only to the distribution of a mixture of unchanged acrylamide and its metabolites and not to individual components of the mixture such as the potentially toxic metabolite glycidamide.

Utility (Adequacy) for CERHR Evaluation Process: This study provides useful semiquantitative information on distribution, and confirms placental transfer as shown in other studies by other techniques. There are relatively high concentrations of acrylamide/metabolites in the testis. The high radioactivity in the intestinal contents 9 days after the acrylamide dose suggests enterohepatic cycling of acrylamide metabolites.

In a study conducted at the FDA, Ikeda et al. *(46*) examined maternal-fetal distribution of acrylamide in pregnant beagle dogs and Hormel miniature pigs. The dog is noted to have a four-layer endothelial-chorial placenta and the pig has a six-layer epithelial-chorial placenta. A single i.v. dose of 5 mg/kg bw acrylamide (reagent grade)/^{14}C-acrylamide (radiochemical purity of ≥95%) was administered to dogs on GD 60 and pigs on GD 109. Dogs and pigs were anesthetized 110 minutes following treatment and fetuses were separated at 2 h. Tissue radioactivity levels were measured in a total of

6 dog litters with 33 fetuses and 7 pig litters with 45 fetuses. Radioactivity was widely distributed in maternal and fetal tissues of both species. In dogs, the placental distribution factor was 17.7%, indicating that 82.3% of radioactivity passed through the placenta based on fetal/maternal blood concentrations. Blood–brain distribution factors were insignificant in maternal (5.9%) and fetal (0%) dogs. A placental distribution factor of 31% in pigs indicated that 69% of the radioactivity passed through the placenta. An insignificant blood–brain distribution (4%) was noted in maternal pigs, while radioactivity levels were higher in brain versus blood of fetal pigs. The authors concluded that both fetal dogs and pigs lack blood–brain barriers and their brains would therefore be exposed to acrylamide present in their circulation.

Strengths/Weaknesses: The 1985 paper by Ikeda et al. *(46*) is very important with respect to uptake by dog and pig fetuses. The data are generally very good compared to the data presented in many other papers. The important conclusion regarding the possible vulnerability of the brain to exposure is warranted. Although the dose is still high (5 mg/kg) compared to anticipated human exposure under most circumstances, it is lower than in many other studies. The evaluation of total radioactivity restricts the interpretation to a mixture of unchanged acrylamide and its metabolites.

Utility (Adequacy) for CERHR Evaluation Process: The general conclusion of this study is valid and useful. The observation of placental transfer in these animals as in laboratory rodents supports the conclusion that placental transfer in humans is likely to occur in a similar manner.

In another FDA study, Ikeda et al. *(47*) sought to determine intra-litter distribution of acrylamide in four animal species with different placenta types. The species examined were Osborne-Mendel rats (single-layer hemoendothelial placenta), New Zealand White rabbits (single-layer hemoendothelial placenta), beagle dogs (four-layer endothelial-chorial placenta), and Hormel miniature pigs (six-layer epithelial-chorial placenta). Animals were given an i.v. dose of ^{14}C-acrylamide (≥95% radiochemical purity)/reagent grade acrylamide late in gestation at 1 or 2 days prior to expected delivery (i.e., GD 20 for rats, GD 30 for rabbits; GD 60 for dogs, GD 109 for pigs). The dose for rats was 10 mg/kg bw and fetuses were removed 1 h following dosing. In the remaining species, the dose was 5 mg/kg bw and fetuses were removed at 2 h following dosing. All fetuses in 6–9 litters were examined for all species. The study authors reported that that radioactivity was uniformly distributed throughout the litters. Fetal uptake of radioactivity was not affected by fetal sex or fetal position within the uterus. Individual tissues were analyzed in fetal dogs and pigs and it was reported that uptake of radioactivity in individual tissues was also unaffected by uterine position.

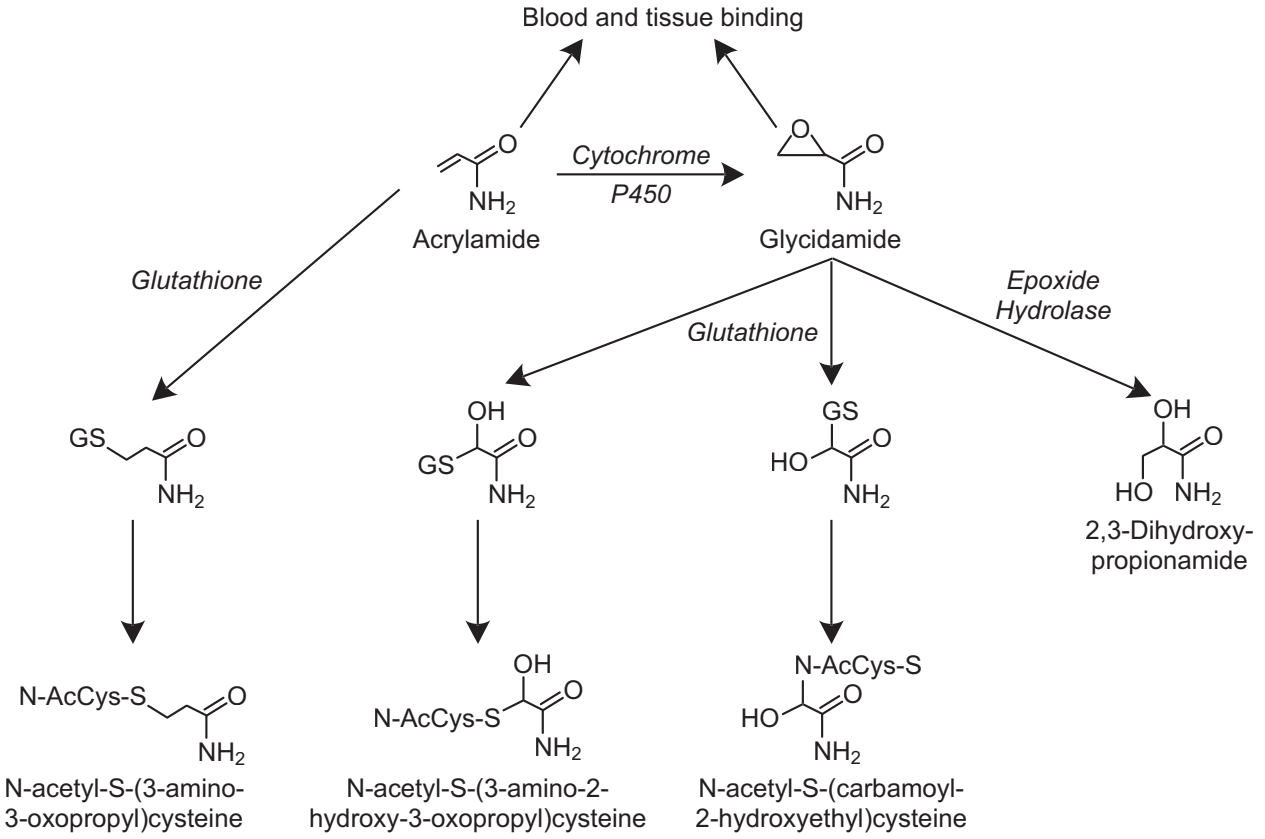
Strengths/Weaknesses: The conclusions regarding distribution of the ^{14}C-acrylamide are well justified by the data. A weakness is that it would have been useful to have more quantitative detail on the tissue distribution of the material that was administered. The evaluation of total radioactivity restricts the interpretation to a mixture of unchanged acrylamide and its metabolites.

Utility (Adequacy) for CERHR Evaluation Process: The Ikeda et al. conclusions add to the overall weight of evidence of the ready uptake of acrylamide into fetuses from maternal circulation. The observation of placental transfer in four species with different types of placentas supports the conclusion that similar placental transfer is likely to occur in humans.

2.1.3 Metabolism

It has been reported that major metabolic pathways for acrylamide are qualitatively similar in humans and experimental animals, but that quantitative differences must be considered when conducting risk assessments for humans *(14)*. A proposed metabolic pathway is illustrated in Figure 2.

Figure 2. Acrylamide Metabolic Pathway, Adapted from Kirman et al. (48).



In experimental animal studies, acrylamide is rapidly eliminated through biotransformation. It has been reported that <2% is excreted unchanged through urine or bile in rats *(2, 4, 39)*. In other rat studies, 80% of radiolabel was excreted within 7 days, 90% as metabolites *(3)*. One major pathway for acrylamide biotransformation is first-order conjugation with glutathione, catalyzed by hepatic glutathione-S-transferase (GST) *(4, 48)*. The pathway leads to the formation of the urinary metabolite N-acetyl-S-(3-amino-3-oxypropyl) cysteine in rats and mice. N-acetyl-S-(2-carbamoylethyl) cysteine is the major metabolite excreted in human urine *(11)*. GST is present in the liver, kidney, brain, and erythrocyte of mice and rats, but the enzyme is three times more efficient at conjugating acrylamide in the liver versus the brain of rats *(39)*. The second major metabolite of acrylamide, glycidamide, is formed through a saturable reaction with cytochrome P450 *(48)*. There is some evidence that acrylamide can induce cytochrome P450 *(28)*. Cytochrome P450 2E1 (CYP2E1) is the specific enzyme involved in this reaction in mice *(49)*. Glycidamide is metabolized through conjugation with glutathione to form mercapturic acids or metabolized by epoxide hydrolase (epoxide hydratase) *(28, 48)*.

The percentage of acrylamide converted through each major pathway may vary by species and dose.

Conversion of acrylamide to glycidamide is greater in mice than in rats as evidenced by the observation that in rats, N-acetyl-S-(3-amino-3-oxypropyl) cysteine represents 70% of urinary metabolites, while this compound represents 40% of urinary metabolites in mice *(39)*. Consistent with that observation, it was reported that the proportion of glycidamide-derived metabolites in urine following a dose of 50 mg/kg bw was 59% in mice and 33% in rats *(8)*. The percentage of unchanged glycidamide excreted in the urine of mice and rats was 16.8 and 5.5%, respectively, following a dose of 50 mg/kg bw *(28)*.

The excretion rate of radiolabel was independent of dose in rats orally administered 1.0–100 mg/kg bw radiolabeled acrylamide *(42)*. In rats, high doses of acrylamide can inhibit GST or deplete GSH *(2, 3, 39)*. One model suggested that appreciable glutathione depletion is not expected in the rat until doses exceed 10 mg/kg bw/day *(48)*. Conversion of acrylamide to glycidamide appears to saturate because it was reported that the proportion of glycidamide produced is inversely related to dose *(14)*. Consistent with that observation was a non-linear dose response for glycidamide adduct formation in rats i.p. injected with acrylamide doses ranging from 5 to 100 mg/kg bw; percent conversion to glycidamide was estimated at 51% following a 5 mg/kg bw dose and 13% following a 100 mg/kg bw dose of acrylamide *(39, 50)*. The formation of acrylamide adduct was linear in rats at doses up to 100 mg/kg bw. It was noted in an IARC *(8)* review that although specific urinary metabolites were not studied at doses below 50 mg/kg bw, increases in glycidamide-derived metabolites and decreases in acrylamide-derived metabolites would be expected at low doses. **[The Expert Panel finds the study of Bergmark et al. *(50)* to be critical in identifying the relationship between acrylamide dose and glycidamide adduct formation.]**

The detection of glycidamide-hemoglobin adducts in workers exposed to acrylamide demonstrates that humans also metabolize acrylamide to glycidamide *(28)*. The average AUC ratio of glycidamide to acrylamide in the workers was 0.3, a value that is lower than the ratio estimated for rats (0.58). Calleman stated that the lower ratio in humans indicates either lower conversion of acrylamide to glycidamide or increased glycidamide elimination in humans. Further investigation revealed that concentrations of urinary mercapturic acids were much lower in humans compared to rats and suggested that the acrylamide elimination rate in humans may be at least five times slower than the rate for rats. Based on estimates of free acrylamide in plasma, hemoglobin valine adducts, urinary mercapturic acid concentrations, and a lower integrated concentration-time ratio for glycidamide to acrylamide in humans, IARC *(8)* estimated that tissue doses of glycidamide may be higher in humans versus rats at equivalent doses of acrylamide. **[The Expert Panel believes the IARC authors may have misunderstood the Calleman *(28)* report. The difference in rates of elimination of both acrylamide and glycidamide in humans and rats will already have been reflected in their respective AUC.]**

2.1.4 Elimination

Half-lives for acrylamide urinary excretion were reported at 2.2 h and 7 h in two male subjects who consumed an unspecified amount of acrylamide by eating potato chips or crisp bread *(27)*. Additional details of this study are included in Section 2.1.1. **[The Expert Panel considers the Sorgel et al. *(27)* data, based on only two individuals, unreliable.]**

Clearance of parent compound in rats is represented by a single compartment model, while clearance of total ^{14}C label is represented by a biphasic curve *(4)*. At doses of 10–20 mg/kg bw acrylamide in rats, the half-life of parent compound in plasma is reported at ~2 h *(4, 14)*. The half-life for the

metabolite glycidamide is also reported at ~2 h following oral exposure of rats to 20 mg/kg bw or i.p. exposure to 50 mg/kg bw acrylamide *(39)*. **[Calculations by the Expert Panel using the Kirman et al. *(48)* rat pharmacokinetic model indicate a half-life for acrylamide itself of about 1.8 h at low doses, and a similar half life for glycidamide of about 3.0 hours.]** Biphasic distribution and elimination is noted for total ^{14}C-label in rats with an initial half-life of 5 h and a terminal half-life of 8 days in most tissues *(2, 4)*. The initial part of the half-life (5 h) is thought to result from biotransformation of acrylamide and binding of metabolites to macromolecules; the terminal portion of the half-life (8 days) is most likely due to the release of metabolites from tissues and degradation of adducts. The initial elimination half-life for testes (8 h) in rats was slightly longer than the 5-h half-life observed in most other tissues *(42)*.

Excretion half-life of parent compound through rat urine is reported at ~8 h *(2, 3)*. In animal studies where radiolabeled acrylamide was given by the oral, dermal, or inhalation route, 40–90% of label was eliminated through urine within 1 week *(28, 39)*. Four to six percent of the dose is eliminated as carbon dioxide in exhaled air (indicating an unidentified metabolic pathway) and 6% of the dose is eliminated in feces within 7 days *(2, 4, 39)*; because the amount of radiolabel entering bile is estimated at 15%, it appears that acrylamide or its metabolites undergo enterohepatic circulation. Calleman et al. *(28)* noted that exhalation of radiolabeled carbon dioxide was not consistently observed in different studies and only occurred when acrylamide was labeled at the carbonyl carbon but not at the vinyl carbon.

2.1.5. Physiologically-based pharmacokinetic (PBPK) models

The JIFSAN/NCFST *(39)* review noted an attempt to develop a PBPK model for acrylamide; the report was eventually published as Kirman et al. *(48)*. It was noted that the model was developed using data from six published studies and provides a good description of acrylamide and glycidamide kinetics in the rat. The model focuses on internal dose measures for possible mechanisms of toxicity, including genetic toxicity, reaction with sulfhydryl groups, dopamine agonist activity, and glutathione depletion. Variations in dose-metrics were found to result from model parameters characterizing tissue binding and biotransformation through cytochrome P450 and GST. **[The Panel notes that although an excellent paper, the Kirman et al. report is limited to rats given a single dose of acrylamide. No fetal compartment was included in the model. This paper is useful, however, in reviewing and modeling tissue-level data.]**

2.2 General Toxicity

2.2.1 Human data

Information on acrylamide toxicity in humans is based upon case studies and occupational epidemiological studies. Exposure levels in such studies are not well characterized due to exposure usually occurring through multiple routes (e.g., oral, inhalation, and dermal) and lack of a reliable biological index to determine total body burden *(3, 5)*.

In cases of acute or subacute poisoning, CNS effects develop within hours or days of exposure *(3)*. Common CNS effects include confusion, memory problems, sleepiness, slurred speech, inability to concentrate, and hallucinations *(3, 4)*. Peripheral neuropathies develop insidiously following a latency period of days to weeks. Axonopathies are most commonly observed and impairment

occurs in sensory fibers prior to motor fibers *(2)*. Common symptoms or clinical signs of peripheral neuropathies include loss of sensation, paraesthesia, numbness, muscle weakness and/or wasting in extremities, and decreased tendon reflexes *(3, 4)*. Tremors and gait disturbances may occur as a result of midbrain and cerebellum disturbances *(2)*. Anorexia, weight loss, and nystagmus have also been observed with acrylamide exposure *(3, 4)*. In some cases, the reporting of symptoms such as sweating, peripheral vasodilation, and difficulty urinating and defecating suggest autonomic nervous system involvement *(3)*. The most consistent electrophysiological finding is reduced nerve action potential amplitude in the distal portion of sensory neurons *(3)*. Generally neurologic symptoms continue to deteriorate for 3–4 weeks after exposure ends and then a gradual improvement occurs over a period of months to years *(2, 3)*. A full recovery occurs in most poisoning victims.

Symptoms consistent with CNS involvement followed by the development of peripheral neuropathies were observed in a 48-kg woman who ingested 18 g of acrylamide (375 mg/kg bw); additional symptoms included seizures, gastrointestinal bleeding, respiratory distress, and liver toxicity *(2, 5)*. CNS symptoms and subsequent development of peripheral nervous system effects were also observed in adults of a Japanese family following contamination of their well water by an acrylamide grout used in sewer repair *(2, 5, 51)*. The adults recovered within 4 months. Less severe effects were observed in one 10-year-old and one 13 year-old child, presumed to be due to lower exposures because of school attendance during the day. An acrylamide concentration of 400 ppm was measured in the well water at a single time point.

In occupational settings where exposures occurred through inhalation and dermal contact, dermatitis characterized by peeling of skin on palms was the first sign of toxicity; it was followed by the development of peripheral neuropathies, as described above *(4)*. Such effects were noted in workers of a Chinese acrylamide factory who did not have adequate personal protection and were exposed dermally to a 27–30% aqueous acrylamide solution from 1 to 18 months. Air concentrations were not measured for most time periods but were reported at 5.6–9.0 mg/m^3 during a 4-month period of heavy activity. Air concentrations were reduced to 0.03 mg/m^3 following renovations at that plant. Some cases of dermatitis and peripheral nervous system effects were noted in additional occupational surveys addressed in a review by the EU *(5)*. The review noted that prevalence of symptoms related to peripheral neuropathies is increased in workers exposed to >0.3 mg/m^3 acrylamide (8-h TWA), but it is not possible to determine contribution from skin exposure.

Effects of occupational acrylamide exposure in workers were reviewed by NICNAS *(52)*. Clinical examination and nerve conduction studies showed abnormalities most consistently in workers with symptoms, but the authors of one study *(53)* concluded, "Electroneuromyographic changes, including a decrease in the sensory action potential amplitude, neurogenic abnormalities in electromyography, and prolongation of the ankle tendon reflex latency, are of greater importance in the early detection of acrylamide neurotoxicity since they can precede the neuropathic symptoms and signs." According to the review, atmospheric acrylamide concentrations in the workplace ranged from 0.03 to 9 mg/m^3, and skin contact with acrylamide-contaminated water also occurred. Estimates of personal doses of affected and unaffected workers were not provided.

2.2.2 Experimental animal data

Neurologic effects such as ataxia, tremors, convulsions, and muscular weakness were observed in

rats, mice, guinea pigs, rabbits, and cats following acute acrylamide poisonings *(3)*. Additional signs observed included circulatory collapse and weight loss. Death can occur following acute exposure to high acrylamide levels and LD_{50}s observed in various species are listed in Table 10.

Table 10. Ranges of LD_{50}s Reported from Acrylamide Exposures

Species (route)	*LD_{50} in mg/kg bw*	*References*
Rat (oral)	107–251	IPCS *(3)*, EU *(5)*, NTP *(54)*
Rat (dermal)	400	IPCS *(3)*, NTP *(54)*
Rat (i.p.)	90–120	IPCS *(3)*, NTP *(54)*
Mouse (oral)	107–170	IPCS *(3)*, NTP *(54)*
Guinea pig (oral)	150–180	IPCS *(3)*, EU *(5)*
Rabbit (dermal)	1,148	EU *(5)*
Cat (i.v.)	85	IPCS *(3)*

Neurologic effects are also observed following repeated exposures of experimental animals to acrylamide. Effects are similar to those noted in humans and result from a peripheral neuropathy that starts at distal portions of limbs, then advances to proximal regions *(3)*. Overt signs are consistent among different species and include tremors, incoordination, motor dysfunction, neuromuscular weakness, and reduced motor-nerve conduction velocity *(3, 39)*. Histologic evidence of neurotoxicity includes degeneration of distal portions of long sensory- and motor-peripheral nerve fibers. Degeneration of long axons in the spinal cord, Purkinje fibers in the cerebellum, the optic nerve, and autonomic fibers have also been reported in experimental animal studies. Demyelination of sciatic, tibial, median, and ulnar nerves has been noted. Dose-responses are best characterized in rats, since various studies were conducted to identify NOAELs. Similar effects were noted in other species including mice, cats, dogs, and monkeys *(39)*. However the majority of studies in those species were not designed to identify NOAELs. In a JIFSAN/NCFST review, it was noted that dose rate appears to determine time of onset but not magnitude of neurologic toxicity, suggesting a cumulative effect of acrylamide exposure.

In the IRIS review of acrylamide, a subchronic drinking water exposure study in rats by Burek et al. *(55)* was used in the risk assessment of neurologic toxicity *(56)*. The NOEL for neurotoxicity was identified at 0.2 mg/kg bw/day. A LOAEL of 1 mg/kg bw/day was identified based on a slight but significant increase in peripheral axolemmal invaginations in the left sciatic nerve as observed by electron microscopy. The study by Burek et al. *(55)* is reviewed in detail below because it included an examination of reproductive organs.

The EU *(5)* used a 2-year drinking water study in rats by Johnson et al. *(57)* to conduct a risk assessment of neurologic toxicity. A NOAEL of 0.5 mg/kg bw/day was identified in that study. A LOAEL of 2 mg/kg bw/day was identified based on degenerative lesions in the tibial nerve. The study by Johnson et al. *(57)* is reviewed in detail in the Carcinogenicity section (Section 2.4.2).

Other organ systems that were affected with higher acrylamide doses in animal studies included kidney, liver, and the hematopoietic system *(3, 5)*.

Burek et al. *(55)* examined subchronic toxicity of acrylamide administered in drinking water to Fischer 344 rats in an industry-sponsored study. At 6 weeks of age, male and female rats were administered acrylamide (>99% purity) in drinking water at doses resulting in exposure to 0, 0.05, 0.2, 1, 5, or 20 mg/kg bw/day. Stability and concentrations of dosing solutions were verified. Males were dosed for 92 days and females for 93 days. Numbers of rats treated included 10 females per group and 23 – 29 males per group. Ten males were used for the subchronic study, 10 were held for a 144-day recovery period, and 3 – 9 were used for interim sacrifices and ultrastructural analysis of nerves by electron microscopy. Data generated in this study were analyzed by one-way ANOVA followed by Dunnett test. During the treatment period, rats were observed daily and body weights and food and water intake were monitored. Body weight gain was significantly reduced in males and females of the 20 mg/kg bw/day group. In the 20 mg/kg bw/day group, water intake was consistently and significantly reduced in female rats beginning on day 21 of the study and was significantly reduced in males during 4 of 13 periods. Hindlimb splay tests were conducted weekly in the control and high dose groups. Splaying was observed in the 20 mg/kg bw/day group on day 22 and became more pronounced on day 29, when the test was stopped. Other clinical signs in the 20 mg/kg bw/day group included curled toes, incoordination, crossing of back legs when held up by tail, and posterior weakness. Clinical signs progressed during the study and eventually led to dragging of back legs. No splaying was noted in the 5 mg/kg bw/day group and none of the dose groups exposed to ≤5 mg/kg bw/day developed clinical signs of neurotoxicity.

At sacrifice, rats were necropsied. Blood was collected for an analysis of hematology and clinical chemistry and urine was collected for urinalysis. All major organs were collected and preserved in phosphate-buffered 10% formalin and a select number of males were prepared for electron microscopic examination of nerves. The only statistically and toxicologically significant clinical chemistry observations were decreased serum-cholinesterase activity and marginally increased serum-alkaline phosphatase activity in females of the 20 mg/kg bw/day group. Packed cell volume, red blood cell count, and hemoglobin concentration were significantly reduced in females of the 5 mg/kg bw/day group and males and females of the 20 mg/kg bw/day group. No treatment-related abnormalities were observed in the urinalysis. Significant organ weight effects in the 20 mg/kg bw/day group included decreased absolute weight of brain, heart, liver, kidneys, thymus, and testis; increased relative weights of brain, heart, liver, and kidneys; and decreased relative weight for thymus (females only) and testis. The authors questioned whether a significant increase in absolute and relative liver weight in the 5 mg/kg bw/day males was related to treatment.

Gross treatment-related observations in the 20 mg/kg bw/day group included perineal soiling, reduced adipose tissue, reduced liver size, dark kidneys, mottled foci on lungs, decreased testicular size or flaccidity, reduced male accessory genitalia size, decreased uterus size, changes in peripheral nerve appearance, skeletal muscle atrophy in posterior body, distended urinary bladder, and diffuse mural thickening of stomach. Histologic evaluations revealed severe degeneration of peripheral nerves and slight degeneration of the spinal cord in the 20 mg/kg bw/day group. Less severe degeneration of the peripheral nerves was observed in the 5 mg/kg bw/day group. In males examined by electron microscopy, very slight nerve degeneration was observed at 1 mg/kg bw/day. Additional histologic findings believed to be treatment-related included skeletal muscle atrophy, slightly increased hematogenous pigment in the spleen (females only), ulcerative gastritis or hyperkeratosis in the stomach (males only), mesenteric fat atrophy (females only), testicular atrophy (n=10/10),

mineral in the seminiferous tubules (n=5/10), cellular debris and decreased spermatogenic elements in epididymides (n=9/10), vacuolization of the urinary bladder smooth muscle, and inflammation in the lungs. **[It was not stated but presumed that these histologic findings were observed in the 20 mg/kg bw/day group.]** No treatment-related lesions were found in the brains of rats administered 20 mg/kg bw/day acrylamide.

Male rats treated with 20 mg/kg bw/day and allowed to recover for 144 days demonstrated improvement of clinical neurologic symptoms and partial or complete reversal of neurological lesions. Complete reversal of neurologic lesions occurred in rats of the 1 and 5 mg/kg bw/day groups. Although some testicular lesions in the 20 mg/kg bw/day group were partially reversed, slight testicular effects remained after the recovery period. The effects included focal or multifocal atrophy of individual seminiferous tubules and mineral and cellular debris in tubules with no effect on spermatogenesis. A slight decrease in red blood cell numbers remained in rats of the 20 mg/kg bw/day group up to 92 days in the recovery period. Body weight gain was recovered in the 20 mg/kg bw/day group.

Strengths/Weaknesses: This study was competently performed and reported and is considered reliable. The inclusion of a recovery period is an important strength.

Utility (Adequacy) for CERHR Evaluation Process: The Burek et al. study is important in showing effects on the nervous system and other organ toxicity at 20 mg/kg bw/day but not generally at lower doses. This paper is very useful in showing a dose-response relationship and has important information not only on nerves but also with regard to other tissues, particularly the testes.

2.3 Genetic Toxicity

The Expert Panel notes the review of Dearfield et al. *(58)*, which includes modeling approaches to assessing heritable genetic risk from exposure to acrylamide. This review concluded that exposure of men to acrylamide in drinking water might result in up to three children with heritable genetic disease among 100 million offspring. The Expert Panel chose to place very little weight on the estimated risks due to the uncertainties associated with the assumptions employed in the model.

2.3.1. Somatic or bacterial cells

Because thorough reviews of the genetic toxicity of acrylamide in somatic or bacterial cells were conducted by numerous authoritative agencies, this section of the report will be based on the most recent and complete review, which was conducted by the EU *(5)*.

Results of *in vitro* genetic toxicity tests are listed in Table 11.

Appendix II

Table 11. In Vitro Genetic Toxicity Studies of Acrylamide

Reference	*Acrylamide Concentration*	*Testing with Metabolic Activation*	*Species or Cell Type/Strain*	*Endpoint*	*Result*
Knaap et. al. (1988) as cited in: EU *(5)*	≤3,000 µg/mL	Yes	V79 Chinese hamster	Chromosomal aberrations	↑ with and without metabolic activation
Tsuda et al. (1993) as cited in: EU *(5)*	≤355 µg/mL	No	V79H3 Chinese hamster	Chromosomal aberrations and polyploidy	↑ without metabolic activation
	71–500 µg/mL	No		Mutation at HPRT locus	↔ without metabolic activation
Godek et al. 1982 as cited in: EU *(5)*	37.5–900 µg/mL	Yes	Chinese hamster ovary	Mutagenicity at HPRT locus	Equivocal with and without metabolic activation, inadequate test due to lack of appropriate toxicity
Godek et al. 1984 as cited in: EU *(5)*	≤1,500 µg/mL	Yes	Chinese hamster ovary	Mutagenicity at HPRT locus	↔ with and without metabolic activation, inadequate test due to lack of appropriate toxicity
Knaap et al. (1988) as cited in: EU *(5)*	300–7,500 µg/mL	Yes	Mouse lymphoma L5178Y $TK^{+/-}$	Mutagenicity at thymidine kinase locus	↑ with and without metabolic activation
Moore et al. (1987) as cited in: EU *(5)*	≤850 µg/mL	No	Mouse lymphoma L5178Y $TK^{+/-}$	Mutagenicity at thymidine kinase locus	↑ at ≥500 µg/mL without metabolic activation (dose-related increase in small colonies, mainly small colonies at ≥750 µg/mL)
Besaratinia and Pfeifer *(59)*	32 nM–16 mM **[0.0023–1,137 µg/mL]**	No	Big Blue mouse embryonic fibroblasts containing λ phage CII transgene	Mutagenicity in CII transgene	↑ at 3.2–320 µM; ↔ at higher doses (increase associated with an excess of G →C transversions and A →G transitions)
Sorg et al. (1982) as cited in: EU *(5)*	≤500 µg/mL	Yes	Chinese hamster ovary	SCE	↔ with and without metabolic activation
Knaap et. al. (1988) as cited in: EU *(5)*	≤3,000 µg/mL	Yes	V79 Chinese hamster	SCE	↑ with and without metabolic activation

Reference	*Acrylamide Concentration*	*Testing with Metabolic Activation*	*Species or Cell Type/Strain*	*Endpoint*	*Result*
Tsuda et al. (1993) as cited in: EU *(5)*	≤213 µg/mL	No	V79H3 Chinese hamster	SCE	↑ without metabolic activation
Naismith and Matthews (1982) as cited in: EU *(5)*	≤100,000 µg/mL	N/A	Rat hepatocyte	Unscheduled DNA synthesis	↑ at 1–33 mg/mL (no clear dose-response)
Miller and McQueen (1986) as cited in: EU *(5)*	≤3,550 µg/mL	N/A	Rat hepatocyte	Unscheduled DNA synthesis	↔
Butterworth et al. (1992) as cited in: EU *(5)*	≤710 µg/mL	N/A	Rat hepatocyte	Unscheduled DNA synthesis	↔ without metabolic activation
Barftnecht et al. (1987, 1988) (available only as abstracts) as cited in: EU *(5)*	≤2,000 µg/mL	N/A	Rat hepatocyte	Unscheduled DNA synthesis	↑
Miller and McQueen (1986) as cited in: EU *(5)*	0.7–710 µg/mL	N/A	Rat hepatocytes	Unscheduled DNA synthesis (tested by autoradiography after exposure of cells to ultraviolet light);	Slight ↑ in net nuclear grain counts compared to UV alone at 710 µg/mL
				DNA repair (centrifugation on cesium chloride)	↔for DNA repair (tested at 710 µg/mL only)
Banerjee and Segal (1986), Microbiological Associates (1984, 1982, 1982), Tsuda et al. (1993) as cited in: EU *(5)*	NS	Yes	BALB/3T3, C3H/10T1/2, or NIH/3T3	Cell transformation	↑ with or without metabolic activation in 4 of the 5 assays

Appendix II

Reference	*Acrylamide Concentration*	*Testing with Metabolic Activation*	*Species or Cell Type/Strain*	*Endpoint*	*Result*
Adler et al. (1993) as cited in: EU *(5)*	≤1,000 µg/mL	No	Chinese hamster V79	Cells with spindle disturbances	↑ without metabolic activation
Sickles et al. 1995 as cited in: EU *(5)*	≤710 µg/mL	NS	Human fibrosarcoma	Adverse effect on chromosomal segregation and migration	↑
Vanhorick and Moens (1983) as cited in: EU *(5)*	≤150 µg/mL	NS	CO60 Chinese hamster	DNA amplification	↔ (significance of finding unclear)
Bull et al. (1984), Godek et al. 1982, Hashimoto and Tanii (1985), Jung et al. (1992), Knaap et al. (1988) Lijinsky and Andrews (1980), Muller et al. (1993), Tsuda et al. (1993), Zeiger et al. (1987) as cited in: EU *(5)*	100–50,000 µg/plate	Yes	*Salmonella typhimurium* strains TA1535, TA1537, TA98, TA100, TA102, TA1538 *E. Coli* strain *WP2 uvrA*	Mutagenicity at the histidine operon in *S. typhimurium*, and the tryptophan operon in *E. coli*	↔ with and without metabolic activation
Knaap et al. (1988) as cited in: EU *(5)*	100–10,000 µg/mL	NS	*Klebsiella pneumoniae*	Mutagenicity to streptomycin resistance genes	↔
Vasavada and Padayatty (1981) as cited in: EU *(5)*	≤10 µg [sic; concentration not given]	NS	*E. coli* CR 63	Inhibited transfection (considered a potential indicator of mutagenicity)	↑

↑ Increased in response to treatment
↔ No effect of treatment
NS: Not specified
N/A Non-applicable

HPRT hypoxanthine-phosphoribosyl-transferase locus
SCE sister-chromatid exchange
$TK^{+/-}$ thymidine kinase

In terms of *in vitro* genotoxicity, the EU *(5)* reported:

- Positive results for clastogenicity in Chinese hamster cells, both with (one study) and without (two studies) metabolic activation, and in mouse lymphoma L5178Y cells, without metabolic activation (one study).
- Positive results for mutagenicity in mouse lymphoma L5178Y cells, with (one study) and without metabolic activation (two studies). In the study that evaluated mutant colony size (without metabolic activation), the increase in mutagenicity was associated with an increase in the frequency of small colonies, an indicator of chromosomal damage rather than the induction of point mutations. This conclusion was supported by the presence of chromosomal damage in these cells.
- Inconsistent results for the induction of point mutations in mammalian cells, with one equivocal (with and without metabolic activation) and two negative studies (with and without metabolic activation) at the hypoxanthine-phosphoribosyl transferase (HPRT) locus in Chinese hamster cells. However, due to the absence of toxicity levels appropriate for negative results, these studies are considered inadequate. More recently, Besaratinia and Pfeifer *(59)* have reported that acrylamide is positive for mutations at the CII transgene in BigBlue® mouse embryonic fibroblasts (without metabolic activation). The increase was associated with an excess of G→C transversions and A→G transitions.
- Consistently negative results for the induction of point mutations in *Salmonella typhimurium, Escherichia coli*, and *Klebsiella pneumoniae*, with and/or without metabolic activation (10 studies). In one *E. coli* study (without metabolic activation), acrylamide was reported to inhibit transfection; however, the significance of this finding in terms of genotoxicity is not clear.
- Inconsistent results in *ex vivo* rodent hepatocyte unscheduled DNA synthesis (UDS) assays (tests to detect DNA damage recognized by excision repair processes), with three positive and two negative studies.
- Inconsistent results for the induction of sister chromatid exchanges (SCE), an indicator of replication on a damaged DNA template, in Chinese hamster cells, with two positive studies (with and without metabolic activation) and one negative study (with and without metabolic activation). The adequacy of the negative study was questioned in the European Review *(5)*.
- Relatively consistent positive responses for cell transformation in BALB/3T3, C3H/10T1/2, or NIH/3T3 cells, with and without metabolic activation (four of five studies).
- Positive results for effects on cell division (e.g., polyploidy, spindle disturbances, malsegregation) in Chinese hamster and human fibrosarcoma cells, in the absence of metabolic activation.
- Negative results for DNA amplification in Chinese hamster cells, without metabolic activation; the significance of this finding is unclear.

[The Panel noted that acrylamide was positive in both the presence and the absence of exogenous metabolic activation and that metabolic activation did not appear to modify its genetic toxicity. This observation suggests either that acrylamide is not metabolized in these *in vitro* systems or, if it is metabolized, the primary metabolite(s) must be as reactive as is acrylamide.]

Results for *in vivo* genetic toxicity tests are listed in Table 12.

Appendix II

Table 12. In Vivo Genetic Toxicity Studies of Acrylamide in Somatic Cells

Reference	*Species*	*Acrylamide Dose (Route)*	*Tissue or Cell*	*Endpoint*	*Result*
Abramsson-Zetterberg *(60)*	Mouse	1–30 mg/kg bw (i.p.)	Peripheral blood	Micronucleus	↑ at ≥6 mg/kg bw
Adler et al. (1988) as cited in EU *(5)*	Mouse	50–125 mg/kg bw (i.p.) × 1	Bone marrow	Micronucleus	↑
Backer et al. (1989), Cao et al. (1993), Cihak and Vontorkova (1988, 1990), Knaap et al. (1988), Russo et al. (1994) as cited in EU *(5)*	Mouse	≤150 mg/kg bw (i.p.), single or repeated dosing	Bone marrow, spleen, or peripheral blood	Micronucleus	↑
Sorg et al. (1982) as cited in: EU *(5)*	Mouse	75 mg/kg bw (gavage) ×1 or ×2	Bone marrow	Micronucleus	↔(EU questioned the sampling times in this study)
Cihak and Vontorkova (1988) as cited in: EU *(5)*	Mouse	100 mg/kg bw (i.p.) ×1	Bone marrow	Chromosomal aberrations	↑
Adler et al. (1988) as cited in: EU *(5)*	Mouse	50–150 mg/kg bw (i.p.) ×1	Bone marrow	Chromosomal aberrations	↑
Shiraishi (1978) as cited in: EU *(5)*	Mouse	500 ppm (~60 mg/kg bw/day in diet) for 1, 2, or 3 weeks	Bone marrow	Chromosomal aberrations, aneuploidy, polyploidy, SCE	↑ (Based on EU conclusion, which is in contrast to author conclusion)
		100 mg/kg bw (i.p.) ×1	Bone marrow	Chromosomal aberrations, aneuploidy, polyploidy	↑ (Based on EU conclusion, which is in contrast to author conclusion)
Backer et al. (1989) as cited in: EU *(5)*	Mouse	50–125 mg/kg bw (i.p.) ×1	Spleen lymphocytes	Chromatid aberrations, SCE	"↑" at 125 mg/kg bw (not statistically significant)
Butterworth et al. (1992) as cited in: EU *(5)*	Rat	30–100 mg/kg bw, single dose or repeated ×5	Liver	Unscheduled DNA synthesis	↔
Hoorn et al. (1993) and Myhr (1991) as cited in: EU *(5)*	Transgenic mouse	50 mg/kg (i.p.) ×5	Bone marrow	LacZ (assay unvalidated)	↑

↑ Statistically significant increase in response to treatment; "↑" Increase in response to treatment characterized by the authors of the report but not statistically significant. ↔ No effect of treatment. NS: Not specified

In *in vivo* studies in somatic cells, acrylamide is reported to be positive for the induction of:

- Structural chromosomal aberrations in bone marrow cells (three studies with one study reported by the author as negative, but by the EU *(5*) as likely positive).
- Numerical chromosomal damage (e.g., aneuploidy, polyploidy) in bone marrow cells of mice administered acrylamide by i.p. injection (one study) and in feed for up to 3 weeks (one study) (reported by the author as negative but by the EU *(5*) as likely positive).
- Micronucleated erythrocytes scored in bone marrow and blood and micronucleated splenocytes (after mitogen stimulation) collected from mice administered acrylamide acutely by i.p. injection or orally by gavage (8 of 9 studies) (micronuclei arise from either structural or numerical chromosomal damage). No efforts were made by the investigators to identify the mode of action by the majority of studies. However, in an extensive flow cytometric analysis of micronuclei frequency and micronuclei DNA content in blood erythrocytes of mice treated i.p. at dose levels between 1 and 30 mg/kg, acrylamide induced a non-linear increase in the frequency of micronucleated polychromatic erythrocytes in blood; the lowest effect level was 6 mg/kg bw. The author concluded that the induced micronuclei were associated with structural rather than numerical chromosomal damage *(60*).
- SCE in mitogen-stimulated splenocytes of mice treated by i.p. injection (one study).
- Mutations at the *LacZ* locus in bone marrow cells of MutaMice® treated five times by i.p. injection.
- Mutations in coat color loci in a mammalian spot test (discussed below).

In contrast to these positive *in vivo* studies, acrylamide was reported as negative for DNA damage in a rat liver UDS study, for chromosomal aberrations in mitogen-stimulated splenocytes collected from treated mice, or for the induction of SCE in bone marrow cells.

Based on these results, the EU *(5*) concluded that acrylamide is genotoxic in cultured mammalian cells and in somatic cells of treated animals, with the pattern of results indicating clastogenicity or interference with chromosomal segregation rather than the induction of point mutations. These conclusions are consistent with those of a JIFSAN *(39*) panel that stated "…acrylamide is not a direct acting mutagen in bacterial or mammalian cell assay systems. Acrylamide does, however, have weak clastogenic effects." However, the adequacy of the *in vitro* mammalian point mutation assays (HPRT) is questionable and the study by Besaratinia and Pfeifer *(59*) demonstrates the ability of acrylamide to induce gene mutations in the CII locus. In addition, acrylamide appears capable of inducing cell transformation *in vitro*. In these *in vitro* studies, acrylamide is genotoxic in both the presence of *and* absence of metabolic activation, and the presence of exogenous metabolic activation does not appear to modify its genotoxic activity, suggesting that acrylamide is not metabolized to an inactive metabolite.

The findings reported for the *in vivo* rodent studies support the conclusions of the *in vitro* studies. The most common positive observation is structural chromosomal damage and micronuclei (representing structural and/or numerical chromosomal damage). The observation that mitogen-stimulated cultured splenocytes collected from treated animals exhibit an increase in the frequency of SCE and micronuclei suggests that persistent DNA lesions are induced by acrylamide. The results obtained for the Muta-Mouse® study are consistent with the ability of acrylamide to be a weak inducer of point mutations.

Neuhäuser-Klaus and Schmahl *(61)* performed a mammalian spot test, supported in part by the Umweltbundesamt, Berlin. T-stock female mice were mated with HT males (two females to one male) and the day of a vaginal plug was counted as GD 1. Females were treated with acrylamide (analytical grade) in distilled water at 50 or 75 mg/kg i.p. once on GD 12 or daily on GD 10, 11, and 12. Control females were injected with distilled water. Five replicate experiments were conducted. The mouse spot test involved non-agouti black mice heterozygous at several coat color loci. Mutations of the dominant wildtype allele at any of the heterozygous coat color loci were detected as "spots of genetic relevance" as distinguished from coat color changes due to pigment cell inactivation or misdifferentiation, which were characterized as not of genetic origin. Offspring with spots of genetic relevance were counted and group comparisons made with the control by Fisher exact test **[thus taking the offspring as the statistical unit]**. After a single injection on GD 12, offspring with spots of genetic relevance were increased in both acrylamide groups. The proportions were compared based on weaned offspring rather than offspring at birth. These proportions in the 0, 50, and 75 mg/kg groups were 5/212 (2.4%), 14/213 (6.6%), and 13/211 (6.1%), respectively. The proportions of weaned offspring with spots of genetic relevance were also increased after the 3-dose regimen in both acrylamide groups: 0, 50 mg/kg × 3, and 75 mg/kg × 3 proportions were 6/225 (2.7%), 26/196 (13.3%), and 21/215 (9.8%), respectively.

Strengths/Weaknesses: The authors assessed the mutagenic activity of acrylamide in the mammalian somatic spot test, which involves *in vivo* treatment at the embryonic stage. Two single acute dose exposures and two multiple dose exposures were included, as well as concurrent controls. Spots were phenotypically distinguished as "spots of genetic relevance;" i.e., spots expressing a homozygous recessive color consistent with mutation of the wildtype allele at one of the seven heterozygous coat color loci screened, or spots due to cell killing or mis-differentiation. All treatment group frequencies of genetically relevant spots were statistically higher than the respective concurrent control values. The original frequency results are presented and allow an independent statistical evaluation. The authors do not state clearly if there was clustering or lack of clustering of spots in the offspring examined. The paradigm of the mammalian somatic spot test is that spots of genetic relevance represent a somatic mutational event in the pigment-producing melanocytes of the treated embryo. Each offspring examined represents the treatment of a population of melanocytes and the susceptibility status between individual pregnant females and the embryos within each pregnant female is assumed to be similar. Thus, results were reported for the individual offspring as the experimental unit. In the present study, the frequency of spots is extremely low and probably not adequate to test this assumption.

Utility (Adequacy) for CERHR Evaluation Process: This study is useful for an evaluation of the mutagenic effect of acrylamide in mammals. The mammalian spot test represents specific locus mutations in somatic cells and is regarded as a short-term test with good predictive value for the mouse germ-cell specific-locus test.

2.3.2. Germ cells

2.3.2.1. Chromosome aberrations and related endpoints in male germ cells

Studies in which males were treated with acrylamide and germ cells evaluated for chromosomal changes (or related endpoints) are summarized in Table 13.

Table 13. Male Germ Cell Studies with Chromosome-Related Endpoints (Chronological Orderv

Reference/ Funding Source	*Species*	*Acrylamide Dose*	*Treated Cell Type (per authors)*	*Endpoint*	*Result*	*Comments*
Shiraishi *(62)*/ Ministry of Education of Japan[a]	ddY mouse	500 ppm (dietary) **[100 mg/kg bw/ day based on 0.2 kg/kg food factor (EPA Biological Reference Values, 1988)]**	Spermatogonium	***Aneuploidy/polyploidy***		**[The original paper does not show statistical comparisons clearly. The results were analyzed by CERHR using one-tailed Fisher exact test, which is equivalent to using the analyzed germ cell as the statistical unit. There were 3–5 mice per treatment group.]**
				Treatment for 7 days	↑	
				Treatment for 14 days	↑	
				Treatment for 21 days	↑	
				Breaks		
				Treatment for 7 days	↔	
				Treatment for 14 days	↑	
				Treatment for 21 days	↑	
				Chromatid exchanges		
				Treatment for 7 days	↔	
				Treatment for 14 days	↑	
				Treatment for 21 days	↑	
		100 mg/kg i.p.	Spermatogonium	***Aneuploidy/polyploidy***		
				12 h after treatment	↔	
				24 h after treatment	↔	
				11 days after treatment	↑	
				12 days after treatment	↑	
				Breaks		
				12 h after treatment	↔	
				24 h after treatment	↔	
				11 days after treatment	↑	
				12 days after treatment	↑	
				Chromatid exchanges		
				12 h after treatment	↔	
				24 h after treatment	↔	
				11 days after treatment	↔	
				12 days after treatment	↔	

Appendix II

Reference/ Funding Source	*Species*	*Acrylamide Dose*	*Treated Cell Type (per authors)*	*Endpoint*	*Result*	*Comments*
Shiraishi *(62)*/ Ministry of Education of Japan[a]	ddY mouse	500 ppm (dietary) **[100 mg/kg bw/ day based on 0.2 kg/kg food factor (EPA Biological Reference Values, 1988)]**	Primary Spermatocyte	***Sex-chromosome univalents***		**[The original paper does not show statistical comparisons clearly. The results were analyzed by CERHR using one-tailed Fisher exact test, which is equivalent to using the analyzed germ cell as the statistical unit. There were 3–5 mice per treatment group.]**
				Treatment for 7 days	↔	
				Treatment for 14 days	↑	
				Treatment for 21 days	↑	
				Autosome univalents		
				Treatment for 7 days	↔	
				Treatment for 14 days	↑	
				Treatment for 21 days	↑	
				Fragments		
				Treatment for 7 days	↔	
				Treatment for 14 days	↑	
				Treatment for 21 days	↑	
				Rearrangements		
				Treatment for 7 days	↔	
				Treatment for 14 days	↔	
				Treatment for 21 days	↔	
		50 mg/kg i.p.	Primary Spermatocyte	***Sex-chromosome univalents***		
				11 days after treatment	↔	
				12 days after treatment	↔	
				Autosome univalents		
				11 days after treatment	↔	
				12 days after treatment	↔	
				Fragments		
				11 days after treatment	↔	
				12 days after treatment	↔	
				Rearrangements		
				11 days after treatment	↔	
				12 days after treatment	↔	

Reference/ Funding Source	*Species*	*Acrylamide Dose*	*Treated Cell Type (per authors)*	*Endpoint*	*Result*	*Comments*
Shiraishi *(62)*/ Ministry of Education of Japan[a]	ddY mouse	100 mg/kg i.p.	Primary Spermatocyte	***Sex-chromosome univalents***		
				11 days after treatment	↔	
				12 days after treatment	↔	
				Autosome univalents		
				11 days after treatment	↑	
				12 days after treatment	↑	
				Fragments		
				11 days after treatment	↑	
				12 days after treatment	↑	
				Rearrangements		
				11 days after treatment	↔	
				12 days after treatment	↔	
Backer et al. *(65)*/EPA	Mouse, C57BL/6J	50, 100, and 125 mg/kg i.p.	Spermatogonium	Percent damaged cells	↔	
				Chromatid break/fragment	↔	
				Isochromatid break/fragment	↔	
				Hyperploidy	↔	
		50, 100, and 125 mg/kg i.p.	Spermatocyte	Autosomal univalents	↔	
				XY univalents	↔	
				Chromatid break/fragment	↔	
				Isochromatid break/fragment	↔	
				Hyperploidy	↔	
				Synaptonemal complex aberrations	↑ by trend testing	
Adler *(66)*/ funding not stated	Mouse (102/E1 x C3H/E1)F_1	100 mg/kg i.p.	Diplotene	Autosomal and sex univalents	↔	
				Gaps	↔	
				Fragments	↑5.3-fold	
			Pachytene	Autosomal and sex univalents	↔	
				Gaps	↔	
				Fragments	↑4-fold	

Appendix II

Reference/ Funding Source	*Species*	*Acrylamide Dose*	*Treated Cell Type (per authors)*	*Endpoint*	*Result*	*Comments*
Adler *(66)*/ funding not stated	Mouse (102/E1 x C3H/E1)F_1	100 mg/kg i.p.	Zygotene	Autosomal and sex univalents	↔	Chromosome aberrations evaluated in diakinesis metaphase I; 5–6 males/group, 100 cells/male. Chi-square statistic used, according to table legend, although mean±SEM is shown.
				Gaps	↔	
				Fragments	↑7.3-fold	
			Leptotene	Autosomal and sex univalents	↔	
				Gaps	↔	
				Fragments	↔	
			Preleptotene	Autosomal and sex univalents	↔	
				Gaps	↔	
				Fragments	↑4-fold	
			Differentiating spermatogonium	Autosomal and sex univalents	↔	
				Gaps	↔	
				Fragments	↔	
Collins et al. *(67)*/US EPA	Mouse, C57BL/6J	***Experiment 1:***				One-tailed trend test used for analysis
		50 mg/kg i.p.	Leptotene-zygotene	Spermatid micronuclei (MN)	↑	
				Kinetochore positive spermatid MN	↑	
		100 mg/kg i.p.		Spermatid MN	↑	
				Kinetochore positive spermatid MN	↑	
		Experiment 2:				
		10 mg/kg i.p.	Leptotene-zygotene	Spermatid MN	↔	
				Kinetochore positive spermatid MN	↔	
		50 mg/kg i.p.		Spermatid MN	↑	
				Kinetochore positive spermatid MN	↑	
		100 mg/kg i.p.		Spermatid MN	↑	
				Kinetochore positive spermatid MN	↑	

Reference/ Funding Source	*Species*	*Acrylamide Dose*	*Treated Cell Type (per authors)*	*Endpoint*	*Result*	*Comments*
Collins et al. *(67)*/US EPA	Mouse, C57BL/6J	10 mg/kg i.p.	Diakinesis-metaphase I	Spermatid MN	↔	One-tailed trend test used for analysis
				Kinetochore positive spermatid MN	↔	
		50 mg/kg i.p.		Spermatid MN	↔	
				Kinetochore positive spermatid MN	↑	
		100 mg/kg i.p.		Spermatid MN	↑	
				Kinetochore positive spermatid MN	↔	
Russo et al. *(68)*/EEC	Mouse, BALB/c	50 mg/kg, i.p.	Golgi phase spermatids, 2 days after treatment	Spermatid micronuclei	↔	Sampling regimen ensured cells were in meiotic (2 days) or in last pre-meiotic S phase (14 and 16 days). G-test, based on the same general assumptions as of chi-square test, used for statistical analyses
			Golgi phase spermatids, #14 days after treatment		↔	
			Golgi phase spermatids, #16 days after treatment		↔	
		100 mg/kg, i.p.	Golgi phase spermatids, 2 days after treatment	Spermatid micronuclei	↔	
			Golgi phase spermatids, #14 days after treatment		↔	
			Golgi phase spermatids, 16 days after treatment		↔	
		50 mg/kg, i.p. ×4	Golgi phase spermatids, 16 days after first treatment	Spermatid micronuclei	↔	

Appendix II

Reference/ Funding Source	*Species*	*Acrylamide Dose*	*Treated Cell Type (per authors)*	*Endpoint*	*Result*	*Comments*
Russo et al. *(68)*/EEC	Mouse, BALB/c	50 mg/kg, i.p.	Cap phase spermatids, 2 days after treatment	Spermatid micronuclei	↔	Sampling regimen ensured cells were in meiotic (2 days) or in last pre-meiotic S phase (14 and 16 days). G-test, based on the same general assumptions as of chi-square test, used for statistical analyses
			Cap phase spermatids, 14 days after treatment		↑	
			Cap phase spermatids, 16 days after treatment		↑	
		100 mg/kg, i.p.	Cap phase spermatids, 2 days after treatment	Spermatid micronuclei	↔	
			Cap phase spermatids, 14 days after treatment		↔	
			Cap phase spermatids, 16 days after treatment		↑	
		50 mg/kg, i.p.×4	Cap phase spermatids, 16 days after first treatment	Spermatid micronuclei	↑	
		50 mg/kg, i.p.	Spermatogonia	SCE	↑	
		100 mg/kg i.p.			↑	
Xiao & Tates[a] *(63)*/EEC	Rat, Lewis	50 mg/kg i.p.	Pre-leptotene spermatocyte	Spermatid micronuclei	↔	One way ANOVA was used, taking the treated male as the statistical unit
		100 mg/kg i.p.			↑	
		50 mg/kg bw/day i.p. ×4			↑	

Reference/ Funding Source	*Species*	*Acrylamide Dose*	*Treated Cell Type (per authors)*	*Endpoint*	*Result*	*Comments*
Xiao & Tates[a] *(63)*/EEC	Rat, Lewis	50 mg/kg i.p.	Leptotene-zygotene spermatocyte	Spermatid micronuclei	↔	One way ANOVA was used, taking the treated male as the statistical unit
		100 mg/kg i.p.			↑	
		50 mg/kg bw/day i.p. ×4			↑	
		50 mg/kg i.p.	Diplotene-diakinesis/ pachytene spermatocyte		↔	
		100 mg/kg i.p.			↔	
		50 mg/kg bw/day i.p. ×4			↔	
Lähdetie et al. *(69)*/ Commission of European Communities	Rat, Sprague-Dawley	50 mg/kg i.p. 100 mg/kg i.p. 50 mg/kg bw/day i.p. ×4	Pre-leptotene spermatocyte, intermediate & type B spermatogonium	Spermatid micronuclei	↔	The treated male was the statistical unit.
					↔	
					↑	
		50 mg/kg i.p.	Leptotene-zygotene spermatocyte	Spermatid micronuclei	↔	
		100 mg/kg i.p.			↔	
		50 mg/kg bw/day i.p. ×4			↔	
		50 mg/kg i.p.	Diplotene-diakinesis/pachytene spermatocyte		↔	
		100 mg/kg i.p.			↔	
		50 mg/kg bw/day i.p. ×4			↔	
		5 µg/mL *in vitro*	Diplotene-diakinesis/pachytene spermatocyte		↔	
		10 µg/ml *in vitro*			↔	
		50 µg/mL *in vitro*			↔	
Gassner & Adler *(70)*/ Commission of European Communities	Mouse, (102/E1 x C3H/E1)F_1	120 mg/kg i.p.	Spermatogonia	Meiotic delay	↑	Postulated chromosome loss in micronuclei.
				Hypoploidy	↑	
				Hyperploidy	↔	

Appendix II

Reference/ Funding Source	*Species*	*Acrylamide Dose*	*Treated Cell Type (per authors)*	*Endpoint*	*Result*	*Comments*
Bjørge et al. *(71)*	Rat, Wistar	100 µM *in vitro*	Mixed testicular cells	Single-strand DNA breaks	↔	
		300 µM *in vitro*			↔	
		1000 µM *in vitro*			↔	
	Human	30 µM *in vitro*			↔	
		100 µM *in vitro*			↔	
		300 µM *in vitro*			↔	
		1,000 µM *in vitro*			↑	
Schmid et al. *(72)*/EU	Mouse, (102/E1 x C3H/E1)F_1	60 mg/kg i.p.	Spermatogonia	***3-color FISH (X,Y,8)***		
				Diploidy	↔	
				Disomy	↔	
		120 mg/kg i.p.		Diploidy	↔	
				Disomy	↔	
Gassner & Adler, *(73)*	Mouse, (102/E1 x C3H/E1)F_1	80 mg/kg i.p.	24 h later	***Immunofluorescent staining***		Different staining methods on cells from the same animals gave different results. Analysis appears to have been per cell (chi square) without regard to treated male of origin.
				Spindle Abnormalities	↔	
				Misplaced Chromatin	↔	
		120 mg/kg	6 h later	Spindle Abnormalities	↑	
				Misplaced Chromatin	↔	
			24 h later	Spindle Abnormalities	↑	
				Misplaced Chromatin	↔	
			24 h later	***Differential staining***		
		80 mg/kg i.p.		Spindle Abnormalities	↔	
				Misplaced Chromatin	↑	
		120 mg/kg	6 h later	Spindle Abnormalities	↔	
				Misplaced Chromatin	↑	
			24 h later	Spindle Abnormalities	↑	
				Misplaced Chromatin		

Reference/ Funding Source	*Species*	*Acrylamide Dose*	*Treated Cell Type (per authors)*	*Endpoint*	*Result*	*Comments*
Dobrzynska & Gajewski *(64)* [a]	Mouse, Pzh: Sfis	75 mg/kg i.p.	1 day later	Mouse sperm morphology test (percent abnormal morphology)	↑	The mouse sperm morphology test assumes morphologic abnormalities are associated with genetic damage.
			7 days later		↑	
			14 days later		↔	
			21 days later		↑	
			28 days later		↑	
			35 days later		↔	
			42 days later		↑	

↑Statistically significant increase compared to control.
↔ No significant difference from control.
[a]See comments in text.

The assumptions made by study authors include the likelihood that genetic toxicity in male germ cells would persist with fertilization and that the resultant offspring would manifest abnormal development. Support for this assumption was provided by dominant lethal and other studies in which conceptuses sired by acrylamide-treated males were shown to develop abnormally, and in some instances, to have identifiable chromosomal or genetic alterations (discussed below). Generally, cytogenetic analysis of male germ cells has proven a reliable means of detecting germ cell mutagens, but certain limitations should be clarified, as follow:

- The majority of (although not all) clastogenic agents are S-phase dependent inducers of aberrations; that is, aberrations are only evident in cells undergoing DNA synthesis at or near the time of exposure. In spermatogenesis, DNA synthesis occurs last in preleptotene spermatocytes (about 17 days prior to meiotic division in the rat). The most active DNA replication in the testis is reported to occur during the pre-mitotic S-phase of B-type spermatogonia and the pre-meiotic S-phase of pre-leptotene spermatocytes.

- When mitotic metaphases are analyzed cytogenetically, the majority will be those of B-type spermatogonia because of their short cell-cycle length relative to that of stem cell spermatogonia. In the rat, for example, more than six cell divisions occur between exposure and analysis at the first meiotic metaphase (when effects in stem cells are most reliably evaluated). However, many chemically induced aberrations will be cell-lethal, killing stem cells containing significant chromosomal deletions or asymmetrical exchanges in their first or second division. Hence, evaluating B-type spermatogonia is not particularly useful for assessing effects in stem cells, since the stem cells and their descendents don't survive long enough; in fact, it is common to see that agents positive in B-type spermatogonia are not positive in stem spermatogonia, probably because of chromosomal damage-related cell death.

- The observations above suggest that a significant stem cell clastogen may be associated with a transient period of infertility related to sperm production. Acrylamide affects the ratio of spermatid stages in mice and has well described fertility effects. Efforts to distinguish the cause of fertilization failure in such cases are discussed in Section 4.

- Induction of aberrations in post-meiotic germ cells can only be evaluated as chromosomal damage after pronuclear DNA synthesis, during the first cleavage metaphase in the fertilized egg (as discussed in Section 2.3.2.3), and chemically induced aberrations in oocytes are also best measured at this stage.

The Expert Panel had the following observations about selected papers from Table 13:

Shiraishi et al. *(62*), though providing extensive data, reflects some problems with the strict time dependency of spermatogenesis. For example, the authors state that spermatocytes were evaluated 11 or 12 days after treatment, "…at which interval these cells were in S-phase and/or early prophase of meiosis." No S-phase occurs during meiosis; the last S-phase occurs in preleptotene spermatocytes and all primary spermatocytes are 4N during differentiation. It is not clear, then, how to interpret the data presented; it is possible that the authors are actually looking at effects in spermatogonia rather than in spermatocytes. Overall, the value of this paper is further limited by both the grouping together

of "spermatogonia" and "primary spermatocytes," which prevents specific assignment of sensitive stages, and the rather scanty experimental detail included.

The study by Xiao and Tates *(63)* in which micronuclei were measured in early spermatids reports increases in micronuclei in spermatids derived from cells exposed as leptotene and zygotene primary spermatocytes. The mechanism whereby acrylamide would be clastogenic in non-S-phase stages like these is unclear; it seems more likely that the authors may have been misled by over-reliance on exact spermatogenic kinetics; that is, that the day-15 elevations may simply represent the most advanced-stage pre-leptotene spermatocytes that were in the final stage of S-phase when exposed 15 days earlier. Estimates of exposed cell stage are relatively imprecise.

The work by Dobrzynska and Gajewski *(64)* is problematic. This study evaluated the induction of abnormal sperm morphology, to which no strict link to genotoxic damage has been demonstrated. It is particularly difficult to accept that abnormal sperm 1 day after exposure can in any way be related to (a) acrylamide exposure and (b) genetic damage therefrom. Interestingly, the authors reported negative results in bone marrow, which is at odds with most other published acrylamide results. This paper is not considered reliable and is included in the table only for completeness.

Finally, it is of interest that chromosome aberration data indicating that spermatogonia may be the most "sensitive" to acrylamide do not correlate well with dominant-lethal test results (Section 2.3.2.2). Embryo death in the dominant lethal test is presumed to be due to induction of major aneuploidies or large chromosomal deletions that cause embryo death in early stages. Dominant lethal assessments of acrylamide indicate that epididymal spermatozoa and late-stage spermatids are the most affected stages, compared to the apparently most sensitive spermatogonia and early spermatocytes reported in the studies in Table 13. No chromosomal aberration study reported evaluated first cleavage metaphases in fertilized eggs, so direct comparisons are not possible.

2.3.2.2. Dominant lethality

Dominant lethal testing in male rodents has been performed with acrylamide exposures in drinking water, by gavage, by i.p. injection, and by dermal application. Studies are summarized in Table 14. The traditional dominant lethal endpoint is the proportional deficit of live fetuses from females mated with treated compared to control males, expressed as a percent of the number of live implants in the control females. The assumption is that the deficit in live fetuses represents pre- and postimplantation embryos that died due to the production of lethal genotoxicity. Some studies use pre- and postimplantation loss as endpoints that together are comparable to percent-dominant lethals. Pre-implantation loss is calculated in rats based on the assumption that all corpora lutea give rise to fertilized oocytes and pre-implantation loss is calculated as the difference between number of identified implants in the uterus and number of corpora lutea in the ovary, expressed as a percentage of the number of corpora lutea. In mice, pre-implantation loss is calculated as the difference in implantation sites between control and treated groups. Postimplantation loss is the difference between the number of live fetuses and the number of implantations, expressed as a percentage of implantations. Fertilization failure is not detectable by any of these methods and will appear as dominant lethality or as pre-implantation loss. In the usual presentation of data, percent-dominant lethality is expressed for each treatment group without statistical analysis. Values are not presented for the control group when, by definition, the control percent is zero. Pre- and postimplantation loss data are presented for all groups, including the control, and are usually

analyzed statistically using the female as the statistical unit. When mating has occurred by cohabiting one male with one female for a given time period, per-female analysis is equivalent to using the male (the treated animal) as the statistical unit. When multiple females are mated to each treated male, the use of the female as the statistical unit may not permit statistical consideration of the treated animal. **[In general, the treated animal (male or female) should be considered the statistical unit for maximum precision. In the event that multiple females are mated with a single treated male, group means may be employed to derive data appropriate for parametric analysis. In cases where a single female is mated to each male during each time period, the female, for practical purposes, may be considered the statistical unit without affecting the precision of the analysis. Additional statistical considerations might include the use of clustering analysis to achieve desirable distribution and variance characteristics to enable the use of parametric testing procedures with attendant greater discrimination. In this process, pregnant females (assuming a single male:female breeding design) are randomly assembled into groups of four or five to achieve approximate normal distributions and homogeneous variances for each clustered variable. Some Expert Panel members believe that these statistical considerations are less important for dominant-lethal studies in which there are uniformity of affected females and a strong treatment effect.]**

Based on the time after treatment that the male is mated, the germ cell type that is sensitive to acrylamide-induced toxicity can be elucidated. The studies involving treatment of male rats and mice with acrylamide show significant increases in pre- and postimplantation loss and in percent-dominant lethals when epididymal spermatozoa and late spermatids are exposed. Lowest effective doses (based on cumulative acrylamide by the time of mating) in rats were 30 ppm in drinking water (about 200 mg/kg cumulative dose by the time of mating *(74)*) and 15 mg/kg bw/day by gavage (75 mg/kg cumulative dose by the time of mating *(75)*). In mice, the lowest effective i.p. dose was 75 mg/kg *(76)* **[based on CERHR chi-square using live and dead implants with mating 5–8 days after treatment]**. The lowest effective dermal dose in mice was 25 mg/kg/day (125 mg cumulative dose by the time of mating *(77)*). The lowest effective dose in drinking water in mice was 6.78 mg/kg bw/day for 20 weeks (cumulative dose 949 mg/kg *(78)*). **[This figure was calculated by CERHR from the NTP final report (RACB90022) based on mean week-16 water consumption of 226 g/kg bw/day with an acrylamide concentration of 30 ppm (Table 2-7 of the report).]**

[The dominant lethal data provide firm *in vivo* post-metabolic evidence of genotoxicity in mammals. Acrylamide was effective via all routes in all species, at comparable doses. Stage effect was consistent. The dominant lethal test is a low-tech alternative to more costly and resource-intensive tests for mutagenic potential. Properly interpreted, the dominant lethal test can be an effective, if gross, predictor of genotoxic effect. For example, the dominant lethal test does not effectively assess damage in spermatogonial stem cells, arguably the cell stage of most interest, since the degree of chemically induced damage is generally so great as to be lethal. Pre-implantation loss, confounded as it is by potential effects on fertilization, can still be a valuable component of the test, since the most potent mutagens may induce only pre-implantation loss. When assessed in conjunction with assessment of mating rate and methods for the direct quantification of fertilization rate (e.g., oviductal or uterine flushing and embryo culture), the dominant lethal test provides an important component for the overall risk analysis. Studies that include long-term exposure and short-term mating are less useful in determining mechanism of effect, but are useful in predicting genotoxic potential. At the same time, caution is necessary in assigning stage-specific effects based on the

kinetics of spermatogenesis, given that some chemical agents (including, perhaps, acrylamide) may alter the kinetics of spermatogenesis. An exception may be the use of flow cytometry-based approaches to assess ploidy. In the case of acrylamide, the dominant lethal studies most likely indicate an effect on the ability of epididymal spermatozoa and spermatids to fertilize an oocyte, along with potential pre- and postimplantation genetic effects. The anti-fertilization effect may well be due to non-genetic actions. Since the dose needed to elicit the anti-fertilization effects is generally higher than that needed to elicit the post-implantation genetic effects, the anti-fertilization effects are of limited utility for predicting human risk.]

It has been proposed (discussed more fully in Section 2.3.2.6) that the dominant lethal effects of acrylamide are due to metabolism to glycidamide. Adler et al. *(79*) tested this hypothesis by inhibiting metabolism of acrylamide to glycidamide with 1-aminobenzotriazole. Dominant lethals were decreased 2 weeks after treatment. During the first week after treatment, however, 1-aminobenzotriazole did not decrease the dominant lethal effect of acrylamide, suggesting either that acrylamide itself has dominant lethal effects or that 1-aminobenzotriazole requires more than 1 week to completely prevent metabolism to glycidamide.

Strengths/Weaknesses: This study demonstrates an attempt to link acrylamide to the demonstrated mutagenicity of glycidamide; however, this study has several weaknesses. There was a lack of a good explanation of the delay before effect and, as the authors note, there is a decrease in the rate of dominant lethals in their study compared to other studies in mice (they suggest that possible differences in mouse colonies might explain the difference). The modest increase of dominant lethals with acrylamide, therefore, would make any antagonistic effect of 1-aminobenzotriazole less dramatic, weakening the statistical power of the study to show an effect. Another weakness includes the interpretation of the effect of 1-aminobenzotriazole on P450 metabolism, which in this study is made difficult by failure to demonstrate a reduction of the acrylamide-metabolizing P450 isoenzyme in either the liver or the testes. Again, the acrylamide and 1-aminobenzotriazole + acrylamide groups had significantly depressed fertilization rates the first 4–7 days after mating, which represents another weakness. A spermiogram (without statistical analysis) indicated that 1-aminobenzotriazole was also spermatotoxic, and did not effectively antagonize the spermatotoxic effect of acrylamide treatment. Given the lack of data about the efficacy of 1-aminobenzotriazole in inhibiting/destroying P450 in this study, the modest decrease in dominant lethality when acrylamide and 1-aminobenzotriazole were given together is insufficient evidence to support a role for P450 or glycidamide in the mechanism of toxicity of acrylamide; however, a non-genotoxic action of acrylamide directly on sperm fertilization ability is indicated; this represents another weakness for CERHR use. Finally, no effort was made to assess possible alterations in libido from fertility or genotoxicity effects and it seems unlikely that the minor differences in "fast" sperm frequency between the acrylamide group and the acrylamide + 1-aminobenzotriazole group could explain the differences in pregnancy rates between these two groups.

Utility (Adequacy) for CERHR Evaluation Process: This paper provides confirmatory data that acrylamide induces dominant lethal mutations in mice. The metabolic inhibitor work, while interesting, is not compelling given the lack of direct confirmatory evidence that 1-aminobenzotriazole is actually affecting acrylamide metabolism and the inconsistency in effect on dominant lethals. The sperm quality studies are a nice addition, but, again, the effect of 1-aminobenzotriazole is somewhat unclear. Overall, the paper does not provide compelling evidence for the effect of 1-aminobenzotriazole treatment.

Appendix II

Table 14. Dominant Lethal Studies (Chronological Orderv

Reference/ Funding	*Speicies*	*Acrylamide Dose*	*Treatment-Fertilization*	*Germ Cell Affected*	*Endpoint*	*Result*	*Comments*
Shelby et al., *(80)* NTP and DOE	Mouse: (C3H × 101)F_1 males Females were T-stock or (SEC × C57BL)F_1 hybrid (Figures in table are for T-stock females)	125 mg/kg i.p., single dose	0.5–3.5 days	Sperm	% Dominant lethals[a]	49	Strain of female influenced dominant lethal results.
			4.5–7.5 days			52	
			8.5–11.5 days	Spermatids		30	
			12.5–15.5 days			15	
			16.5–19.5 days			1	
			20.5–23.5 days	Spermatocytes		5	
			24.5–27.5 days			–	
			28.5–31.5 days			12	
			32.5–35.5 days			1	
			36.5–39.5 days	Spermatogonia		1	
			40.5–43.5 days			–	
			44.5–45.5 days			–	
Smith et al., *(74)* EPA	Long-Evans rat	15 ppm water = 112.6 ± 7.4 mg/kg	Drinking water exposure for 80 days prior to mating	All germ cell types would have been exposed	Pre-implantation loss[b]	↔	Dose = cumulative dose in drinking water at time of mating, mean ± SEM. Statistical unit = the male
					Postimplantation loss[c]	↔	
		30 ppm in water = 204.2 ± 22.5 mg/kg			Pre-implantation loss	↔	
					Postimplantation loss	↑2.3-fold	
		60 ppm in water = 432.2 ± 24.4 mg/kg			Pre-implantation loss	↑2.4-fold	
					Postimplantation loss	↑6.4-fold	
Zenick et al., *(81)* EPA	Long-Evans rat	100 ppm in water = 544 mg/kg cumulative dose	Drinking water exposure for 10 weeks prior to mating	All germ cell types would have been exposed	Postimplantation loss	↑4-fold	Statistical unit = the male.

Reference/ Funding	*Speicies*	*Acrylamide Dose*	*Treatment-Fertilization*	*Germ Cell Affected*	*Endpoint*	*Result*	*Comments*
Working et al. *(82)* CIIT	Fischer 344 rat	30 mg/kg bw/day by gavage × 5 days	1 week	Sperm	Pre-implantation loss	↑4.6-fold	Statistical unit = the female.
					Postimplantation loss	↑4-fold	
					% Dominant lethal	36	
			2 weeks		Pre-implantation loss	↑6.3-fold	
					Postimplantation loss	↑10-fold	
					% Dominant lethal	60.7	
			3 weeks	Spermatids	Pre-implantation loss	↑3.8-fold	
					Postimplantation loss	↑4.4-fold	
					% Dominant lethal	49.1	
			4 weeks		Pre-implantation loss	↑2.4-fold	
					Postimplantation loss	↔	
					% Dominant lethal	20.6	
			5 weeks	Spermatocytes	Pre-implantation loss	↔	
					Postimplantation loss	↔	
					% Dominant lethal	-	
			6 weeks		Pre-implantation loss	↔	
					Postimplantation loss	↔	
					% Dominant lethal	-	
			7 weeks	Spermatogonia	Pre-implantation loss	↔	
					Postimplantation loss	↔	
					% Dominant lethal	-	
			8 weeks		Pre-implantation loss	↔	
					Postimplantation loss	↔	
					% Dominant lethal	7.8	
			9 weeks		Pre-implantation loss	↔	
					Postimplantation loss	↔	
					% Dominant lethal	0.5	

Appendix II

Reference/ Funding	*Speicies*	*Acrylamide Dose*	*Treatment-Fertilization*	*Germ Cell Affected*	*Endpoint*	*Result*	*Comments*
Working et al. *(82)* CIIT	Fischer 344 rat	30 mg/kg bw/day by gavage × 5 days	10 weeks	Spermatogonia	Pre-implantation loss	↔	
					Postimplantation loss	↔	
					% Dominant lethal	-	
Shelby et al. *(83)*/ NIEHS + DOE	Mouse: Males (C3H × 101)F_1, female (SEC × C57BL)F_1	40 mg/kg bw/day i.p. × 5 days	7-10 days	Sperm and spermatids	% Dominant lethals	73	
Sublet et al., *(75)* EPA	Long-Evans rat	5 mg/kg bw/day by gavage × 5 days	1 week	Sperm	Pre-implantation loss	↔	Statistical unit = the female
					Postimplantation loss	↔	
			2 weeks		Pre-implantation loss	↔	
					Postimplantation loss	↔	
			3 weeks	Spermatids	Pre-implantation loss	↔	
					Postimplantation loss	↔	
			4 weeks		Pre-implantation loss	↔	
					Postimplantation loss	↔	
		15 mg/kg bw/day by gavage × 5 days	1 week	Sperm	Pre-implantation loss	↑3.8-fold	
					Postimplantation loss	↔	
			2 weeks		Pre-implantation loss	↔	
					Postimplantation loss	↑2.7-fold	
			3 weeks	Spermatids	Pre-implantation loss	↔	
					Postimplantation loss	↑2.3-fold	
			4 weeks		Pre-implantation loss	↔	
					Postimplantation loss	↔	
		30 mg/kg bw/day by gavage × 5 days	1 week	Sperm	Pre-implantation loss	↑5-fold	
					Postimplantation loss	↔	
			2 weeks		Pre-implantation loss	↔	
					Postimplantation loss	↑4.5-fold	

Reference/ Funding	*Speicies*	*Acrylamide Dose*	*Treatment-Fertilization*	*Germ Cell Affected*	*Endpoint*	*Result*	*Comments*
Sublet et al., *(continued)*	Long-Evans rat	30 mg/kg bw/day by gavage × 5 days	3 weeks	Spermatids	Pre-implantation loss	↔	
					Postimplantation loss	↑5.2-fold	
			4 weeks		Pre-implantation loss	↔	
					Postimplantation loss	↔	
			7 weeks	Spermatogonia	Pre-implantation loss	↔	
					Postimplantation loss	↔	
			10 weeks		Pre-implantation loss	↔	
					Postimplantation loss	↔	
		45 mg/kg bw/day by gavage × 5 days	1 week	Sperm	Pre-implantation loss	↑4.4-fold	
					Postimplantation loss	↔	
			2 weeks		Pre-implantation loss	↑2.9-fold	
					Postimplantation loss	↑10.7-fold	
			3 weeks	Spermatids	Pre-implantation loss	↑5.2-fold	
					Postimplantation loss	↑8.2-fold	
			4 weeks		Pre-implantation loss	↔	
					Postimplantation loss	↔	
			7 weeks	Spermatogonia	Pre-implantation loss	↔	
					Postimplantation loss	↔	
			10 weeks		Pre-implantation loss	↔	
					Postimplantation loss	↔	
		60 mg/kg bw/day by gavage × 5 days	1 week	Sperm	Pre-implantation loss	↑5-fold	
					Postimplantation loss	↔	
			2 weeks		Pre-implantation loss	↑6.4-fold	
					Postimplantation loss	↑13.7-fold	
			3 weeks	Spermatids	Pre-implantation loss	↑8.6-fold	
					Postimplantation loss	↑7.4-fold	
			4 weeks		Pre-implantation loss	↑7.5-fold	
					Postimplantation loss	↑3.4-fold	

Appendix II

Reference/ Funding	*Speicies*	*Acrylamide Dose*	*Treatment-Fertilization*	*Germ Cell Affected*	*Endpoint*	*Result*	*Comments*
Sublet et al., *(continued)*	Long-Evans rat	60 mg/kg bw/day by gavage × 5 days	7 weeks	Spermatogonia	Pre-implantation loss	↔	
					Postimplantation loss	↔	
			10 weeks		Pre-implantation loss	↔	
					Postimplantation loss	↔	
Dobrzynska et al. *(84)*/ National Institute of Hygiene (Poland)	Mouse, Pzh: SFISS outbred	75 mg/kg i.p.	1 week	Sperm	% Dominant lethals	0.73	
			2 weeks			9.44	
			3 weeks	Spermatids		Negative	
			4 weeks			0.2	
			5 weeks	Spermatocytes		6.68	
			6 weeks			Negative	
			7 weeks	Spermatogonia		negative	
		125 mg/kg i.p.	1 week	Sperm		23.76	
			2 weeks			22.48	
			3 weeks	Spermatids		3.59	
			4 weeks			5.44	
			5 weeks	Spermatocytes		negative	
			6 weeks			4.22	
			7 weeks	Spermatogonia		negative	
		75 mg/kg i.p. + x-ray 0.25 Gy	1 week	Sperm		negative	
			2 weeks			13.49	
			3 weeks	Spermatids		negative	
			4 weeks			negative	
			5 weeks	Spermatocytes		negative	
			6 weeks			negative	
			7 weeks	Spermatogonia		negative	
		125 mg/kg i.p. + x ray 1.00 Gy	1 week	Sperm		43.78	
			2 weeks			43.45	
			3 weeks	Spermatids		29.71	

Reference/ Funding	*Speicies*	*Acrylamide Dose*	*Treatment-Fertilization*	*Germ Cell Affected*	*Endpoint*	*Result*	*Comments*
Dobrzynska et al. *(continued)*	Mouse, Pzh: SFISS outbred	125 mg/kg i.p. + x ray 1.00 Gy	4 weeks	Spermatids	% Dominant lethals	17.61	
			5 weeks	Spermatocytes Spermatogonia		22.24	
			6 weeks			27.7	
			7 weeks			22.59	
Ehling and Neuhäuser-Klaus *(76)*/ Commission of the European Communities	Mouse: (102/E1 × C3H/E1)F_1 males mated to test stock females	50 mg/kg i.p.	1–4 days	Sperm	% Dominant lethals	4.4	Dominant lethal testing performed in conjunction with specific locus mutation testing.
			5–8 days			3.6	
			9–12 days	Spermatids		5.2	
			13–16 days			5.2	
			17–20 days			4.5	
			21–24 days	Spermatocytes		negative	
		75 mg/kg i.p.	1–4 days	Sperm		9.6	
			5–8 days			8.3	
			9–12 days	Spermatids		negative	
			13–16 days			4.5	
			17–20 days			0.5	
			21–24 days	Spermatocytes		4.6	
		100 mg/kg i.p.	1–4 days	Sperm		18.7	
			5–8 days			14.1	
			9–12 days	Spermatids		12.3	
			13–16 days			7.6	
			17–20 days			5.9	
			21–24 days	Spermatocytes		1.5	
		125 mg/kg i.p.	1–4 days	Sperm		40.5	
			5–8 days			28.7	
			9–12 days	Spermatids		30.3	
			13–16 days			6.5	
			17–20 days			negative	
			21–24 days	Spermatocytes		1.1	

Appendix II

Reference/ Funding	*Speicies*	*Acrylamide Dose*	*Treatment-Fertilization*	*Germ Cell Affected*	*Endpoint*	*Result*	*Comments*
Ehling and Neuhäuser-Klaus *(continued)*	Mouse: (102/E1 × C3H/E1)F_1 males mated to test stock females	125 mg/kg i.p.	25–28 days	Spermatocytes	% Dominant lethals	negative	
			29–32 days			1	
			33–36 days			6	
			37–40 days	Spermatogonia		negative	
			41–44 days			4.9	
			45–48 days			0.2	
Gutierrez-Espeleta et al. *(77)*	Mouse: (C3H/RI × 101/R1)F_1 males and (C3H/RI × C57Bl)F_1 females	25 mg/kg bw/day dermal × 5 days	7–8 days	Sperm	% Dominant lethals	10	
			9–10 days	Spermatids		negative	
		50 mg/kg bw/day dermal × 5 days	7–8 days	Sperm		25	
			9–10 days	Spermatids		4	
		75 mg/kg bw/day dermal × 5 days	7–8 days	Sperm		70	
			9–10 days	Spermatids		38	
		100 mg/kg bw/day dermal × 5 days	7–8 days	Sperm		83	
			9–10 days	Spermatids		49	
		125 mg/kg bw/day dermal × 5 days	7–8 days	Sperm		91	
			9–10 days	Spermatids		77	
NTP *(78)*	Mouse, CD-1 Swiss	3 ppm in water = 0.72 mg/kg bw/day	20 weeks	all germ cell stages would have been exposed	Early resorptions	Significant trend across doses	Daily dose calculated from table of water intake at week 16 or 20-week dosing period.
					Late resorptions	↔	
					Dead fetuses	↔	
					Total post-implantation death	Significant trend across all doses	
		10 ppm in water = 2.2 mg/kg bw/day			Early resorptions	Significant trend across all doses	
					Late resorptions	↔	

Reference/ Funding	*Speicies*	*Acrylamide Dose*	*Treatment-Fertilization*	*Germ Cell Affected*	*Endpoint*	*Result*	*Comments*
NTP *(continued)*	Mouse, CD-1 Swiss	10 ppm in water = 2.2 mg/kg bw/day	20 weeks	all germ cell stages would have been exposed	Dead fetuses	↔	
					Total posti-mplantation death	Significant trend across all doses	
					Early resorptions	↑2-fold	
		30 ppm in water = 6.78 mg/kg/day			Late resorptions	↔	
					Dead fetuses	↔	
					Total post-implantation death	↑2-fold	
Nagao *(85)*/ funding not indicated	Mouse, ICR	62.5 mg/kg i.p.	1–21 days	Post-meiotic Spermatogonial stem cells	Implants/female	↔	% early death (fetuses < 6 mm long) reportedly increased when post-meiotic cells treated with 125 or 5 × 50 mg/kg, expressed per pregnant female
		125 mg/kg i.p.				↔	
		50 mg/kg/d i.p. × 5				↓15%	
		62.5 mg/kg i.p.	64–80 days			↔	
		125 mg/kg i.p.				↔	
		50 mg/kg/d i.p. × 5				↔	
Holland et al. *(86)* NIEHS	Mouse: C57Bl/6J males and C3H/J females	50 mg/kg i.p. × 5 days	1–2 weeks	Sperm and spermatids	Pre-implantation loss	72.10%	Statistical comparison to control not given; difference implied at all time points.
					Postimplantation loss	12.70%	
			3–4 weeks	Spermatids and spermatocytes	Pre-implantation loss	41.30%	
					Postimplantation loss	8.20%	
			5 weeks	Spermatocytes	Pre-implantation loss	18.50%	
					Postimplantation loss	10.10%	

Appendix II

Reference/ Funding	*Speicies*	*Acrylamide Dose*	*Treatment-Fertilization*	*Germ Cell Affected*	*Endpoint*	*Result*		*Comments*
Adler et al. *(79)* Funding source not indicated	Mouse, (102/E1 × C3H/E1)F_1 males and females					Exp 1	Exp2	ABT = 3 × 50 mg/kg 1-aminobenzo-triazole to inhibit metabolism to glycidamide
		125 mg/kg i.p.	Week 1	Sperm		19.5	49.5	
		125 mg/kg + ABT				12.6	50.0	
		125 mg/kg	Week 2	Spermatids		33.6	21.6	
		125 mg/kg + ABT				4.7	3.0	
		125 mg/kg	Week 3			8	29.4	
		125 mg/kg + ABT				-4.1	15.8	
		125 mg/kg	Week 4	Spermatocytes		3.6	11.2	
		125 mg/kg + ABT				2.3	1.0	
Tyl *(87)* Acrylamide Producers Association	Rat, Fischer 344	0.5 mg/kg bw/day in drinking water	2 days after a 64-day treatment	All germ cell stages would have been exposed	Implantations/dam	↔		Part of a multi-generational study; presented also in Table 32.
					Live implants/litter	↔		
					Postimplantation loss	↓40%		
		2.0 mg/kg bw/day in drinking water			Implantations/dam	↔		
					Live implants/litter	↔		
					Postimplantation loss	↔		
		5.0 mg/kg bw/day in drinking water			Implantations/dam	↓14%		
					Live implants/litter	↓20%		
					Postimplantation loss	↑2.3-fold		

[a]Dominant lethals = [1 – (live fetuses in treated)/(live fetuses in control)] × 100
[b]Pre-implantation loss = {[(number of corpora lutea) – (number of implants)]/number of corpora lutea]} × 100
[c]Postimplantation loss = {[(number of implants) – (number of fetuses)]/number of implants]} × 100
↑,↓ Statistically significant increase, decrease compared to vehicle-treated control.
↔ No significant difference from vehicle treated control.
For % dominant lethal, actual numbers are given without statistical analysis.
For Holland study, % given in place of statistical results due to lack of presentation of statistical analysis.
Dash appears in table when original table contained a dash with no explanation.

2.3.2.3. Chromosome aber rations in conceptuses after treatment of the male

Pacchierotti et al. *(88*), in a study supported by the Commission of the European Community, administered acrylamide **[purity not given]** in Hanks' balanced salt solution (HBSS) i.p. to male B6C3F_1 mice at single acute doses of 0, 75, or 125 mg/kg or 5 divided daily doses adding to 250 mg/kg (5×50 mg/kg bw/day). All males were mated 7 days after the last treatment to untreated females and the 125-mg/kg treated males were also mated 28 days after treatment. Females were superovulated with pregnant mare's serum followed by hCG. Plug-positive females were given colchicine 26 h after the hCG and were killed 5 h later. Zygotes were flushed from the oviducts and treated with hyaluronidase to remove cumulus cells and to partially digest the zona pellucida. Fixed cells were air-dried and C-banded. First cleavage metaphases were evaluated if they contained at least 35 chromosomes (2n=40). At least 100 metaphases were evaluated per dose group **[they were apparently pooled within dose group without regard to sire or dam]** except in the 5×50-mg/kg dose group for which 55 zygotes were analyzed. Proportions of abnormal metaphases were evaluated by chi-square. The proportion of zygotes with chromosome aberrations increased in a dose-related fashion. With mating 7 days after treatment in the 0-, 75-, 125-, and the 5×50-mg/kg groups, the percent of zygotes with aberrations was, respectively, 0.8, 7.6, 26.3, and 85.4. Most of the aberrations were fragments and dicentrics, with much lower proportions of rings and translocations. Chromatid breaks and exchanges were also unusual (0–0.02 events/zygote), regardless of treatment group. When 125 mg/kg group males were mated 28 days after treatment, only 5.1% of zygotes had aberrations, which did not differ significantly from controls. A subset of male mice underwent flow cytometric evaluation of testicular germ cell populations (discussed in Section 4.2.2). There was a decrease in percent-mated females 7 days after the last acrylamide treatment that was not dose-related. The percent mated (plug-positive) was 86.7, 57.1, 54.1, and 61.0 in the 0-, 75-, 125-, and 5×50-mg/kg groups, respectively. When males in the 125-mg/kg group were cohabited with females 28 days after treatment, 86.7% of females showed evidence of mating, a result identical to that in the control group. The results of the mating studies are discussed more fully in Section 4.2.2.

Strengths/Weaknesses: This study was well-designed and carefully conducted and includes an extensive evaluation of the induction of chromosomal aberrations in male germ cells as assessed in first-cleavage metaphase zygotes, coupled with specific analysis of mating rates, fertilization rates, and toxic effects on spermatogenic cells, which permits a definitive analysis of the effect of acrylamide. A strength of this study is its multi-dimensional comparison of treatment effects. The low (and possibly variable) recovery of zygotes per female may have required that zygotes be pooled per group. The statistical issue of pooling zygotes and not treating the male as the statistical unit is minor in the context of the findings; however, the number of males per group was not specified in the paper. Flow cytometry experiments referred to subsets within each time and dose group of 5 and 6 male mice taken for analysis (16 solvent controls), but the total group size was not stated. The results of evaluating chromosomal and chromatid abnormalities indicated that the dose response was curvilinear. However, the curve of the authors' Figure 3, percent zygotes with aberrations plotted against dose, is forced through the origin. A straight-line fit to the 3 positive responses could just as well have indicated a threshold dose of about 50 mg/kg.

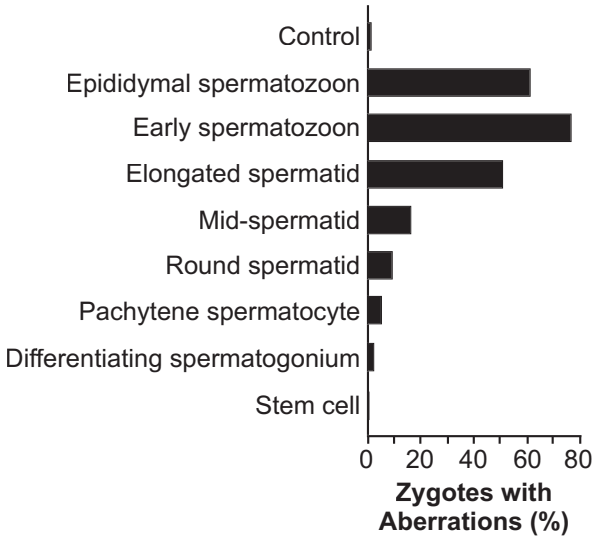
Utility (Adequacy) for CERHR Evaluation Process: This study is very useful in suggesting mechanisms of acrylamide reproductive toxicity. Although the conclusions the authors draw from the data are consistent with work by others in the field, ignorance of the group size and therefore unknown recovery

of zygotes per female make it impossible to assess the variability of the data. Although i.p. dosing is common in studies of acrylamide genetic effects in mice, and may be appropriate for mechanistic studies, the route is not relevant to humans and limits the utility of this study for the evaluation of human risk.

Marchetti et al. *(89*), supported by DOE and NIEHS, gave acrylamide **[purity not specified]** to male B6C3F$_1$ mice at 50 mg/kg bw/day by i.p. injection for 5 consecutive days. Mice were mated with untreated females of the same strain at 2.5, 6.5, 9.5, 12.5, 20.5, 27.5, 41.5, and 48.5 days after the last acrylamide injection, to produce fertilization by sperm that had been exposed to acrylamide at the epididymal spermatozoon, early spermatozoon, elongated spermatid, mid-spermatid, round spermatid, pachytene spermatocyte, differentiating spermatogonium, and stem cell stages, respectively. Females were superovulated with pregnant mare's serum followed by hCG, then mated. Plugged females were given colchicine 24 h after hCG to arrest zygote development at metaphase of the first cleavage. Females were killed 6 h after colchicine and zygotes were harvested. Chromosomes were evaluated using fluorescence *in situ* hybridization with five probes (chromosomes 1, 2, 3, X, Y). Chromosomes with color junctions were identified as translocations or dicentrics, with the distinction made by identification of the centromere using 4',6-diamidino-2-phenylindole (DAPI) fluorescence. The authors report, based on previous work, that this method permits detection of 36.5–38.1% of chromosome exchanges in the male pronucleus. **[The frequencies of translocations and dicentrics were analyzed by the Fisher test, which takes the harvested zygote as the statistical unit. The sire of origin was not indicated; in fact, the number of males is not stated except that matings were 1:1 and "[z]ygotes harvested from 10–15 females were pooled…".]** The proportion of zygotes with chromosome aberrations was increased with mating from 2.5 to 27.5 days after acrylamide treatment, indicating an effect on pachytene spermatocytes and later stages. The incidence of aberrations is shown in Figure 3, suggesting particular susceptibility of late spermatids and spermatozoa, paralleling the stages sensitive to dominant lethality.

The authors included a figure comparing their results with the dominant lethal results of Shelby et al. *(80*) with the proportion of zygotes with unbalanced rearrangements in the current study. The comparison showed good agreement and supported the belief that zygotes with unbalanced rearrangements would be most likely to die *in utero*. **[These authors conclude that meiotic cells are also affected. To support this conclusion, they cite their data (4.8% zygotes with aberrant chromosomes after exposure of spermatocytes) plus the data of Pacchierotti et al. *(88*) (showing 5.1% of zygotes with aberrations when mating occurred 28 days after treatment) and Adler *(66*), which did not involve assessment of conceptuses. The Expert Panel notes that the Pacchierotti et al. finding was not statistically significant.]**

Figure 3: Incidence of Chromosome Aberrations among Zygotes Harvested from Females Mated with Mice after Acrylamide Treatment (5×50 mg/kg), from Data Presented by Marchetti et al. (89).[a]



[a]The timing of mating was used to identify the germ cell stage that was affected.

Strengths/Weaknesses: Statistical mistreatment of the data has led to an over-interpretation of results in this study, limiting the value of some of its more far-reaching conclusions. While the data are supportive of similar data collected by Pacchierotti et al. (88) as relates to late stage spermatids and epididymal spermatozoa, the conclusions about pachytene spermatocyte effects are not supported. Only 6 of 125 zygotes examined at this time point had increased chromosomal aberrations, and the use of the rather forgiving and non-discriminating Fisher exact test contributed to the problem. Dominant lethal testing, as summarized in Section 2.3.2.2, does not confirm the clastogenic activity of acrylamide in this stage spermatogenic cell, further casting doubt on the claim. The decreased fertility rate reported late (41.5 days after treatment) could be accounted for by clastogenic effects in early spermatogonia since they tend not to survive the four to six cell divisions required to get to the spermatid stage. The finding, however, is likely skewed by the statistical treatment. The spermatocyte data may be problematic because qualitatively they involved only DAPI acrocentrics with no PAINT exchanges. These results need to be evaluated and compared to negative and positive findings in other studies evaluating chromosomal aberrations. The paper attempts to demonstrate that a strong correlation exists between the ability of acrylamide to induce chromosomal abnormalities and dominant lethal and heritable translocation events. A dose regimen of acrylamide was used that, based on previous studies, would be predicted to induce a maximum number of dominant lethal events; therefore, no dose-response evaluation was attempted. This study involves technically demanding and patient scoring of pronuclei with aberrant chromosomes. However, the reader is referred to previous publications for many of the experimental details and how the zygotes were counted, and how the number on a slide was determined is not stated. Between 100 and 284 zygotes were examined by in situ hybridization for chromosomal structural abnormalities at selected time points, but this number obviously represents a selected population, and how the population was selected is not specified in the article. The authors' Figure 2 implies that multiple experiments were performed, but does not indicate the number, except for data from single experiments at 20.5 and 41.5 days. Given the design

of the experiments, only statistical analysis based on the unit of a zygote is possible. This analysis is appropriate only if the selection of the zygotes was truly random and consistent, and the slides were read blind. The observation of a low level of abnormality inflicted on spermatocytes that is the same value (about 5%) as reported by Pacchierotti et al. is intriguing but coincidental at this time. However, subsequent work by Holland et al. (86), discussed below, supports the authors' conclusion. The authors' data support the random nature of the chromosomal damage, and are consistent with the suggestion that chromosomal protein, rather than DNA, is the target of acrylamide.

Utility (Adequacy) for CERHR Evaluation Process: Despite the structural weaknesses of this paper in describing methodology and weak statistical analysis, for the purpose of risk assessment, the paper offers insight into the mechanism of acrylamide toxicity, consistent with an ability of acrylamide to induce chromosomal abnormalities in late stages of spermatogenesis. An effect on spermatocytes may occur. This paper is supportive of the Pacchierotti et al. study but misuse of statistics limits the value of additional conclusions.

Titenko-Holland et al. *(90)*, in a study sponsored by NIEHS, treated male C57BL/6J mice with acrylamide **[purity not given]** 50 mg/kg bw/day (n=92) or PBS (n=80) i.p. for 5 days. About 10% of acrylamide-treated males were lost within 24 h of the last injection. Males were mated with untreated C3H/J females by placing three or four females with each male overnight. Mating was assumed to have occurred at midnight. Females were killed at 86–88 h after mating and 1 h after treatment with colcemid to increase the proportion of metaphase embryonic cells. Corpora lutea were counted and were taken to represent the number of ovulated oocytes. The uterine horns were flushed with tissue culture medium and embryos or oocytes recovered. Embryos were evaluated under a dissecting microscope for morphology. All abnormal embryos and an approximately equal number of normal-appearing embryos were taken from each treatment group for cytologic analysis **[how distributed by sire of origin is not indicated]**. Embryos were fixed in methanol:acetic acid:ice-cold water (4:1:5) followed by drop-wise methanol:acetic acid (1:1) until the embryos broke and spread. Spread embryos were evaluated by phase contrast microscopy after which they were stained with DAPI for epifluorescence microscopy. Cells were assessed for nuclear fragmentation and the presence of micronuclei. A modified FISH procedure was applied using a pancentromeric probe to evaluate the less expensive DAPI method used for micronucleus identification. Statistical analysis was by Fisher exact test using proportions of embryos or proportions of cells without regard to sire of origin**.** There was an increase in the frequency of abnormal embryos (per dose group) in pregnancies sired by acrylamide-treated males compared to controls (88.7 vs. 14.8%). Single-cell "embryos," which were either unfertilized oocytes or uncleaved zygotes, accounted for 38.2 and 8.1% of embryos in the acrylamide and control groups, respectively. Acrylamide-group embryos had a smaller cell number and a lower incidence of metaphases than embryos from the control group. **[Single-cell "embryos" that may include unfertilized oocytes, were included in the analysis; an accompanying figure lumps single-cell "embryos" with embryos having up to 10 cells, suggesting that unfertilized oocytes may have been included in the determination of embryo cell number and frequency of metaphase cells.]** Using the embryonic cell as the unit of analysis, micronucleus frequency increased from 4/1,000 cells in morphologically normal embryos of the control group to 41/1,000 cells in morphologically normal embryos of the treated group. Micronucleus frequency was 93/1,000 cells in morphologically abnormal embryos of the treated group. On a per embryo basis, the frequency of micronuclei was 13.6% in the control group and 21.9% in the treated group ($P \leq 0.05$). Within

the treated group, 47.0% ($P \leq 0.001$ compared to control) and 8.3% of the normal and abnormal embryos, respectively, had micronuclei. There was no significant difference between the frequency of micronuclei in abnormal treated embryos and normal control embryos. The number of micronuclei per embryo was not different among normal control, normal treated, abnormal treated, or total treated embryos, according to study, although the text states that the number of micronuclei per embryo was significantly greater in the treated group than in the controls. **[CERHR used the Kruskal-Wallis test and found no significant difference among groups. Pair-wise testing by CERHR of the control embryos with normal treated embryos, abnormal treated embryos, and total treated embryos showed significant differences by unpaired *t*-test with Welch correction for unequal variances, using the number of embryos to determine degrees of freedom because number of sires was not given.]** Other findings in this study included an effect of paternal acrylamide on decreasing nuclear area and increasing fragmented nuclei in morphologically normal embryos.

Strengths/Weaknesses: Overall, this paper represents a poorly presented and analyzed study, which is unfortunate since it represents a tremendous effort on the part of the investigators and, in fact, is supportive of the published literature. Specific weaknesses are as follows:

(a) Incomplete data presentation. The authors' Table I is said to show that male mating behavior was not compromised by acrylamide treatment. It does not show this. The number of females mated to each male is not specified, but averages about 2.5.

(b) It is not entirely clear, but all data collected between days 5 and 17 seem to be pooled, perhaps to raise the *n*. In the Methods section, the author stated that embryos were evaluated at specific breeding intervals post-treatment, but the data are not presented separately. The rationale for this reporting method is not clear, particularly given the well-known time relationship of acrylamide effects. This is a questionable approach at best.

(c) Inclusion of uncleaved/unfertilized embryos in the "abnormal" category. While it is true that one cannot distinguish unfertilized embryos from those that are fertilized but fail to divide because of treatment effects, the practice of including them potentially overestimates the imputed genotoxic effects of acrylamide. This problem is particularly important here since acrylamide is *known* to have effects on fertilization (Sublet et al. *(75*), among others). If embryos are eliminated from this category, the fraction of abnormal embryos falls to 50.5% in the treated group and 6.6% in the control group, which still demonstrates genotoxic effect.

(d) Use of the embryo as the statistical unit, which inflates statistical significance. For example, 21.9% of pre-implantation embryos in the treated group had micronuclei, compared to 13.8% in the control group, a difference reported as statistically significant ($P<0.05$; authors' Table III). If the analysis instead used the treated male as the statistical unit, which would be correct, would this difference still be statistically significant?

(e) There is a high background of aberrations and inappropriate grouping of single-cell forms with embryos having up to 10 cells.

(f) Clearly the "normal" embryos from treated animals had fewer cells. This disparity distorts the calculation of micronuclei per embryo (the authors' Table III), and creates a large difference in micronuclei per 1,000 cells. If the "abnormal" embryos from the treated animals are included in this statistic (which apparently includes unfertilized/single cell zygotes), the distortion becomes even greater. Why, for example, does the number of nuclei per embryos with micronuclei in the treated group become so high (567 vs. 150 for the control) while the number of nuclei per embryo without micronuclei in the treated group becomes fewer

than control (290 vs. 390) (the authors' Table IV)? The authors' conclusion that acrylamide treatment resulted in smaller embryos, delayed proliferation, and more cell death is supported by their data, but a large gap lies between chromosomal events and the apparent induction of micronuclei in treated animals.

Utility (Adequacy) for CERHR Evaluation Process: The lack of distinction between unfertilized eggs and early embryos detracts from the utility of this study in the evaluative process. The authors try to bridge the gap between the chromosomal abnormalities induced in late-stage sperm and mechanisms of embryotoxicity. They succed partially, but ignorance of the mechanism of micronucleus formation precludes a mechanistic explanation for the delay of proliferation other then the general one of chromosome abnormalities leading to cell death.

Holland et al. *(86*) performed a mouse dominant lethal study and measured chromatin adducts as part of a larger study on effects of acrylamide on pre-implantation embryo development. The study was performed with Department of Energy and NIEHS funding. In the dominant lethal study, acrylamide **[purity unstated]** was given to C57Bl/6J male mice by daily i.p. injection, 50 mg/kg bw/day, for 5 days. An unspecified number of males was mated with approximately six females per group **[the term "group" probably represents a 1-week mating period]** each week for 5 weeks from the end of treatment. Females were killed at 15–16 days **[plug day unspecified]** and evaluated for pre- and postimplantation loss. A control level of 12.3 and 7.3% for pre- and postimplantation loss was subtracted to give an acrylamide-induced loss rate. The protocol was not specified except by reference to Shelby et al. *(80*). The data were expressed and analyzed as total percent loss **[without regard to sire].** Pre-implantation loss in the groups mated at 1–2 weeks, 3–4 weeks, and 5 weeks after treatment of the male **[representing exposure of, respectively, spermatozoa, spermatids, and spermatocytes],** was 72.1, 41.3, and 18.5%, respectively. Postimplantation loss at these intervals was 12.7, 8.2, and 10.1%. A comparison of the pre-implantation loss rates at these times with the incidence of abnormal embryos reported in this paper showed similar rates (72.9, 40.1, and 10.1%), at least in the first two time intervals, suggesting to the authors that the pre-implantation loss in the dominant lethal study was attributable to abnormal pre-implantation embryos. In the evaluation of abnormal embryos, however, unfertilized eggs and zygotes were not distinguished. During weeks 1 and 2 after treatment of the male, 57% of day-4 "embryos" were represented by these single-cell forms, and during weeks 3 and 4, 22% were represented by these single-cell forms. It appears possible, then, that a substantial portion of what was called pre-implantation loss could have been failure of fertilization rather than toxicity to the early embryo.

Holland et al. *(86*) also measured chromatin adducts in mouse sperm using accelerator mass spectrometry. Ten males were treated with 50 mg/kg ^{14}C acrylamide (3 mCi/mol **[10.7 mCi/dose]**) **[route not specified, but all other treatments in this paper were i.p.]**. Two males were killed every 3 days and sperm were isolated from caudae epididymides. Sperm nuclei were separated by sonication and centrifugation. The dried pellet was converted to graphite by combustion to carbon dioxide followed by reduction of the carbon dioxide to graphite on cobalt. ^{14}C content relative to ^{13}C content was expressed as acrylamide equivalents in μg/g sperm **[when or how the sperm were weighed is not indicated]**. The results indicated to the authors that chromatin adducts peaked 9 days after treatment **[although day-6 data were not provided]**, consistent with involvement of late-step spermatids, testicular sperm, and epididymal sperm. The authors acknowledge that they could not

distinguish protamine adducts from DNA adducts using their technique.

Three experiments were performed to evaluate the effects of male treatment with acrylamide on the morphologic development of early embryos. Acrylamide **[purity not given]** was administered i.p. in sterile PBS. In the first experiment, males were treated with 0, 40, or 50 mg/kg bw/day acrylamide for 5 days. There were 8 males in each of the acrylamide-dosed groups and 15 control males **[it appears that controls may have been combined from different experiments].** Untreated C3H/J females were mated with the treated males four or five times/week for up to 5 weeks. Matings at 1, 2–3, and 4–5 weeks after exposure were taken to represent acrylamide effects on spermatozoa, spermatids, and spermatocytes, respectively. Males were housed overnight with three or four females for mating. The presence of a vaginal plug in the morning was assumed to represent pregnancy onset at midnight. Females were killed about 86–88 h after the assumed pregnancy onset. Corpora lutea were counted and uterine horns were flushed with warm tissue culture medium. Embryos and unfertilized eggs were counted and evaluated for morphologic abnormalities using a dissecting microscope. The frequencies of abnormalities in acrylamide-exposed and control embryos were compared using Fisher exact test. Logistic regression was used to evaluate the effects of acrylamide dose and time of acrylamide treatment on pre-implantation abnormalities. More complex logistic regression models were used to evaluate experiment, female body weight, and number of corpora lutea, as well as dose and time. The effect of sire was not significant by multifactorial regression and so embryos within time- and dose-groups were pooled for analysis.

Acrylamide treatment at the 50 mg/kg bw/day dose resulted in the death of about 10% of males within 24 h of the last injection, but treatment did not affect the mating success of surviving males, expressed as the proportion of females that were placed with a male and were plug-positive the next morning. The number of corpora lutea per female did not differ between dose groups. The mean (± SD) numbers of embryos recovered per female were 8.1 ± 1.2, 7.4 ± 1.3, and 6.4 ± 1.5 after treatment of males with, respectively, 0, 40, and 50 mg/kg bw/day acrylamide. These numbers were reported by the authors not to be statistically different from one another **[however, ANOVA by CERHR shows an overall *P* value of 0.0211. Comparing the 50 mg/kg bw/day group with the control, *P*<0.05 by post-hoc Dunnett test. Use of a trend test might have been more powerful in flagging the 40 mg/kg group as significantly different from control. Using the benchmark dose calculation, the BMD_{10} for this endpoint was 42 mg/kg bw/day and the BMDL was 21 mg/kg bw/day.]** There were no differences in mean percent efficiency of recovery (embryos per corpora lutea). Abnormal embryo data are shown in Table 15.

The number of embryos recovered was variable among groups at different weeks, perhaps due in part to the variability in number of mated females, which ranged from 0 to 9 per group per week. The proportion of the total embryos that was abnormal appeared highest 1 week after treatment in the 50 mg/kg bw/day group and decreased thereafter, reaching the control proportion by 5 weeks after treatment. The 40 mg/kg bw/day group data suggested a plateau effect over weeks 1–4. Embryos were evaluated as either retarded (fewer than 10 blastomeres), lysed (abnormal cell structure), or single cells. The latter were called “unfertilized eggs” or “zygotes that failed to undergo cleavage.”

Table 15. Percent Abnormal Embryos (of total number of embryos recovered) by Week of Mating after Treatment of the Male. Experiment 1 from Holland et al. (86)

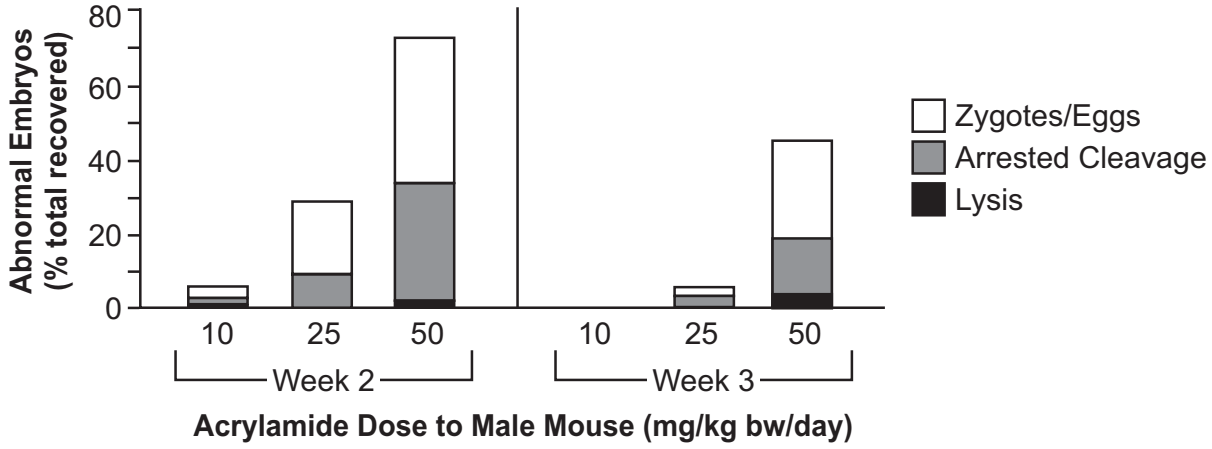
Week	Acrylamide dose to the male (mg/kg bw/day for 5 days)		
	0	40	50
1	5.0% (of 40)	61.1% (of 54)[a]	86.2% (29)[a,b]
2	5.0% (of 20)	62.1% (of 37)[a]	69.5% (46)[a]
3	0% (of 32)	59.1% (of 71)[a]	50.0% of 46)[a]
4	no females mated	57.4% (of 54)[a,c]	30.8% (of 26)[a]
5	4.2% (of 24)	22.8% (of 35)[a]	15.1% (of 33)

[a] Different from pooled control
[b] Different from 40 mg/kg bw/day group
[c] Different from 50 mg/kg bw/day group
All comparisons used Fisher exact test (embryo-based)

In a second experiment, Holland et al. *(86)* further explored the dose-response relationship by using 10 (n=10), 25 (n=10), and 50 (n=9) mg/kg bw/day acrylamide i.p. in male mice for 5 consecutive days. Males were mated with unexposed females 2 and 3 weeks after treatment, apparently using the same protocol as in the first experiment. Mating success was not found to be affected by treatment. The mean (± SD) numbers of embryos/female in the 0 (pooled controls), 10, 25, and 50 mg/kg bw/day groups were 8.1 ± 1.2, 7.1 ± 1.4, 7.5 ± 1.1, and 6.4 ± 0.9, respectively. There was no reported difference between groups in the number of embryos recovered per female or the number of embryos recovered per corpus luteum **[again, the 50 mg/kg bw/day group shows a significant decrease in embryos/female by CERHR analysis. Using the benchmark dose approach, the BMD_{10} was 27 mg/kg bw/day and the BMDL was 18 mg/kg bw/day. The Expert Panel notes that the data table refers to this experiment as Experiment 3, whereas the text identifies it as the second experiment.]**

The results of the second experiment are shown in Figure 4, taken from a data table in the original paper.

Figure 4. Types of Abnormal Embryos in Experiment 2 of Holland et al. (86).

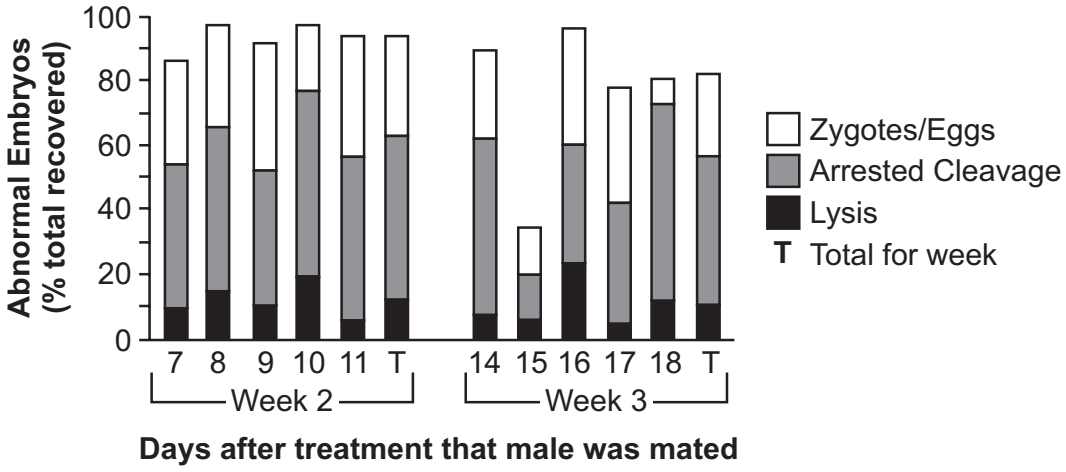


[Significant differences in the data table appear to be mismarked with respect to the 10 and 25

mg/kg bw/day groups at the second week.] There did not appear to be a formal comparison of the 10 mg/kg bw/day dose to the pooled control, but the implication in the text is that the 10 mg/kg bw/day dose was inactive. **[There is a statement of no difference between the second and third week in the 10 mg/kg bw/day group, but then "P<0.01" is inexplicably written.]** Total abnormalities decreased in the 25 and 50 mg/kg bw/day groups between the second and third weeks. Arrested cleavage decreased in the 50 mg/kg bw/day group between the second and third weeks.

In a third experiment, Holland et al. *(86)* treated 42 male mice with 50 mg/kg bw/day i.p. for 5 days. Males were mated 2 and 3 weeks later, and results given by day of mating **[number of males on any given day is not stated]**. Results are shown in Figure 5. Time-dependency was reported by the authors to show a significant negative trend.

Figure 5. Abnormal Day-4 Embryos Recovered from Female Mice Mated with Males Dosed with Acrylamide at 50 mg/kg bw/day i.p. for 5 Days. Experiment 3 of Holland et al. (86).



The results of all three experiments by Holland et al. *(86)* were pooled to evaluate dose- and time-dependency by logistic-regression modeling. Dose, time since treatment of the male, and experiment were the most important parameters with exposure of spermatozoa producing the strongest effect. When the three different types of abnormal embryo were evaluated in the model, a significant dose-response relationship was found for zygotes/eggs and for retarded cleavage, but not for blastomere lysis.

Strengths/Weaknesses: Similar to the previously discussed paper by these authors *(90)*, this report represents an interesting approach to looking at pre-implantation developmental effects. This study is also flawed by significant inconsistencies in data presentation, methods description, the use of often inadequate methods and insufficient rigor, and a questionable statistical approach. Specific weaknesses include:

(a) the number of embryos used for each stage is too small at many time points, with a low of 20 in the authors' Table 2 and 50 in the authors' Table 3. These numbers are entirely too small to draw such sweeping conclusions. Misuse of statistical analysis by using the embryo as the statistical unit amplifies the problem since it gives the impression that something has actually been demonstrated.

(b) The grouping of unfertilized eggs with abnormally developed embryos all as "abnormal embryos" is incorrect. Such a practice classifies a fertility effect as a genotoxic effect (the abnormal development).
(c) Methods are unclear. For example, it is never clear to how many females each treated male was mated, what the division of mated females between chromosomal aberration studies and dominant lethal testing was, how decisions were made regarding grouping of data, and why only two males per time point were used for adduct quantification. The text indicates that corpora lutea were counted before embryos, thus accounting for inconsistencies in recovery, but the authors' Table 1 notes state that embryos were counted before corpora lutea "to avoid bias."
(d) Fertilization rate is said to be unaffected by acrylamide treatment, but the fertilization rate in the control group is abnormally low (~20%), with no comment made.
(e) The authors' Table 1 appears to contain several calculation errors.
(f) Successful mating performance (which would correctly be defined as the number of plugged females per male) is said not to vary, but is a mean of 11.2 in treated animals at 50 mg/kg × 5 vs. 14.3 in controls and was as low as 4 in lower dose groups.
(g) The authors' Tables 3 and 4 do not include data from control animals and it is not possible to tell how many males were treated or from which females the embryos were retrieved, further confounding data interpretation. The authors' Table 2 includes some control data, but data from selected time points are missing.
(h) Data are often summarized inappropriately in the tables, grouping data from embryos collected at different time periods after treatment and then conducting a statistical analysis on them as if combining these data were appropriate.
(i) The discussion of the effect, or lack of it, of female body weight and corpora lutea number, is puzzling, in part because body weights did not differ among groups (so there was no effect) and in part because it is difficult to envision an effect of this type on females when the males were treated; the authors do, however, concede that body weight had little impact.
(j) There is uncertainty that the tracer experiment measured adducts vs. drug and metabolites reaching the tissue compartment; that is, there is no evidence the drug is bound to target of interest from this experiment alone.

On the positive side, the number of abnormal embryos (as defined by the authors' criteria) match well with reported dominant lethality data. Significant numbers of high-dose males yielded abnormal embryos out to 5 weeks post-treatment, supporting the Marchetti et al. *(89)* conclusion of chromosomal events in spermatocytes. These effects occurred even though acrylamide binding to mouse sperm was essentially at background by 18 days post-treatment.

Utility (Adequacy) for CERHR Evaluation Process: This series of studies identifies a male-mediated effect on abnormal pre-implantation embryo development, consistent with the dominant lethal studies reviewed in Section 2.3.2.2. Even if all of these effects could be attributed to just a few of the males in each group, the male-mediated toxicity would have approximately a 20% incidence, which would be a highly meaningful finding, and a genetically based finding at that. The LOAEL is probably 25 mg/kg bw/day in the 4-dose study, although the published report is not consistent on whether 10 mg/kg bw/day is an effect level. The LOAEL of 25 mg/kg bw/day is supported by a calculated BMD_{10} of 27 mg/kg bw/day and BMDL of 18 mg/kg bw/day.

Nagao *(85)* (support not indicated) gave ICR mice 62.5 or 125 mg/kg acrylamide or 5 daily doses of 50 mg/kg/day by i.p. injection **[purity not stated]**. In addition to the evaluation of number implants, and early/late implant death (presented earlier in Table 14), the author reported that there was no increase in external malformations among live fetuses sired by acrylamide-treated males. **[Data were analyzed by combining all fetuses within a dose group, without regard to sire of origin.]** There were 20 males per dose group, with at least 2 pregnant females per male. Reduction of implantation was observed only in high-dose, post-meiotic exposed sperm and increased postimplantation loss occurred at the 5 × 50 mg/kg and 125 mg/kg doses. The concurrent control rate of external abnormalities was higher than historical control.

Strengths/Weaknesses: It was not clear whether the lower number of pregnant females in the second period reflected reduced opportunity or reduced mating frequency. When so-called early and late deaths are combined, dominant lethal effects were observed at the mid and high doses during the first mating period (the post-meiotic germ cell stage), but not at the low dose. No effects were seen in animals mated during the spermatogonial germ cell time period. The separation of embryonic deaths into 'early' and 'late' is probably unnecessary and the conclusion that 'early' deaths were affected is perhaps misleading given the subjective nature of the classification.

Utility (Adequacy) for CERHR Evaluation Process: This study is supportive of other studies, but is not of use on its own.

2.3.2.4. Heritable translocations

Shelby et al. *(83)* (supported by NTP and DOE) administered acrylamide (> 99% purity) i.p. to male mice at 50 or 40 mg/kg/day for 5 days in 2 experiments. The 40 mg/kg bw/day dose was used in the second experiment in an attempt to increase numbers of progeny by decreasing the rate of dominant lethality. Acrylamide solutions were prepared in HBSS. Male (C3H × 101)F_1 mice were mated with female (SEC × C57BL)F_1 mice. The female offspring were killed and the male offspring retained and weaned. Male progeny were mated and if the first litter contained 10 or more offspring, the male was considered fertile. If the first litter contained fewer than 10 offspring, a second litter was evaluated. If the second litter contained 10 or more offspring, the male was considered fertile. If the second litter contained fewer than 10 offspring, the male was considered potentially partially sterile and was mated with three females. The females were killed on about GD 14 (plug day not specified) and uterine contents evaluated. The procedure of mating with three females was repeated to confirm reduced fertility. A random sample of ten males with reduced fertility were analyzed cytogenetically for the presence of reciprocal translocations in diakinesis metaphase I spermatocytes **[the method of analysis is not given except by reference to Evans et al. 1964]**. The proportions of male progeny that were sterile or semi-sterile after paternal treatment with 50 and 40 mg/kg bw/day for 5 days were 49/125 and 39/162 compared with 17/8,095 in the historical control **[statistical analysis not performed; sire of origin not considered]**. All ten semi-sterile males sampled for cytogenetic analysis of spermatocytes showed translocations.

Strengths/Weaknesses: The authors estimate the frequency of heterozygous translocation male offspring derived from parental males treated with acrylamide. The timing of fertilizations was such that the offspring screened for translocations resulted from acrylamide exposures of spermatozoa or spermatids. The authors concentrated on these spermatogenic stages based on a strong dominant-lethal

response in these stages. Ten randomly chosen semi-sterile males from the 5 × 50 treatment group were cytogenetically analyzed and all confirmed as reciprocal translocation heterozygotes. The individual chromosomes involved in the translocations were not determined. Data were presented as the frequency of semi-sterile or sterile males for each treatment group and allow independent statistical analysis. The authors compared the frequency of combined semi-sterile and sterile males in treatment vs. control groups. Thus, single screened male offspring was the experimental unit for comparisons. The implied assumptions in this study are that translocations are induced by treatment of the late spermatogenic germ cell stages and that the resultant offspring, even littermates, represent the independent treatment of different male germ cells. If these assumptions are true, a statistical analysis without consideration of the breeding structure of the population is justifiable. The authors do not mention the presence or absence of clustering (more than one semi-sterile or sterile male offspring recovered from a particular treated male). Since all semi-sterile and sterile males were not cytogenetically analyzed and the cytogenetic analyses did not identify the chromosomes involved in the translocation, the results as presented cannot definitively exclude the occurrence of clustering. However, based on the number of parental males treated and the number of male offspring screened per dose group, there were approximately 1–1.3 male offspring screened for litter-size reduction/sterility per parental male. This observation strongly suggests that clustering was absent and supports the statistical analysis as reported.

Utility (Adequacy) for CERHR Evaluation Process: This study is one of three published studies that estimates the effect of acrylamide treatment on transmitted germ-line cytogenetic endpoints and is critical for the evaluation of acrylamide. This study clearly demonstrates that acrylamide is an effective inducer of translocations in post-meiotic germ cells of rodents, but the study lacks adequate dose-response information.

Adler *(66*) (European Community) administered acrylamide **[purity not specified]** i.p. to C3H/E1 mice at 50 mg/kg bw/day for 5 consecutive days. Each male was mated to 2 female 102/E1 mice 7–11, and again 36–42, days after the end of treatment. No control group was reported. The author states that the litter size was reduced in the first mating interval due to the dominant lethal effect of acrylamide **[statistical analysis was not performed by the author. CERHR performed an ANOVA with post-hoc Neuman-Keuls multiple comparison test on the two replicates at each mating interval. The overall ANOVA gave a *P* value of < 0.0001 with the post-hoc test showing a difference between both 7–11 day matings and both 36–42 matings in litter size, with a reduction from about 6 pups/litter to about 2 pups/litter at birth]**. The male and female offspring from the 7–11 day matings were mated to unexposed (102/E1 × C3H/E1)F_1 mice and the male and female offspring from the 36–42 day matings were mated to one another (avoiding sibling matings). Male offspring were suspected of being translocation carriers based on reduced litter size. These animals were unilaterally orchidectomized and meiotic chromosome preparations were used to confirm translocation status. There were 23 translocation heterozygotes among 105 progeny from the offspring of the 7–11 day mating interval **[the number of treated males giving rise to these offspring is not stated]**. Among the offspring of the treated males, there were 17 male translocation carriers among 58 male offspring, and 6 female translocation carriers among 48 female offspring (male vs. female, $P<0.05$). In the second mating interval (36–42 days after treatment), 1,004 offspring were produced, of which 2 males were translocation carriers. This rate did not differ from the historical control in the author's laboratory when considered on a total-offspring basis, but was significantly greater than the historical control ($P = 0.03$) if considered on a male-offspring basis.

Strengths/Weaknesses: In this study, repeated acrylamide exposure was employed. In the first group, treated spermatozoa and spermatids were assayed for the occurrence of heterozygous reciprocal translocation carriers in the resultant offspring. Both male and female offspring were screened for semi-sterility or sterility. All suspect reciprocal translocation carriers were cytogenetically analyzed and the individual chromosomes involved, with breakpoints, were identified. The data are reported for the numbers of semi-sterile, sterile, and confirmed translocation carrier offspring among the animals screened, which allows an independent analysis of the results. The screened offspring was the experimental unit for comparison (breeding structure from which the population was derived was ignored), which is justifiable if the assumptions that the translocations are induced by treatment of the late spermatogenic germ cell stages and that the resultant offspring, even littermates, represent the independent treatment of different male germ cells are correct. The authors do not mention the presence or absence of clustering of semi-sterile or sterile offspring among the descendents of a particular treated parental male. However, results of the cytogenetic analyses confirm the assumption that clustering did not occur (all reciprocal translocations recovered were unique). The observed difference in the frequencies of translocation carriers identified in male vs. female offspring should be considered when comparing these results to Shelby et al., where only male offspring were screened (*80*). The Expert Panel suspects that the testing procedure for semi-sterility may be dependent on the genetic background of the females mated. The second experimental group is potentially very interesting. Offspring resulting from treated early spermatogenic stages (36–42 days post-treatment fertilizations) were screened for reduced fertility by mating male offspring from the treated parental males to female offspring from treated parental males. The observed increase of translocation carriers in male offspring needs to be repeated or utilized cautiously in the acrylamide evaluation.

Utility (Adequacy) for CERHR Evaluation Process: This study is one of three published reports on the frequency of heritable reciprocal translocations in germ cells of the mouse and is essential for an evaluation of acrylamide. First, it provides an independent assessment of the effects of acrylamide in treated late-stage spermatogenic stages of the mouse on the frequency of translocations. Second, it provides definite cytogenetic data on the recovered semi-sterile and sterile males. These results are important in addressing the question of clustering in both studies and the occurrence of multiple translocation events in some offspring. This study provides clear evidence that acrylamide induces structural chromosomal damage in post-meiotic cells of rodents, but lacks dose-response information.

Adler et al. *(91)* (European Community) treated male C3H/El mice with 50 or 100 mg/kg bw acrylamide. Each male was mated to 2 102/El mice 7–16 days post-treatment. Male and female offspring were tested for semi-sterility/sterility as described above in Adler 1990 *(66)*. All suspect translocation carriers were cytogenetically analyzed to confirm the presence of chromosomal rearrangements and to identify the chromosomes involved and the positions of the breakpoints. The frequency of confirmed translocation carriers was 2/362 in the 50 mg/kg treatment group and 10/367 in the 100 mg/kg treatment group. Both frequencies were significantly greater than the historical control, 3/8,700. As in the previous studies (above), the experimental unit of comparison was the individual offspring screened for the presence of a translocation. Clustering was not apparent as indicated by the fact that all translocations were unique. Even two independent T(5;6) mutations could be distinguished based on the positions of the breakpoints. There was a possible prevalence of male translocation carriers (9/12); however, the frequency data were neither reported nor analyzed

separately by sex of offspring screened. These results and the 5×50 mg/kg treatment results from Adler's lab were submitted to a dose-response analysis. Results suggested that the 5×50 treatment is more effective than a linear extrapolation from the single acute dose points to the accumulated total dose as the determinant of response.

Strengths/Weaknesses: The use of cytogenetic analysis to determine the involved chromosomes and the positions of the breakpoints is an important strength in this study.

Utility (Adequacy) for CERHR Evaluation Process: This study is one of three published reports on the frequency of heritable reciprocal translocation in germ cells of the mouse and is essential for an evaluation of acrylamide. This study provides clear evidence that acrylamide induces structural chromosomal damage in post-meiotic cells of rodents, and is the only study for transmitted genetic effects in mammals in which a dose-response analysis was attempted.

2.3.2.5. Specific locus

Russell et al. *(92)* used (101/R1 × C3H/R1)F_1 male mice treated with acrylamide (>99% pure) 50 mg/kg i.p. every day for 5 days. This dose regimen was used to decrease the lethality associated with single i.p. doses higher than 125 mg/kg. Males were mated at specific intervals after mating to T-stock females homozygous for *a* (non-agouti), *b* (brown), c^{ch} (chinchilla), *p* (pink-eyed dilution), *d* (dilute), *se* (short ear), and *s* (piebald). Offspring of matings were evaluated at about 3 weeks of age for mutant phenotypes associated with these loci and for other recognizable external variations. Presumed mutants were bred to determine whether a heritable mutation was present. Findings included a marked decrease in the production of offspring when mating occurred 1 or 2 weeks after acrylamide treatment (attributed by the authors to dominant lethality). Specific locus mutations occurred in 5/28,971 offspring with exposures 1 – 7 weeks after treatment, which was significantly higher than the historical control rate of 43/801,406 (P=0.026 in a Fisher one-tailed exact test **[which assumes the offspring as the statistical unit]**. The two mutants arising from matings 1 and 2 weeks after treatment represented a significantly higher mutation rate than the three mutants arising from matings in weeks 3 – 7; the rate in this latter period was not significantly higher than the control rate. No mutations were recovered in 17,112 offspring derived from treated stem cell spermatogonia (fertilizations occurring >49 days post-treatment). The authors indicate that this observation excludes at the 5% level an induced mutation rate more than 2.3 times the historical control rate, following the procedure of Selby and Olson. The historical control rate used the combined historical control data of Oak Ridge, Harwell, and Neuherberg, 43/801,406.

Strengths/Weaknesses: The authors have sampled all spermatogenic stages in treated males within the limits of laboratory capacity. Original mutation frequency results were presented and allow statistical evaluation. Where possible, all recovered mutations were genetically confirmed, characterized for homozygous viability, and cytogenetically analyzed. The major conclusions are that acrylamide is mutagenically active in the late spermatid – spermatozoa stages, the recovered mutations are associated with chromosomal aberration-type events (deletions and/or translocations), and acrylamide is not mutagenically active in stem-cell spermatogonia. The statistical analysis is based on the screened F_1 offspring as the unit of analysis (not the treated male), which is acceptable in treating the development of each germ cell as an independent event. There was no clustering of repeat mutations at a particular locus within the offspring of a single treated male as evidenced by the allelism test results of the

mutations recovered. If such clustering had occurred, the recovered mutations could have been pre-existing rather than induced. Further, ignoring the family structure of the offspring provides an unbiased estimate of the mutation frequency when clustering is absent.

Utility (Adequacy) for CERHR Evaluation Process: These results represent one of two studies on transmitted germ cell specific-locus mutations and are essential for a consideration of the genotoxicity of acrylamide.

Ehling and Neuhäuser-Klaus *(76)* performed a mouse specific-locus test sponsored by the Commission of the European Communities. Male mice were (102/E1 × C3H/E1)F_1 hybrids, treated with acrylamide **[purity not stated]** in distilled water at 0, 100, or 125 mg/kg i.p. Immediately after treatment, males were housed with untreated, test-stock females homozygous for *a* (non-agouti), *b* (brown), c^{ch} (chinchilla), *p* (pink-eyed dilution), *d* (dilute), *se* (short ear), and *s* (piebald). Females were replaced every 4 days for 20 days. On day 21, 100-mg/kg males were housed with females for an unspecified period of time **[but at least 43 days]**. Offspring were evaluated for mutant phenotypes. Their conception was dated as their day of birth minus a presumed 20-day gestation period. Evaluation for mutant phenotypes began at the day of birth and continued until 21 days of age. Statistical evaluation was by Fisher exact test **[thus taking the offspring as the statistical unit]**. At 5–8 and 9–12 days after treatment, specific locus mutation and dominant lethals (see Table 14) were increased. There were 3 mutant offspring among 4,647 total offspring at these time points in the 100-mg/kg group and 3 mutant offspring among 3,872 total offspring in the 125-mg/kg group. The control rate was 22 mutants among 248,413 offspring. The acrylamide group rates differed significantly from the control rate. With mating ≥43 days after treatment (indicating fertilization with sperm exposed as spermatogonia), there were 6 mutants among 23,489 offspring, which was significantly increased compared to the control rate ($P = 0.03$).

Strengths/Weaknesses: Two single acute doses of acrylamide were employed in this specific-locus mutation test. Original mutation frequency results were presented and allow statistical evaluation. As in the Oak Ridge study, all recovered mutations were genetically confirmed and characterized for homozygous viability, where possible. The major conclusions from the sampled post-spermatogonial stages are that acrylamide is mutagenically active in spermatozoa and late spermatids and that the recovered mutations are deletion-type events. The authors sampled treated post-spermatogonia up to day 21 post-treatment in shorter mating intervals than the Oak Ridge study. Offspring arising from fertilizations occurring 21–42 days post-treatment were combined into a single treatment group. Because both the Oak Ridge and the Neuherberg results indicated no increased mutation frequencies in post-spermatogonial stages outside of spermatozoa–late spermatid stages, this combination is acceptable. Statistical analyses were based on F_1 offspring being the experimental unit, not the treated parental male. As in the Oak Ridge experiment, no clustering of specific locus mutations was reported and ignoring the family structure of the offspring for statistical analysis was justified. In general, there are no discrepancies in the results from Oak Ridge and Neuherberg for the post-spermatogonial stages.

For treated spermatogonia, the observations from Oak Ridge and Neuherberg differ and are statistically significant (Fisher test, P=0.0430). There is a difference in experimental protocol, which Ehling and Neuhäuser-Klaus discuss: Oak Ridge employed a 5×50 mg/kg bw dosing, whereas the Neuherberg

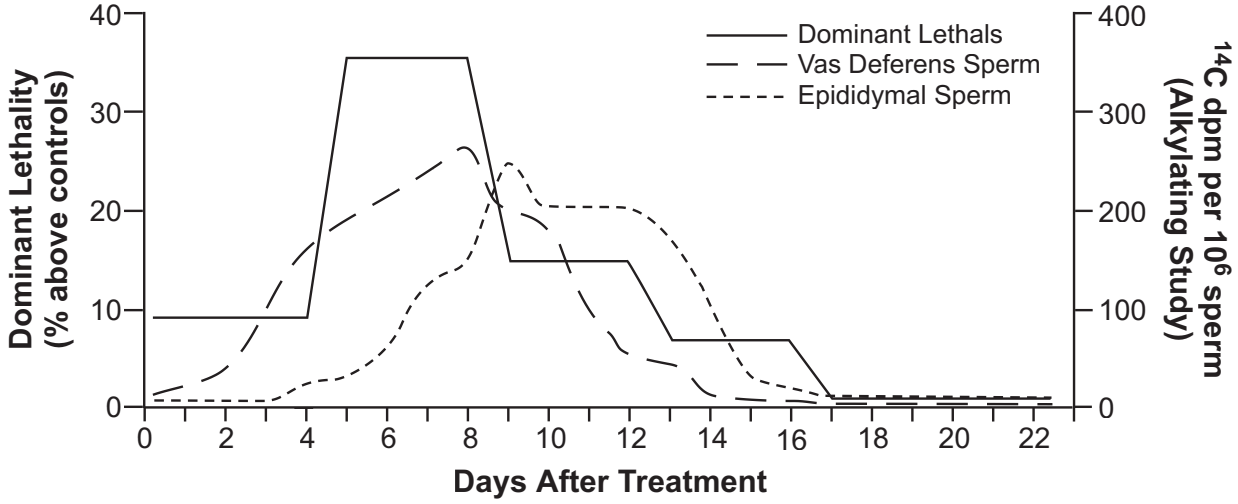
experiment used single, acute exposure dosing.

Utility (Adequacy) for CERHR Evaluation Process: The Neuherberg results are one of only two experiments providing transmitted germ-line specific-locus mutation estimates in the mouse and are essential for an evaluation of the genotoxicity of acrylamide. The study provides evidence for specific-locus mutations in spermatid and spermatozoal stage germ cells of male mice, but lacks dose-response information.

2.3.2.6. Effects on DNA and protamine in male germ cells

Sega et al. *(93)* injected male (C3H × 101) F_1 mice with ^{14}C-labeled acrylamide (1.00 mCi/mmole) at an i.p. dose of 125 mg/kg. Six males per time point were killed 4 h later and then daily for 23 days after the injection. Vasa deferentia and caudae epididymides were dissected. Sperm heads were isolated by filtration and sonication followed by centrifugation through sucrose. Radioactivity in sperm heads was measured using scintillation counting after the addition of scintillation fluid. Separate aliquots of sperm heads were used for isolation of DNA and of protamines, and radioactivity in these fractions was measured using scintillation counting. The time-course of sperm head radioactivity in this study was compared to the time-course of dominant lethality in the same strain of mice in Shelby et al. *(80)*. Statistical comparisons were not performed, but inspection of the data suggested parallel effects, with late spermatids and early spermatozoa the most affected stages (**Figure 6**). Very little radioactivity was found in the DNA fraction, whereas protamine radioactivity and total sperm-head radioactivity following superimposable time-course curves. Amino acid analysis of hydrolyzed sperm protamine showed a radioactivity peak that co-chromatographed with *S*-carboxyethylcysteine. The authors postulated that acrylamide alkylation of cysteine sulfhydryl groups in protamine occurred, resulting in *S*-formamidoethyl cysteine. The acid hydrolysis step could have resulted in *S*-carboxyethylcysteine through loss of the amino group. The same data and conclusions were presented in a subsequent publication *(94)*.

Figure 6. Comparison of Timing of Dominant Lethality and Sperm Head Alkylation. [Dominant Lethal Data from Shelby et al. (80) and Alkylation Data from Sega et al. (93)]



Sega and Generoso *(95)* (supported by DOE/NICHD) measured DNA breakage in the germ cells

of male (C3H × C57BL/10)F_1 mice using an alkaline elution procedure. Radiolabeled DNA from treated and control animals was applied to a 4-μm pore-size polycarbonate filter and exposed to a buffer at pH 12.0. The amount of DNA passing through the filter was taken to represent fragmented DNA. Males were treated with acrylamide (99.9% purity) at a dose of 100 mg/kg i.p. the day after intratesticular injection of labeled thymidine. Sperm were obtained from the vas deferens 1–21 days after acrylamide injections. Additional experiments were conducted using doses of acrylamide from 25 to 125 mg/kg i.p. with harvesting of sperm from the vas deferens 10 days later. Pachytene spermatocytes and spermatids were isolated from testes by centrifugal elutriation for evaluation 90 minutes, and 1, 2, 3, and 4 days after acrylamide treatment (100 mg/kg i.p.). Statistical analyses were not presented and the number of males contributing germ cells was not given; however, the data tables indicate the number of "independent experiments" **[not further explained]**. The percent of sperm-DNA eluted was increased compared to an untreated control when sperm were obtained 1–16 days after treatment with 100 mg/kg acrylamide **[identified as increased based on ANOVA with post-hoc Dunnett test performed by CERHR]**. Seventeen to twenty-one days after treatment, the percent eluted sperm-DNA was similar to the untreated control value. The percent of sperm-DNA eluted 10 days after acrylamide was related to acrylamide doses between 25 and 75 mg/kg; higher doses up to 125 mg/kg had no additional effect. **[The data are shown only in graphic form with no indication of the number of independent observations; the identification of statistical difference from control was made by CERHR using unpaired *t*-tests and assuming 21 observations in the control (which appeared to be the same control used for the previous comparison) and at least two observations per acrylamide-treated group.]** Pachytene spermatocytes showed a significant increase in DNA eluted 90 minutes, 1 day, 2 days, and 3 days after acrylamide treatment. By 4 days after treatment, the DNA-elution percentage was similar to that of the control **[based on ANOVA with post-hoc Dunnett test performed by CERHR from data presented in a table]**. The authors stated that DNA elution was increased in early spermatids with the greatest effect occurring 1 day after acrylamide treatment. **[ANOVA with post-hoc Dunnett test by CERHR shows a difference from the control only for the day 1 value. This analysis may not be appropriate given the large standard errors for some of these data.]** The authors state that DNA breakage appeared to be greatest in mid/late spermatids. **[ANOVA with post-hoc Dunnett test by CERHR shows significant increases compared to control and 1, 2, 3, and 4 days post-treatment.]** The authors interpreted their results as consistent with DNA breakage due to DNA alkylation in spermatocytes and early spermatids. By day 17 after treatment, treated germ cells would have entered a phase during which DNA repair occurs, resulting in elimination of the damaged DNA. The increase in DNA breakage of mid/late spermatids and spermatozoa was attributed by the authors to alkylation of protamines with DNA breakage secondary to stresses imposed on chromatin by the damaged protamines. The authors concluded that the demonstration of sensitivity of mid/late spermatids and spermatozoa was consistent with the sensitivity of dominant lethality to acrylamide treatment during these stages.

Sega et al. *(96)* (supported by DOE and NIEHS) evaluated unscheduled DNA synthesis (UDS) in the germ cells of male (C3H × 101)F_1 mice after treatment with acrylamide (99.9% purity). Radiolabeled thymidine was injected into the testes of mice. Acrylamide was given at doses of 0, 7.8, 15.6, 31.2, 62.5, and 125 mg/kg i.p. from 0 to 48 h prior to injection of labeled thymidine. Cauda epididymal sperm were obtained 16 days after treatment, representing sperm that were in the early spermatid stage at the time of acrylamide treatment. The maximal incorporation of radiolabeled thymidine occurred 6 h after acrylamide treatment, suggesting that time was required for direct acrylamide-

mediated DNA damage or for metabolism of acrylamide to the proximate DNA-damaging agent. Evaluation of the slope of the dose-response curves for radiolabeled thymidine incorporation showed a five-fold steeper curve when the labeled thymidine was given 6 h after acrylamide, compared with simultaneous administration of labeled thymidine and acrylamide. The authors state that intratesticular radiolabeled thymidine is available for only about 4 h; thus, the lack of incorporation of radiolabeled thymidine when injected simultaneously with the acrylamide treatment supported the conclusion that acrylamide-associated DNA repair was delayed at least 4 h.

In a second experiment reported in the same paper, male (C3H × BL10)F_1 mice were treated i.p. with 0 or 125 mg/kg acrylamide with evaluation of epididymal sperm every 2 or 3 days between 1 and 30 days after treatment. Radiolabeled thymidine was given 6 h after acrylamide. There were four mice per dose group at each sampling time point. An increase in radiolabeled thymidine incorporation into DNA was evident 12–27 days after treatment **[statistical analyses were not presented and the graph cannot be analyzed statistically due to the pooling of sperm from the four males per dose group at each time point]**. According to the authors, the sensitive time period corresponds to treatment of germ cells at the early-spermatocyte to mid-spermatid stage.

In a final experiment, radiolabeled acrylamide was given to male (C3H × BL10)F_1 mice by i.p. injection at a dose of 46 mg/kg bw. Testes and livers were recovered from each of 4 animals per time point from 1, 2, 4, 6, 8, and 24 h after acrylamide treatment for evaluation of radioactivity incorporated into the DNA. The peak number of adducts (expressed per million deoxynucleotides) was reached in the testis at 6 h; whereas in liver, the peak occurred at 1 or 2 h. **[No statistical analysis was presented and it is not possible to analyze the graphed data statistically due to pooling of samples from the four animals used at each time point; in the liver, the 1- and 2-h values could be statistically similar.]** In addition, the number of adducts in the liver was an order of magnitude higher than in the testis.

The authors pointed out that no other chemical in their experience showed such a long delay between administration and UDS as did acrylamide. They considered the possibility that direct damage of DNA by acrylamide was a slow process unlikely, due in part to the *in vitro* observation that acrylamide binding to DNA is rapid. They concluded that their experiments supported the hypothesis that acrylamide effects on DNA are mediated through metabolism to an active intermediate such as glycidamide.

Strengths/Weaknesses: By using the same protocol as that used for dominant lethal studies, this series of mechanistic studies in mice was able to correlate alkylation of protamine (and lack of alkylation of DNA) with dominant lethal effects (percent dead implants) attributed to exposures of late spermatids and early spermatozoa. Aliquots of the same samples were analyzed for both protamine and DNA adducts *(94, 95*), allowing direct comparisons. Protamine alkylation was shown convincingly to involve reaction with free sulfhydryls in protamine and to occur at times when protamine is present in mature spermatids (late stages of spermatogenesis) and before inter- and intra-molecular disulfide bonds cross-link the protamine. Thus, the vulnerable window of development for this aspect of acrylamide toxicity is defined based on a molecular mechanism**.** The alkaline elution studies *(96*) confirmed the presence of DNA breakage in late spermatids and early spermatozoa (thought to be secondary to protamine alkylation) and also in pachytene spermatocytes (thought to be direct, but reparable, hence not resulting in dominant lethality). The time course for the latter is consistent with a delay and implicates a requirement for metabolism to an active molecule. The results of the UDS

experiments *(97*) are consistent with DNA damage to spermatocytes and early spermatids being repaired before the cells become sperm, and hence the lack of dominant lethality. Thus, the studies in this series logically complement one another and provide a compelling model to explain the dominant lethality (percent dead implants) of acrylamide. Weaknesses of this series of papers are as follow. Sega et al. *(94*) attributed all labeling by radioactive acrylamide in sperm heads to covalent binding to protamine. According to the authors, all radioactivity in the sperm head was bound to protamine, presumably to Cys, as carboxyethyl-Cys was demonstrated. But other proteins in sperm have Cys. Why weren't these proteins labeled? Since sperm from the vas and epididymis were taken, prior labeling of histones would have been lost, since the histones are replaced by the protamines at this stage of development. Sega et al. *(96*) demonstrate that DNA strand breakage occurred in pachytene spermatocytes **[purified fractions were described as 80% pure, but the method of determining purity was not described, although scanning electron micrographs of pachytene spermatocytes and round spermatids were presented]**. The damage demonstrated 1 day after exposure in the pachytene spermatocytes had disappeared by the time the pachytene spermatocytes had advanced to post-meiotic stages, presumably by DNA repair. DNA repair was the subject of the fourth paper of this series, whereby UDS was measured after acrylamide exposure. UDS peaked 6 h after acrylamide exposure; a time when free acrylamide would have been cleared from the tissue. UDS measured 6 h post-acrylamide showed a strong acrylamide dose-dependency. Error bars representing SEM are given on the graphs in the figures, but no indication of the number of experiments is provided, so the basis for the SEM is unclear.

Utility (Adequacy) for CERHR Evaluation Process: These studies provide a model by which acrylamide (or a metabolite) may produce dominant lethality (increased percent dead implants) when exposures occur at a particular stage of spermiogenesis by binding to protamine in spermatids and early spermatozoa before protamine is cross-linked as the sperm move from the caput to cauda epididymis. The model also accounts for only minimal, if any, DNA alkylation at the time when protamine appears to protect DNA from alkylation. This biologically plausible model would be expected to be pertinent to both rodents and humans. Thus, the model provides at least one basis for extrapolation from rodent test species to humans when characterizing reproductive risks of acrylamide.

Support for glycidamide as the mediator of acrylamide genotoxicity was provided by Generoso et al. *(97*), funded by DOE and NIEHS. Glycidamide (100% stated purity) was administered i.p. to male (C3H/RL × 101/RL)F_1 mice. Tests were performed for dominant lethality, heritable translocations, and UDS. The glycidamide doses were selected based on preliminary studies to provide the highest dose that did not impair survival or mating ability. **[No attempt was made to use doses comparable to acrylamide doses in previous studies. Although acrylamide and glycidamide are nearly identical in molecular mass (differing only by a single hydrogen atom), the authors did not know the extent to which i.p. acrylamide in male mice would be metabolized to glycidamide.]** Dominant lethal testing was performed with a glycidamide dose of 125 mg/kg. Results of the dominant lethal study were analyzed on a per female basis and showed a decrease in live implants and an increase in resorptions, with mating 0.5 – 11.5 days after treatment of the male. **[Analysis per sire was not possible with the information given. Males were mated with two females/day according to the methods, but there appears to have been a decrease in mating ability. During the first 3-day period, there were reported to have been 36 treated males. There should have been 216 mated females (36 males × 2 females/male/day × 3 days). The reported number is 54 mated females. A similar deficit**

appears in the control group for which 24 males were reported, giving the expected number as 144 mated females, with only 48 actually reported. Other time periods show more than 48 mated females per 3-day period. Therefore, it remains unclear how many females were used per male per time period. If the protocol were similar to Shelby et al. *(80)*, two females were housed with each male, but only replaced when one showed evidence of breeding; that is, *not* two new females per day unless both bred the night before. Since the authors state there is no difference in the number of females bred per time interval, data on implants per female seem valid (despite lack of male as experimental unit). The only "suspicious" period is 0.5–3.5 days, when the number of mated females that became pregnant was lower than at other times (44 vs. ~60–70% in this study); and only 33 vs. 70–100% in Shelby et al. *(80)*), implying that some males were not fertile at this time and were not therefore part of the analysis of percent dead implants. This possible discrepancy does not appear to affect the overall interpretation of this study.]

The heritable translocation test was performed using 100 mg/kg i.p. glycidamide. There were 669 male progeny of glycidamide-treated sires. Among the progeny, 91 were semi-sterile (defined in a previous study by these authors as producing fewer than 10 offspring per litter in two consecutive litters), 3 could not be completely tested (they became sterile before semi-sterility testing was completed), and 52 were sterile. Semi-sterility was taken as evidence of chromosome rearrangements based on the authors' prior experience. The 52 sterile males and the 3 incompletely tested males underwent cytogenetic analysis and were confirmed as heterozygous translocation carriers. The percent translocations was 20.18 (91 semi-sterile males + 52 sterile males + 3 incompletely tested males/669 progeny), compared to 0.06 from historical control data.

The UDS experiment used glycidamide 150 mg/kg i.p. with vehicle-injected males as controls. Radiolabeled thymidine was given 0, 2, 4, or 6 h after the injection of glycidamide. UDS was increased in the glycidamide-treated animals at all time points, with the maximum effect seen when radiolabeled thymidine was given 2 h after glycidamide. **[Statistical testing was not indicated in the paper, but *t*-tests by CERHR show significant differences at all time points.]** These results were considered by the authors to be consistent with direct DNA damage by glycidamide. According to the authors, comparison of the UDS response to glycidamide in this paper with the UDS response to acrylamide reported in Sega et al. *(96)* showed reasonable agreement with the theory that acrylamide-associated UDS is due to metabolism to glycidamide, accounting for the differences in injected radioactivity, moles of chemical, and experimental uncertainty.

2.4 Carcinogenicity

2.4.1 Human data

The EU *(5)* and IARC *(8)* concluded that human data were inadequate to assess the carcinogenic status of acrylamide. These conclusions were based on two occupational-mortality cohort studies *(98, 99)*. These studies reported negative results. IARC concluded that power to detect cancer at any specific site was extremely limited in the Sobel et al. *(99)* study due to small sample, short exposure duration, and short latency. In their review of the Collins et al. *(98)* study, the EU stated that no firm conclusions could be drawn. The study by Collins et al. *(98)* was later updated and published as Marsh et al. *(100)* and reviewed in JIFSAN/NCFST *(39)*. A JIFSAN/NCFST *(39)* panel reviewed the Marsh et al. *(100)* study, which examined cohorts of workers, in three plants, who were hired between

1925 and 1973, and followed through 1994. The cohorts originally consisted of 8,854 males but were later reduced to 8,508 workers due to incomplete records for some workers. Workers were considered exposed to acrylamide if cumulative exposure was >0.001 mg/m^3/year. No statistically significant excess mortality from cancer at any specific site was noted when compared to expected rates. An increase in respiratory cancer in one plant occurred primarily in workers exposed to muriatic acid. An excess of pancreatic cancer was noted in workers exposed to >0.30 mg acrylamide per·year, but Marsh et al. *(100)* noted that information on smoking, a major risk factor for pancreatic cancer, was not available for each member of the cohort. Marsh et al. *(100)* concluded that study results provide little evidence of a relationship between acrylamide exposure and cancer mortality.

CERHR identified two additional epidemiologic studies examining the relationship between diet and cancer. Because those studies have not been addressed in major reviews to date, they are being reviewed and summarized here in detail.

Pelucchi et al. *(101)* examined the association between fried or baked potato consumption and cancer by reviewing a series of hospital-based, case control studies conducted in Italy and Switzerland between 1991 and 2000. Potatoes were used as an indicator of acrylamide intake, although the authors acknowledged that numerous other starchy foods may contain acrylamide. The types of cancer (n=cases, controls) considered were oral cavity/pharynx (n=749, 1772), esophagus (n=395, 1,066), larynx (n=527, 1,297), colon (n=1,225, 4,154), rectum (n=728, 4,154), breast (n=2,569, 2,588), and ovary (n=1,031, 2,411). Median ages of subjects ranged from 55 to 62 years. Subjects were questioned about dietary intake during the past 2 years. Odds ratios were calculated and adjusted for age, gender, location, education, body mass index, energy intake, alcohol intake, smoking, physical activity, and/or parity. No association between potato intake and cancer was noted as indicated by odds ratios between 0.8 and 1.1 for each type of cancer.

Mucci et al. *(102)* examined the association between dietary acrylamide intake and cancer of the large bowel, kidney, and bladder by reanalyzing data from a Swedish population-based, case control study originally designed to determine the relationship between heterocyclic amines in fried foods and cancer. Subjects of the study were born in Sweden between 1918 and 1942 and resided in Stockholm for at least 1 month between November 1992 and December 1994. Subjects included 538 healthy controls (50.6% male), 591 with large bowel cancer (58.5% male), 263 with bladder cancer (75.7% male), and 133 with kidney cancer (53.4% male). At the time of the study, subjects ranged in age from 51 to 77 years. Subjects were questioned about their intake of 188 food types during the 5 years prior to this study. Acrylamide concentrations were measured in more than 100 kinds of foods. Acrylamide doses were estimated based on intake frequency of different food types. Odds ratios were estimated using unconditional logistic regression with adjustment for age and gender, as well as confounding factors (e.g., smoking, body mass index, alcohol intake, fruit and vegetable intake, saturated fat density, red meat density, and total energy). There was no evidence of excess risk or trends for large bowel, bladder, or kidney cancer in subjects who ingested large quantities of 14 food types with high (300–1,200 µg/kg) or moderate (30–299 µg/kg) acrylamide concentrations. No association with bladder or kidney cancer was found in an analysis of acrylamide-dietary intake quartiles. A 40% reduced risk of large bowel cancer was observed in the highest compared to the lowest quartile of acrylamide intake (P=0.01 in trend analysis). **[The Expert Panel notes that the negative results of Pelucchi et al. *(101)* and of Mucci et al. *(102)* may have been due to inadequate power to detect**

the magnitude of an increase suggested by experimental animal studies. The Panel does not consider these papers to discount the experimental animal results.]

The FAO/WHO *(14)* noted that an absence of positive cancer findings in epidemiologic studies does not prove that the substance does not cause cancer because such studies have limited power to detect small increases in the incidence of tumors. It was also noted by the FAO/WHO that the epidemiologic studies did not consider dermal exposure. **[The Expert Panel agrees that the human data are inadequate for a determination of acrylamide carcinogenicity.]**

2.4.2 Experimental animal data

Two animal carcinogenicity studies were identified and both were reviewed in detail since acrylamide exposure was found to result in cancer of reproductive organs.

In an industry-sponsored study, Johnson et al. *(57)* examined carcinogenicity in Fischer 344 rats following chronic exposure to acrylamide (enzyme grade; 96–99% purity). At 5–6 weeks of age, 90 Fischer 344 rats/sex/group were administered acrylamide through drinking water for 2 years at concentrations that resulted in doses of 0, 0.01, 0.1, 0.5, or 2.0 mg/kg bw/day. Dose selection was based upon the subchronic study by Burek et al. *(55)*. Dosing solutions and drinking water samples were regularly analyzed for acrylamide content by HPLC. Rats were observed daily and weighed monthly. Blood and urine samples were collected from 10 rats/sex/group at 3, 6, 12, and 18 months. Ten rats/sex/group were randomly examined at 6, 12, and 18 months. Non-histologic data were evaluated by Gehan-Wilcoxon test, ANOVA, and Dunnett t-test. Cumulative mortality of male and female rats in the 2.0 mg/kg bw/day group was significantly increased beginning at the 21st month of the study. A slight but significant decrease in body weight gain occurred in male rats of the 2.0 mg/kg bw/day group, but there were no changes in food or water intake **[data not included in published study]**. Small and infrequent changes in body weight gain were noted for females in the 2.0 mg/kg bw/day group and males in the 0.5 mg/kg bw/day group. There was moderate degeneration of the tibial nerve in males. Study authors reported no adverse treatment-related effects on hematologic, clinical chemistry, or urinalysis parameters **[data not shown]**.

Johnson et al. *(57)* conducted histopathologic analyses in 60 rats/group/sex; a variety of organs, including cervix, epididymides, mammary glands, ovaries, oviducts, prostate, seminal vesicles, testes, uterus, vagina, and central and peripheral nervous tissues were fixed in 10% formalin and examined. Histopathologic data were evaluated by Fisher exact probability test with Bonferonni correction in cases of ≥6% control incidence. Cochran-Armitage test for linear trend was conducted in the absence of a positive Fisher test and adjusted for mortality if appropriate and informative. Table 16 lists the incidence of histopathologic findings for which statistical significance or dose-related trends were reported at one or more doses. An increased incidence and severity of tibial nerve degeneration was observed in rats of the 2.0 mg/kg bw/day group; the effect was more pronounced in male rats. No clinical signs of neuropathy were observed. Incidence of testicular mesothelioma was significantly increased at 0.5 and 2.0 mg/kg bw/day. The incidence of testicular mesothelioma in the 0.1 mg/kg bw/day group was not significantly increased, but was said by study authors to be greater than concurrent and historical control values. All other increases in tumor incidences were noted in the 2.0 mg/kg bw/day group and included tumors of the mammary gland (benign and malignant), CNS (malignant), thyroid follicular epithelium (benign and malignant considered together), oral tissues

(benign), uterus (malignant), and clitoral gland (benign) in females and thyroid follicular epithelium (benign) and CNS in males. An increase in CNS tumors of glial origin in control male rats exceeded historical control values and the authors concluded that the increase in the 2.0 mg/kg bw/day males was most likely treatment related. An increase in benign pituitary adenomas in female rats and benign pheochromocytomas in male rats were considered to be of questionable biologic significance by study authors due to high incidence in aging rats and low concurrent control value compared to historical controls, respectively. **[It was not stated if non-neoplastic lesions were observed in reproductive organs.]**

Table 16. Selected Histopathologic Effects in Rats Exposed to Acrylamide in Drinking Water for Two Years, Johnson et al. (57)

Observation	*Sex*	*Number of Rats Affected/Number Examined, by Dose (mg/kg bw/day)*				
		0	*0.01*	*0.1*	*0.5*	*2.0*
Severe degeneration of tibial nerve	m	1/60	1/60	0/60	0/60	4/60[a]
Malignant mesothelioma of testes, with or without metastasis	m	3/60	0/60	7/60	11/60*	10/60*
Benign primary adenoma of thyroid follicles	m	1/60	0/58	2/59	1/59	7/59*
Focal hyperplasia of hard palate epithelium	m	0/60	1/60	1/60	4/60*	5/60*
Benign primary pheochromocytoma of adrenal gland	m	3/60	7/59	7/60	5/60	10/60*
Total with glial CNS tumor or glial proliferation	m	5/60	2/60	0/60	3/60	8/60
Moderate degeneration of tibial nerve	f	0/60	0/60	0/60	0/60	3/61
Malignant primary adenocarcinoma of mammary gland	f	2/60	1/60	1/60	2/58	6/61[a]
Total with one or more benign mammary tumors	f	10/60	11/60[b]	9/60	19/58[b]	23/61*
Total with metastatic or nonmetastatic adenocarcinoma of uterus	f	1/60	2/60	1/60	0/59	5/60*
Benign primary adenoma of clitoral gland[e]	f	0/2	1/3	3/4	2/4	5/5*
Total with either adenocarcinoma or adenoma of thyroid follicles	f	1/58	0/59	1/59	1/58	5/60*[d]
Benign primary squamous papilloma of hard palate, lip, or tongue	f	0/60	3/60	2/60	1/60	7/61*
Total with CNS tumor or glial proliferation	f	1/60	2/59	1/60	1/60	9/61*[c]
Benign primary adenoma of pituitary	f	25/59	30/60	32/60	27/60	32/60*

m=male, f=female
[a] Linear trend
[b] One rat had two different types of mammary tumors
[c] One rat had both a tumor and glial proliferation
[d] One rat had both an adenocarcinoma and adenoma
[e] Only tissues with gross lesions were examined
*P=0.05 using mortality adjustment by Mantel-Haenszel procedure

A second carcinogenicity study in Fischer 344 rats was sponsored by industry *(103)* in order to clarify some of the results observed in the Johnson et al. *(57)* study. The study was designed with sufficient power to detect a 5% increase in scrotal mesothelioma incidence compared to an expected 1.3% incidence in control rats. The other purpose of the study was to characterize dose-response for tumors in female rats. At 44–45 days of age, rats were administered acrylamide (electrophoresis grade with 99.9% purity) in drinking water for 106–108 weeks. Doses administered to males (n=number in each dose group) were 0 (n=102), 0 (n=102), 0.1 (n=204), 0.5 (n=102), or 2.0 (n=75) mg/kg bw/day. Doses given to female rats were 0 (n=50), 0 (n=50), 1.0 (n=100), or 3.0 (n=100). Two control groups were used to better characterize low-incidence tumors. Twenty-five rats of each sex served as sentinels to monitor for infectious diseases. Stability and concentrations of acrylamide in dosing solutions were verified. During treatment, the animals were monitored for weight gain, clinical signs, and food and water intake. Included among the organs collected and fixed in 10% formalin for histopathologic examination at necropsy were epididymides, ovaries, prostate, seminal vesicles, mammary gland, testes, uterus, and vagina. Also examined were tissues observed to have lesions or neoplasms in the Johnson et al. *(57)* study, such as adrenal glands, central and peripheral nerves, thyroid, oral structures, and pituitary. Examinations were initially conducted in high-dose and control groups and intermediate-dose animals were examined as necessary. Statistical analyses included ANOVA, Dunnett *t*-test, and/or pair-wise *t*-tests for non-histopathologic data. For the analysis of tumor data, survival estimates were obtained by the Kaplan-Meier method, log rank test, and dose-trend tests. Statistical analyses for lifetime tumor rates that were not time-adjusted included the Cochran-Armitage trend test, Tarone method, interval-based methods, and/or logistic score test.

Mortality was increased in the 2.0 mg/kg bw/day males starting at month 17 and the 3.0 mg/kg bw/day females beginning at month 24. Body weight gain was reduced in males of the 2.0 mg/kg bw/day group and females of the 3.0 mg/kg bw/day group. Table 17 and Table 18 list the incidence of histopathologic findings of the Friedman et al. *(103)* study, primarily for effects that identified statistical significance at one or more doses and in tissues found to have lesions or neoplasms in the Johnson et al. *(57)* study. An increased incidence of minimal-to-mild sciatic nerve degeneration was noted in males dosed with 2.0 mg/kg bw/day and females dosed with 3.0 mg/kg bw/day. None of the rats had visible signs of neurotoxicity. Statistically significant increases in tumor incidences included testicular mesotheliomas (2 mg/kg bw/day), mammary gland fibroadenomas and also combined adenocarcinomas and fibroadenomas (≥1 mg/kg bw/day), and combined thyroid follicular adenomas and carcinomas (females: ≥1 mg/kg bw/day; males: 2 mg/kg bw/day). **[The statement about thyroid tumors was made in the results section, which is in contrast with results shown in tables. The study tables indicated a significant increase in follicular cell adenomas in males of the 2 mg/kg bw/day group and combined follicular cell adenomas and carcinomas in females of the 3 mg/kg bw/day group.]** Friedman et al. *(103)* noted that tumors observed in testis, mammary gland, and thyroid were consistent with results of the previous study *(57)*, and that the present study demonstrated no significant increase in testicular mesotheliomas at 0.5 mg/kg bw/day. **[The level of significance in the Johnson et al. *(57)* was 0.05, while the level of significance in the Friedman study was <0.001.]** In contrast to results from the previous study, the tumor incidence was not increased in CNS glial cells, the oral cavity, clitoral gland, or uterus **[with the exception of CNS glial cells, data were not shown for these tissues]**.

Table 17. Selected Histopathologic Effects in Male Rats Exposed to Acrylamide in Drinking Water for 2 Years, Friedman et al. (103).

Observation	*Number of Rats Affected/Number Examined [%], by Dose (mg/kg bw/day)*				
	0	***0***	***0.1***	***0.5***	***2.0***
Sciatic nerve degeneration	30/83 [36.1]	29/88 [33.0]	21/65 [32.3]	13/38 [34.2]	26/49 [53.1]
Tunica mesothelioma of testes	4/102 [3.9]	4/102 [3.9]	9/204 [4.4]	8/102 [7.8]	13/75* [17.3]
Follicular cell adenoma of thyroid	2/100 [2.0]	1/102 [0.98]	9/203 [4.4]	5/101 [5.0]	12/75* [16.0]
Total with follicular cell neoplasms (adenomas and carcinomas) of thyroid	3/100 [3.0]	3/102 [2.9]	12/203 [5.9]	5/101 [5.0]	17/75 [22.6]
Total with CNS tumor of glial origin[a]	1/(102+82)	1/(102+90)	2/(98+68)	1/(50+37)	3/(75+51)

*$P<0.001$

[a] Denominator represents number of (brain+spinal cord) samples analyzed

Table 18. Selected Histopathologic Effects in Female Rats Exposed to Acrylamide in Drinking Water for 2 Years, Friedman et al. (103)

Observation	*Number of Rats Affected/Number Examined [%], by Dose (mg/kg bw/day)*			
	0	***0***	***1.0***	***3.0***
Sciatic nerve degeneration	7/37 [18.9]	12/43 [27.9]	2/20 [10.0]	38/86 [44.2]
Fibroadenoma in mammary gland	5/46 [10.9]	4/50 [8.0]	20/94* [21.3]	26/95* [27.4]
Total with mammary gland neoplasms (adenomas and carcinomas)	7/46 [15.2]	4/50 [8.0]	21/94* [22.3]	30/95* [31.6]
Total with follicular cell neoplasms (adenomas and carcinomas) of thyroid	1/50 [2.0]	1/50 [2.0]	10/100 [10.0]	23/100* [23.0]
Total with CNS tumor of glial origin[a]	0/(50+45)	0/(50+44)	2/(100+21)	3/(100+90)

*$P<0.001$

[a] Denominator represents number of (brain+spinal cord) samples analyzed

In a later publication *(104*), the testicular tumors from the Friedman et al. *(103*) study were examined by light and electron microscopy. It was found that tumors developing in the tunica vaginalis of the testes did not differ morphologically in acrylamide-treated versus control animals. Though current practice is to classify all mesotheliomas in the rat as malignant, Damjanov and Friedman *(104*) suggested that the testicular mesotheliomas in acrylamide-treated rats may be benign based on their cellular uniformity, small lesion size, and absence of peritoneal seeding and metastasis.

2.4.3 Carcinogenicity classifications

IARC *(8)* classifies acrylamide as a Group 2A compound, probably carcinogenic to humans. The classification was based upon inadequate evidence in humans but sufficient evidence in experimental animals. Also considered in the evaluation were positive genetic toxicity results in *in vivo* and *in vitro* assays, formation of acrylamide and glycidamide DNA adducts in mice and rats, and formation of acrylamide and glycidamide hemoglobin adducts in humans and rats.

NTP classifies acrylamide as a compound that is reasonably anticipated to be a human carcinogen *(9)*.

The US EPA *(56)* classifies acrylamide as a B2 compound, probable human carcinogen. The classification is based upon inadequate human data and sufficient evidence of carcinogenicity in animals.

ACGIH *(30)* classifies acrylamide as an A3 compound, Confirmed Animal Carcinogen with Unknown Relevance to Humans.

2.5 Potentially Sensitive Subpopulations

2.5.1 Age-related susceptibility to neurotoxicity in humans and animals

In a case study of a Japanese family poisoned by acrylamide in their well water, more severe neurologic symptoms were reported in adults (aged 40 – 65 years) than in children (aged 10 – 13 years) *(51)*. The study author noted that it was unknown if the children were less susceptible than adults or drank less water from the well due to the time they spent at school.

A limited number of animal studies examined susceptibly of young versus mature animals to acrylamide-induced neurotoxicity, but findings were inconsistent.

As part of a series of experiments examining electrophysiologic and histologic evidence of acrylamide-induced neurotoxicity, Fullerton and Barnes *(105)* administered 4 doses of 100 mg/kg bw acrylamide by gavage at weekly intervals to 5-, 8-, 26-, and 52-week-old male and female Porton rats (n=6/group). The 52-week-old animals were severely affected after 3 doses, while the 26-week-old animals were severely affected and youngest animals were only mildly affected after 4 doses. **[Parameters examined in these animals were not specified and data were not shown.]**

Kaplan and Murphy *(106)* examined age-related effects of acrylamide exposure on rotarod performance in male Holtzman rats in a university study funded by a NIOSH grant. At the ages of 5, 7, 11, and 14 weeks, 12 rats/age group were tested daily on a rotarod and then given 50 mg/kg bw/day acrylamide in water by i.p. injection. Older rats failed sooner on the rotarod test with mean failure days (±SEM) of 5.3 ± 0.19, 5.5 ± 0.20, 6.4 ± 0.22, and 7.3 ± 0.22 in rats aged 14, 11, 7, and 5 weeks, respectively. Differences between the 5-week-old and 11- and 14-week old rats were statistically significant. However, the recovery period occurred later in young rats (19.2 ± 0.4, 15.6 ± 0.5, 13.8 ± 0.66, and 14.8 ± 0.48 days in 5-, 7-, 11-, and 14-week-old rats, respectively). Results in the youngest group of rats were statistically significant compared to all other age groups. The study authors concluded that adult rats were more susceptible to acrylamide toxicity than young rats.

In a study funded by an NIH grant, Suzuki and Pfaff *(107)*, conducted light or electron microscopy

examinations of nervous system structures from 30 suckling Osborne-Mendel rats ("day 1" 5.0–8.0 g) and 28 adult rats (150–300 g) that were i.p. injected with 50 mg/kg bw acrylamide, 3 times weekly, up to 18 times. A control group was injected with saline. There was a shorter latency for appearance of clinical symptoms in the immature animals (5 or 6 injections) versus adult rats (7 or 8 injections), but symptoms were more severe in the adult animals. **[The Expert Panel considers the difference between 5–6 and 7–8 injections to be of questionable significance.]** In the immature animals, slight weakness in hindlimbs became more pronounced and progressed to an inability to stand on hind legs as dosing continued, but some animals showed signs of recovery during the time period while they were still receiving acrylamide injections. Mature animals experienced hindlimb weakness that eventually led to complete paralysis and wasting of hindlimb muscles; weakness persisted for 1 month following the injection period. Axonal and myelin alterations were seen in the younger rats at earlier stages of neuropathy, but the changes became more pronounced and complicated in adult rats. Evidence of neurologic regeneration (e.g., growth cones and axonal sprouts) appeared in immature rats during the injection period, but was not seen in adult rats until 20 days following the last injection. The study authors concluded that young rats are more susceptible to acrylamide but also have a greater ability for regeneration than do adult rats.

Ko et al. *(108)* examined the effects of age on acrylamide-induced neurotoxicity in male ICR mice in a study conducted at a Taiwanese university. Groups of 3-week-old and 8-week-old mice were given drinking water containing 400 ppm acrylamide. Acrylamide intake was estimated at (mean ± SD) 91.8 ± 20.6 mg/kg bw/day in the 3-week-old mice and 90.8 ± 10.9 mg/kg bw/day in the 8-week-old mice. Control mice for each age group were given drinking water without acrylamide. Time to reach three different stages of neurologic symptoms was recorded in the treated mice. An initial stage was characterized by normal appearance, but decreased performance on rotarod and swelling of motor nerve terminals. Signs observed in the early stage included paraparesis and terminal nerve swelling. Symptoms of the late stage included quadriparesis, denervation, and decreased amplitude of muscle-action potential. Total numbers of mice treated were not specified but 3–24 mice/group were examined pathologically during 3 different periods. Each of the stages occurred significantly earlier in the 3-week-old mice than in the 8-week-old mice (mean days ± SD): 7.1 ± 1.1 vs. 15.6 ± 4.0 days, respectively, for the early stage and 15.3 ± 2.1 vs. 31.7 ± 6.0 days, respectively, for the late stage. The study authors concluded that younger mice are more susceptible to acrylamide-induced toxicity and that pathologic symptoms occur prior to neurologic symptoms.

Husain et al. *(109)* studied the effects of acrylamide exposure on brain neurotransmitters in developing and mature male Wistar rats in a study conducted at an Indian research center. In the first study, dams were orally administered saline or 25 mg/kg bw/day acrylamide during the entire lactation period. The male offspring of the dams were sacrificed at 2, 4, 8, 15, 30, 60, or 90 days of age for an examination of brain neurotransmitter levels. During each time period, brains from 1 to 3 rats were pooled and six observations were made. Compared to rats in the control group, the rats exposed to acrylamide through milk had significantly lower levels of brain noradrenaline and dopamine at 2–15 days of age and 5-hydroxytryptamine at 2–30 days of age. Monoamine oxidase activity was significantly increased and acetylcholinesterase activity was significantly decreased at 2–30 days of age. In a second study, male rats were orally administered saline or 25 mg/kg bw/day acrylamide for 5 days at 12, 15, 21, or 60 days of age. Neurotransmitter levels were measured in various brain regions. It appears that at least six animals per group were examined and it was stated that reported values represented the mean of

five observations. Significant reductions in neurotransmitter levels in treated compared to control rats that were observed only in immature rats (≤21-days-old) included noradrenaline in the pons medulla and basal ganglia and dopamine in the pons medulla. Neurotransmitter levels reduced in all ages of treated compared to control rats included noradrenaline in midbrain; dopamine in cerebellum and midbrain; and 5-hydroxytryptamine in pons medulla, hypothalamus, and cerebral cortex. The study authors concluded that immature rats are more vulnerable to neurotoxicity induced by acrylamide exposure and that effects are localized within certain brain regions.

Due to unpublished observations that younger rats are more susceptible to acrylamide-induced paralysis, Dixit et al. *(110*) compared hepatic GST activity and glutathione content in young and mature albino rats. The study was conducted at an Indian research center. At the ages of 9, 15, or 26 days, or 4 months, rats were given 50 mg/kg bw/day acrylamide by i.p. injection for 5 days **[number of rats in each group not specified]**. Control rats were injected with sodium chloride vehicle. One day following the last injection, livers were homogenized for a determination of hepatic GST activity and glutathione content. Generally, GST activity increased with age and acrylamide treatment reduced GST activity in all age groups. The magnitude of GST reduction was greatest in the 15-day-old rats, in which early development of paralysis was reported **[neurotoxicity data not shown]**. Acrylamide treatment resulted in significant decreases in reduced and oxidized glutathione content only in the 26-day-old rats. **[Methods of statistical analysis were not discussed for any of the data reported in this study.]**

[The Expert Panel finds the literature on age-related susceptibility to be difficult to interpret, with some studies showing greater susceptibility in young animals and others not showing such differences in susceptibility.]

2.5.2 Ontogeny, polymorphism, and other factors affecting metabolism

2.5.2.1 GST and glutathione

As noted in Section 2.1.3, a major pathway of acrylamide biotransformation is conjugation with glutathione, catalyzed by GST. Cytosolic GST is a family of soluble dimeric enzymes consisting of 13 different subunits from 5 different subclasses *(111*):

1. alpha (GSTA1, GSTA2, GSTA3, GSTA4)
2. mu (GSTM1, GSTM2, GSTM3, GSTM4, GSTM5)
3. pi (GSTP1)
4. theta (GSTT1, GSTT2)
5. sigma (GSTZ1)

Subunits can dimerize only with members of the same class to form homodimers or heterodimers *(111*). The alpha, mu, and pi enzymes are the most abundant GST classes in mammalian species *(112*).

McCarver and Hines *(111*) reviewed the ontogeny of GST and other phase II metabolizing enzymes. Limited information is available on the ontogeny of human hepatic GST. The ontogeny of human hepatic GST is summarized in Table 19. GSTA1 and GSTA2 are expressed in the fetus and expression reaches adult levels at 1 – 2 years of age, following a 1.5 – 4-fold increase. Low levels of GSTM are also detected in the fetus, and expression increases 5-fold at birth to reach adult levels. GSTP1 expression

is highest in 10–22-week-old fetuses and decreases during the second and third trimesters; GSTP1 is expressed in neonates but not adults. McCarver and Hines *(111)* concluded that though limited, the information on GST ontogeny demonstrates that substantial changes occur during development. Such changes can affect chemical disposition and clinical outcomes, which also depend upon the balance of other phase I and phase II enzymes. Currently, the information is inadequate to predict adverse reactions or determine appropriate therapies for fetuses, neonates, infants, and children.

Table 19. Ontogeny of Human Hepatic GST, McCarver and Hines *(111)*.

Gene	*Prenatal Trimester*			*Neonate*	*1 Month-1 Year*	*1-10 Years*	*Adult*
	1	*2*	*3*				
GSTA1/A2	+	+	+	+	+	+	+
GSTM	+	+	+	+	+	+	+
GSTP1	+	+	+	+	–	–	–

GST polymorphisms are recognized, most notably null phenotypes for the GSTM1 (GSTM1*0) and GSTT1 (GSTT1*0) alleles *(112)*. No gene products are expressed in individuals who are homozygous for the null phenotype. Frequency of GSTM1*0 homozygosity is 58% in Chinese, 52% in English, 48% in Japanese, 43% in French, and 22% in Nigerian individuals *(112)*. Frequency of GSTT1*0 homozygosity is 16% in English, 12% in German, 38% in Nigerian, and 32% in West Indian individuals.

Friedman *(11)* noted that reductions in glutathione levels can increase susceptibility to acrylamide-induced toxicity by leaving cell membranes less protected against oxidative stress. Factors that can reduce glutathione levels include diets low in the amino acids cystine and methionine; oxidative stress; and liver damage.

2.5.2.2 Cytochrome P450

As noted in Section 2.1.3, a second major pathway of acrylamide biotransformation is oxidation to glycidamide through cytochrome P450. CYP2E1 was identified as the enzyme responsible for biotransformation of acrylamide in mice and rats, but no information on the specific enzyme in humans could be located. **[The Expert Panel finds it reasonable to suspect that CPY2E1 is the isoform responsible for acrylamide biotransformation in humans.]** Hines and McCarver *(113)* noted that fetal liver contains 30–60% of total adult cytochrome P450 content; levels continue to increase at birth and reach adult levels at 10 years of age. However, significant expression differences are noted among individual P450 enzymes. Anzenbacher and Anzenbacherova *(114)* noted that polymorphisms among cytochrome P450 enzymes could result in defective, qualitatively different, reduced, or enhanced activities of the enzymes. Enzyme activities could also be affected by factors that induce or inhibit enzymes, including diet, age, and health. Calleman et al. *(28)* noted that mixed results were found in animal studies examining the effects of inducers or inhibitors of oxidative metabolism on acrylamide-induced neurotoxicity. Calleman noted that some inducers or inhibitors can impact other metabolic enzymes, including GST.

2.5.3 Gender-related differences

There is no indication that males or females are more susceptible to general toxicity induced by

acrylamide exposure. Acrylamide has adverse effects on the reproductive systems of males, but not females, as discussed in Section 4.

2.6. Summary of General Toxicology and Biologic Effects

2.6.1. Toxicokinetics and Metabolism

Qualitative absorption of acrylamide after food ingestion was demonstrated in humans *(27)* and other studies provided evidence of acrylamide absorption through oral, inhalation, and dermal exposure in humans, rats, mice, dogs, and/or pigs *(2-5, 8, 28, 39, 40)*. Acrylamide absorbed through any exposure route is rapidly distributed throughout the bodies of rats, pigs, and dogs *(4)*. Higher concentrations were found in livers and kidneys of rats *(2)*, but there was no evidence of bioaccumulation in neural tissues *(4)*. Acrylamide and/or its metabolite glycidamide react with sulfhydryl and amino groups on hemoglobin to form persistent (long-lived or stable) adducts in red blood cells, which are useful as a biomarkers of exposure *(2, 4, 28, 39)* and with protamines in sperm *(94, 96, 97)*. Glycidamide but not acrylamide was observed to form DNA adducts at detectable levels in rats *(16, 28)*.

Studies in rats indicate that acrylamide is rapidly metabolized with more than 90% of the dose excreted as metabolites in urine within 1 week *(2-4, 39)*. In one major biotransformation pathway, hepatic glutathione-S-transferase (GST) catalyzes the first-order conjugation of acrylamide with glutathione, ultimately leading to the formation of the urinary metabolites N-acetyl-S-(3-amino-3-oxypropyl) cysteine in rats and mice and N-acetyl-S-(2-carbamoylethyl) cysteine in humans *(4, 11, 48)*. In another major biotransformation pathway in humans and experimental animals, glycidamide is formed through a saturable enzymatic pathway involving cytochrome P450 *(48)*. Cytochrome P450 2E1 (CYP2E1) is the specific enzyme involved in this reaction in mice *(49)*. Glycidamide is further metabolized through conjugation with glutathione to form mercapturic acids or is metabolized by epoxide hydrolase (epoxide hydratase) *(28, 48)*. Percent acrylamide conversion through each major pathway varies by species and dose. A greater percentage of acrylamide is converted to glycidamide in mice than in rats *(8, 28, 39)*, and relatively more glycidamide is produced per unit of acrylamide dose at lower dose rates *(28)*. High doses of acrylamide can inhibit GST and deplete GSH *(2, 3, 39)*, but a model suggests that appreciable GSH depletion is not expected to occur in rats until doses exceed 10 mg/kg bw/day *(48)*. A critical study in rats demonstrated nonlinearity (saturation) of glycidamide adduct formation at i.p. doses between 5 and 100 mg/kg bw/day, as evident by the change in the percentage of acrylamide converted to glycidamide at high dosage. Glycidamide formation was estimated at 51 and 13% at the low (5 mg/kg) and high (100 mg/kg) dose, respectively *(50)*. There is no information on metabolic saturation in humans.

Available human data are unreliable for quantitatively estimating acrylamide elimination. In experimental animal studies, plasma half-lives of 2 h were reported for the parent compound and for glycidamide following administration of acrylamide at doses up to or exceeding 20 mg/kg bw *(4, 14, 39)*. Calculations by the Expert Panel using the Kirman (2003) rat pharmacokinetic model indicate a half life for acrylamide itself of about 1.8 h at low doses, and a similar half life for glycidamide of about 3.0 hrs. Different half life observations are produced based on measurements of total radioactivity (including all metabolites and acrylamide bound to macromolecules). Dosing of rats with ^{14}C labeled acrylamide results in biphasic tissue distribution and elimination of total radioactivity, with an initial half-life of 5 h and a terminal half-life of 8 days *(2, 4)*. The urinary excretion half-life of total

radioactivity was reported at 8 h in rats *(2, 3)*. The majority of ^{14}C label (40–90%) is eliminated through urine in rats *(28, 39)*, while a smaller percentage (15%) is thought to undergo enterohepatic circulation with elimination of 6% radiolabel through feces *(2, 4, 39)*. Elimination through exhaled air accounts for a small fraction of the administered dose *(28)*.

Human placental transfer of acrylamide was demonstrated in a study that found the acrylamide hemoglobin adduct, N-2-carbamoylethylvaline, in maternal and umbilical cord blood (n=11), with concentrations in fetuses estimated to be equivalent to mothers when adjusted on a weight basis per unit time *(43)*. The results of the human study are consistent with studies in rats, mice, dogs, rabbits, and pigs, which also demonstrated placental transfer of acrylamide *(44-47)*. In one study conducted with a single i.v. dose of 5 mg/kg bw radiolabeled acrylamide, radiolabel passed through the placenta of dogs on GD 60 (fetal/maternal blood ratio 0.823) and pigs on GD 109 (fetal/maternal blood ratio 0.69) *(46)*. Brains of fetal dogs and pigs contained high concentrations of acrylamide and indicated no effective blood-brain barrier at the ages studied *(46)*.

Transfer of acrylamide to human milk was demonstrated in a study conducted with two women. Ingestion of 800–1,000 μg acrylamide through potato chips resulted in milk concentrations of 3.17–18.8 ng/mL acrylamide within the time period of 3–8 h following ingestion *(27)*.

In male mice gavaged with 116–121 mg/kg bw radioactive acrylamide, movement of radiolabel within the male reproductive tract paralleled that of spermatids, with detection of radiolabel in testis parenchyma at 1 h, in seminiferous tubules and head of epididymis at 9 h, and in the tail of epididymis and crypts of glans penis epithelium at 9 days *(45)*. In experimental animal studies, there is a delay in reaching peak radiolabel levels in testis *(2, 4)*. The first phase of the elimination half-life of total radioactivity (8 h) in testis is slightly longer than the elimination half-life observed in other tissues (5 h) *(42)*.

2.6.2. General Toxicity

2.6.2.1 Human

Effects of acute or subacute acrylamide poisoning are described in numerous reviews. CNS symptoms consisting of confusion, memory problems, sleepiness, slurred speech, inability to concentrate, and hallucinations develop within hours or days of poisoning *(3, 4)*. A latency period of days to weeks is followed by insidious development of peripheral neuropathies characterized by loss of sensation, paresthesia, numbness, muscle weakness, and/or wasting in extremities, and decreased tendon reflexes *(3, 4)*. Axonopathies are most commonly observed and impairment occurs in sensory fibers prior to motor fibers *(2)*. Toxicity to midbrain or cerebellum may result in tremors and gait disturbances *(2)*. Possible autonomic nervous system involvement was suggested by reports of sweating, peripheral vasodilation, and difficulty urinating and defecating in some cases *(3)*. Anorexia, weight loss, and nystagmus have also been observed with acrylamide exposure *(3, 4)*. Reduced action potential in distal sensory neurons is the most consistent electrophysiologic finding *(3)*. Most individuals who survive acrylamide poisoning recover fully over a period of months to years *(2, 3)*. Symptoms consistent with CNS involvement followed by peripheral neuropathies were reported in a woman who ingested 375 mg/kg bw acrylamide *(2, 5)*. Similar symptoms were also reported in 3 adults from a Japanese family who were poisoned by acrylamide in their well water (400 ppm at a single time point), but they recovered fully within 4 months *(2, 5, 51)*. Two children in the family (ages 10 and 13 years) were

less severely affected than adults, possibly as a result of lower exposures due to school attendance during the day.

In cases of occupational exposure to acrylamide through inhalation and dermal contact, common symptoms included peeling of skin at the site of contact (i.e., palms), followed by development of peripheral neuropathies *(4, 5*). It is difficult to determine exposure levels in workers experiencing toxicity since air concentrations are infrequently measured and it is difficult to determine the extent of dermal exposure. A review by the EU *(5*) noted that prevalence of symptoms related to peripheral neuropathies is increased in workers exposed to >0.3 mg/m^3 acrylamide (8-h TWA), but contribution from skin exposure is unknown. NICNAS *(52*) concluded that electroneuromyographic changes such as decreased sensory action potential amplitude and prolonged ankle tendon reflex can precede neuropathic symptoms and are therefore important in early detection of neurotoxicity in workers. Calleman *(28*) reported some success in correlating an index of neurotoxicity with acrylamide hemoglobin adducts in a group of highly exposed workers.

2.6.2.2 Experimental Animal

Symptoms of acute acrylamide exposure in laboratory animals such as rats, mice, guinea pigs, rabbits, and cats include ataxia, tremors, convulsions, muscular weakness, circulatory collapse, weight loss, and/or death *(3*).

Neurologic effects observed with repeated acrylamide dosing of animals such as rats, mice, cats, dogs, and monkeys are qualitatively consistent with those observed in humans *(3, 39*). Animals develop peripheral neuropathy and overt signs that include tremors, incoordination, motor dysfunction, neuromuscular weakness, and reduced motor-nerve conduction velocity *(3, 39*). Histologic findings include degeneration of distal long sensory and motor peripheral nerve fibers, long axons in the spinal cord, Purkinje fibers in the cerebellum and optic nerve, and autonomic fibers. Demyelination of sciatic, tibial, median, and ulnar nerves has also been observed.

Studies designed to identify NOAELs were limited to rats. In risk assessments conducted by IRIS *(56*) and the EU *(5*), subchronic and chronic drinking water studies in rats *(55, 57*) were used to select neurotoxicity NOAELs ranging from 0.2 to 0.5 mg/kg bw/day and LOAELs of 1–2 mg/kg bw/day based on neurological lesions. Severity of neurological lesions increased with dose. Clinical signs of neurotoxicity were only observed in doses exceeding LOAELs and partial-to-full reversal of lesions was observed during a recovery period. Organs affected at higher acrylamide doses in animal studies included kidney, liver, and the hematopoietic system *(3, 5*).

Reproductive organs in rats were targets of toxicity following 92–93 days of dosing with 20 mg/kg bw/day acrylamide in drinking water *(55*). Effects included decreased size of uterus, testis, and male accessory sex organs; testicular atrophy; mineral in seminiferous tubules; and cellular debris and decreased spermatogenic elements in epididymides. Following a 144-day recovery period, there was partial reversal of testicular effects. Neoplastic lesions observed in reproductive organs are discussed in Section 2.4.2.

2.6.3 Genetic Toxicity

Genetic toxicity in somatic or bacterial cells was reviewed by the EU *(5*). *In vitro* studies in

mammalian cells consistently demonstrated clastogenicity, cell transformation, and cell division effects (e.g., polyploidy, spindle disturbances, and malsegregation). With the exception of studies examining cell division effects, metabolic activation was included in at least one study examining each endpoint. In mammalian cells, inconsistent results were obtained for the induction of point mutations, unscheduled DNA synthesis, and sister chromatid exchanges. In bacterial cells, with and without metabolic activation, acrylamide did not induce point mutations. *In vivo* somatic cell tests conducted mostly in mice treated by i.p. dosing, and in a few cases by diet or gavage, demonstrated the induction of chromosomal aberrations, aneuploidy, polyploidy in bone marrow, and micronuclei in erythrocytes *(5, 60*). In the flow cytometric micronucleus study conducted by Abramsson-Zetterberg *(60*), acrylamide administered i.p. to mice at dose levels between 1 and 30 mg/kg induced a non-linear increase in the frequency of micronucleated polychromatic erythrocytes in blood; the lowest effect level was 6 mg/kg bw. A mouse spot test in GD 12 mice demonstrated the susceptibility of fetal somatic cells to mutation after acrylamide treatment of the dam *(61*). Negative results were obtained in *in vivo* tests of unscheduled DNA synthesis (liver), sister chromatid exchanges (bone marrow, mitogen-stimulated splenocytes), and chromosomal aberrations in mitogen-stimulated splenocytes from mice. The EU *(5*) and JIFSAN *(39*) concluded that acrylamide is likely clastogenic and interferes with chromosomal segregation but that it does not cause point mutations. However, an *in vitro* study using embryonic fibroblasts from BigBlue® mice demonstrated that acrylamide induced mutations at the CII transgene, while an *in vivo* MutaMouse® study reported the induction of mutations at the LacZ locus in bone marrow cells *(59*). Therefore, the Panel noted that acrylamide could be a weak inducer of point mutations. The Panel noted that acrylamide was positive in both the presence and the absence of exogenous metabolic activation and that metabolic activation did not appear to modify its genetic toxicity. This observation suggests either that acrylamide is not metabolized in these *in vitro* systems or, if it is metabolized, the primary metabolite(s) must be as reactive as is acrylamide itself.

Germ cell genetic toxicity of acrylamide has been evaluated primarily in male mice and to a lesser extent in male rats. No studies on germ cell genotoxicity have been reported for female rodents. A number of reports were reviewed in which acrylamide treatment was associated with germ cell aneuploidy, chromosome breaks, fragments, exchanges, and univalents *(62, 65, 66, 70, 71*) in germ cells or with micronuclei (which represent the consequence of structural or numerical chromosome damage) in spermatids *(63, 67-69*). Based on the timing of exposure prior to collection of the germ cells, sensitive germ cell stages have been estimated. Most investigators have reported chromosome abnormalities after exposure of spermatocytes but some authors *(62, 68, 70*) have described chromosome damage after treatment of spermatogonia.

Dominant lethal studies have been performed with acrylamide administered in drinking water to rats or mice *(74, 78, 81*), by gavage in rats*(75, 82*), by i.p. injection in mice *(76, 80, 83-86*), and by dermal application in mice *(77*). Late spermatids and early spermatozoa appear to be the germ cell stages most sensitive to acrylamide-induced dominant-lethal effects. Lowest effective doses of acrylamide are reported to be 30 ppm in drinking water in rats (a cumulative dose of about 200 mg/kg by the time of mating) *(74*), 6.78 mg/kg bw/day in drinking water in mice (a cumulative dose of 949 mg/kg over the 20 week exposure period *(78*)), 15 mg/kg bw/day for 5 days by gavage in rats *(75*), 75 mg/kg i.p. in mice (single dose) *(76*), and 25 mg/kg bw/day for 5 days applied dermally to mice *(77*). The possible role of glycidamide in mediating acrylamide-induced dominant lethal effects

was investigated by Adler et al. *(79*), who gave 1-aminobenzotriazole to prevent cytochrome P450 metabolism. The dominant lethal effect of acrylamide was attenuated during the second but not the first week after treatment with 1-aminobenzotriazole, raising the possibility that acrylamide itself has dominant lethal effects (or anti-fertility effects that were interpreted as dominant lethal effects).

The administration of acrylamide i.p. to male mice was associated with chromosome abnormalities in first metaphase zygotes sired by treated males *(88, 89*). The lowest effective dose was 75 mg/kg bw *(88*). Consistent with results of dominant lethal testing, the late spermatid and spermatozoa stages were the most sensitive in the production of this effect. Studies by Holland et al. *(86, 90*) were generally supportive of the production of abnormal pre-implantation conceptuses through induction of sperm-mediated genetic damage by acrylamide. Three studies *(66, 83, 91*) identified heritable reciprocal translocations in the offspring of male mice treated i.p. with acrylamide at dose levels as low as 40 mg/kg bw/day × 5 treatments or 50 mg/kg bw as a single treatment, and 2 studies *(76, 92*) identified specific locus mutations in the offspring of male mice treated with i.p. acrylamide at dose levels of 50 mg/kg × 5 treatments and 100 mg/kg, respectively. Along with the dominant lethal studies, these reports demonstrate the germ-line genetic effects of acrylamide in male mice. The mechanism of toxicity of acrylamide to the genetic material of male germ cells is correlated with protamine binding, possibly by glycidamide rather than by acrylamide itself, with DNA breakage secondary to stresses imposed on the chromatin by protamine binding *(94, 96, 97*).

2.6.4 Carcinogenicity

2.6.4.1 Human

Epidemiological studies examining the relationship between cancer and occupational or dietary exposure to acrylamide reported negative findings *(98-102*). However, the EU *(5*) and IARC *(8*) judged the studies to be inadequate for assessing cancer risk due to inadequate power to detect the magnitude of effect suggested by experimental animal studies.

2.6.4.2 Experimental animal

Two cancer studies were conducted in rats exposed to acrylamide through drinking water for 2 or more years *(57, 103*). The more recent study was conducted to clarify some of the effects observed in the first study. Neoplastic effects (and doses) that were consistently increased in the two studies were testicular mesotheliomas (0.5 and 2 mg/kg bw/day), benign and malignant mammary gland tumors (1 and 2 mg/kg bw/day), and benign and malignant thyroid tumors (1 and 2 mg/kg bw/day). Increased incidence of tumors in CNS glial cells, clitoral gland, and oral tissues in rats exposed to 2 mg/kg bw/day acrylamide in first study was not replicated in the second study.

2.6.4.3 Carcinogenicity Classifications

Table 20 lists acrylamide cancer classifications by national and international agencies.

Table 20. Acrylamide Cancer Classifications

Agency	*Classification*	*Explanation*
IARC	2A	Probably carcinogenic to humans
US EPA	B2	Probably human carcinogen
ACGIH	A3	Confirmed animal carcinogen with unknown relevance to humans
NTP	Reasonably anticipated to be a human carcinogen	

2.6.5 Potentially Sensitive Subpopulations

In a Japanese family poisoned by acrylamide in their well water, children (aged 10 and 13 years) experienced less severe neurotoxic effects than adults, but it could not be determined if the children were less susceptible or received a lower exposure due to time spent at school *(51*). A number of studies compared neurotoxicity in young versus mature rats or mice, but the Expert Panel was unable to draw conclusions about age-related susceptibility due to inconsistent findings *(105-109, 110.*).

As noted in Section 2.5, GST-catalyzed conjugation of acrylamide with glutathione represents a major pathway of acrylamide biotransformation. Biotransformation of acrylamide to glycidamide by cytochrome P450 is another major metabolic pathway. CYP2E1 was identified as the enzyme responsible for acrylamide biotransformation in mice *(49*), and the Panel finds it reasonable to suspect that CYP2E1 is the isoform that biotransforms acrylamide in humans. Since all metabolic activities can be affected by ontology, polymorphisms, diet, and health *(11, 111, 112*), the current information is insufficient for predicting the effects of variable metabolic enzyme activity on acrylamide-induced toxicity in humans.

3.0 DEVELOPMENTAL TOXICITY DATA

3.1 Human Data

No human data on acrylamide developmental effects were located.

3.2 Experimental Animal Data

3.2.1. Non-neurologic developmental endpoints

Edwards *(44)* treated Porton strain rats with acrylamide **[purity not specified]** in the diet. In the first experiment, 8 females were given 200 ppm in powdered feed from the day a plug was found until parturition. Offspring were apparently reared by their dams and were followed until 6 weeks of age with weekly weights taken and observations made for abnormal gait. The dams were described as showing "slight abnormalities of gait" at the times the litters were born. There were no external abnormalities. The birth weights were similar to a control group **[it is not clear if this control group was the same as the control group used in the second experiment, described below]** and litters were described as gaining weight normally until weaning, without abnormalities of gait. No detailed information was presented.

In a second experiment by Edwards *(44)*, 6 pregnant females were given 400 ppm acrylamide in the diet from the day of mating until 20 days thereafter when they underwent cesarean section. Six control dams were fed powdered diet without acrylamide. Uteri were examined for resorptions **[presumably uteri: the text says that placentas were examined for resorptions]**. One third of fetuses underwent Wilson sectioning and the remaining fetuses were processed in alizarin red for skeletal evaluation. Maternal feed intake was reduced in the acrylamide group (12.0 ± 0.8 g/rat/day, mean ± SEM) compared to the control group (23.0 ± 1.8 g/rat/day). The weights of the rats were not given **[assuming a 300-g pregnant rat, 12 g/rat/day feed containing 400 ppm acrylamide represents a daily dose of 16 mg/kg bw/day]**. Fetal weights were reduced by acrylamide treatment (acrylamide 2.4 ± 0.05 g, control 3.2 ± 0.05 g, mean ± SEM). **[The *P* value reported by the authors using Student *t*-test is > 0.2; however, the *t*-test performed by CERHR gave *P* < 0.0001.]** Four fetuses were found dead in one uterine horn in the acrylamide-treated group and three resorptions were present in one litter in the control group. There were no fetuses with abnormalities and "there was no increase in the occurrence (approx. 10%) of a naturally occurring defect in the rib structure." No data were shown.

In a third experiment, Edwards *(44)* administered 100 mg/kg acrylamide in water i.v. to each of four pregnant rats on GD 9 **[plug date unspecified]**. The rationale for this timing was the statement that GD 9 is when the nervous system is most susceptible to teratogenic effects. Pups were apparently delivered and reared by their dams and on the third day of life, pups were examined for external appearance and righting reflex. Offspring were followed for 6 weeks during which the day of eye opening was noted and animals were evaluated for gait and were weighed (weekly). Two rats from each litter **[sex unspecified]** were perfused with formaldehyde/acetic acid/methanol, and brains, spinal cord, and peripheral nerves were evaluated by light microscopy **[sectioning and staining unspecified]**. Two rats per litter **[sex unspecified]** were killed with a barbiturate for dissection for gross abnormalities. Brain weight was recorded. Four pregnant control rats were injected with saline and presumably handled in the same manner. There were no differences between groups in birth weight, pup weight 24 h or 3 days after birth, righting reflex, or day of eye opening **[data were not shown]**. There were

no abnormalities of nervous system tissues by gross examination or by light microscopy.

Strengths/Weaknesses: Weaknesses include a limited number of doses, a very limited number of pregnant rats per group, and a limited number of outcomes measured. Because data necessary for full evaluation are missing from this report, and only a few litters were used in each experiment, the conclusions of the report are questionable.

Utility (Adequacy) for CERHR Evaluation Process: This study is suggestive only that the developing rat may be less sensitive than the dam to the standard neuronal toxicity of acrylamide. The protocol is inadequate to detect subtle changes or draw conclusions regarding dose-response.

An industry-sponsored study conducted at Bio/dynamics Inc. *(115*) examined developmental toxicity in Sprague-Dawley CD rats. Twenty female rats/group were given acrylamide (100% purity) in the diet at 0, 25, or 50 ppm for 2 weeks prior to mating. The rats were mated with untreated males and following the first sign of mating (GD 0), resumed dietary acrylamide intake for the first 19 days of gestation. The study authors estimated acrylamide intake at 1.75–1.90 and 3.45–3.82 mg/kg bw/day in the 25 and 50 ppm dose groups, respectively. Rats were allowed to give birth and litters were culled to three male and three female pups on PND 4. Pups were examined for postnatal growth and mortality through the lactation period (PND 21). Statistical analyses included *F*-test and Student *t*-test, Cochran approximation, and chi-square. The only effect reported for maternal body weight was a slight but significant reduction in body weight gain in the 50 ppm dams during the pre-mating period. There were no differences in food intake among treatment groups. Alopecia was noted in dams from both acrylamide-treatment groups. Mating and pregnancy indices were comparable between all treatment groups. A total of 13, 15, and 16 litters were available for evaluation in the control, 25 ppm, and 50 ppm dose groups, respectively. There were no differences in mean gestation length, fetal viability at birth, number of live pups at birth, litter size on PND 4, pup weights, or pup survival on PND 4, 14, and 21.

At weaning (PND 21), 4 pups (2/sex) from the control group and 8 pups (4/sex) from the 50 ppm dose group were sacrificed for histopathologic evaluation of brain, spinal cord, and sciatic, tibial, and plantar nerves *(116*). The samples were fixed in Dalton chrome osmium solution, dehydrated in ethanol, cleared with propylene oxide, and embedded for examination by light microscopy. Acrylamide exposure did not produce major teratogenic effects in the brain. Some fine structural differences were noted between control and acrylamide-treated animals, including scattered nerve fiber degeneration in the sciatic and optic nerves. The study authors noted that nerve fibers from treated animals were more prone to preparation artifacts than were nerve fibers from control animals. **[Details concerning the incidence and severity of neurologic lesions were not provided in the report.]**

Strengths/Weaknesses: The data presented are suggestive of specific neuronal susceptibility, and the observation that fibers are apparently more fragile with acrylamide treatment raises the following concern: the observation could mean the findings were over-interpreted or nerve fibers from exposed animals actually may have been affected in additional ways not directly measurable within the evaluation. The group size was large, but the sample size used for neuropathology evaluation was small. The standard endpoints of reproductive performance and litter measurements do not suggest toxicity in this study; only the suggestive neuronal effects at weaning suggest developmental toxicity. This study would be stronger if it included either functional offspring measurements or more extensive

neuropathology evaluations, either at weaning or at later ages, to evaluate persistence or recovery of the reported findings. Another weakness is the limited dose range. Strengths include estimation of intake and the inclusion of treatment prior to breeding, which can be viewed as a strength for detecting reproductive as well as developmental effects, but a weakness if trying to define sensitive period of exposure (because the results were negative, this potential issue is not critical).

Utility (Adequacy) for CERHR Evaluation Process: From a non-neurologic perspective, there appears to be no indication of standard reproductive and developmental toxicity. The sample size and procedures are adequate for use in this regard. The evidence for lack of developmental toxicity covers a limited dose range.

In a study from NIEHS, Walden et al. *(117*) evaluated the activity of five intestinal enzymes in the offspring of acrylamide-treated Sprague-Dawley rats. Animals were treated from GD 6 to 15 (insemination = GD 0) with acrylamide **[purity not given]** 20 mg/kg bw/day or water by gavage. There were 17 dams in each treatment group. On the day of birth (PND 0), pups in each treatment group were pooled and divided among dams to produce four groups: control dams with control pups; treated dams with treated pups; control dams with treated pups; and treated dams with control pups. Four pups were removed from each litter without regard to sex for intestinal enzyme analysis on PND 14, 21, and 60. **[This design suggests that pups were reassigned to dams so that litter size initially was 12/litter. If not, it is unclear how there were 4 pups/litter/age.]** The first 10–15 cm of intestinal mucosa was scraped and homogenized **[the report implies that the scrapings of the four animals were pooled]**. Kinetic spectrophotometric assays were performed for alkaline phosphatase, citrate synthase, and lactate dehydrogenase. Endpoint spectrophotometric assays were performed for acid phosphatase and β-glucuronidase. Dams were killed on PND 24, after weaning, and intestinal enzymes were measured by the same methods. Statistical analysis was performed by Mann-Whitney *U* test using a *P* value < 0.05 as the criterion for statistical significance. **[The question of multiple comparisons is not addressed. Five enzymes measured at 3 time points in 4 groups of animals yields 60 possible comparisons. The Expert Panel notes that if the comparisons were completely independent (which is not likely), 60 comparisons would give a 95% likelihood of identifying a significant difference at a nominal *P* value of 0.05.]**

There were no differences in maternal body weight, or in litter averages for pup number, weight, or sex ratio. Dam intestinal enzyme levels did not differ by treatment status. Results for offspring are summarized in Table 21. The authors concluded, "…prenatal and lactational exposure to acrylamide does significantly change intestinal enzyme levels…during the early stages of development…"

Strengths/Weaknesses: While the enzyme data were likely over-interpreted statistically, the pattern of findings presented in Table 21 are suggestive of changes in alkaline phosphatase and perhaps a "developmental" effect (delay or acceleration in normal pattern of enzyme changes) on PND 21 in β-glucuronidase. The meaning of such changes to animal status and health was not made clear by the authors and is not obvious to the Panel.

Utility (Adequacy) for CERHR Evaluation Process: The very lack of significant findings in a developmental study with adequate sample size is useful in the evaluation. The utility of this study is limited by use of a single dose and the consequent lack of dose–response information.

Table 21. Enzyme Levels in Proximal Intestine of Rat Pups after Prenatal Exposure to Acrylamide. From Walden et al. (117)

	Alkaline Phosphatase	*Citrate Synthase*	*Lactate Dehydrogenase*	*Acid Phosphatase*	β-*Glucuronidase*
Prenatal effect (C-T vs. C-C)					
PND 14	↑	↔	↔	↑	↔
PND 21	↑	↔	↔	↔	↑
PND 60	↓	↔	↔	↓	↔
Lactational effect (T-C vs. C-C)					
PND 14	↔	↔	↔	↑	↔
PND 21	↑	↔	↑	↔	↑
PND 60	↓	↔	↔	↔	↔
Combined effects (T-T vs. C-C)					
PND 14	↑	↔	↔	↔	↓
PND 21	↑	↔	↔	↓	↑
PND 60	↑	↔	↔	↑	↔

C-C: Control dam raising control pups
C-T: Control dam raising treated pups
T-C: Treated dam raising control pups
T-T: Treated dam raising treated pups
↑,↓ Significantly increased, decreased for indicated comparison at $P<0.05$, taken from bar graphs shown in the paper.
↔ Indicated comparison did not show a statistical difference at $P<0.05$.

In a study sponsored by the US EPA, Zenick et al. *(81)* gave acrylamide **[purity not specified]** to female Long-Evans hooded rats at 0, 25, 50, or 100 ppm in drinking water. There were 15 females with regular estrous cycles per group. **[CERHR estimated doses from graphs of body weight and fluid intake over the course of the experiment (**see Table 22**). The weight-adjusted acrylamide dose increased during lactation in all groups and increased during pregnancy in the 100-ppm group due largely to a lack of weight increase in spite of increased fluid intake.]**

Table 22. CERHR Estimates of Mean Acrylamide Doses (mg/kg bw/day) in the Female Reproduction Study of Zenick et al. (81)

Treatment Group	*Baseline*	*GD 1*	*GD 21*	*PND 3*	*PND 21*
25 ppm	4	4	4	4	9
50 ppm	6	5	9	8	14
100 ppm	11	10	14	12	24

Estimates rounded to the nearest whole number were made from graphic representations of mean body weight and mean fluid intake over the course of the study.

After 2 weeks of exposure of females to treated drinking water, untreated males were placed with the females overnight, without a water bottle. **[Presumably, water bottles were replaced when males were removed, and presumably, acrylamide treatment was continued through weaning; however, the study report is not specific on these questions.]** Females were given 7 days to mate. When presence of sperm in the vagina or a copulatory plug was noted, that day became GD 1. After 7 days of cohabitation without evidence of mating, acrylamide exposure was continued and females were monitored as though pregnant and were killed 23 days later if they had not produced a litter. **[In the male reproduction study reported in the same paper, a reverse 10:14 light:dark photoperiod is described with lights on at 10:00 pm. The photoperiod for the female reproduction study was not described.]** Dams were allowed to deliver spontaneously and rear their pups until weaning. On PND 4, litters were culled to four males and four females. **[It is presumed that exposure of the dam ceased at weaning.]** At weaning, litters were culled to two males and two females. Vaginal patency of the pups was evaluated beginning PND 28. Offspring were killed on PND 42. Data were analyzed with repeated measures ANOVA or one-way ANOVA with post-hoc Duncan test. Linear regression was applied to evaluate the possible contribution of dam body weight, cumulative acrylamide intake, cumulative fluid consumption, and their interactions on per litter birth and weaning weights.

Body weight was significantly decreased at several time points in the 100-ppm group compared to the control group, from 2 weeks of exposure until the study end. Body weight in the 50-ppm group was decreased compared to control at 3 time points from day 7 of lactation. **[Mean body weights in all groups appeared to follow uniform trends; the statistical significance of the body weight comparisons may have varied due to changes in the variance, which was not shown.]** Fluid intake was lower in the 100- and 50-ppm groups than in the control group during the lactation period, and in the 100-ppm group during late gestation. Litter results are summarized in Table 23.

Table 23. Litter Parameter Summary from Female Reproductive Study by Zenick et al. (81)

Endpoint	*Treatment group*		
	25 ppm	*50 ppm*	*100 ppm*
Maternal weight gain	↔	↓	↓
Mating performance	↔	↔	↔
Pregnancy rates	↔	↔	↔
Litter size at birth	↔	↔	"↓" 18% ($P \leq 0.1$)
Survival to PND 4	↔	↔	↔
Survival to PND 21	↔	↔	↔
Male pup weight from PND 7	↔	↓[a]	↓
Female pup weight from PND 7	↓[b]	↓	↓
Vaginal patency	↔	↔	delayed 2.8 days

↑,↓ Statistically significant increase, decrease compared to 0 ppm control value.
"↓" Decrease indicated by the authors, although criterion for statistical significance not satisfied.
↔ No significant difference from control value.
[a]Mean offspring weight not statistically different from control group on PND 42.
[b]Mean pup weight significantly reduced at PND 1 and 7 in 25 ppm group.

There were 2 litters in the 100-ppm group with 80 and 100% mortality by PND 4, but survival in the remaining litters was greater than 90%. Litter size and percent survival were not affected by acrylamide exposure. Hindlimb splaying occurred in the first 2 weeks in females exposed to 100 ppm acrylamide, and feed and water intake required facilitation, showing a biologic effect at this acrylamide dose. No other dose groups showed hindlimb splay. The main effect of acrylamide treatment of the dam was on pup weight, which was consistently depressed in the two highest dose groups in a dose-related manner and transiently depressed during the first week after birth in female pups born to dams exposed to 25 ppm. Because of the incapacitation of the dams given 100 ppm acrylamide, their data were excluded from the regression analysis, which showed that birth weight was not influenced by body weight, fluid intake, or cumulative acrylamide intake, or their interactions. Litter weaning weights were, however, influenced by cumulative acrylamide intake ($P \leq 0.01$). The authors concluded that exposure of the dam to 50 or 100 ppm acrylamide in drinking water results in a decrease in offspring weight due either to gestational or lactational exposure or both. **[Possible exposure of pups to drinking water prior to weaning was not discussed.]**

Strengths/Weaknesses: This study was adequately performed and interpreted. Although the study was designed as a female reproduction study, useful developmental endpoints were included. The use of a high dose that produced hindlimb splay in dams provides an evaluation of the dose range up to the dose producing the non-reproductive endpoint (neurotoxicity) of greatest interest in humans. The graphic presentation of the data does not readily permit modeling of the dose-response relationship.

Utility (Adequacy) for CERHR Evaluation Process: This study offers an indication of general postnatal toxicity using standard endpoints in rats; however, the developmental effects may have been due to maternal toxicity. Since the extended treatment period included gestation, this study provides useful information on developmental toxicity over the dose range of 25–100 ppm. The authors selected 50 ppm as a developmental LOAEL, but the Expert Panel selected a developmental LOAEL of 25 ppm based on the transient decrease in pup weight . The maternal LOAEL is 50 ppm.

Neuhäuser-Klaus and Schmahl *(61*) performed what they called a teratogenicity study in conjunction with a mouse spot test (discussed in Section 2.3.1), supported in part by the Umweltbundesamt, Berlin. T-stock females were mated with HT males (two females to one male) and the day of a vaginal plug counted as GD 1. Females were treated with acrylamide (analytical grade) in distilled water at 75 mg/kg i.p. once on GD 12 or 50; or 75 mg/kg daily on GD 10, 11, and 12. Control females were injected with distilled water. Females were killed on GD 18 and implantation sites, resorptions, and live fetuses counted. Litters with fewer than four embryos were not included in the evaluation, because the authors stated that these embryos would be better nourished and could more easily recover from fetotoxic effects. There were 14 litters examined after 1 injection of distilled water and 15 litters examined after 3 injections of distilled water. There were 13 litters examined after 1 injection of 75 mg/kg acrylamide, and 10 and 14 litters examined after 3 daily injections of 50 and 75 mg/kg acrylamide, respectively. Fetuses were fixed in 8% formalin. Malformed fetuses and five normal fetuses were randomly selected for sagittal sectioning and histologic evaluation (5–6 μm sections stained with hematoxylin and eosin). **[The method of determining that a fetus was malformed is not indicated, but was presumably based on external evaluation inasmuch as the designation was made prior to sectioning.]** The frequency of fetuses with malformations was analyzed by chi-square test **[thus taking the fetus, not the litter, as the experimental unit]**. The difference between mean

fetal weights was evaluated by *t*-test. A decrease in litter size was described in the group receiving acrylamide 75 mg/kg bw/day for 3 days (4.7 fetuses vs. 7.3 fetuses; **[SEM or SD not provided]**). The proportion of growth-retarded fetuses (defined as fetuses weighing less than 0.6 g) was also said to be increased in this group (18.8 vs. 4.9%, **[SEM or SD not provided: it is likely that these are proportions calculated on pooled fetuses in the dose group rather than per litter figures]**) leading to a decrease in mean fetal weight in this group compared to the control (0.63 ± 0.091 vs. 0.76 ± 0.073 g). **[It is not stated whether these errors are SEM or SD. Even assuming these are SD, *t*-test performed by CERHR does not show a significant difference. The lack of statistical significance may be because of the higher than normal variability seen in this endpoint, in part already noted by the incidence of "growth retarded fetuses" even in the control group. Regardless of statistical findings or whether litter or fetus was used as the unit for analysis, a 17% decrease in fetal weight is considered by the Expert Panel to be a meaningful change even with small litters excluded.]** The malformation noted by the authors was kinked tail, occurring in 9.8% of weaned offspring in the 75 mg/kg × 3 group compared to none of the controls in the accompanying mouse spot test. In the teratology evaluation on GD 18, kinked tails were seen in all groups, including the control. The data from the published table for single treatments are 1.0 and 5.9, for 0 and 75 mg/kg, respectively. For the 3 daily injections, the data from the published table are 1.6, 1.4, and 4.7, for 0, 50 mg/kg × 3, and 75 mg/kg× 3, respectively. **[It is not stated whether these are percent of all fetuses, litter percents, or mean number of fetuses per litter.]** The results of the histologic evaluation read, "…examination of 8 fetuses showed hypoplasia of the lymphatic organs as well as of the centers for hematopoiesis in liver and bone marrow. In the placenta hemorrhages were observed frequently." The authors concluded that the mesenchyme "may be the main target of [acrylamide] fetotoxicity."

Strengths/Weaknesses: Extending fetal evaluation to the histologic level is a strength of the study. Methods for summarizing fetal findings are poorly described, and were likely carried out on a per fetus basis. For evaluation of these types of effects, it is preferable to present the data on both a per litter and a per fetus basis, and statistical analyses should use the litter as the unit. The decision not to evaluate surviving fetuses from litters with high resorption rates is a poor one; a litter already determined to be "affected" may provide a few surviving fetuses that could represent the best opportunity for characterizing morphologic changes that occur, in the absence of death, in the embryo/fetus.

Utility (Adequacy) for CERHR Evaluation Process: On its own, the study is only suggestive because there are too many design/analysis issues. The tail findings on an observational level correlate well with the skeletal variations reported in the mouse study by Field et al. (discussed below). The histologic findings extend to soft tissues the suggestion of developmental sensitivity in this apparently more sensitive species.

Field et al. *(118*), under contract to NTP, evaluated the developmental toxicity of acrylamide in Sprague-Dawley rats (29–30/group) and Swiss CD-1 mice (30/group) in a GLP-compliant study. After cohabitation, the day vaginal sperm (in rats) or a copulation plug (in mice) was found was designated GD 0. Treatments were by gavage on GD 6–20 in rats and on GD 6–17 in mice. Acrylamide was 98% pure, and HPLC prior to and after use showed dosing solutions to be 92–108% of intended concentrations. The dose volume of each treatment was 5 mL/kg in rats and 10 mL/kg in mice, adjusted daily based on actual animal weights. Concentrations were made up in de-ionized distilled water. Doses were selected based on preliminary studies and were designed to produce significant

maternal or fetal toxicity at the high dose and no toxicity at the low dose. Rats received acrylamide by gavage at 0, 2.5, 7.5, or 15 mg/kg bw/day. Mice received acrylamide by gavage at 0, 3, 15, or 45 mg/kg bw/day. Dams were killed on the final day of treatment. Fetuses all underwent soft tissue dissection and half the fetuses underwent Wilson sectioning of decapitated heads. All carcasses were double-stained for bone and cartilage **[clearing is not mentioned, but is assumed]**.

In rats, maternal weight was decreased in a dose-dependent manner (Table 24). Absolute and relative liver weight was unchanged **[data were not shown]**. There were no dose-related clinical signs in dams. The only significant fetal parameter associated with treatment was a dose-related increase in the percent fetuses per litter with variations and the percent litters with variations on trend testing (but not on pair-wise comparison). The most common variation was extra lumbar rib, but statistical analysis of percent fetuses per litter with extra ribs or of litters with extra ribs did not show a significant association with acrylamide treatment.

Table 24. Summary of Rat Developmental Toxicity Study, Field et al. (118)

Parameter	*Doses (mg/kg bw/day)*			
	0	***2.5***	***7.5***	***15***
No. dams placed on test	30	29	30	29
No. dams withdrawn (dosing errors)	3	2	1	2
No. dams pregnant at termination	23	26	26	24
Maternal weight gain (corrected for uterine weight)[a]	Reference	↔	↓12%	↓18%
Implantation sites/litter		↔	↔	↔
Resorptions/litter		↔	↔	↔
Live fetuses/litter		↔	↔	↔
Male fetal weight/litter		↔	↔	↔
Female fetal weight/litter		↔	↔	↔
% Fetuses or litters with malformations		↔	↔	↔
% Fetuses or litters with variations[b]		↔	↔	↔

[a]There was a statistically significant inverse linear trend for dose and maternal weight over gestation, over the treatment period, and corrected for uterine weight.

[b]There was a significant linear trend for % fetuses per litter with variations and % litters with variations in rats.

↑,↓ Statistically significant increase, decrease on pair-wise comparison with control value

↔ statistically similar on pair-wise comparison with control value.

In mice, there were decreases in maternal weight gain over the gestation period and the treatment period by linear trend testing as well as by pair-wise comparison in the high dose group (Table 25). When corrected for uterine weight, the trend test remained significant while the pair-wise comparisons did not. Gravid uterine weights were decreased 12 and 14% in the 15 and 45 mg/kg bw/day groups, respectively, and fetal weight per litter was decreased 15% in each sex in the high dose group. Maternal absolute, but not relative, liver weight showed a decreasing linear trend with dose.

In the high dose group, hindlimb splay was observed in nearly half the dams. The percent litters with resorptions showed a significant increasing linear trend and a significant increase in the 15 mg/kg bw/day group; however, at the 45 mg/kg bw/day dose, there was no increase in resorptions; 24% of litters at the high dose had resorptions, compared to 32.1% of litters in the control group. There was a significant linear trend for percent fetuses/litter with extra ribs and percent litters with extra ribs, although none of the pair-wise comparisons showed a significant increase compared to control.

Table 25. Summary of Mouse Developmental Toxicity Study, Field et al. (118)

Parameter	***Doses (mg/kg bw/day)***			
	0	***3***	***15***	***45***
No. dams placed on test	30	30	30	30
No. dams withdrawn	0	0	1[c]	2[d]
No. dams pregnant at termination	28	26	29	25
Maternal weight gain (corrected for uterine weight)[a]	Reference	↔	↔	↔
Implantation sites/litter		↔	↔	↔
Resorptions/litter		↔	↔[e]	↔
Live fetuses/litter		↔	↔	↔
Male fetal weight/litter		↔	↔	↓15%
Female fetal weight/litter		↔	↔	↓15%
% Fetuses or litters with malformations		↔	↔	↔
% Fetuses or litters with variations[b]		↔	↔	↔

[a]There was a statistically significant inverse linear trend for dose and maternal weight over gestation, over the treatment period, and corrected for uterine weight.
[b]There was a significant linear trend for % fetuses/litter and % litters with extra ribs in mice.
[c]Removed due to liver mass.
[d] One removed due to dose error and one removed due to morbidity, unrelated to test article.
[e]% Litters with resorptions was increased from 32.1 to 58.6% in this dose group only.
↓ Statistically significant decrease on pair-wise comparison with control value
↔ statistically similar on pair-wise comparison with control value.

In their evaluation of the data, the authors proposed that an increase in extra ribs "may be an indirect reflection of the adverse maternal effects and stress of treatment rather than chemical-specific fetotoxicity." They concluded that, "[acrylamide] exposure during the post-implantation phase of gestation resulted in fetal growth retardation in mice, but only in the presence of well-defined maternal toxicity. The no-observed-adverse-effect level (NOAEL) for maternal and fetal toxicity in mice was 15 mg/kg/day. In rats, [acrylamide] treatment did not alter measured endpoints of embryo/fetal viability, growth, or development at doses [that] depressed maternal weight gain. The NOAEL for [acrylamide]-induced maternal toxicity in rats was 2.5 mg/kg/day, and 15 mg/kg/day represented a NOAEL for developmental toxicity in rats under the conditions of this study. Neither embryo/fetal viability nor morphological development of rat and mouse offspring were affected by [acrylamide] exposure."

Strengths/Weaknesses: This study is very strong and was designed specifically to meet/exceed testing guidelines in dosing period, number of animals/group, and multiple means of expressing outcome (e.g., number/litter, number of litters affected). The study includes all standard endpoints evaluated in a developmental toxicology study. Although the authors conclude some endpoints were not meaningfully affected, or that effects may be related to maternal toxicity, a decrease in maternal weight gain of 18% is not severe stress/toxicity; it is simply a maternal effect level. A decrease in maternal weight of that degree would likely be associated with the types of changes seen here in fetuses strictly on a maternal basis.

Utility (Adequacy) for CERHR Evaluation Process: This study is useful for the process and the quantitative evaluation is considered reliable.

Rutledge et al. *(119*) presented data from studies in which female mice **[strain not stated, but SEC × C57Bl F1 females were used in a different experiment described in the same paper]** were mated for a 30-minute period, then treated with acrylamide **[purity and source not stated]** at 125 mg/kg **[i.p.]** 1, 6, 9, or 25 h later. The intervals represented fertilization, early pronuclear stage, pronuclear DNA synthesis, and the 2-cell stage, respectively. Control animals were given HBSS at the respective times **[there is only 1 control listed for the 9- and 25-h groups; it is not known when that control was treated]**. On GD 17 **[plug day not identified]**, the uteri were inspected for resorptions, embryonic death, and live fetuses. Live fetuses were inspected for external abnormalities. Results are shown in Figure 7.The data table did not indicate statistical differences **[superscripts were missing from the table]**, but the text indicates that live fetuses were decreased and resorptions increased at all treatment times. Among live fetuses, abnormalities were said to have been increased with treatment at 6, 9, and 25 h after mating. The specific malformations are reported for the group treated 6 h after mating, which appeared to represent the most sensitive time for the production of resorptions and of abnormal live fetuses. These malformations are given in Table 26 **[some fetuses had more than one abnormality]**.

Strengths/Weaknesses: The idea for the treatment schedule is good. Missing aspects of methods are a weakness. The number of fetuses available for evaluation presented in the data table suggests that an adequate number of litters was included, as least for the 6-h evaluation. A strength is the testing of a specific critical window in pre-implantation development that is not assessed by standard developmental toxicity tests. A weakness is the use of only a single high dose, albeit a dose permitting comparison with male dominant lethal data for acute toxicity at critical times.

Utility (Adequacy) for CERHR Evaluation Process: This study shows that a single high dose of acrylamide can produce very early embryo death and malformation, presumably through a mutagenic mechanism. The study provides insight regarding risks of acute high exposures that would be extremely difficult to detect in humans (women attempting conception). The study is not useful for setting safe levels for chronic exposures.

Figure 7. Pregnancy Outcome in Mice as a Percent of Implantations/Female and as a Percent of Live Embryos by Number of Hours between Mating and Treatment with Acrylamide 125 mg/kg. [From Data Presented in Rutledge et al. (119)]

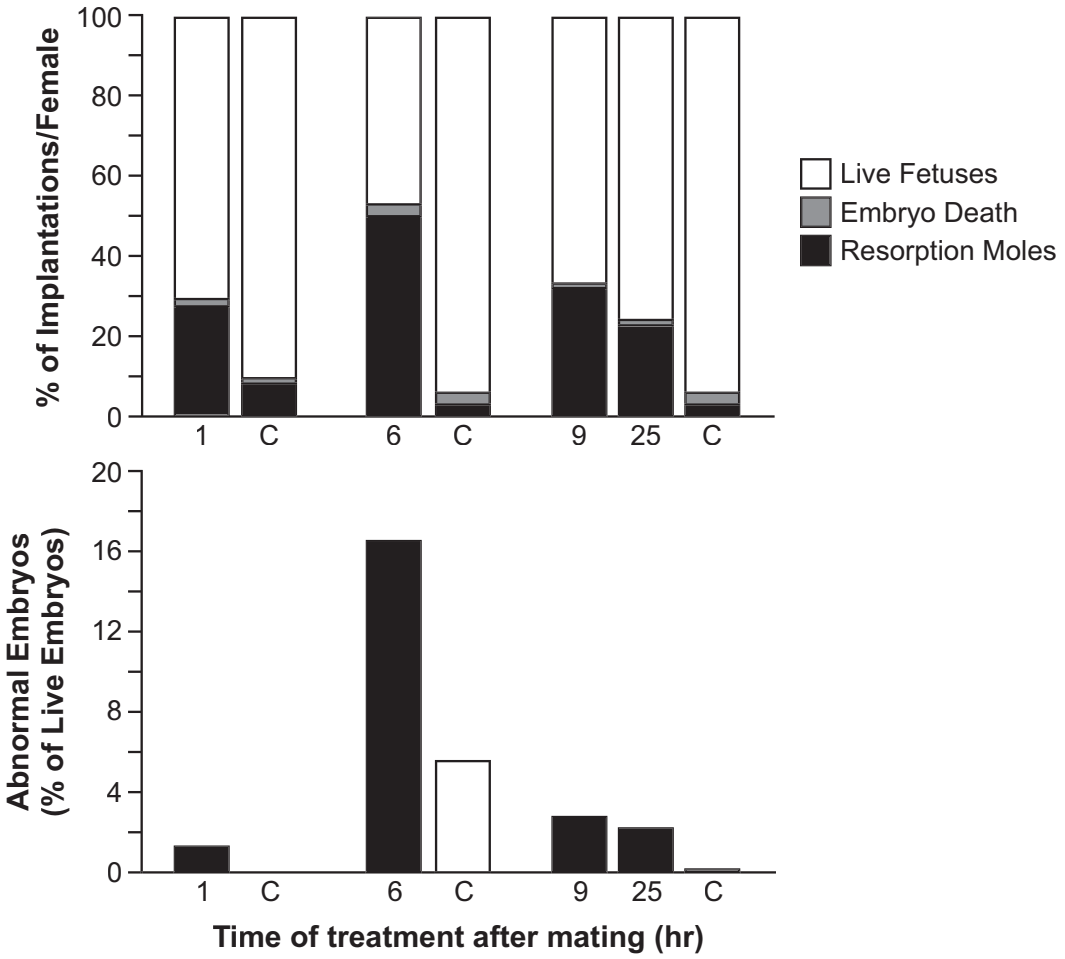


Table 26. Abnormalities in Mouse Fetuses from Dams Treated with 125 mg/kg Acrylamide or Control and Mated 6 Hours Later, Rutledge et al. (119)

Abnormality	*Acrylamide*[a]	*HBSS (control)*[a]
No. live fetus evaluated	203	180
Bent tail	10	3
Bent limbs	8	0
Hydrops	6	0
Eye defect	5	1
Cleft palate	5	0
Abdominal wall defect	3	1
Exencephaly	2	4

[a]Results presented as frequency of fetuses affected

3.2.2 Developmental neurotoxicity—pregnancy dosing

Agrawal and Squibb *(120*) evaluated the effect of gestational acrylamide exposure on dopamine receptor binding in offspring brain. Time-bred pregnant Fischer 344 rats were treated with acrylamide **[purity not specified]** in water at 0 or 20 mg/kg bw/day by gavage from GD 7 to 16 **[plug day not defined]**. Animals were apparently permitted to litter and on PND 1 pups were randomized by dose group and re-allocated to a control or an acrylamide-exposed dam in a standard cross-fostering manner, yielding four groups: acrylamide-exposed dams (n=7) rearing acrylamide-exposed pups, acrylamide-exposed dams (n=5) rearing vehicle-exposed pups, vehicle-exposed dams (n=5) rearing acrylamide-exposed pups, and vehicle-exposed dams (n=6) rearing vehicle-exposed pups. The litters were standardized to four males and four females. On PND 14 and 21, 1 male and 1 female pup were randomly selected from each litter and decapitated. The corpus striatum was dissected from the brain and frozen in liquid nitrogen for later analysis. Striatal tissue was homogenized in 0.32 M sucrose and centrifuged to isolate membranes. Membrane preparations were incubated with radiolabeled spiroperidol to estimate dopaminergic receptors.

Dam body weight and litter size were said not to have been affected by treatment **[data are not shown, and it is not indicated when or how often dams were weighed; a one-way ANOVA was used for dam weight during treatment or following birth at PND 1]**. Pup weights did not differ by treatment group at 2 or 3 weeks of age **[pup weight appears to have been analyzed by foster litter rather than by litter of origin. The initial two-factor analyses indicated that fostering was not a significant contributor to overall variance, so it was not considered in the subsequent pair-wise analyses of either weight or dopamine-receptor endpoints]**. At 2 weeks of age, dopamine-receptor binding of spiroperidol was decreased by about 20% in male pups that had been antenatally exposed to acrylamide, regardless of rearing by treated or control dams. For female pups, acrylamide-treated status of the birth dam was associated with a 16–19% decrease in spiroperidol binding, whether the pup was raised by an acrylamide- or a vehicle-exposed dam. At 3 weeks of age, there were no differences between groups in spiroperidol binding. Scatchard analysis of spiroperidol binding was determined using membrane preparations pooled from pups within the same treatment condition **[the age of the pups was not given, but may be assumed to be PND 14, when there were significant decreases in specific binding]**. Receptor affinity in acrylamide-exposed pups reared by acrylamide-exposed dams was lower than the "control" **[presumably vehicle-exposed pups reared by vehicle-exposed dams, but "control" may be a reference to prenatal vehicle exposure from two-way ANOVA, regardless of fostering condition]**. The K_D values were 0.25×10^{-9} M vs. 0.43×10^{-9} M. "Dosed rats" also had lower receptor density than "control:" 18.2 vs. 31.5 pmol/100 mg protein.

Strengths/Weaknesses: This study did not describe several aspects of methodology and analysis clearly enough to permit certainty in its interpretation. The neurochemical variables assessed made sense at the time the study was conducted, and specifically relate to the CNS areas/transmitter involved in motor control (CNS signs of acrylamide toxicity in adult rats are motor oriented). The study only included one treated group and used Fischer rats, which is not a strain that has shown sensitivity to some agents that result in CNS malformations. A strength is the evaluation of both sexes.

Utility (Adequacy) for CERHR Evaluation Process: This study can be viewed as suggestive of transient (though not dramatic) changes in the postnatally developing dopaminergic system and is adequate for use on this basis only. The acrylamide dose level used is similar to or higher than some

of the other studies reporting developmental neurotoxicity-type findings.

Wise et al. *(121)* from Merck Research Laboratories performed a developmental neurotoxicity evaluation of acrylamide in Sprague-Dawley rats according to then-current EPA guidelines for developmental neurotoxicology studies. After cohabitation, females with copulation plugs in their cage pans or vaginas were considered to be at GD 0. These animals were randomized (balanced for weight) to receive acrylamide (99.9% pure) in de-ionized water at 0, 5, 10, 15, or 20 mg/kg bw/day by gavage from GD 6 through PND 10. Dams were permitted to litter and rear their own offspring. On PND 3, litters were culled to five pups of each sex (based on pups identified randomly on the day of birth). There was a single control litter that had two pups of each sex fostered into it in order to make a litter of five of each sex; the fostered pups were not used in the analysis. One pup of each sex from each litter was killed on PND 11 for evaluation of brain, spinal cord, and peripheral nerve. Pups were removed from their dams during postnatal week 4 and housed one or two (same sex) to a cage until postnatal week 5–6, when they were singly housed. Behavioral assessments included open-field motor activity, auditory startle habituation, and passive avoidance.

Open-field motor activity was assessed on the same single animal/sex/litter on PND 13, 17, and 21. On one of PND 58–60, open-field testing was performed on a second animal/sex/litter, that second animal being one that was previously evaluated for auditory startle habituation on PND 22. Open-field testing was performed under red light using ~70 dB background white noise. Endpoints in the open-field test included the numbers of beam interruptions in each of six 10-minute periods. Only three 10-minute periods were used for PND 13 animals.

Auditory startle habituation was evaluated on PND 22 and on 1 day between PND 58 and PND 60, using animals at this second time point that had previously undergone open-field testing. After a 3-minute acclimation period, during which animals were exposed to 72-dB background white noise, animals were exposed to 60 120-dB 50-msec bursts of white noise with a 5-sec interval between trials. Endpoints included the peak amplitude of each startle movement and the interval between acoustic stimulus and startle movement **[evaluated by deflection of a platform and expressed as millivolts]**.

A passive avoidance test was used to assess short-term learning. Animals naïve to the test were evaluated on PND 24 and 1 day between PND 58 and PND 60, with retesting 1 week later. The test involved a shuttlebox with one light and one dark compartment. Rats entering the dark compartment received a 1-sec foot shock. Test criteria were met when the animal remained on the lighted side of the shuttlebox for 2 consecutive 60-sec trials.

Statistical analysis was performed by trend testing. When a significant test for trend was obtained, the high dose group was eliminated and the testing was repeated until significance was lost.

Dams in the 20 mg/kg bw/day group all demonstrated hindlimb splay, a sign of acrylamide neurotoxicity, on PND 1–4, and all dams and pups in this group had died or were euthanized by PND 4 due to excessive pup mortality. In the 15 mg/kg bw/day group, dams all displayed hindlimb splay between PND 4 and PND 9, although some dams appeared to improve after discontinuation of acrylamide treatment on PND 10. There were no clinical signs in the 5 and 10 mg/kg bw/day

Table 27. Summary of Rat Developmental Neurotoxicity Study (continued)

dams, although maternal toxicity became apparent in the 10 mg/kg bw/day group during the lactation period, when there was a significant decrease in weight gain compared to control animals.

Pregnancy outcome and neurobehavioral testing results are summarized in Table 27.

Table 27. Summary of Data in the Wise et al. (121) Rat Developmental Neurotoxicity Study

Parameter		*Dose, mg/kg bw/day (n)*				
		0 (10)	*5 (9)*	*10 (8)*	*15 (12)*	*20 (12)*
Implants/female						Not reported
Live pups/litter	PND 0		↔	↔	↔	↓37%
Pup deaths	PND 1–3		↔	↔	↔	↑33%
	PND 4–21		↔	↔	↑13.3%	Not reported
Pup weight, female	PND 0		↔	↔	↓	↓
	PND 3		↓	↓	↓	↔
	PND 7		↓	↓	↓	killed
	PND 14		↔	↓	↓	
	PND 21		↔	↓	↓	
Pup weight, male	PND 0		↔	↔	↓	↓
	PND 3		↔	↓	↓	↔
	PND 7		↔	↓	↓	killed
	PND 14		↔	↓	↓	
	PND 21		↔	↓	↓	
Weight, week 4–9, female	Average		↔	↓	↓	
	Gain		↔	↔	↓	
Weight, week 4–9, male	Average		↔	↔	↓	
	Gain		↔	↔	↔	
Open-field activity, female	PND 13		↔	↔	"↓" (P=0.08)	
	PND 17		↔	↔	↔	
	PND 21		↔	↔	↑	
	Adult		↔	↔	↔	
Open-field activity, male	PND 13		↔	↔	"↓" (P=0.06)	
	PND 17		↔	↔	↔	
	PND 21		↔	↔	↔	
	Adult		↔	↔	↔	

Table 27. Summary of Wise et al. (121) Rat Developmental Neurotoxicity Study (continued)

Parameter		Dose, mg/kg bw/day (n)				
		0 (10)	5 (9)	10 (8)	15 (12)	20 (12)
Auditory startle habituation, peak	PND 22, female		↔	↔	↓	
	Adult female		↔	↔	↓	
	PND 22, male		↔	↔	↓	
	Adult male		↔	↔	↔	
Time to peak	All ages Both sexes		↔	↔	↔	
Passive avoidance	Both sexes		↔	↔	↔	
Brain weight, absolute	PND 11, female		↔	↔	↓15%	
	PND 11, male		↔	↔	↓15%	
	11 weeks, female		↔	↔	↓ 9%	
	11 weeks, male		↔	↓ 6%	↓12%	
Brain weight, relative	PND 11, female		↔	↑23%	↑65%	
	PND 11, male		↔	↔	↑66%	
	11 weeks, female		↔	↔	↔	
	11 weeks, male		↔	↔	↑17%	

↑,↓ Higher, lower than control group, statistical significance determined, except for brain weight, by trend testing with sequential elimination of highest doses until significance of trend lost. For absolute and relative brain weight, significance not tested in the original paper, but assigned by CERHR based on data presented in the paper using ANOVA with post-hoc Dunnett test.
↔ Statistically not difference from control value.
"↓" refers to a statement by the authors that open-field activity was reduced at this dose, but lack of formal statistical significance at $P \leq 0.05$.

The authors noted that perinatal mortality was prominent in the 20 mg/kg bw/day group and that postnatal pup death occurred in the 15 mg/kg bw/day group. Given the important degree of maternal toxicity in the 15 and 20 mg/kg bw/day dose groups, the authors suggested that the pup mortality in these groups might not have been a direct effect of acrylamide exposure, but rather might have been due to the severely compromised condition of the dams. There were no histologic changes in the nervous system tissues in the 15 mg/kg bw/day group. Behavioral testing was altered only in the 15 mg/kg bw/day group. A decrease in brain weights in the 15 mg/kg bw/day group was attributed by the authors to a greater decrease in body weight, reflected as an increase in relative brain weight**.** The decrease in offspring weight at exposure levels higher than 5 mg/kg bw/day was attributed by the authors to maternal toxicity. The decrease in female pup weight in the 5 mg/kg bw/day group on PND 3 and 7 was considered by the authors possibly not to have been treatment-related, given the transitory nature of this weight decrease, its confinement to one sex, and the lack of a similar effect on pup weight in the Field et al. study *(118*) at maternal acrylamide doses lower than 15 mg/kg bw/day. The authors concluded, "These results suggest that acrylamide is not a selective developmental neurobehavioral toxicant because conventional measures of pup toxicity (i.e., body weight) were observed at dosages lower than those [that] affected behavioral parameters." They identified a NOAEL for developmental toxicity at <5 mg/kg bw/day and a NOAEL for developmental neurotoxicity at 10 mg/kg bw/day.

Strengths/Weaknesses: This study came close to following EPA developmental neurotoxicity testing guidelines (except for pup assignments to behavioral testing). A weakness is the use of the EPA guideline as a rigid protocol design, without more specific assessments that might be predicted (as the authors admit) to be effective in more clearly defining a LOAEL/NOAEL within the study (i.e., their reference in the discussion to grip strength).

Utility (Adequacy) for CERHR Evaluation Process: This study is adequate, based on regulatory guidance. The Panel agrees with the bottom-line NOAELs and that there was no selective developmental neurotoxicity "within the context of measures assessed" in this study, and that 5 mg/kg bw/day was a marginal developmental effect/no effect level. The dose-responsive nature of the pup body weight effect in the presence and absence of maternal effect suggests that maternal toxicity probably contributed to (enhanced) the pup effect at the higher doses, but was not totally responsible for the finding at those doses.

Walum and Flint *(122*) evaluated the effect of acrylamide **[purity not given]** on rat midbrain cells (obtained from embryos collected on day–13 post-mating) in culture. This brain area is one rich in both dopamine and gamma-amino butyric acid (GABA) receptors developmentally. In this assay, sometimes called micromass culture, neural epithelial cells in suspension aggregate into foci of interconnected cells. A reduction in the number of such foci without a reduction in cell number or viability is taken as evidence of disruption of developmental processes. In this study, 10 μg/mL acrylamide was determined to reduce the number of foci by 25% without decreasing cell number, assessed by neutral red staining and protein content. Uptake of dopamine and of GABA were also decreased by acrylamide exposure **[the text indicates that GABA uptake was "virtually" unaffected; the data table shows a statistically significant 8% reduction in GABA uptake. The Expert Panel agrees that an 8% change in this particular variable is likely within the normal variation of the procedure and unlikely to be biologically meaningful, statistics notwithstanding]**. The authors concluded that acrylamide may reduce the "differentiation and development of dopaminergic projections" in the developing rat brain.

Strengths/Weaknesses: This study provides an *in vitro* assessment of a potential mechanism of acrylamide toxicity, and a suggestion of how this mechanism might be established. This approach is a good beginning for whole-animal researchers to follow up concerning these events within an *in vivo* model.

Utility (Adequacy) for CERHR Evaluation Process: This study is suggestive of a mechanism and is adequate for use in that manner only.

3.2.3 Lactation

A study by Husain et al. *(109*), which included a lactational exposure component, was summarized in Section 2.5.1. That study found alterations in neurotransmitters in the brains of young rats exposed to acrylamide through milk ingestion.

Friedman et al. *(123*) stated that they were attempting to replicate the findings of Husain et al. *(109*) by using the same strain of rat (Wistar) and the same dosing regimen during the lactation period in a GLP-compliant study funded by the Acrylamide Monomer Producers Association. **[The Expert**

Panel notes that this study used the same exposure paradigm as Husain et al., but did not include any of the assessments (neurochemical) used in that study.] Acrylamide (99.7% pure) in 0.9% saline was administered to dams at 0 or 25 mg/kg bw/day by gavage beginning on PND 0 (the day of parturition) and continuing though PND 21 (n=15 dams per dose group). Dams were weighed on PND 0, 4, 7, 14, and 21 and the most recent body weight was used for dose adjustment. Clinical observations were made twice daily, including 2–4 h post-dosing, and dams were evaluated by Functional Observation Battery on PND 7, 14, and 21. The Functional Observational Battery consisted of home cage, handling, open-field, and sensory/neuromuscular observations. Maternal grip strength was measured on the same days as the Functional Observational Battery. Litters were reared by their own dams and were not culled. Pups were examined and weighed on PND 4, 7, 14, and 21, when weaned. Female pups were killed at weaning on PND 21 and 1 female/litter was necropsied. Male offspring were weighed on PND 28 and every 7 days thereafter until PND 91 (13 weeks of age). Grip strength was assessed in 10 males/dose group (from different litters if possible) at PND 30, 60, and 90. Statistical analysis used ANOVA for parametric data (with homogeneous variance by Bartlett test) and chi-square or Kruskal-Wallis tests for nonparametric data.

Of the 15 dams selected in each dose group, there were 15 and 10 litters remaining at weaning on PND 21 in the 0 and 25 mg/kg bw/day groups, respectively. One dam in the 25 mg/kg bw/day group delivered a dead litter prior to the onset of acrylamide dosing. One dam in this group died after a misdirected dose of acrylamide. One entire litter died by PND 7. Two dams were found in moribund condition and killed, 1 each, on PND 18 and 20. Maternal weight was equivalent between dose groups at parturition. All subsequent weights were lower in the 25 mg/kg bw/day dose group than in the control, and acrylamide-treated dams lost weight over the lactation period. Their feed and water consumption were also significantly lower than those in the control group at all time points except PND 0–4, when water consumption was equivalent. Acrylamide-exposed dams exhibited clinical signs of toxicity including hindlimb splay and tremors, as well as nonspecific signs of stress. There were differences between the groups in the Functional Observational Battery, with decreases in arousal and increases in indifference as well as neurologic abnormalities in gait and hindlimb splay. There were no histologic abnormalities of the sciatic nerves in dams.

Litters were comparable in size, weight, and sex ratio on PND 0. The proportion of offspring surviving to PND 21 was reduced in the 25 mg/kg bw/day group (72.5 ± 11.0%) compared to the control group (98.4 ± 0.9, $P<0.05$ by Student *t*-test). Mean pup weight per litter was lower in the acrylamide-treated group from PND 4 until weaning, and remained lower in weaned males from weaning until termination at PND 91. Necropsy of pups that died or were moribund prior to weaning showed no milk in the stomach and intestines distended with air. Male offspring surviving to weaning in the acrylamide-exposed group showed clinical signs of inanition in the early post-wean period, with recovery over time. Fore- and hindlimb grip strength were reduced in post-wean males in the acrylamide group at PND 30 but had recovered by PND 60 in spite of a continued body weight effect. The authors concluded that acrylamide-induced maternal toxicity had compromised the ability of the dam to nourish her pups. Pups that were able to survive to weaning and were not too weak to eat or drink thrived once they had a food and liquid source other than their dams. The authors considered it unlikely that acrylamide exposure of the offspring occurred through milk. They believed that the alterations in brain amines reported by Husain et al. *(109)* in pups nursed by acrylamide-exposed dams were confounded by the overall toxicity of acrylamide on the dam, with subsequent impairment of lactational competence.

Strengths/Weaknesses: The Husain et al. article does not describe how the number of pups was selected, (e.g., whether entire litters were used to make up the samples evaluated). In addition, whole levels of neurotransmitters are relatively uninformative endpoints. In spite of the failure to report the pups' origin, many of the regional values for activity levels (monoamine oxidase or acetylcholinesterase) did show a developmental trend in the control group, and the majority of major (perhaps biologically meaningful) changes in the acrylamide group occurred early in the study during treatment. The Friedman et al. conclusion that these apparently treatment-related changes may have been due to maternal toxicity (poor nursing/pup nutrition) could account for at least a portion of the body weight effects and apparent developmental delay in several of the neurochemical parameters measured in the Husain et al. study. It is unfortunate that additional doses that did not result in severe toxicity were not included in either the Husain et al. or Friedman et al. study, so that a characterization of maternal/general developmental/developmental neurotoxicity effects could be made.

Utility (Adequacy) for CERHR Evaluation Process: As both of these studies stand, without a dose-response assessment there is no way to separate maternal from developmental findings, or direct vs. indirect (maternally mediated) developmental toxicity. What the studies do show together is that with less-than-optimum study design, both neurochemical and overt functional developmental endpoints are altered by maternal lactational treatment at this dose of acrylamide.

3.3 Utility of developmental toxicity data

There are no human data on acrylamide developmental effects. The database is sufficient for an evaluation of acrylamide developmental effects in rats *(81, 118*) and mice *(118*), although only the Field et al. study *(118*) included a complete assessment of external, visceral, and skeletal abnormalities in offspring. The database includes an adequate developmental neurotoxicity study *(121*). A study conducted at Bio/dynamics Inc. *(115*) provided supportive information on developmental outcomes, not including structural malformations. The database also contains additional studies offering supplemental information. Of particular interest were studies by Rutledge et al. *(119*), which demonstrated an increase in abnormal embryos after acrylamide treatment of pregnant mice during pre-implantation stages, and by Holland et al. *(86*), showing an increase in abnormal pre-implantation embryos in pregnancies sired by acrylamide-treated males.

3.4 Summary of developmental toxicity data

3.4.1 Human Data

No human data on acrylamide developmental effects were located.

3.4.2 Experimental Animal Data

The Expert Panel notes that there are a number of genotoxicity studies with endpoints that might be considered developmental (e.g., abnormality of conceptuses after parental treatment). Studies that were designed to evaluate genotoxicity were grouped in Section 2. These studies include those with dominant lethal (section 2.3.2.2), heritable translocation (Section 2.3.2.4), and specific locus mutation (Section 2.3.2.5) endpoints. In addition, the mouse spot test (Section 2.3.1) involves changes in the offspring after treatment of the pregnant animal, and could be construed as a developmental test. Although these studies are placed for organizational purposes under the heading of genotoxicity rather than developmental or reproductive toxicity, the Expert Panel considers these studies important

in evaluating the reproductive and developmental effects of acrylamide. Key studies on acrylamide developmental toxicity are summarized in **Table 28 (**shown on page II-118**)**. The most useful studies were those by Zenick et al. *(81*), Field et al. *(118*), and Wise et al. *(121*).

The study by Zenick et al. *(81*) was designed as a female reproductive toxicology study, but included data relevant to an assessment of developmental toxicity as well. Acrylamide was given in drinking water to female rats at 0, 25, 50, or 100 ppm **[0, 4, 5–9, 10–14 mg/kg bw/day]**. After 2 weeks of treatment, untreated males were placed overnight with the females for up to 7 nights. Acrylamide-treated water was withheld during mating, but availability of treated water resumed during pregnancy and lactation. Dams delivered their young and litters were culled to four males and four females on PND 4. Endpoints included maternal weight gain, mating performance, pregnancy rate, pup survival and weight, and day of vaginal patency in female offspring. Neurologic toxicity (hindlimb splay), total or near total litter loss, and reduced body weight and fluid intake occurred in dams given 100 ppm acrylamide; dam body weight and fluid intake also were reduced at several time points in the animals given 50 ppm acrylamide. Pup weight was decreased in a dose-dependent manner in the 50 and 100 ppm groups and was transiently depressed in the first week of life in the 25 ppm group. A regression analysis performed without the 100 ppm group, due to incapacity of the dams, showed a significant effect of cumulative acrylamide intake on litter weaning weight. The developmental findings at 50 and 100 ppm may have been due, at least in part, to maternal toxicity seen at these doses. A LOAEL for developmental toxicity of 25 ppm (~4 mg/kg bw/day) was selected by the Expert Panel based on transiently decreased pup weight. It could not be determined if developmental toxicity was due to maternal gestational or lactational treatment, or both.

Field et al. *(118*) evaluated developmental toxicity of acrylamide in Sprague-Dawley rats (29–30/group) and Swiss CD-1 mice (30/group). Rats received acrylamide by gavage at 0, 2.5, 7.5, or 15 mg/kg bw/day on GD 6–20. Mice received acrylamide by gavage at 0, 3, 15, or 45 mg/kg bw/day on GD 6–17. Maternal weight decreased in a dose-dependent manner in both species. In rats, there was a dose-related increase in the percent fetuses per litter with variations and the percent litters with variations on trend testing but not on pair-wise comparison. In mice, fetal weight per litter was decreased 15% in both sexes in the highest dose group. There was a significant linear trend for percent fetuses/litter with extra ribs and percent litters with extra ribs, although none of the pair-wise comparisons showed a significant increase compared to control. The NOAEL for maternal and fetal toxicity in mice was 15 mg/kg bw/day. The NOAEL for maternal toxicity in rats was 2.5 mg/kg bw/day, and the NOAEL for fetal toxicity was 15 mg/kg bw/day, the highest tested dose **[the increase in variations was not considered an adverse effect]**.

Wise et al. *(121*) conducted a developmental neurotoxicity study of acrylamide in Sprague-Dawley rats. Animals received acrylamide at 0, 5, 10, 15, or 20 mg/kg bw/day by gavage from GD 6 through PND 10. Behavioral assessments included open-field motor activity, auditory startle habituation, and passive avoidance. Dams in the 20 mg/kg bw/day group all demonstrated hindlimb splay and all dams and pups in this group died or were euthanized by PND 4 due to excessive pup mortality. In the 15 mg/kg bw/day group, dams all displayed hindlimb splay between PND 4 and 9. Maternal toxicity also became apparent in the 10 mg/kg bw/day dose group during the lactation period, when there was a significant decrease in weight gain compared to control animals. Perinatal mortality occurred in the 15 and 20 mg/kg bw/day groups and was attributed by the authors to the severely

compromised condition of the dams. Open field activity and startle amplitudes were altered in the 15 mg/kg bw/day exposure group. Absolute brain weights decreased while brain weights relative to body weights increased in offspring in the 15 mg/kg bw/day group, attributed by the authors to the marked decrease in body weight. The decrease in offspring weight at exposure levels higher than 5 mg/kg bw/day was attributed, at least in part, to maternal toxicity. The decrease in pup weight in the 5 mg/kg bw/day group on PND 3 and 7 was significant only in females, and was considered possibly not treatment-related by the authors, given the transitory nature of this weight decrease, statistical significance achieved only in one sex, and the lack of a similar effect on pup weight in the Field et al. study *(118*) at maternal acrylamide doses under 15 mg/kg bw/day. The authors identified a NOAEL for developmental toxicity at <5 mg/kg bw/day and a NOAEL for developmental neurotoxicity at 10 mg/kg bw/day. The Panel agrees with the NOAELs, with the conclusions that there was no selective developmental neurotoxicity observed in this study, and that 5 mg/kg bw/day was a marginal developmental effect/no effect level.

A study conducted at Bio/dynamics Inc. *(115*) in Sprague-Dawley CD rats administered acrylamide in the feed to females at 0, 25, or 50 ppm for 2 weeks prior to mating and from GD 0 to 19. Acrylamide intake was estimated at 1.75–1.90 and 3.45–3.82 mg/kg bw/day in the 25 and 50 ppm dose groups, respectively. Litters were standardized to 3 male and 3 female pups on PND 4 and pups were examined for postnatal growth and mortality until weaning (PND 21). There was a slight but significant reduction in body weight gain in the 50 ppm dams during the pre-mating period. Mating and pregnancy indices, gestation length, neonatal viability, live litter size at birth, pup survival throughout the lactation period, and pup weights were similar in all treatment groups. On histopathologic evaluation of brain and spinal cord and sciatic, tibial, and plantar nerves *(116*), acrylamide-associated changes were confined to scattered nerve fiber degeneration in the sciatic and optic nerves. Details on the incidence and severity of these histologic effects were not provided, reducing the utility of these findings.

A study by Rutledge et al. *(119*) is unique in that female mice were dosed with acrylamide selectively during the perifertilization period at 125 mg/kg bw i.p. 1, 6, 9, or 25 h after mating. These times represented fertilization, the early pronuclear stage, pronuclear DNA synthesis, and the 2-cell stage, respectively. On GD 17 the uteri were inspected for resorptions, embryonic death, and live fetuses. Live fetuses were inspected for external abnormalities**.** The number of live fetuses was decreased and the number of resorptions was increased at all treatment times. Among live fetuses, abnormalities were increased with treatment 6, 9, and 25 h after mating. In spite of the lack of important details in the paper and a discrepancy between text and table in reporting the results, this study showed that an acute administration of acrylamide at a high dose during the perifertilization period can produce very early death or structural malformations.

Additional studies were limited in their utility. Edwards *(44*) used single-dose dietary exposures in a series of experiments in pregnant rats; however, the lack of experimental detail and small number of litters prevented this study from being useful. Neuhäuser-Klaus and Schmahl *(61*) performed what they termed a "teratogenicity study" in conjunction with a mouse spot test (discussed in Section 2.3). Acrylamide was given i.p. as a single dose or as three daily doses, a route and/or dosing schedule that are not relevant to human exposures. Design and analysis issues prevented this study from being useful in the evaluation of developmental toxicity, although the findings generally supported results

from other studies. A study by Agrawal and Squibb *(120)* that administered acrylamide at 20 mg/kg bw/day by gavage from GD 7–16 to rats was suggestive of transient changes in the postnatally developing dopaminergic system, although this study did not describe several aspects of methodology and analysis clearly enough to permit any certainty in its interpretation. A study by Husain et al. *(109)* and a study by Friedman et al. *(123)* addressed effects of acrylamide administered at 25 mg/kg bw/day by gavage during lactation. Toxicity in both dams and pups was prominent and there was no way to separate maternal toxicity from developmental findings, or direct from indirect (i.e., maternally mediated) developmental toxicity.

The Expert Panel found no human data with which to directly evaluate possible developmental toxicity of acrylamide. Data are sufficient to conclude that acrylamide is a developmental toxicant in rats, as manifested by a decrease in pup weight with maternal drinking water or gavage doses of approximately 4–5 mg/kg bw/day. The Expert Panel noted that a well-conducted gavage study and a dietary study failed to find this adverse effect at maternal doses of close to 15 mg/kg bw/day and 4 mg/kg bw/day, respectively; no explanation for the discrepant findings between studies was apparent. **Further, the Expert Panel concluded that acrylamide can produce developmental neurotoxicity, manifested as alterations in open field activity and decreased auditory startle amplitude in rat offspring at a maternal gavage dose of 15 mg/kg bw/day, a dose that also produced signs of maternal neurotoxicity. The Expert Panel concluded that acrylamide is a developmental toxicant in mice as manifested by decreased fetal weight per litter at maternal gavage doses of 45 mg/kg bw/day. The Expert Panel was unable to separate the effects of acrylamide on rat or mouse offspring from effects that may have been due to maternal toxicity at exposures ≥10 mg/kg bw/day, or to determine whether maternal gestational or lactational treatment, or both, was the critical period for producing developmental toxicity in rodents.** The rat and mouse data are assumed relevant to the assessment of potential effects in humans.

Table 28. Key Developmental Studies

Species/strain	*Exposures*	*Maternal/paternal Effect level*	*Critical Developmental Effects*	*Developmental Effect Level*	*Reference*
Long-Evans rat	Drinking water: 0, 25, 50, 100 ppm 2 weeks prior to mating through weaning of litter	LOAEL=50 ppm (6–9 mg/kg bw/day) [decreased fluid intake and decreased body weight gain] NOAEL=25 ppm (4 mg/kg bw/day)	Decreased pup weight	LOAEL=25 ppm (4 mg/kg bw/day; lowest tested level)	Zenick et al. *(81)*
			Decreased litter size	LOAEL=100 ppm (10-14 mg/kg bw/day)	
Sprague-Dawley rat	Gavage: 0, 2.5, 7.5, 15 mg/kg bw/day GD 6–20	LOAEL=7.5 mg/kg bw/day (decreased body weight gain) NOAEL=2.5 mg/kg bw/day	No adverse developmental effects	NOAEL=15 mg/kg bw/day (the highest tested dose)	Field *(118)*
Sprague-Dawley rat	Dietary: 0, 25, 50 ppm 2 weeks prior to mating and GD 0–19	LOAEL=50 ppm (3.45–3.82 mg/kg bw/day) (decreased body weight gain) NOAEL=25 ppm (1.75–1.90 mg/kg bw/day)	No adverse developmental effects (full teratology evaluation not performed)	NOAEL=50 ppm (3.45–3.82 mg/kg bw/day)	Bio/dynamics Inc *(115)*
Sprague-Dawley rat	Gavage: 0, 5, 10, 15, 20 mg/kg bw/day, GD 6–PND 10	LOAEL=10 mg/kg bw/day (decreased body weight gain in lactation period) NOAEL=5 mg/kg bw/day	Transient decrease in female pup weight	Borderline NOAEL/LOAEL= 5 mg/kg bw/day	Wise *(121)*
			Behavioral testing, brain weight	LOAEL=15 mg/kg bw/day NOAEL=10 mg/kg bw/day	
Swiss CD-1 mouse	Gavage: 0, 3, 15, 45 mg/kg bw/day GD 6–17	LOAEL=45 mg/kg bw/day (decreased body weight gain) NOAEL=15 mg/kg bw/day	Decreased fetal weight per litter	LOAEL=45 mg/kg bw/day NOAEL=15 mg/kg bw/day	Field *(118)*

LOAEL= lowest observed adverse effect level
NOAEL= no observed adverse effect level.

4.0 REPRODUCTIVE TOXICITY DATA

4.1 Human Data

No human data on acrylamide reproductive effects were located.

4.2 Experimental Animal Data

4.2.1. Female reproduction

In a study by Sakamoto and Hashimoto *(124)*, 24 female ddY mice were exposed to a single concentration of acrylamide in drinking water (1.2 mM, **[85.2 mg/L; 16.1 mg/kg bw/day based on mean body weight given in the paper and mean water consumption]**) for 4 weeks, then mated (1 male to 3 females) for up to 8 days with an untreated male of the same strain. Half of the pregnant mice were killed on GD 13 **[plug day unspecified]** and uterine contents were evaluated. The other half were permitted to deliver and rear their young, with observations of weight and behavior for 4 weeks. **[It is not stated whether there was acrylamide in the drinking water during the cohabitation period or whether pregnant animals were exposed to acrylamide.]** Statistical testing was performed using the Fisher exact test or ANOVA followed by the Duncan multiple comparison test. **[It appears from the tables that the treated females were the statistical unit of analysis.]** There was said to be a "slight but significant" increase in the number of resorptions per dam at GD 13 in the acrylamide-exposed group (1.9 ± 1.5 **[presumed mean ± SD]**) compared to the control (0.1 ± 0.3). The offspring of females allowed to litter and raise their young were said not to differ by treatment group with respect to weight gain or behavior over the first 4 weeks of life **[no data were shown]**.

Strengths/Weaknesses: One weakness of this study was a real paucity of specifics about study conduct and findings, which significantly limits the Panel's ability to use this study. The study showed that this exposure scenario was not overtly toxic to dams, nor did it cause massive full resorption, but even these tentative conclusions are clouded by the lack of detail provided in the published report.

Utility (Adequacy) for CERHR Evaluation Process: This study was considered to be inadequate for use in the Evaluation Process.

In a study sponsored by the US EPA, Zenick et al. *(81)* conducted a female reproduction study in which acrylamide was given in drinking water to female rats at 0, 25, 50, or 100 ppm. After 2 weeks of treatment, untreated males were placed overnight with the females for up to 7 nights. Untreated water was available during mating, but acrylamide-treated drinking water was resumed during pregnancy and lactation. Dams delivered their young and litters were culled to four males and four females on PND 4. At the end of the lactation period, litters were culled to two males and two females. Endpoints included maternal weight gain, mating performance, pregnancy rate, pup survival and weight, and day of vaginal patency in female offspring. Neurologic toxicity (hindlimb splay) was seen in dams given 100 ppm acrylamide. Dam body weight and fluid intake were reduced at several time points in animals given 50 or 100 ppm acrylamide. There were 2 of 15 dams in the 100 ppm group with full or nearly full litter loss. Pup weight was decreased in a dose-dependent manner in the 50 and 100 ppm groups and was transiently depressed in the first week of life in the 25 ppm group. Vaginal opening in female offspring was delayed 2.8 days in the high-dose group. A regression analysis performed without the 100 ppm group, due to incapacity of the dams, showed a significant effect of

cumulative acrylamide intake on litter weaning weight. This study included considerable information on developmental effects and was discussed in detail in Section 3.2.

Strengths/Weaknesses: This study was reasonably comprehensive in that it covered a reasonable pre-mating duration and gestation and lactation. The Panel has confidence in the quality of the data. The duration of treatment, however, was not clear, and there was no clear calculation of the dose received by the animals; this weakness is compounded by the fact that the doses surely changed dramatically as the animals underwent huge changes in water requirements and body weights. It is also unclear how many animals delivered at each dose. The study would have benefited from a histologic examination of the treated dams to uncover any pre-functional changes or changes in ovarian dynamics that would only show up several litters into the future. A histologic exam of the pups was also missing, reflecting an unfortunate weakness of this study.

Utility (Adequacy) for CERHR Evaluation Process: These data are adequate to conclude that acrylamide exposure at approximately these dose levels shows limited full-litter loss at the highest concentration (so, no graded reduction in litter size). The full-litter loss and the decrements in pup weight are interpreted by the Expert Panel as evidence of developmental toxicity rather than female reproductive toxicity. While not perfect, this paper contributes to the perception that female reproduction is not vulnerable to doses of acrylamide up to 100 ppm in drinking water.

In a summary paper, Bishop et al. *(125*) reported tests of female "total reproductive capacity" involving 29 chemicals tested over a 10-year period. Female mice were treated with a single i.p. dose of acrylamide **[purity not stated]** in HBSS at 0 or 125 mg/kg. The following day, females were paired with males for approximately 1 year. When litters were produced, pups were removed, counted, and killed. The number of litters produced over either 347 or 366 days **[the design changed during the course of these studies, and the specific length for the acrylamide study was not given]** and the total number of offspring produced was used to assess total reproductive capacity. For acrylamide, the female mice were F_1 hybrid SEC × C57BL6 and the males were F_1 hybrid C3H/R1 × C57BL10. There were no significant differences between the acrylamide- and vehicle-treated females in number of offspring/female (acrylamide 142.6, control 146.2) or number of litters/female (acrylamide 14.3, control 14.6). The paper lists 34 breeding pairs; it is assumed **[but not stated]** that this number refers to the acrylamide-treated animals. In a separate table describing vehicle groups used for the 29 chemicals, the HBSS group with 146.2 offspring/female and 14.6 litters/female contained 7 animals. **[It is not stated that controls were run concurrently. Neither standard error nor standard deviation is given.]**

Strengths/Weaknesses: The strengths of this paper lie primarily in the size of the effort that it represents: 29 chemicals from a variety of classes, though heavily laden with chemotherapeutic agents. One strength is that this type of design explicitly evaluates the fertility of future waves of oocytes, a strategy not commonly found in the literature. Because this is a summary of a large number of studies, the specifics of the acrylamide study are neither available nor presented, which represents a weakness for the Panel's use. Since the paper rightly focuses more space on those compounds that altered total reproductive capacity, it is difficult to ascertain the specifics of the acrylamide experiment, or whether there were any characteristics that might flag the results as unusual or give grounds for caution, another weakness in the acrylamide portion of this study.

Utility (Adequacy) for CERHR Evaluation Process: This study explicitly evaluates future generations of oocytes, and is useful for evaluating genotoxic potential of compounds in female reproduction. The lack of specifics and details moderate the Panel's certainty that acrylamide has no effect on female reproductive function.

4.2.2 Male reproduction

Shiraishi *(62)*, in a study supported by the Ministry of Education of Japan, treated male ddY mice with acrylamide **[purity not given]** in the diet or by i.p. injection. The purpose of the study was to evaluate chromosome aberrations (results given in Table 13); however, testicular weight data were also reported. Mice were 4 weeks old at the start of treatment, with 3 or 5 animals per group. The dietary group was given 500 ppm in the diet for either 1, 2, or 3 weeks before being killed**.** The authors also state that animals were killed 1, 2, or 3 weeks after the end of administration, although only 3 (and not 9) groups are shown in the aberration results. Because food consumption and daily body weights were not measured, the actual dose can only be estimated. **[The Panel estimates 1,000 mg/kg bw/day based on 0.2 kg/kg food factor (EPA Biological Reference Values, 1988).]** The i.p. group was given 50 or 100 mg/kg and killed 11 or 12 days later. Details of testis harvest and weighing were not provided and statistical methods were not given. The authors state that testis weights were decreased in the dietary group after 3 weeks on the diet **[a statistically significant 32% reduction in testis weight was confirmed by CERHR using the Student *t*-test]**. The text states that there was a decrease in testis weight 11 and 12 days after i.p. injection of 100 mg/kg **[*t*-test by CERHR shows no significant difference]**, and indeed, the absolute weight of the treated testes remained the same, while the weight of the controls increased over the duration of the dosing period.

Strengths/Weaknesses: This study used mice and gave significant doses of acrylamide (up to half the LD_{50}), which represents a strength. However, only a small number of animals was used; there was no histology performed; and there was no statistical treatment of the data. Thus, the Panel can only infer that this exposure paradigm for acrylamide in mice did not cause massive early cell death.

Utility (Adequacy) for CERHR Evaluation Process: This study is of no utility for the evaluation process.

Hashimoto et al. *(126)* (funding source not stated) treated male ddY strain mice with 0 or 0.5 mmol/kg **[35.5 mg/kg bw]** acrylamide (>95% purity) by gavage twice/week for 8 weeks (n=6/group). This dose was selected as it represents one-third of the LD_{50}. The mice underwent rotarod testing during the dosing period, after which they were killed and testes were harvested. Testes were fixed in 10% neutral formalin and 10-μm sections were stained with hematoxylin and eosin. Body weight was not affected by acrylamide treatment but relative testis weight was decreased 16% (control 0.36 ± 0.051, acrylamide 0.30 ± 0.016; $P<0.05$). Histopathology was said to be adversely affected with degeneration of germ cells but sparing of Sertoli and interstitial cells. **[This study used a number of acrylamide analogs, and histologic findings are summarized for all of them. Low-power photographs were provided but are not helpful in delineating the cell types affected.]** Neurotoxicity was apparent as evidenced by inability to maintain rotarod walking by the end of the treatment period.

An additional 7 animals per dose group were treated with phenobarbital 50 mg/kg bw/day i.p., 5 days/week, for 1 week prior to and throughout a 10-week dosing period using acrylamide at 0 or 0.5

mmol/kg **[35.5 mg/kg]** twice/week. Both neurotoxicity and decreased relative testicular weight were prevented in acrylamide-treated mice by phenobarbital co-treatment, leading the authors to propose that the induction of hepatic microsomal enzymes had fostered the transformation of acrylamide to non-toxic metabolites. **[The authors report in the Discussion that "testicular damage was completely prevented" by phenobarbital, but it is not apparent from their Methods or Results sections that histopathologic examination of the testes was performed in phenobarbital co-treated animals.]**

Strengths/Weaknesses: One strength of this study is that the dosing was by gavage, providing for closely controlled exposure. Testis architecture was also evaluated, and the epithelium was thinner and less populated in the acrylamide-treated mice, which is concordant with the reduced testis weight. Weaknesses of the study included the small number of animals per group and the fixative and other methods used may conspire to produce uninterpretable histologic sections. While only small photomicrographs are presented, it is clear that if these are representative, then the images cannot be used to support the conclusions the authors draw about the Sertoli or Leydig cells being unaffected. Also, since only a single time-point was evaluated, the authors cannot reach a conclusion about the target cell type; they can only conclude which cell populations appear to be present in reduced numbers. Because only body and organ weight data are presented for the phenobarbital co-administration study, the authors over-interpret their data when they state in the Discussion that "The testicular damage was completely prevented by [phenobarbital]… ." No cell counts were performed, and only a single duration of exposure was evaluated. Additionally, the reader lacks information about how the metabolite profile of acrylamide is changed by phenobarbital, which limits the confidence the Panel can put in the conclusions of this experiment.

Utility (Adequacy) for CERHR Evaluation Process: This paper provides marginal improvements over previous papers, in that some histology is performed and reported, and the reported effects are consistent with the moderate weight reductions. This study is almost adequate to conclude that 35 mg/kg bw/day, twice/week for 8 weeks, reduces cellularity in murine testes.

Sakamoto et al. *(127*) administered acrylamide (95% purity) to ddY mice as a single oral dose **[presumably gavage]** of 100 or 150 mg/kg at age 30 days (prepubertal) or 60 days (adult). Animals were killed 1, 2, 3, 5, 7, or 10 days after dosing. Testes were fixed in Bouin's fluid for 1 h, cut, and then further fixed in formalin. Sections were stained with periodic acid-Schiff stain and hematoxylin and eosin. Four animals were used for each treatment condition and evaluation time point. The 150-mg/kg dose was lethal to 50% of the 30-day-old and 65% of the 60-day-old mice. In the prepubertal mice, body weight was significantly decreased at 1 and 5 days after dosing with 150 mg/kg acrylamide. The numeric values for mean body weight at 2 and 3 days after dosing were similar to the 1- and 5-day values, but the larger standard deviation prevented identification of statistical significance. In the adult mice, body weight was significantly reduced 1, 2, and 3 days after dosing with 150 mg/kg acrylamide. There were no significant alterations in testicular weight at either dose of acrylamide. There were no deaths and no significant effects on body weight at 100 mg/kg acrylamide in either age group. Histologic abnormalities in the testes of prepubertal animals treated with 150 mg/kg acrylamide appeared in spermatids, particularly round spermatids (Golgi and cap phase) 1 day after treatment. Nuclear vacuolization and swelling were the most common lesions in the spermatids. Degeneration of spermatocytes and spermatogonia was also noted. By the second day after treatment,

spermatid degeneration was more prominent. On day 3, multi-nucleated giant cells were frequent. By days 7–10, clearing of the histologic abnormalities was evident. The description of the pattern of histologic alteration was similar after treatment with 100 mg/kg and in adult animals. Overall, spermatogonia, spermatocytes, Sertoli cells, and Leydig cells appeared more resistant to acrylamide-induced cell death than did spermatids.

Strengths/Weaknesses: A significant strength of this paper is that it used appropriate methods to analyze microscopic testis structure. The single-dose paradigm effectively uncovered round spermatids as a vulnerable population, although it is still possible that these effects were mediated through initial changes in the Sertoli cell. A weakness is that a slightly lower dose was not also used, since as dose increases, the window of vulnerability opens wider, and more cells become affected. A minor weakness is the modest number of animals per treatment group (n=4), which is only reported in a table footnote.

Utility (Adequacy) for CERHR Evaluation Process: This study has utility for the evaluation process in that it histologically identifies a vulnerable testis cell population in mice, and based on the methods used, the Expert Panel has reasonable confidence that this information is correct.

Lähdetie et al. *(69*), in a germ cell genotoxicity study sponsored by the Commission of European Communities, used flow cytometry to characterize testicular cell population proportions 18 days after acrylamide **[purity not specified]** was administered i.p. at 50 or 100 mg/kg in Sprague-Dawley rats. Stage I tubules were isolated for evaluation. The investigators planned to use two tubule segments at Stage I from each testis (four segments per male) of five or six males per dose group, compared to a saline-injected control. In actuality, 5 control males contributed 28 segments, and the 6 and 5 males of the 50- and 100-mg/kg acrylamide groups contributed 21 and 12 segments, respectively. ANOVA with post-hoc Tukey test was used. The number of cells at each DNA peak was said to be altered significantly only by 100-mg/kg acrylamide, which was associated with a 35% reduction in the number of stem cell spermatogonia. **[CERHR performed an ANOVA with post-hoc Tukey test and identified a significant 30% reduction in stem cell spermatogonia at 50 mg/kg as well as 100 mg/kg.]**

Strengths/Weaknesses: One weakness of the study was reflected by a lack of detail of the methods used (it would be impossible to reproduce these studies based on the methods given in this paper); there was also uncertainty whether the controls were evaluated for statistical difference before being pooled, and uncertainties surrounding the purity of the compound and composition of the dosing solution. In addition, the certainty that the cell populations identified in their table of flow cytometry data are truly limited to those cells (i.e., there are many other 2C cells in the testis that could be present in the "stem cell spermatogonia" population) is questioned. Finally, there were no internal quality control indicators that the stages intended to be segregated were actually the ones recovered. The strengths of this study included the use of coded slides for the analysis, direct analysis of the tissue of interest, appropriate timing, and intelligent design. The Panel's moderate confidence in these data is supported by the expertise and experience of the authors in performing these techniques, but reduced somewhat by the lack of methodologic detail and absence of data showing that the intended stages and cells were really those captured and analyzed. It is not clear that 18 or 19 days of treatment affect only the early spermatocytes, as this 19-day treatment period also targets the long meiotic prophase and meiosis itself. From these data, one may reasonably conclude that acrylamide causes micronuclei

in male germ cells, although the precise cell type affected cannot be stated with absolute confidence.

Utility (Adequacy) for CERHR Evaluation Process: By itself, this study is not useful but is generally supportive of other literature in this area.

Pacchierotti et al. *(88*), in a study supported by the Commission of the European Community, administered acrylamide **[purity not given]** in HBSS i.p. to male B6C3F$_1$ mice at single doses of 0, 75, or 125 mg/kg, or 50 mg/kg bw/day for 5 days for a total dose of 250 mg/kg. Males were mated to untreated females 7 days after the last acrylamide treatment, following which subsets of the males were killed at 7, 14, 21, 28, and 35 days **[following the end of treatment]** for flow cytometric analysis of testicular cell populations (at least 5 mice per time sample per group). Additional mice were killed 3 days after the treatments (at least 6 per dose group), and additional groups of 6 mice each were given 100 and 150 mg/kg and killed 35 days later. Testes were minced, treated with pepsin, and filtered through a 37 μm-pore nylon mesh to produce single-cell suspensions. Suspensions were fixed in ethanol and frozen at –20°C for up to several weeks. For flow cytometry, DNA was stained with 4',6-diamidino-2-phenylindole (DAPI).

The mating portion of the study was used to generate zygotes for evaluation of chromosome aberrations (discussed in Section 2.3.2.3). There was a decrease in percent mated females 7 days after the last acrylamide treatment; this decrease was not dose-related. The percent mated (plug-positive) was 86.7, 57.1, 54.1, and 61.0 in the 0, 75, 125, and 5 × 50-mg/kg bw/day groups, respectively. When males in the 125-mg/kg group were cohabited with females 28 days after treatment, 86.7% of females showed evidence of mating, a result identical to that in the control group. When meta-phases were evaluated as part of the chromosome aberration portion of the study, among cells scored from mated females with 5 × 50-mg/kg bw/day consorts, there was a 31.7% incidence of second meiotic meta-phases. In the other treatment groups and in the control, the incidence of second meiotic meta-phases ranged from 0.5 to 1.6% of cells scored. This finding was taken as evidence that sperm from the high-dose males failed to fertilize these oocytes.

There were no changes in proportional testicular cell populations 2, 3, and 4 weeks after treatment. **[Data were not shown, and no comment was made concerning proportions 1 week after treatment. It is possible that the Methods section indication that males were killed "after mating at sequential time intervals (7, 14, 21, 28 and 35 days)" refers to time intervals after mating, and hence 14, 21, 28, 35, and 42 days after treatment. If so, the 42-day data are missing.]** Data are reported for the 3- and 35-day post-treatment time points. Statistically significant findings at 3 days include a ~25% decrease in 4C cells (said to represent primary spermatocytes and G_2 spermatogonia) after 75 and 125 mg/kg acrylamide, a 50% increase in elongating/elongated diploid spermatids after 5 × 50 mg/kg bw/day acrylamide, and a 10–11% increase in elongated and round spermatids after 125 mg/kg acrylamide. Statistically significant findings 35 days after treatment with 100, 125, or 150 mg/kg acrylamide included a 30% decrease in elongated spermatids at the high dose and about a 50–100% increase (not dose-related) in diploid spermatids at all doses. This latter finding caused the authors to speculate that acrylamide impairs chromosome segregation during mitosis in spermatogonia. **[The Expert Panel finds this to be the only plausible explanation.]**

Strengths/Weaknesses: Strengths of this paper include the expertise of the authors use of appropriate

methods and statistics, and the concordance between these findings and others reported on this issue. Weaknesses of this study include some inconsistencies in reporting the data (i.e., the 42 day are missing) and the fact that the reductions observed at day 3 are not also observed at higher doses and after longer durations.

Utility (Adequacy) for CERHR Evaluation Process: These data are adequate for the evaluation process, and are sufficient to conclude that there are transient genotoxic effects that occur in specific cell populations in the testis. The confidence in this conclusion is only slightly reduced by the ad hoc nature of some of the doses and experiments and by occasional data gaps. The chromosomal aberration data at the high dose (125 mg/kg, 7 days) are supportive of other dominant lethal data *(76, 80*), and of an effect on fertility *(75*), as evidenced by the increase in unfertilized eggs. Like many acute genetic toxicology studies for this compound, the dosing paradigm does not lend itself to extrapolation to long-term exposures, but the effects described are consistent with other reports in the literature, and provide some mechanistic underpinnings for some of these other effects.

Costa et al. *(128*) examined the role of acrylamide and glycidamide in causing reproductive and neurotoxic effects in male Sprague-Dawley rats. The study was conducted at the University of Washington, but sponsorship is unknown. In the reproductive toxicity portion of the study, 8 sexually mature rats/group (350 g) were treated with 50 mg/kg bw/day acrylamide **[purity not specified]** for 7 days or 50 mg/kg bw/day glycidamide for 14 days. A control group was treated with the distilled water vehicle. **[Based on the protocol description for the neurotoxicity portion of this study, it appears that rats were treated by the i.p. route.]** The rats were examined for reproductive organ weight, testicular protein content, and sperm count and viability. Statistical significance of results was analyzed by one-way ANOVA followed by Fisher exact test for comparison between groups. Body weights of the glycidamide-treated rats were significantly lower than controls but did not differ from the acrylamide-treated rats. Neither compound affected testicular weight, but glycidamide significantly reduced epididymal weight. Treatment with glycidamide also resulted in significant reductions in testis protein content, sperm count, and sperm viability. **[Although the Results Section states that acrylamide treatment did not result in any of these effects on testes or sperm, Figure 3 in the study indicates that sperm counts were significantly reduced in the acrylamide-treated rats.]** Results were compared to the neurotoxicity test in which a separate group of rats were i.p. injected with acrylamide or glycidamide for 8 days. Results included impaired rotarod performance at 50 mg/kg bw/day acrylamide and 100 mg/kg bw/day glycidamide and hindlimb splay at ≥25 mg/kg bw/day acrylamide. The study authors concluded that glycidamide is involved in the reproductive toxicity, but not the neurotoxicity, associated with acrylamide exposure.

Strengths/Weaknesses: A weakness of this study is that the doses of glycidamide were not based on any sort of molar conversion from acrylamide; molar equivalence would make the data more readily interpretable. Neither is there any rationale in this paper for the measures of reproductive "toxicity" that were chosen, the relationship of protein content to toxicity is loose and unspecified, and there is no precedent in the literature for showing that acrylamide reduces sperm viability. To improve the study, authors might have measured glycidamide levels in the neurons, reproductive organs, and hemoglobin of all animals in this study, which would in turn have allowed a more meaningful link between exposure and effect to be illustrated. Further weaknesses include that no histopathology was examined; there was no indication that these durations of exposure were sufficient to show an effect

on testis weight if one were to occur at these doses; insufficient specifics on the methods of analysis for the protein and viability were provided; and the text and figures are inconsistent in reporting sperm count effects. However, the concept is interesting, and the statistics appear to be appropriate.

Utility (Adequacy) for CERHR Evaluation Process: From these data, we can conclude that glycidamide produces some effect on the testis and on sperm content in the vas, but we are uncertain of the nature and degree of these effects. These data are not very useful for the Evaluation Process, due to the superficial nature of the exploration, the uncertainty of the relationship between what was measured and what was concluded, the apparent lack of correlation between the chosen doses and times for acrylamide and glycidamide, and the lack of histology.

Marchetti et al. *(89*), supported by DOE and NIEHS, gave acrylamide **[purity not specified]** to male B6C3F1 mice at 50 mg/kg bw/day i.p. for 5 consecutive days as part of a study to assess chromosome exchanges in the male pronucleus (discussed in Section 2.3.2.3). This study was performed to assess a new method of detecting multiple cytogenetic abnormalities, and was not intended to be used to identify a lowest effective dose. This purpose also led to unique designs, and a recognition that some details important in Guideline-driven studies were not main focuses here (e.g., details of numbers of animals, or analysis of dosing solutions). Mice were mated with untreated females of the same strain at 2.5, 6.5, 9.5, 12.5, 20.5, 27.5, 41.5, and 48.5 days after the last acrylamide injection, to produce fertilization by sperm that had been exposed to acrylamide at the epididymal spermatozoon, early spermatozoon, elongated spermatid, mid-spermatid, round spermatid, pachytene spermatocyte, differentiating spermatogonium, and stem cell stages, respectively. Females were superovulated with pregnant mare's serum followed by hCG, then mated. Plugged females were given colchicine 24 h after hCG to arrest zygote development at metaphase of the first cleavage. Females were killed 6 h after colchicine and zygotes were harvested. The proportion of fertilized eggs (of all eggs harvested) was decreased by treatment at all time points except 48.5 days prior to mating. The proportion of zygotes (of all fertilized eggs) was decreased in the 2.5–12.5 day period, that is, from the mid-spermatid through epididymal spermatozoon stages, which the authors point out as repair-deficient stages. **[The proportions were analyzed by chi-square, which takes the harvested cell as the statistical unit. The sire of origin was not indicated; in fact, the number of males is not stated except that matings were 1:1 and "[z]ygotes harvested from 10–15 females were pooled…".]**

Strengths/Weaknesses: Strengths of this study include the expertise and experience of the authors in these techniques; the relevance of other data in this study, which provide information about mechanism and vulnerable stages of spermatogenesis; and the availability of appropriate statistics. Some weaknesses of the study are that the unique design does not allow for the usual determination of effects on specific males (which was, in fact, quite beside the point of the paper, so is only a weakness for CERHR purposes), and the lack of analysis of the dosing solution or neat agent.

Utility (Adequacy) for CERHR Evaluation Process: From a reproductive perspective, this study adds to our understanding of precisely which stages of germ cell development are affected by the specific exposure to acrylamide at 50 mg/kg bw/day for 5 days. It confirms that fertilization is a vulnerable process, that testicular spermatids are a vulnerable stage, and adds a cell cycle-delay effect not previously identified.

Adler et al. *(79)* (support source not indicated) treated male mice with acrylamide **[purity not given]** 125 mg/kg i.p. with or without 1-aminobenzotriazole, an inhibitor of hepatic and renal P-450. The 1-aminobenzotriazole was given at 50 mg/kg i.p. daily for 3 days with acrylamide given on the fourth day. Control animals for each treatment received vehicle, which was saline for 1-aminobenzotriazole and double-distilled water for acrylamide, and an additional control group received daily injections of saline for 3 days and an injection of double-distilled water on the fourth day. The inhibition of P-450 was believed to prevent metabolism of acrylamide to glycidamide. Two dominant lethal studies were performed using (102/E1 × C3H/E1)F_1 males and females. The dominant lethal results are summarized in Table 14. The second dominant lethal study included four males per group from which epididymides were obtained 1 week after completion of the 4-day treatment regimen. Both caudae were incised and sperm allowed to diffuse or swim out in fetal calf serum for 1 h. Sperm concentration was determined using a hemocytometer. Motility was estimated by light microscopy as percent fast, slow, non-progressive, and "immobile." Morphology was also determined. **[Method of determination not given except by reference to the 1992 WHO manual, which is a manual for evaluation of human sperm.]** Sperm concentration and percent normal forms were not affected by any treatment. Motility was decreased by acrylamide with the mean percentage of immotile sperm increasing from 38.8 ± 8.9 in the control to 76.8 ± 4.2 in the acrylamide-treated group. Percent immotile sperm in the two groups given 1-aminobenzotriazole were intermediate, without a significant impact of acrylamide (1-aminobenzotriazole + acrylamide: 66.3 ± 4.2%; 1-aminobenzotriazole + water: 60.0 ± 10.0%; *P* NS).

Strengths/Weaknesses: The strengths of this study are that both the study and its results were repeated, which gives significant credibility to the results; the data are provided in detail in extensive tables; sperm data were collected from some males to eliminate (or simply explore) possible effects on sperm count or motility; and that there was a sufficient number of animals used. Weaknesses of the study included the lack of independent determination that 1-aminobenzotriazole actually inhibited P450 activity in these animals, and the lack of measurement of glycidamide concentrations in the acrylamide-and-1-aminobenzotriazole-treated mice. These lacks do not allow one to know that the intended mechanism was truly at work. Also, there is no reference to support using 1-aminobenzotriazole for such an effect; inappropriate statistical methods seem to have been used; the figures are not clear, they lack any indication of variance, and are very poorly described. Finally, the sperm methods are unique and described in such insufficient detail (i.e., no criteria are given for 'fast' or 'slow' sperm, or for malformed sperm), that this study cannot be repeated using only these descriptions.

Utility (Adequacy) for CERHR Evaluation Process: If the P450 inhibition by 1-aminobenztriazole is taken at face value, and assuming that such an inhibition occurred in these animals, these results provide insight into mechanism and into the active metabolite that is responsible for the dominant lethality in mice. Together with data from Hashimoto et al. *(126)* (who showed lower toxicity after pre-administration of phenobarbital) and Costa et al. *(128)* (who dosed with glycidamide and found effects on testis weight and protein concentrations), the implication of metabolism is elucidated. At face value, it would seem that Hashimoto et al. and Adler et al. are contradictory. However, since neither study confirmed the alterations in P450 metabolic profiles, the metabolism must be assumed important. Indeed, all three studies indicate only the imputed involvement of glycidamide as the active intermediate; this hypothesis awaits a rigorous proof. Once proven in animals, glycidamide could become a biomarker of exposure in humans, with consequent increased confidence that toxicity

is or is not likely in humans given exposure to X amount of acrylamide (which produced Y amount of glycidamide). The reduced proportion of "fast" sperm is not consistent with the increased beat/cross frequency noted by Tyl et al. *(129*) (discussed below), although this inconsistency might be partially explained by the subjectivity of current measurement methods and the different species involved. Invoking sperm-tail motor proteins as a target for acrylamide (or glycidamide) is premature, since the effect was not demonstrated in sperm treated *in vitro*. While this effect could be due to effects on the epididymis, prostate, seminal vesicles, or coagulating gland, a direct effect on sperm is admittedly reasonable, given the timing of exposure and measurement. This is assuming that an effect truly exists, which is uncertain, given these methods. These data imply that metabolism is important, but these data alone do not prove it.

Sakamoto and Hashimoto *(124*) gave male mice (ddY strain) acrylamide in drinking water at 0.3, 0.6, 0.9, and 1.2 mM **[21.3, 42.6, 64.0, and 85.2 mg/L, respectively]**. Water intake was not influenced by treatment and the mean water consumption in the high dose group was reported as 6.2 g/animal/day. **[Using the mean body weight at the end of the dosing period in the high dose group (35.4 g), water consumption would have averaged 214 mL/kg bw/day. These drinking water concentrations would produce acrylamide doses of 4.6, 9.1, 13.7, and 18.2 mg/kg bw/day.]** There were 9 males each in the 3 lowest acrylamide doses and 14 males each in the control and high dose groups. Animals in the high dose group were described as having "very slight hindlimb weakness." Males were given the treated water for 4 weeks, following which half the males in each group were mated 1:3 for up to 8 days with untreated females of the same strain. **[It is not stated whether there was acrylamide in the drinking water during the cohabitation period.]** Half of the pregnant mice were killed on GD 13 **[plug day unspecified]** and uterine contents were evaluated. The other half were permitted to deliver and rear their young, with observations of body weight and behavior for 4 weeks. The remaining males were killed at the end of the treatment period and used for evaluation of liver and reproductive organ weight and evaluation of epididymal sperm, obtained by mincing the tissue in 10% neutral buffered formalin. Sperm concentration was evaluated in a hemocytometer and morphology was evaluated in Eosin Y-stained smears. Statistical testing was performed using the Fisher exact test or ANOVA followed by Duncan multiple comparison test. **[It appears from the tables that the treated male was the statistical unit of analysis.]** Results of these studies are summarized in Table 29 **[there appeared to have been 3 or 4 males used per dose group in the mating studies.]** The highest two concentrations of acrylamide appeared active with dose-related decreases in the number of fetuses/dam. Other reproductive endpoints were adversely affected at the high dose (Table 29). The offspring of females that were allowed to litter and raise their young were said not to differ by treatment group with respect to weight gain or behavior over the first 4 weeks of life **[no data were shown]**.

Strengths/Weaknesses: This study used mice, a species relatively resistant to neurologic damage. The study is also weakened by a lack of detail about exposure levels. The unusual method of preparing sperm for analysis is a minor weakness (as mincing can mis-shape the sperm, and formalin fixation of the epididymis during sperm extraction might reduce the efficiency of extraction, although this reduced efficiency would apply to all groups). Other minor weaknesses are the modest number of animals and the lack of histopathology (although histopathology was evaluated and reported in a previous study). A strength of the study is that half the high-dose animals were allowed to deliver their young; a consequent weakness is that this procedure reduced the number of animals available

for any analysis, and details of the observations made on the young are omitted.

Utility (Adequacy) for CERHR Evaluation Process: These data are adequate to allow a conclusion that in mice, 4–6 weeks of exposure to about 13 mg/kg bw/day acrylamide reduces litter size from treated males, while about 18 mg/kg bw/day also reduces the impregnation rate and sperm count, and increases resorptions. Using the benchmark dose approach and the authors' estimates of acrylamide intake at the stated water concentrations, the 10% effect level may be as low as 3 mg/kg bw/day for resorptions/dam after paternal treatment. The Panel's certainty about the strength of these effects and the effective doses is reduced because of the relatively small numbers of animals examined.

Table 29. Pregnancy Outcome in Females Mated to Male ddY Mice after Exposure of Males to Acrylamide in Drinking Water for 4 Weeks. From Sakamoto and Hashimoto (124)

Parameter	*Concentration of acrylamide in drinking water (mM)* **[mg/L]**			
	0.3 **[21.3]**	***0.6*** **[42.6]**	***0.9*** **[64.0]**	***1.2*** **[85.2]**
Estimated dose (mg/kg bw/day)	4.6	9.1	13.7	18.2
Pregnant/mated females (GD 13)	↔	↔	↔	↓67%
Fetuses/dam (GD 13)	↔	↔	↓31%	↓78%
Resorptions/dam (GD 13)[a]	↔	↔	↔	↑10-fold
Pregnant/mated females (at term)	Not reported	Not reported	Not reported	↓60%
Offspring/dam (at term)	Not reported	Not reported	Not reported	↓67%
Offspring birth weight	Not reported	Not reported	Not reported	↔
Relative liver weight	↔	↔	↔	↔
Relative testis weight	↔	↔	↔	↔
Relative seminal vesicle weight	↔	↔	↔	↔
Epididymal sperm				
Count (per g epididymis)	↔	↑1.2-fold	↑1.3-fold	↓35%
Percent abnormal forms	↔	↔	↔	↑2.2-fold

↑,↓ Statistically significant increase, decrease compared to control.
↔ Not statistically different from control.
[a] Standard deviations were larger than means, suggesting that ANOVA was not the preferred statistical option.

In a study supported by the US EPA, Zenick et al. *(81)* gave acrylamide **[purity not specified]** in drinking water to male Long-Evans hooded rats at 0, 50, 100, or 200 ppm for up to 10 weeks. **[Based on graphs of mean water intake and body weight, CERHR estimates the mean acrylamide intake at the beginning of exposure to have been about 5, 7, and 12 mg/kg bw/day, and at the end of the study (10 weeks in the 50 and 100 ppm groups, 6 weeks in the 200 ppm group) to have been 5, 8, and 12 mg/kg bw/day in the low, medium, and high exposure groups, respectively. The authors assessed cumulative acrylamide intake as 544 and 547 mg/kg in the 100 and 200 ppm groups. Assuming the cumulative intake refers to intake over 10 and 6 weeks, respectively, for these 2 dose groups, the mean acrylamide intake over the study period was 7.8 and 13.0 mg/kg bw/day in the middle and high dose groups, respectively.]** Males (70 days old) were acclimated to a reversed 14:10 light:dark photoperiod with lights on at 10:00 pm and were exposed to ovariectomized, hormonally primed females for mating experience. This acclimation period lasted 3 weeks. During

the study period, a female was presented each week. Mating was monitored visually every 2 weeks. At baseline and during exposure week 9, females were killed after mating and ejaculate was recovered from the genital tract **[the method of recovery was not given]**. The recovered ejaculate was evaluated for copulatory plug weight and sperm count, motility, and morphology. Assignment to exposure group was balanced for baseline body weight, sperm count, and latency to ejaculation. During week 10, males in the 0 and 100 ppm groups were mated with intact estrous females. Females were killed on GD 17 **[plug day not specified, but in another experiment in this paper, plug day was GD 1]**. Fetuses and implantations were counted **[staining for implantations is not mentioned]**. Males were killed at week 11 for histologic evaluation of one testis and epididymal fluid **[fixed in Bouin's fluid, stain not indicated].** The other testis was homogenized for spermatid count and the other epididymis was minced for sperm count **[detailed methods not given]**. Repeated measures ANOVA was used for most analyses; ratios for fertility and postimplantation loss were evaluated by chi-square. Duncan post-hoc test was used after some of the ANOVAs. The unit of analysis appears to have been the male or the female **[based on the number of females reported in the tables, it appears that mating was 1:1, making the female equivalent to the male as the statistical unit for mating data]**.

The data tables show 14 males in the 0 ppm group, although initial group size was 15. In the 200 ppm group, hindlimb splay occurred by week 4. Three of 15 males in this group died or were killed in moribund condition by week 5 and the remaining 12 males were killed at week 6. The 200-ppm males showed a decrease in body weight and water intake compared to controls. There was less severe hindlimb splay in "some" of the 100-ppm males. Body weight was numerically lower at all time points in the 100-ppm males compared to controls, but there were reportedly no significant differences compared to controls **[standard error or standard deviation was not given]**.

Prior to the onset of hindlimb splay, males in the 100- and 200-ppm groups showed an increased number of mounts during cohabitation with prepared females. The authors indicated that they could not tell if some of these mounts were incomplete intromissions. The authors also indicated an increase in mounts in the 50-ppm group during the last week of observation (week 9), although this putative increase was not statistically significant **[the square root transformation of mount data are shown without error bars]**. Intromissions were increased in the 200-ppm group at week 4 and in the 100-ppm group at week 9. Mount latency was not affected by treatment. During the final week of assessment (week 6 in the 200-ppm group and week 9 in the 100-ppm group), only 4/12 and 11/15 males in the high- and middle-dose groups, respectively, ejaculated during the 30-minute mating period. Of those animals ejaculating, ejaculation latency was not affected by treatment. Among the 11 females mated with 100-ppm males that ejaculated, sperm were recovered from only 1 uterus **[the text says semen, but surely sperm is meant]**. Sperm were identified in all vaginas of these 11 females, but sperm counts here were significantly lower than in the vaginas of females mated with 0-ppm males ($14 \pm 20 \times 10^6$ vs. $56 \pm 18 \times 10^6$; $P \leq 0.01$). Motility and morphology could not be assessed in the vaginal sperm from females mated to males of the 100-ppm group; there was no effect of acrylamide treatment on these parameters in sperm from females mated to 50-ppm males. Copulatory plug weights were not different among females mated to 50- or 100-ppm males compared to controls. After cohabitation with intact estrous females, all 14 control and all 15 100-ppm males produced evidence of mating within 5 days; however, only 5/15 females (33%) mated to 100-ppm males showed evidence of pregnancy compared to 11/14 females (79%) mated to 0-ppm males ($P<0.01$ according to the authors **[$P=0.025$ by Fisher test performed by CERHR]**). Postimplantation loss in the females mated to 100-ppm males was $31.7 \pm 3.8\%$ compared to $8.0 \pm 1.1\%$

in females mated to 0-ppm males (P<0.01). Individual postimplantation losses in the 5 females mated to 100-ppm males were 0, 21, 38, 50, and 50% **[which gives a mean ± SEM of 31.8 ± 9.6% in contrast to the mean and SEM given by the authors]**. By contrast, of the 11 pregnant females in the control group, 2 litters showed postimplantation losses above 10% and 8 had 0 postimplantation losses **[these data are given in the Discussion section of the paper]**.

At week 6, the 12 surviving males from the 200-ppm treatment group were killed along with 3 untreated males from the same initial shipment. There were no differences between the treated and untreated males in body weight, absolute or relative organ weights, or sperm parameters **[data were not shown]**. At week 11, all remaining males were killed and comparisons were made between acrylamide-treated groups and 0-ppm controls. There were no differences in body weight, organ weights (including separate prostate + seminal vesicle, vas deferens, and epididymis weights), sperm per gram cauda epididymis, or spermatids per gram testis. Testicular histology was comparable in the 100- and 0-ppm groups. The authors interpreted the results as consistent with impaired fertility due to disturbances in copulation. They believed that the abnormalities of mounting and intromission may have reflected neurologic dysfunction, albeit prior to the appearance of hindlimb splay. The abnormal copulatory function on the part of the male may have resulted in insufficient stimulation of the female genital tract for normal facilitation of sperm transport into the uterus, accounting for uterine sperm in only 1 of the 11 females with vaginal sperm after mating with 100-ppm treated males, and pregnancy in only 33% of intact females successfully mated (by copulatory plug criteria) with males in the same dose group.

Strengths/Weaknesses: The thoroughness of the analysis of male reproductive function is a big strength for this paper, as are the large numbers of animals used, and appropriate statistical analyses. Good histology is a strength, but the numerous cell counts are even better, and allow a good "dissection" of site of effect. Recovering ejaculate from the females' tracts is a unique strength in that it assesses that which was delivered to the female, not what was captured in the male at necropsy, which may differ. While other explanations may account for the fertility differences observed (such as impaired sperm discharge during ejaculation due to nerve damage), these other explanations do not reduce the fundamental strengths of this paper. Significant strengths are methods of testis fixation and cell counting on the contralateral side. Imprecision in exposure assessment is a weakness, as is imprecision in reporting the results (e.g., numbers of affected males, variance around the means).

Utility (Adequacy) for CERHR Evaluation Process: The uncertainties in exposure only moderately reduce the fundamental utility of this paper for the evaluation process. From this work, the Panel concludes that male rats consuming 7–8 mg/kg bw/day will have reduced fertility—not because of a lesion in sperm production, but because of a defect in the delivery of sperm to the female. These data do not exclude the possibility that genetic damage is partly responsible for the reduction in fertility. These data show that a defect in delivery occurs at doses lower than those that affect spermatogenesis, leaving the conclusion that other reports of a lesion in spermatogenesis also imply an existing occult defect in delivery in the same animals.

Sublet et al. *(75)*, in a study sponsored by the US EPA, exposed male Long-Evans hooded rats to acrylamide (>99% pure). The study included a dominant lethal design plus an evaluation of mating and fertilization success to investigate what proportion of apparent dominant lethality and pre-implantation loss might be attributable to impaired fertility as opposed to death of the conceptus

prior to implantation. The dose range was selected to avoid neurotoxicity (hindlimb incoordination). In the first study, males received acrylamide in distilled water by gavage at 0, 30, 45, or 60 mg/kg bw/day for 5 days and were mated during weeks 1, 2, 3, 4, 7, and 10 after treatment. In the second study, males received acrylamide in distilled water by gavage at 0, 5, or 15 mg/kg bw/day for 5 days and were mated during weeks 1–4. Sperm in the vaginal lavage of the female was taken to indicate GD 0. Females were killed on GD 15. Corpora lutea, implantations, and live and dead fetuses were counted. Uteri that appeared non-pregnant were stained with 10% ammonium sulfide. The results, summarized in Table 14, showed an increase in pre- and postimplantation loss with mating 1–3 weeks after treatment of males with acrylamide doses at or above 15 mg/kg bw/day for 5 days.

Because previous work *(81)* suggested that subchronic acrylamide treatment of male rats produced copulatory disturbances and impaired transport of sperm to the uterine lumen, the current study *(75)* evaluated similar parameters after the acute, 5-day gavage exposure. For this study, male rats were kept in a 14:10 reverse light:dark cycle with lights off at 10 am and were treated with acrylamide 0, 15, or 45 mg/kg bw/day for 5 days by gavage (n=10 males/dose group). Hormonally-primed ovariectomized females were introduced for mating beginning 2 days after the last acrylamide dose and continuing for 4 weeks. Each female was killed 15 minutes after ejaculation **[the Results section says 10–15 minutes],** and the uterus and vagina opened at laparotomy. Fluid was aspirated from the uterus and examined for sperm by light microscopy. **[Microscopy of vaginal fluid is not described but must also have occurred given that results are given for vaginal sperm.]** No abnormalities of male copulatory behavior were observed at any dose **[data not shown]**. All females had sperm in the vagina at all time points after treatment of males with any dose of acrylamide. One week after treatment of males with vehicle, 10/10 females had sperm in the uterus. Comparable figures after treatment of males with 15 mg/kg bw/day and 45 mg/kg bw/day were 6/10 and 2/10, the latter proportion being statistically different from the control. There were no differences in the proportions of females with uterine sperm 2, 3, or 4 weeks after treatment of males with either dose of acrylamide.

An additional 10 males per dose group were treated with acrylamide in distilled water at 0 or 45 mg/kg bw/day for 5 days by gavage and mated with hormonally primed, ovariectomized females each week for 4 weeks, as above. Females were killed 15 minutes after copulation and uterine fluid aspirated at laparotomy. Sperm concentration, percent motility, curvilinear and straight-line velocity, and linearity were evaluated using a computer-assisted sperm analysis system. There were no differences among these parameters at any time in any dose group, except for a decrease in motile sperm and curvilinear velocity in females 3 weeks after treatment of males with acrylamide 45 mg/kg bw/day for 5 days (control motility 75%, acrylamide-treated motility 58%, $P<0.05$; control curvilinear velocity 132.12 ± 7.02 μm/sec, acrylamide-treated curvilinear velocity 122.06 ± 3.32 μm/sec, $P<0.05$). **[The Panel notes that there were 20 comparisons (5 sperm parameters at four time points each), without attention to a possible multiple comparison problem.]**

An estimate of fertilization was made in a final study in which males were treated with acrylamide in distilled water at 0, 15, or 45 mg/kg bw/day for 5 days by gavage. Two days after treatment and every week for a total of 3 weeks, males were housed with pro-estrous females from 2:00 pm until the following morning. Sperm on vaginal lavage was taken as evidence of pregnancy and females were killed at 10:00 am, about 10–14 h after the estimated time of mating. Ovaries, oviducts, and uteri were dissected and cumulus masses recovered from the oviducts. Hyaluronidase was used to disperse the

cumulus cells and oocytes were viewed using Nomarski optics. The oocyte was assessed as having been fertilized if either a sperm head and tail or two pronuclei were present within the oocyte. The experiment was replicated for week 3. The percent oocytes fertilized per female was reduced in a dose-dependent manner in Week 1 (0, 15, and 45 mg/kg bw/day fertilization rates were 84, 41, and 29% in 14, 13, and 16 females, respectively). A decrease in fertilization was also seen during week 3 in the 45 mg/kg bw/day group (control 65% [n=8], treated 12% [n=15] in the first replicate; control 92%, treated 9% in the second replicate **[n not given]**).

The authors suggested that impaired fertilizing ability of acrylamide-exposed sperm may play a role in the apparent pre-implantation loss rate seen after treatment. They proposed that although copulatory behavior appeared normal in their experiments, and acrylamide doses were below those associated with gross neurologic impairment, there might be subtle abnormalities of copulation resulting in either a failure to deposit the ejaculate appropriately against the cervix or a failure of adequate stimulation of the female to result in facilitation of sperm transport. They noted that in some instances, the implantation rates appeared higher than fertilization rates under the same conditions, and proposed that there might be an acrylamide-associated delay in fertilization such that at 10–14 h after the estimated time of mating, sperm might not yet have fertilized but would ultimately have done so.

Strengths/Weaknesses: The thoroughness of design and evaluation is a plus, as is the analysis of the acrylamide at the beginning of the experiment. Pilot studies and adequate numbers of animals are additional strengths, as are the sperm transport and fertilization studies. The fact that this paper reports a series of related experiments that successively drill further down into a mechanism of effect makes it uniquely valuable. The consistency of the effects and the inter-relation of the findings lend credence to the conclusions. Weaknesses of the study include inappropriate statistics for at least some of the endpoints, and the absence of histology in treated males to verify that the later fertility reduction might be due to reduced sperm output from the testis, secondary to a testis lesion similar to that seen by Sakamoto et al. The Panel has high confidence in the quality of these data.

Utility (Adequacy) for CERHR Evaluation Process: This study has significant value for the evaluation process in that it further dissects the fertilization and mating processes, and identifies these processes as likely targets of acrylamide action in rats dosed with 15 and 45 mg/kg bw/day for 5 days.

Tyl et al. *(129*), sponsored by the Acrylamide Monomer Producers Association, extended the study design of Sublet et al. *(75*) to include neurologic assessments. The stated purpose of the study was "to confirm the potential of oral (gavage) exposure o[f] male Long-Evans rats to acrylamide monomer for 5 days to produce reproductive and/or dominant lethal effects in the males detected by mating exposed males to unexposed females, and to determine whether there was a relationship between reproductive toxicity and neurotoxicity…"

The species, strain, and dosing parameters were identical to those used by Sublet et al. *(75*) and the study design matched the first week of the Sublet et al. *(75*) study. Virgin male Long-Evans rats were exposed by daily gavage (5 mL/kg) for 5 consecutive days to acrylamide (>99.7% pure) at 0, 5, 15, 30, 45, or 60 mg/kg bw/day. Dosing solutions were made in sterile distilled water and were 90–100% of target concentrations. There were 25 animals in each dose group. Males were 11 weeks old and were randomized by weight. On the third day after the last acrylamide dose, males were paired 1:1

with virgin proestrous or estrous female rats, also randomized by weight. Males and females were paired at 2:00 PM and females were evaluated the next morning for vaginal sperm or a copulation plug. The morning of vaginal examination was designated GD 0.

Following the overnight mating, males underwent grip testing after which they were killed. Five males/group were perfusion-fixed with glutaraldehyde; the remaining 20 males/group were used for evaluation of cauda epididymal sperm, including computerized automated sperm analysis (CASA) parameters. Sciatic nerves from perfusion-fixed males were evaluated with hematoxylin and eosin and with Holm Silver/Luxol Fast Blue (to differentiate axons and myelin sheath). Females were killed on GD 15 for evaluation of uterine contents including the status of each implantation. Uteri without apparent implantations were stained with 10% ammonium sulfide for evaluation of possible implantation sites. Females without evidence of successful mating were handled similarly.

Statistical analysis of data meeting the Bartlett test for homogeneity of variances was performed by general linear model procedures to evaluate trends, with ANOVA followed by the Dunnett multiple comparison test for evaluating differences of acrylamide dose group data from control data. Nonparametric tests included the Kruskal-Wallis test followed by post-hoc Mann-Whitney *U* test, Jonckheere test for dose-response trends of continuous data, chi-square (followed by Fisher test) for frequency data, and the Cochran-Armitage test for linear trend on proportions.

Data from this study are summarized in Table 30. Males receiving acrylamide at doses higher than 5 mg/kg bw/day gained less weight or lost weight during the dosing interval. Some weight recovery occurred during the 3-day post-dosing interval, but overall weight gain during the study (days 1–8) was less in males treated with acrylamide at 15 mg/kg bw/day or higher. During the entire 8-day study period, males at the highest dose lost about 25 g compared to about a 30-g gain in weight in the controls **[estimated from figure].** Hind limb grip strength was decreased in the high dose group but in no other groups, and there were no histologic alterations in the sciatic nerve at any dose. Reproductive data were presented in two ways: considering only confirmed-pregnant females as pregnant or, as in the study of Sublet et al. *(75*), considering sperm-positive females as pregnant. In the latter analysis, a mated female with no implantation sites would be considered to have 100% pre-implantation loss, while in the former analysis, a mated female with no implantation sites would be considered non-pregnant (i.e., as having failed to undergo fertilization). The number of males that mated during the single overnight cohabitation was 16/25 in the control group and 9/24 in the 60 mg/kg bw/day acrylamide group. Among the control males, 13 produced a litter, while only 2 of the 60 mg/kg bw/day acrylamide-treated males produced a litter.

A decrease in live implants per litter and an increase in resorptions/litter were identified in the top two dose groups based on pair-wise statistical testing. In their discussion, the authors consider the 45 and 60 mg/kg bw/day doses to be effect levels based on the pair-wise comparisons, although they write that 15 mg/kg bw/day and higher were arguably active doses based on the trend testing results. There is no other discussion of the significance of trend testing; however, if the authors' data on live implants/sperm-positive female or postimplantation loss/litter are graphed using a linear model (Figure 8), it is not obvious that a NOAEL has been identified based on pair-wise testing. Using these linear models, a benchmark dose approach is shown in Table 31.

Table 30. Results from Tyl et al. (129) Study of Male Reproductive Toxicity and Neurotoxicity of Acrylamide

Parameter		Dose (mg/kg/day)				
		5	15	30	45	60
Male body weight	On study day 5 (prior to last dose)	↔	↔	↓	↓	↓
	On study day 8 (prior to mating)	↔	↔	↓	↓	↓
	Δ Study day 1–5 (dosing interval)	↔	↓	↓	↓	↓
	Δ Study day 5–8 (postdosing, premating)	upward trend ($P<0.001$); no pair-wise differences				
	Δ Study day 1–8	↔	↓	↓	↓	↓
Grip strength	Forelimb	↔	↔	↔	↔	↔
	Hindlimb	↔	↔	↔	↔	↓21.4%
Males that mated/males that were paired		↔	↔	↔	↔	↓41%
Males siring litters/males that mated[a]		↔	downward trend; no pair-wise differences			
Implantation sites/sperm-positive female		downward trend ($P<0.01$); no pair-wise differences				
Implantation sites/confirmed pregnant female		↔	↔	↔	↔	↔
Live implants/sperm-positive female		downward trend ($P<0.001$)			↓54%	↓86%
Live implants/confirmed pregnant female		downward trend ($P<0.05$); no pair-wise differences				
Pre-implantation loss/confirmed pregnant female		↔	↔	↔	↔	↔
Resorptions[b]/confirmed pregnant female		upward trend ($P<0.01$)			↑ 9-fold	↑ 15-fold
Sperm parameters	Concentration	↔	↔	↔	↔	↔
	Percent motile	↔	↔	↔	↔	↔
	Percent progressively motile	downward trend; no pair-wise differences				
	Beat cross frequency	upward trend ($P<0.001$)				↑36%

Δ = change in parameter.

[a] This parameter, called the fertility index, is equivalent in this study to the pregnancy index (pregnant females/males that mated).

[b] Postimplantation loss/confirmed pregnant female.

There were 25 males per group except at 60 mg/kg bw/day (n=24, 1 male removed for fractured tibia).

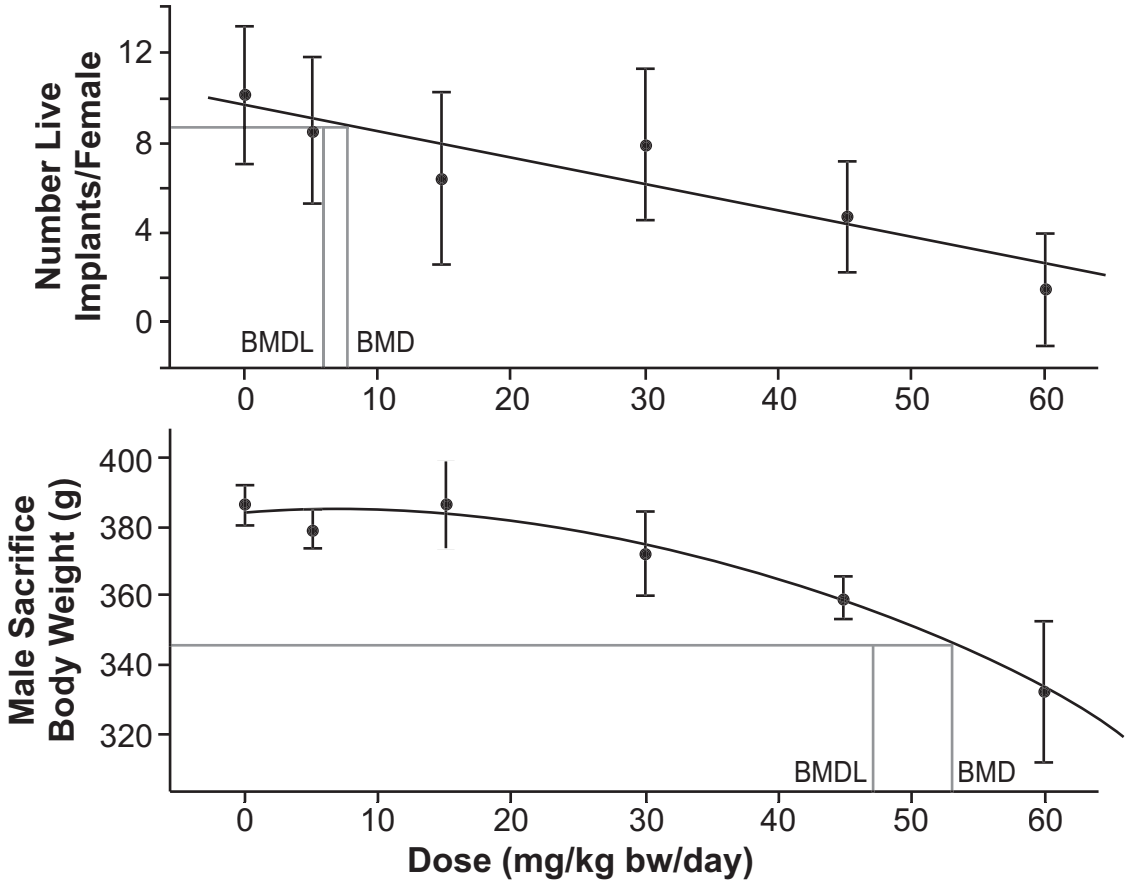
Table 31. Benchmark Doses (mg/kg bw/day, gavage) Calculated by CERHR Based on Linear Model for Reproductive Endpoints and Power Model for Weight Using Data from Tyl et al. (129)

Endpoint	BMD10	BMDL
Live implants/sperm-positive female	8	6
Male sacrifice body weight (estimated from graph)	53	47

BMD_{10} Exposure level associated with a 10% response, estimated from a mathematical dose–response model.

BMDL Dose associated with the lower bound of the 95% confidence interval around the BMD_{10}.

Figure 8. Results of Tyl et al. (129) Plotted by CERHR using US EPA Benchmark Dose Software.



BMD: Exposure level associated with a 10% relative response increase, estimated from a mathematical dose-response model.

BMDL: Dose associated with lower 95% confidence interval around the BMD.

Data are expressed as mean ± SD, n = 25/dose group except n=24 for the 60 mg/kg/day group.

The authors consider whether acrylamide is a "primary reproductive toxicant" or whether the reproductive toxicity was likely to have been due to systemic toxicity, specifically neurotoxicity. In one part of the discussion, the changes in body weight at 15 mg/kg bw/day and higher were considered to be unrelated to the reproductive effects, based on a cited reference that indicated no adverse male reproductive effects with a 30% weight reduction from feed restriction. In another part of the discussion, the weight data were used to identify 15–60 mg/kg bw/day as being associated with acute systemic toxicity. The authors write, "In this study, statistically significant indicators of acute systemic toxicity occurred at 45 to 60 mg/kg/day, and statistically significant indicators of reproductive toxicity occurred at 45 to 60 mg/kg/day, and arguably at 15 to 30 mg/kg/day based on trend testing, which is at least consistent with the systemic toxicity, specifically neurotoxicity, being causative (or contributory) to the observed reproductive toxicity." **[It is not clear why the authors refer specifically to neurotoxicity, which was demonstrated only at the 60 mg/kg bw/day dose.]**

Strengths/Weaknesses: Strengths of this study include sufficient numbers of animals and dose levels, analysis of dosing solutions and apparently correct statistical analysis, and thorough analysis of effects. Alert technicians noticing differences in sperm motility during necropsy, and prompting a more widespread and thorough analysis of this finding, is one example of the quality of science demonstrated in this report. Weaknesses are the relatively poor mating performance of these animals (it might have been useful to mate one male with two females); and large variances for the postimplantation loss data, which make the benchmark dose modeling less useful due to lack of confidence in the mathematical model.

Utility (Adequacy) for CERHR Evaluation Process: These data are very useful for the Evaluation Process, given the confidence that the Panel has in the quality of the data and the analysis. The fact that these data effectively replicate the effects noted by Sublet et al. *(75*) validates the effects. A benchmark dose approach would seem the best way to utilize all these data, as there are clearly trends of effect in the dataset at doses lower than those asterisked in the pair-wise comparison. Reproductive toxicity appears to occur in a dose range lower than that associated with decreased male body weight. While the authors were unable to separate unambiguously the reproductive from the dominant lethal effects, they did a thorough job of evaluating this relationship, and the Panel is confident that doses for these effects overlap considerably.

4.2.3 Continuous breeding or multigeneration design

Chapin et al. *(130*) performed a Reproductive Assessment by Continuous Breeding (RACB) on acrylamide and three analogs (*N,N'*-methylenenisacrylamide, methacrylamide, and *N*-(hydroxy-metlyl)acrylamide under the sponsorship of the NTP. The study animal was the Swiss mouse. The RACB protocol consisted of four tasks. The first task was a 28-day dose-range finding study. Task 2 started with a 7-day dosing period followed by 98 days of continued dosing with animals housed together as mating pairs. During the continuous cohabitation phase, pups were removed from their dams after birth and destroyed. At the end of the 98 days, the male and female were separated and continued to be dosed for a 6-week holding period. During this time, pregnant females were allowed to deliver and raise their last litters until weaning. The dams continued to be dosed during pregnancy and lactation and pups were dosed with the same drinking water solutions after weaning. Task 3 was a cross-over mating trial during which high-dose treated animals were cohabited with untreated control animals to identify which sex was affected. Treatment was withheld during this 1-week mating trial. Task 4 was a fertility study using the F_1 animals from the last litter in the 98-day cohabitation phase. These animals were tested at 74 ± 10 days of age, having been dosed since weaning. A dominant lethal test was also conducted in some high-dose males at the end of the 98-day cohabitation phase. Each male was mated with three untreated females for up to 4 nights, and the females allowed to carry their pregnancies until GD 16, at which time they were killed and uteri examined for live, dead, and resorbing implants.

Acrylamide (97–99% pure) was diluted in de-ionized filtered water and supplied to animals as their sole drinking water source. Concentrations were 100 ± 10% of target except for two isolated occasions. Based on the dose-range finding results, concentrations selected for Task 2 were 3, 10, and 30 ppm. The limiting toxicity in the dose-range finding study was neurologic with decreases in fore- and hindlimb grip strength. Based on water consumption in female mice, the acrylamide doses were estimated as 0.81, 3.19, and 7.22 mg/kg bw/day. Water consumption in males was highly variable and was considered

unreliable due to presumed palatability-related manipulation of sipper tubes by the males.

There were no effects of treatment on the proportion of fertile pairs (pairs delivering at least one litter), percentage of pairs delivering each litter, number of litters per pair (4.8–5 litters/pair), or proportion of pups born alive. There were no alterations in live pup weight, pup weight adjusted for litter size, or time to litter. When litters were considered individually by their order, there was an 8–15% decrease in the number of live pups per litter for litters 2 and 3 in the top dose compared to the control but no significant alteration in live pups per litter for litters 1, 4, or 5, causing the authors to propose that the lack of progressive reproductive toxicity made the biologic importance of the finding "suspect." Considering all litters together in each dose group, the authors indicated that there was a dose-related trend for decreased live pups/litter, with a significant decrease on pair-wise testing between the high dose group and the control: mean pups/litter ± SEM (n) for the 0, 3, 10, and 30 ppm groups were 13.6 ± 0.5 (39), 13.9 ± 0.4 (20), 13.6 ± 0.5 (20), and 12.2 ± 0.5 (19), respectively. **[Analysis by CERHR did not confirm a statistically significant test for trend.]** On crossover testing, there was no difference between the high dose male × control female matings or the high dose female × control male matings and the control male × control female matings with respect to any parameter, including live pups/litter. Numerically, however, the high dose male × control female matings produced 9.4 pups/litter, compared to 11.4 and 11.5 pups/litter for the control × control and high dose female × control male matings, respectively. The authors noted that this 18% apparent decrease in pups/litter from treated males was similar in magnitude to the 10% decrease in pups/litter at the high dose when all litters were considered in the continuous cohabitation phase. They proposed that the lack of significant decrease in live pups/litter may have been due to the lower power of the single-litter crossover trial.

In the dominant lethal testing, there were significant increases in early resorptions (+102%) and total postimplantation losses (+99%) in the 30 ppm group compared to the control group, with dose-related tests for trend across the full dose range. There was an 8% decrease in live fetuses in the 30 ppm group.

After use in the 98-day cohabitation study plus 6-week holding period, and after the crossover trials, adults were killed and reproductive tracts were evaluated. There were no alterations in gross or histologic examination of male or female reproductive tissues except for a 10–12% decrease in spermatids/g testis in the middle and high dose groups. There were no alterations in total spermatids/testis, however, and no changes in epididymal sperm concentration, motility, or frequency of abnormal forms. Estrous cyclicity was not altered by treatment.

There were no alterations in postnatal survival or body weight at weaning in the F_1 generation. Female body weight at the time of the Task 4 mating showed a dose-related decreasing trend with a significant 8% decrease from the control value in the top dose group on pair-wise testing. There were no effects in the F_1 matings on percentage of females with a vaginal plug, percentage of plugged females delivering offspring, or pup weight. The number of live pups in the top dose group was decreased by 47% compared to control and a dose-related trend was shown across dose groups in live pups/litter. **[Benchmark dose calculation by CERHR was performed on live pups/litter in the F_1 generation. The BMD_{10} was 17 ppm and the BMDL was 8 ppm.]** When F_1 animals were killed, there were no treatment effects on reproductive organ weight or histology except for a decrease in absolute, but not relative, prostate weight in the high dose group and testicular degeneration in 1 of

10 animals each in the middle and high dose groups. There were no alterations in this generation in spermatid heads per gram testis. Based on water consumption as adults, exposure to acrylamide in the F_1 generation was estimated as 0.86, 2.9, and 7.7 mg/kg bw/day in the 3, 10, and 30 ppm groups, respectively. **[These estimates give a BMD_{10} of about 5 mg/kg bw/day and a BMDL of about 2 mg/kg bw/day based on the reduction in live pups/litter.]**

Grip strength decreases were identified in high-dose animals. For the F_0 (continuously cohabited) animals, decreased grip was shown in the forelimbs of males and females exposed to 30 ppm acrylamide and in the forelimbs of females exposed to 10 ppm acrylamide. Male hindlimb grip was decreased in the 30 ppm group. In the F_1 animals, only male forelimb grip strength was reduced significantly. Grip strength was evaluated differently in the two generations: in the parental generation, grip strength was assessed as the percent difference between weeks 0 and 17, while in the F_1 generation, grip strength was assessed at week 10. The authors interpreted the decreases in grip strength in the parental generation as minimal, and they believed that the F_1 generation reduction only in male forelimbs at a single time point may have represented "some degree of biological 'noise.'"

The authors concluded that based on the findings in the dominant lethal study and the lack of effects of acrylamide on female reproductive parameters, "the primary site for the reproductive toxicity of [acrylamide] is the male, that this can be entirely accounted for by the dominant-lethal activity of [acrylamide], and that it occurs independently of changes in any epididymal sperm measure."

Strengths/Weaknesses: This study is careful, exhaustive, and is one of few that independently monitored acrylamide concentration and purity throughout the course of the study. The authors conclude that dominant lethal effects can explain the male reproductive toxicity of acrylamide. It is not known if this experiment would have revealed an increase in the number of sterile and semi-sterile F_1 males. In other words, it is not known if heritable translocations influenced the depression of litter size at the high dose group of F_1 males. Another weakness is the use of mice, a species commonly used for genetic toxicity testing, but perhaps less suitable in comparing reproductive toxicity to neurotoxicity for compounds that depend on a greater length of motor neurons to express their toxicity. Rats would have been the better choice for these studies. Also, the relative paucity of genetic/reproductive investigations reflects a weakness (i.e., the authors only evaluated dominant lethality, not the mechanisms underlying any possible effects). A strength of the study is the explicit simultaneous comparison of reproductive toxicity and neurotoxicity across several different congeners of acrylamide with suspected (or known) variations in reproductive toxicity, although this information is of little relevance to the CERHR process.

Utility (Adequacy) for CERHR Evaluation Process: A higher dose of acrylamide might have made a sharper distinction between reproductive toxicity and neurotoxicity (based on grip strength in F_0 males and females) and between 10 and 30 for reproductive toxicity (based on reductions in litter size in the crossover mating trial, and resorptions and postimplantation loss in the dominant lethal trial). The choice of congeners for this study, however, does not appear to have been made to further illuminate the mechanism of toxicity of acrylamide, and little information can be taken from the results of the congener studies. The study shows that reproductive effects may occur in the absence of, or before, neurologic symptoms appear.

Tyl et al. *(87)* performed a two-generation reproduction and dominant lethal study sponsored by the Acrylamide Producers Association/Synthetic Organic Chemical Manufacturers Association (SOCMA). Male and female Fischer 344 rats were given acrylamide (>99.9% pure) in drinking water. Drinking water concentrations were adjusted weekly based on animal body weight and water consumption to provide doses of 0, 0.5, 2.0, or 5.0 mg/kg bw/day with 30 animals per dose group. Concentrations in water were 84–112% of the nominal concentrations.

F_0 animals were obtained at 28 days of age, and then begun on test for a 10-week prebreeding exposure period. Following this period, males and females in the same dose group were cohabited 1:1 for up to 7 days. Females with a copulation plug or vaginal sperm were considered to be at GD 0 and were housed singly. Females without evidence of mating after 7 days were moved to the cage of a male that had successfully mated with a another female, and were cohabited for up to an additional 7 days. During cohabitation, the acrylamide concentration in the water bottle was based on the female's weight and water consumption prior to mating, likely resulting in underdosing of the males during this time period. This concentration was maintained during gestation and the first week of lactation without adjustment. During the second and third week of lactation, the concentration of acrylamide in the drinking water was reduced to one-half and one-third, respectively, of the prebreeding concentration, to allow for increased water consumption during lactation and to avoid overtreating offspring that were beginning to drink the water. During the fourth week of lactation, the one-half concentration was used to acclimate the offspring. Until all F_1 offspring were weaned, weanlings were given water with the same acrylamide concentration as had been given to the F_0 animals during their first week of treatment. When the last F_1 litter reached 35 days of age, 30 male and 30 female pups were randomly selected to produce the F_2 generation and were maintained for a total of 11 weeks on acrylamide at the dose used for their parents. **[It is assumed that the 11 weeks started at 35 days of age. It is not stated whether selection of F_1 animals was balanced across litters.]** The procedures for mating of F_1 animals were identical to the procedures used for the F_0 animals.

After F_0 males had been used for mating, dosing was continued for up to an additional 64 days on acrylamide in case the animals were needed for additional mating. They were then removed from acrylamide treatment for 2 days prior to being used in the dominant lethal study. In the dominant lethal study, males were paired 1:2 with untreated females. Females were killed on GD 14 (plug or sperm=GD 0) and ovaries and uteri inspected for corpora lutea and implantation sites, respectively. Uteri that appeared nongravid were stained with ammonium sulfide to identify early resorption sites.

Statistical testing was performed using ANOVA and *t*-tests for parametric data and Kruskal-Wallis followed by the Mann-Whitney *U*-test for nonparametric data. Frequency data were compared using the Fisher exact test, according to the Methods section, although some of the tables make reference to chi-square testing.

Selected data for F_0 animals are summarized in Table 32. Reductions in weight gains were seen at all acrylamide doses during at least some of the study period.

Table 32. Selected F0 Data from Tyl et al. (87)

Parameter		*Day*	*Acrylamide dose (mg/kg bw/day)*		
			0.5	*2.0*	*5.0*
Male body weight (by week)	Prebreeding	0	↔	↔	↔
		7	↔	↔	↔
		14	↔	↔	↔
		21	↔	↔	↔
		28	↔	↓	↓
		35	↔	↓	↓
		42	↓	↓	↓
		49	↓	↓	↓
		56	↓	↓	↓
		63	↓	↓	↓
		0–70	↓6%	↓7%	↓10%
	Mating	70	↓	↓	↓
		77	↓	↓	↓
		84	↔	↔	↔
Female body weight, by week	Prebreeding	0	↔	↔	↔
		7	↔	↔	↔
		14	↔	↓	↓
		21	↔	↔	↔
		28	↔	↓	↓
		35	↔	↔	↔
		42	↔	↔	↔
		49	↔	↓	↓
		56	↓	↓	↓
		63	↔	↓	↓
		0–70	↓4%	↓9%	↓36%
	Mating	70	↔	↓	↓
	Gestation	0	↔	↔	↔
		7	↔	↔	↔
		14	↔	↔	↔
		21	↔	↓	↓
		0–20	↔	↔	↓28%
	Lactation	1	↔	↔	↔
		4	↔	↔	↓
		7	↔	↔	↓
		14	↔	↔	↓
		21	↔	↔	↓
		28	↔	↔	↔
		1–28	↔	↔	↑41%
Plug/sperm-positive females			↔	↔	↔
Implantations/dam			↔	↔	↓35%
Live pups/litter			↔	↔	↓54%
Postimplantation loss			↔	↔	↑4.4-fold

↑,↓ Statistically increased, decreased compared to control value.
↔ Not statistically different from control value.

The text states that all acrylamide-exposed F_0 males exhibited a higher incidence of head tilt and leg splay than did control males; however, the data table gives the incidence of head tilt as 2/30 in the control group, and 6/30, 2/30, and 6/30 in the 0.5, 2.0, and 5.0 mg/kg/day groups. The incidence of foot splay was 3/30, 10/30, 7/30, and 10/30 in the 0, 0.5, 2.0, and 5.0 mg/kg/day dose groups. **[The Study table does not indicate statistical significance for any comparisons with the control, and Fisher exact test performed by CERHR confirms a lack of statistical significance for these comparisons.]** None of the females in any group had head tilt. The incidence of foot splay was 1/30, 2/30, 6/30, and 6/30 in the 0, 0.5, 2.0, and 5.0 mg/kg/day groups, also not statistically significant.

Rates of mating and pregnancy were similar among dose groups in the F_0 generation. The authors note that an unexpectedly low proportion of control males (17 of 30) produced pregnancies, but that after providing a second week of mating with a proven male, 25/30 control females became pregnant. The proportion of mated females that became pregnant was not altered by acrylamide treatment, and gestation length was similar among groups. The number of live pups/litter was reduced in the top dose group, and postimplantation loss was increased in this group (Table 33). Necropsy of F_0 adults showed no gross lesions.

Table 33. Selected F1 Litter Parameters during Lactation from Tyl et al. (87)

Parameter	*Acrylamide dose (mg/kg bw/day)*			
	0	***0.5***	***2.0***	***5.0***
Litters delivered (n)	20	24	26	17
Live litter size (n, mean ± SD)	9.8 ± 3.1	9.8 ± 3.5	9.7 ± 2.4	4.5 ± 2.6**
4-day survival (%, mean ± SD)	99.5 ± 2.2	94.8 ±20.6	99.4 ± 2.2	86.2 ± 34.0*
Pup weight, male				
PND 1	↔	↔	↔	↔
4	↔	↔	↔	↔
7	↔	↔	↔	↔
14	↔	↔	↔	↓11%
21	↔	↔	↔	↓10%
28	↔	↔	↔	↓8%
Pup weight, female				
PND 1	↔	↔	↔	↔
4	↔	↔	↔	↔
7	↔	↔	↔	↔
14	↔	↔	↔	↔
21	↔	↔	↔	↔
28	↔	↔	↔	↔

*,**$P \leq 0.01$, 0.001 compared to control value.
↑,↓ Statistically increased, decreased compared to control value.
↔ Not statistically different from control value.

dose group during the last half of the lactation period. The decrease in pup survival during the first 4 days of life was attributed to the loss of single-pup litters. **[The data table in the paper mentions Day–4 pre- and post-cull data; however, no cull is described in the Methods section until day 28.]** Necropsy of the F_1 offspring that were not selected to reproduce did not show gross lesions or histologic changes in reproductive organs or nervous system tissues. Head tilt was found in 4/30 males in the 5.0 mg/kg bw/day group but in no other dose groups and in no females. This proportion (4/30) was statistically different from 0/30. Foot splay was not identified in any F_1 animals. Selected F_1 parameters are given in Table 34. A decrease in weight gain was seen in the middle and top dose groups. As in the F_0 matings, there was a decrease in live pups/litter at the top dose. A five-fold increase in the numerical value for postimplantation loss in the 5.0 mg/kg bw/day dose group compared to the control group was not statistically significant, likely because of large variance. **[The SD for each dose group is greater than the mean, suggesting that mean ± SD will not give an accurate picture of the central tendency and distribution. According to the methods section, postimplantation loss was expressed as an index, (([No. of implantations–no. of live pups]/No. of implantations)× 100) and evaluated using the Fisher exact test; however, the expression of mean ± SD in the table does not provide confidence that a nonparametric test was used.]** The proportion of F_1 males impregnating F_1 females and the proportion of mated females that became pregnant did not differ by dose group.

Dominant lethal results for F_0 males are summarized in Table 35 and are consistent with the postimplantation loss data reported for the F_0 matings **[consistent also with the numerical (but statistically non-significant) increase in postimplantation loss in the F_1 matings]**. The dominant lethal data also appear in Table 14.

Strengths/Weaknesses: The quantification of and care associated with knowing the administered dose is a major strength of this study (including analysis of dosing solutions), as is the expertise with which doses were chosen (based on the moderate but significant weight effects that were seen, and the absence of mortality or overwhelming neurotoxicity symptoms). Other strengths are the use of robust numbers of animals, appropriate statistics (although clouded slightly by different statistics mentioned in the Methods section and some tables), the evaluation of a large number of relevant endpoints (signs of neurotoxicity and behavioral/carriage alterations in both generations, and high quality neuropathology, for example), and the testing of dominant lethality and reproductive capability in the same design, using the same males. The consistency of effects across the generations lends added weight to their validity. There are no meaningful weaknesses in the study design, or the conduct of this design or the interpretation of the data. A modest weakness is that sperm parameters were not evaluated; it would lend weight to the conclusion of a primary effect of dominant lethality if the authors had shown by cell counting and motility evaluation that these measures were unaffected. However, the study was performed at a time when such endpoints were not routinely measured or expected in Guideline studies; therefore the authors or sponsers are not at fault. Similarly, in retrospect, it would have been useful to explicitly evaluate female fertility, which is inferred as a target based on the slightly greater effects in the F_0 and F_1 matings compared to the male dominant lethal mating, but one cannot fault the authors for not forseeing future requirements.

Table 34. Selected F_1 Data from Tyl et al. (87)

Parameter		*Day*	*Acrylamide dose (mg/kg bw/day)*		
			0.5	*2.0*	*5.0*
Male body weight, by week	Prebreeding	0	↔	↔	↓
		7	↔	↔	↔
		14	↔	↓	↓
		21	↔	↔	↓
		28	↔	↓	↓
		35	↔	↓	↓
		42	↔	↓	↓
		49	↔	↓	↓
		56	↔	↓	↓
		63	↔	↓	↓
		70	↔	↓	↓
		0–77	↔	↔	↔
	Mating	77	↔	↓	↓
		84	↔	↓	↓
		91	↔	↓	↓
Female body weight, by week	Prebreeding	0	↔	↔	↔
		7	↔	↔	↔
		14	↔	↔	↔
		21	↔	↓	↔
		28	↔	↓	↓
		35	↔	↓	↓
		42	↔	↓	↓
		49	↔	↓	↓
		56	↔	↓	↓
		63	↔	↓	↓
		70	↔	↓	↓
		0–77	↔	↔	↓12%
	Mating	77	↔	↓	↓
	Gestation	0	↔	↔	↔
		7	↔	↔	↔
		14	↔	↔	↓
		21	↔	↓	↓
		0–20	↔	↓14%	↓35%
	Lactation	1	↔	↔	↔
		4	↔	↓	↓
		7	↔	↔	↓
		14	↔	↔	↓
		21	↔	↔	↔
		28	↔	↔	↔
		1–28	↔	↔	↑49%
Plug/sperm-positive females			↔	↔	↔
Implantations/dam			↔	↔	↓14%
Live implants/litter			↔	↔	↓20%
Postimplantation loss			↔	↔	↔

↑,↓ Statistically increased, decreased compared to control value.
↔ Not statistically different from control value.

Table 35. Dominant Lethal Results from Tyl et al. (87)

Parameter	Acrylamide dose (mg/kg bw/day)		
	0.5	2.0	5.0
Plug/sperm-positive females	↔	↔	↔
Implantations/dam	↔	↔	↓14%
Live implants/litter	↔	↔	↓20%
Postimplantation loss	↓40%	↔	↑2.3-fold

↑,↓ Statistically increased, decreased compared to control value.
↔ Not statistically different from control value.

Utility (Adequacy) for CERHR Evaluation Process: These data are of high quality, and are adequate and informative for the Evaluation Process. They are adequate to identify a male dominant lethal dose (~5 mg/kg bw/d), to show that the neurotoxicity seems to occur at doses similar to those that affected fertility, and to infer that female fertility might be affected as well. These data shed no light on mechanism, but the study was not designed to do so.

4.3 Utility of data

Based on the studies by Zenick et al. *(81)*, Sublet et al. *(75)*, and Tyl et al. *(129)*, the Expert Panel determined that there are sufficient data to evaluate male and female reproductive toxicity in rats exposed to acrylamide in drinking water or by gavage using litter size, viability, and pup weight as traditional endpoints, as well as less traditional endpoints involving the delivery of sperm to the female reproductive tract. The studies of Sakamoto and Hashimoto *(124)* and of Chapin et al. *(130)* are judged adequate to permit the evaluation of the effects on male and female reproduction in mice of acrylamide in drinking water using traditional reproductive endpoints. In addition to these studies, there are several studies using i.p. dosing that provide supplemental information on possible genotoxic mechanisms of acrylamide reproductive toxicity.

4.4 Summary

4.4.1 Human data

No human data on acrylamide reproductive effects were located.

4.4.2 Experimental animal data

Key reproductive toxicology studies are summarized in Table 36 (see page II-149).

4.4.2.1 Female reproduction

The key study for the assessment of female reproduction was Zenick et al. *(81)* in which acrylamide was given in drinking water to female rats at 0, 25, 50, or 100 ppm **[0, 4, 5–9, 10–14 mg/kg bw/day].** After 2 weeks of treatment, untreated males were placed overnight with the females for up to 7 days. Endpoints included maternal weight gain, mating performance, pregnancy rate, pup survival and weight, and day of vaginal patency in female offspring. Neurologic toxicity (hindlimb splay) was seen in dams given 100 ppm acrylamide. Two of fifteen dams in the 100 ppm group had full or nearly full litter loss. Pup weight was decreased in a dose-dependent manner in the 50- and 100-ppm

groups and was transiently depressed in the first week of life in the 25 ppm group. Full litter loss and decreased pup weight were considered by the Expert Panel to represent developmental toxicity rather than female reproductive toxicity (see Section 3.4.2).

Other studies that included evaluations of female reproductive function *(124, 125*) were reported with insufficient detail to be used in the evaluation.

4.4.2.2 Male reproduction

The Expert Panel notes that there are a number of genotoxicity studies with endpoints that might be considered reproductive (e.g., pre-implantation loss after parental treatment). Studies that were designed to evaluate genotoxicity were grouped in Section 2. These studies include those with dominant lethal (Section 2.3.2.2), heritable translocation (Section 2.3.2.4), and specific locus mutation (Section 2.3.2.5) endpoints. Although these studies are placed for organizational purposes under the heading of genotoxicity rather than developmental or reproductive toxicity, the Expert Panel considers these studies important in evaluating the reproductive and developmental effects of acrylamide. Because genotoxicity studies were reviewed and summarized in Section 2, attention in this section is focused on studies for which the primary endpoints were not genotoxic, although some reproductive outcomes from genotoxicity studies are repeated here.

Three studies of adequate design were reported in sufficient detail to permit an evaluation of acrylamide effects on male reproduction *(75, 81, 129*). Zenick et al. *(81*) gave acrylamide in drinking water to male rats at 0, 50, 100, or 200 ppm (5, 7–8, and 12 mg/kg/day, respectively) for up to 10 weeks. Mating was visually monitored and sperm count, motility, and morphology determined during week 9. Sperm in the uterus were also assessed. During week 10, males in the 0 and 100 ppm acrylamide groups were mated with intact estrous females, which were killed on GD 17 for evaluation of intra-uterine contents. Males were killed at week 11 for histology of one testis and epididymal fluid, and homogenization resistant spermatid count determination from the other testis. Morbidity and mortality led to termination of the high dose males at week 6. This group displayed neurological toxicity (hindlimb splay). There was a decrease in vaginal sperm in females mated to 100-ppm males compared to control males and only 1/15 females mated to a 100-ppm male had sperm in the uterus. Only 5/15 100-ppm males established a pregnancy, compared to 11/14 in the control group. Postimplantation loss was higher in females that were mated to 100-ppm sires (31.7 ± 3.8%) compared to 0-ppm sires (8.0 ± 1.1%). Testicular histology did not show abnormalities associated with 100-pm acrylamide treatment. The authors concluded that the male reproductive toxicity of acrylamide at 100 ppm (~,7–8 mg/kg bw/day) was due to abnormalities of copulatory behavior, delivery of sperm to the female genital tract, and postimplantation loss.

Sublet et al. *(75*) used a dominant lethal design plus an evaluation of mating and fertilization success to confirm and extend the work of Zenick et al. *(81*). Male rats were treated with acrylamide 0, 15, or 45 mg/kg bw/day for 5 days by gavage and mated to untreated hormonally primed, ovariectomized females. Females were killed 10–15 minutes after ejaculation and sperm were recovered and examined by light microscopy. No abnormalities of male copulatory behavior were observed at any dose, and all females had sperm in the vagina, but there was a significant decrease in the proportion of females with uterine sperm after mating with males in the 45 mg/kg bw/day group 1 week after treatment. There were no differences in the proportions of females with uterine sperm 2, 3, or 4 weeks

after treatment of males with either dose of acrylamide. Uterine sperm were evaluated by computer-assisted sperm analysis after females mated with 0 and 45 mg/kg bw/day acrylamide-treated males. The only difference was a decrease in motile sperm and curvilinear velocity 3 weeks after treatment of males with acrylamide at the high dose. In an experiment where males were gavage dosed with 0, 15, or 45 mg/kg bw/day acrylamide for 5 days, the percent oocytes fertilized per female was reduced in a dose-dependent manner in weeks 1 (both acrylamide doses) and 3 (45 mg/kg/day acrylamide). The authors suggested that impaired fertilizing ability of acrylamide-exposed sperm may play a role in the apparent pre-implantation loss seen after treatment. They proposed that although copulatory behavior appeared normal in their experiments, and acrylamide doses were below those associated with gross neurologic impairment, there might be subtle abnormalities of copulation.

Tyl et al. *(129*) repeated a portion of the study of Sublet et al. *(75*), using a design that matched the first week of the Sublet et al. study. Male rats were exposed by daily gavage for 5 consecutive days to acrylamide at 0, 5, 15, 30, 45, or 60 mg/kg bw/day, 25 animals/dose group. Three days after the treatment period, males were cohabited with untreated females for a single overnight period, then males underwent grip testing and were killed for evaluation of cauda epididymal sperm parameters. Mated females were killed on GD 15 for evaluation of uterine contents. There was reduced grip-strength at 60 mg/kg bw/day, though without detectable histopathology. Fewer males in the 60 mg/kg/day group than control group mated or produced litters. Pair-wise comparison showed statistically significant decreases in weight gain at 15 mg/kg bw/day and higher. Trend tests on the pregnancy index showed significance for trend at 15 mg/kg bw/day and above, and pair-wise statistically fewer litters and reduced litter size (and increased post-implantation loss) at 45 and 60 mg/kg bw/day. The fertility and pregnancy data are compelling, and the Panel believes an incremental effect exists at and above 15 mg/kg bw/day.

Other studies provided supporting information. Hashimoto et al. *(126*) treated male ddY mice by gavage with acrylamide 35.5 mg/kg bw twice/week for 8 weeks and demonstrated a decrease in relative testicular weight. Sakamoto et al. *(127*) administered acrylamide to ddY mice as a single oral dose of 100 or 150 mg/kg at age 30 days (prepubertal) or 60 days (adult) and found the round spermatid to be the cell type most sensitive to acrylamide toxicity. Pacchierotti et al. *(88*) treated male $B6C3F_1$ mice with single i.p. acrylamide doses of 0, 75 , or 125 mg/kg bw or with 5 daily i.p. doses of 50 mg/kg. Males were mated to untreated females 7 days after the last acrylamide dose and killed weekly for flow cytometric analysis of testicular cell populations. The percent females showing evidence of mating after cohabitation with treated males was reduced in all acrylamide groups without regard to acrylamide dose. The reduction in mating success resolved by 28 days after treatment in the 125 mg/kg group. Changes in relative germ cell populations indicated probable impairment of chromosome segregation during spermatogonial mitosis. Marchetti et al. *(89*) gave acrylamide i.p. to male $B6C3F_1$ mice at 50 mg/kg bw/day for 5 consecutive days (discussed in Section 2.3). Treated males were mated with untreated females at different time intervals. Acrylamide treatment was associated with a decrease in fertilization except with treatment of males at the stem cell stage. Sakamoto and Hashimoto *(124*) gave male ddY mice acrylamide in drinking water at 0.3, 0.6, 0.9, and 1.2 mM **[21.3, 42.6, 64.0, and 85.2 mg/L, respectively]** for 4 weeks prior to mating or prior to evaluation of reproductive organ weight and epididymal sperm. There were dose-related decreases in the number of fetuses/dam in the top two dose groups; at the top dose, there were decreases in the proportion of pregnant dams and offspring per dam, and increases in resorptions per dam. Epididymal

sperm count was decreased and abnormal sperm forms increased at the top dose.

Two studies by Costa et al. *(128)*, *(79)* provided evidence that the male reproductive toxicity of acrylamide is mediated by glycidamide; however, these studies did not provide conclusive evidence to establish glycidamide as the proximate reproductive toxicant.

4.4.2.3 Continuous breeding or multigeneration designs

Chapin et al. *(130)* performed a Reproductive Assessment by Continuous Breeding in Swiss mice on acrylamide or one of three analogs. Acrylamide was given in drinking water at 0, 3, 10, and 30 ppm. Doses in F_0 females were estimated to be 0, 0.81, 3.19, and 7.22 mg/kg bw/day. Doses in males could not be estimated due to highly variable water intake. There were no effects of treatment on the proportion of fertile pairs (pairs delivering at least one litter), percentage of pairs delivering each litter, number of litters per pair (4.8–5.0 litters/pair), or proportion of pups born alive. Considering all litters together, there was a significant decrease at the high dose in mean pups/litter. Early resorptions and postimplantation loss were increased on dominant lethal testing at the top dose as well. Cross-over matings (treated males to untreated females) suggested that the acrylamide effect on mean pups/litter was mediated through the treated male. Reproduction in F_1 mice that were exposed during gestation and again from weaning was not impaired except for a decrease in live pups/litter that was significant on pair-wise comparison in the top dose group and that showed a dose-related trend across all dose groups. Estimated adult acrylamide intake in the F_1 generation was 0, 0.86, 2.9, and 7.7 mg/kg bw/day. The authors interpreted the reproductive effects of acrylamide in males as attributable to dominant lethal activity at 30 ppm.

Tyl et al. *(87)* performed a two-generation reproduction and dominant lethal study in Fischer 344 rats given acrylamide in drinking water. Drinking water concentrations were adjusted weekly based on animal body weight and water consumption to provide doses of 0, 0.5, 2.0, or 5.0 mg/kg bw/day in 30 animals per dose group. Animals were mated after a 10-week exposure period. Drinking water concentrations were adjusted during lactation. Offspring were weaned to the same acrylamide exposure groups as their dams. Offspring were mated (30/sex/treatment group) to produce the F_2 generation. Some of the F_0 males were continued in a dominant lethal study. Increased incidences of head tilt, but not foot-splay, was significant in the high-dose F_1 but not the F_0 animals. The number of live pups/litter was decreased and postimplantation loss was increased at the top dose for both F_0 and F_1 matings, although statistical confirmation was not obtained for postimplantation loss in the F_1. This was evidence of reduced fertility and increased dominant lethality in the mice of both generations at the high dose.

Appendix II

Table 36. Key Reproductive Studies

Sex/Species/ Strain	*Exposure Regimen*	*Critical effects*	*Effect level*	*Reference*
Female Long-Evans rats	Drinking water: 0, 25, 50, 100 ppm	Decreased pup weight[a]	Reproductive LOAEL=100 ppm (~10–14 mg/kg bw/day) Developmental LOAEL=25 ppm (lowest tested level=4 mg/kg bw/day)	Zenick et al. *(81)*
Male ddY mice	Drinking water: 21.3, 42.6, 64.0, 85.2 ppm **[converted from mM]**	Decreased litter size	LOAEL=64.0 ppm (~14 mg/kg bw/day)	Sakamoto *(124)*
		Decreased pregnancy rate and increased resorptions	LOAEL=85.2 ppm (~18 mg/kg bw/day)	
Male Long-Evans rats	Drinking water 0, 50, 100, 200 ppm	Impaired ejaculation, decreased vaginal and uterine sperm and pregnancy rates and increased postimplantation loss in cohabited females	LOAEL=100 ppm (about 7–8 mg/kg bw/day)	Zenick et al. *(81)*
Male Long-Evans rats	Gavage: 0, 0, 5, 15, 30, 45, 60 mg/kg bw/day × 5 days	Increased pre- and postimplantation loss	LOAEL=15 mg/kg bw/day	Sublet *(75)*
	Gavage: 0, 15, 45 mg/kg bw/day × 5 days	Decreased uterine sperm in cohabited females, decreased uterine sperm motility	LOAEL=45 mg/kg bw/day	
		Decreased fertilization of oocytes	LOAEL=15 mg/kg bw/day (lowest tested level)	
Male Long-Evans rats	Gavage: 0, 5, 15, 30, 45, 60 mg/kg bw/day × 5 days	Decreased mating; fewer litters produced	LOAEL=45 mg/kg bw/day	Tyl *(129)*
Swiss mice, cohabiting pairs	Drinking water: 0, 3, 10, 30 ppm	Decreased live litter size in two generations	LOAEL=30 ppm (7–8mg/kg bw/day)	Chapin *(130)*
Fischer 344 rats, 2-generation	Drinking water: 0, 0.5, 2.0, 5.0 mg/kg bw/day	Decreased live litter size and increased postimplantation loss in two generations	LOAEL=5 mg/kg bw/day	Tyl *(87)*

LOAEL lowest observed adverse effect level; NOAEL= no observed adverse effect level.
[a]Considered by the Expert Panel to represent developmental toxicity rather than reproductive toxicity.

The Expert Panel found no human data with which to directly evaluate possible reproductive toxicity of acrylamide. The data are sufficient to conclude that acrylamide is a reproductive toxicant in male rats bred to untreated females manifested as impaired delivery of sperm to the female genital tract, and a reduction in litter size due to increased postimplantation loss at exposure levels of about 5–8 mg/kg bw/day in drinking water. The data suggest that acrylamide is not a female reproductive toxicant in rats at exposures up to 100 ppm in drinking water (about 10–14 mg/kg bw/day). **Data are sufficient to conclude that acrylamide is a reproductive toxicant in male mice bred to untreated females as manifested by a decrease in litter size with drinking water exposures of about 7–14 mg/kg bw/day.** The data suggest that acrylamide has no effects on female reproductive function in mice at doses up to 7–8 mg/kg bw/day. The Expert Panel found the data suggestive that the male reproductive toxicity of acrylamide in rodents is due to multiple effects, including impairment of mating ability and genetic damage in sperm, and possibly sperm function. In addition, there are sufficient data to conclude that acrylamide induces transmissible genetic damage in male germ cells of mice in the form of reciprocal translocations and gene mutations. Such effects can lead to genetic disorders and infertility in subsequent generations. An analysis of genetic risk associated with acrylamide was conducted by Dearfield et al. *(58)*. Such risks were not considered by the Expert Panel in their evaluation of LOAELs because of the lack of testing at low dose levels where reproductive and developmental toxic effects are observed. However, considering the incidence in treated and control animals of the response detected for heritable translocations at the lowest dose level tested (40 mg/kg bw/day × 5 days), it is likely that such effects would occur at lower dose levels. The rat and mouse data are assumed relevant to assessment of human reproductive risk.

5.0 SUMMARY AND CONCLUSIONS

5.1 Developmental Toxicity

Developmental toxicity has been assessed in rats and mice following maternal treatment with acrylamide during gestation, and also in rats following oral exposures that included the gestation and lactation periods. These data are sufficient to conclude that acrylamide is a developmental toxicant in rats, as indicated by marginally decreased pup weight, with maternal drinking water or gavage doses of approximately 4–5 mg/kg bw/day, and in mice, as indicated by decreased fetal weight, with maternal gavage doses of 45 mg/kg bw/day. In a rat developmental neurotoxicity study, alterations in activity patterns and decreased auditory startle amplitudes occurred in rat offspring at 15 mg/kg bw/day, a gavage dose that also resulted in overt signs of maternal neurotoxicity. It was not possible to separate the effects of acrylamide on rat or mouse offspring from effects that may have been due to maternal toxicity at exposures ≥10 mg/kg bw/day, or to determine whether maternal gestational or lactational treatment, or both, was critical for producing developmental toxicity in rodents. These data are assumed relevant to the assessment of potential human hazard. No information was available on developmental outcome after acrylamide exposure in humans.

5.2 Reproductive Toxicity

Male effects

Subchronic and multi-generation continuous dosing studies which administered acrylamide in the drinking water to mice *(124 Chapin, 1995 #152*) and rats found significantly decreased litter size *(87*) and increased post-implantation loss *(87))*. Mating treated animals with untreated partners and measuring dominant lethal outcomes in these studies confirmed that the decreased litter size and/or increased post-implantation loss is male-mediated, indicative of genetic effects in sperm. In mice, LOAELS were ~14 mg/kg bw/day *(124*) or 7–8 mg/kg bw/day *(130*). In male rats, the LOAEL was 5-8 mg/kg bw/day *(87 Zenick, 1986 #485*).

Numerous short and long term studies in rats and mice indicate that genetic effects (expressed as dominant lethality) are the major component of the male reproductive toxicity; spermatids appear to be the sensitive germ cell stage. In some instances sperm delivery (ejaculation or uterine transport) were impaired. The lowest doses tested (all in mice and all with positive results) were 40 mg/kg bw/day for 5 days and 50 mg/kg as a single dose for heritable translocations and 100 mg/kg bw for specific locus mutations.

Female effect

While not conclusive, the existing data do not indicate female reproductive toxicity at doses up to 100 ppm **[10–14 mg/kg bw/day]** in drinking water for rats and 30 ppm (7–8 mg/kg bw/day) in drinking water for mice.

Collectively, these data clearly show the reproductive toxicity of acrylamide in rats and mice, mediated largely by dominant lethality. These data are assumed relevant to the assessment of potential human hazard. No information was available on reproductive outcome in humans exposed to acrylamide.

5.3 Summary of Human Exposures

Humans may be exposed to acrylamide by ingesting food or drink, cigarette smoking, through dermal contact with acrylamide-containing materials, such as cosmetics and other personal care products, and by occupational exposures to acrylamide vapors or particles. Data available to characterize many of these routes are very limited. However, the relative intake of acrylamide from a variety of sources, including dietary, cigarette smoking, and occupational exposures can be estimated from measurements of acrylamide adducts on hemoglobin.

Additional trace exposures and uptake of acrylamide residues can occur as a result of acrylamide residues in polyacrylamide resin used in common products. These exposures include leaching from food container coatings, ingestion of gelatin medication capsules, dermal contact with some gardening products, paper and pulp products, coatings, and textiles. Very low acrylamide concentrations in air have been observed with the preparation of acrylamide gels in scientific laboratories.

Table 37. Summary of Exposure Estimates (µg/kg bw/day[a]) by Sources and Population Groups

Sources of exposure		***Mean or median***	***90th Percentile or upper boundary***
Diet	General population	0.43	0.92
	2–5-year-olds	1.06	2.31
Drinking Water		No data	<0.01
Personal Care Products		~0.5	1.1 (female)
Cigarette Smoking		0.67 (from cigarette data)	1.3
		2.6 (from adduct data)[b]	~6
Occupational exposures		1.4 – 18	43 (based on PEL)
General population (adults, totals)			
Nonsmokers		0.98[c] 0.85 (from adduct data)	2.0
Smokers		1.7 (from cigarette data) 3.6 (from adduct data)	3.2
Occupational exposure[d] (adults, totals)			***45–52***
Non-smokers		2.4–19	45
Smokers		3.1–20 (cigarette data)	46
		5–22 (adduct data)	51

[a]Dose levels in experimental animal studies are expressed as mg/kg bw/day; human exposures are expressed in µg/kg bw/day. To convert figures in table to mg/kg/day, divide by 1,000.

[b]Acrylamide exposure in smokers based on adduct formation was estimated by taking the value for total exposure in smokers (3.4 µg/kg bw/day) and subtracting the value for total exposure in non-smokers (0.85 µg/kg bw/day).

[c]Estimated from diet, water, and personal care products. The adduct-derived estimates are considered more comprehensive.

[d]Occupational exposures include monomer and polymer production and grouting applications.

Dietary Intake

A systematic estimate of US population dietary exposures has recently been presented by scientists at the US FDA (DiNovi and Howard, 2004). FDA workers have compiled a substantial, though not

necessarily statistically representative, set of measurements of acrylamide in major types of foods consumed in the US Utilizing these measurements, and the results of broad population surveys of the consumption of different foods by large representative samples of the US population, the dietary exposures of the general US population (age 2 and over) were estimated as a mean of 0.43 μg/kg bw/day, with a 90th percentile of 0.92 μg/kg bw/day. These estimates were approximately lognormally distributed. Children in the 2–5 year old age group were estimated to have greater exposures (mean 1.06 μg/kg kg bw/day and 90th percentile 2.31 μg/kg bw/day). These findings correspond reasonably closely to similar types of estimates made in other developed countries.

Based on hemoglobin adduct data from nonsmokers, Schettgen et al. *(36)* estimated an overall median intake of 0.85 μg/kg bw/day from all dietary and nonoccupational sources.

Drinking Water Intake

Drinking water is commonly treated with polyacrylamide resins to remove suspended particles. This practice was estimated to produce acrylamide concentrations much lower than 0.5 μg/L because of limits on the amount of free acrylamide in the polymer used, <0.05% w/w. The estimated upperbound exposure is 0.01 μg/kg bw/day from drinking 2 L water/day.

Cigarette Smoking Exposures

Mainstream cigarette smoke contains acrylamide, 1–2 μg/cigarette. Assuming that a 70 kg adult smokes 20 cigarettes per day, the average inhaled dose is 0.67 μg/kg bw/day. Smoker's exposure measurably increases their hemoglobin adducts to 3–4 fold higher than nonsmokers with no occupational exposure. Smokers had a median hemoglobin valine adduct concentration of 85 pmol/g globin, which was estimated to correspond to an estimated median acrylamide exposure of 3.4 μg/kg bw/day. Subtracting the nonsmoker background, gives a median acrylamide exposure of 2.6 μg/kg bw/day, which is 4 fold higher than the intake estimated from the acrylamide content of mainstream smoke. It is not clear which of these is a better estimate because both have several key assumptions. Side-stream smoke has not been measured, but probably also contains acrylamide, which will lead to indoor environmental tobacco smoke exposures for nonsmokers.

Nonsmoking subjects without occupational exposures had a adduct concentration of 21pmol/g globin. These values are consistent with values from two other studies. Given a median adduct concentration about four times higher in smokers, smoking appears to be a much more important source of acrylamide exposure than daily dietary intake.

Personal Care Products

There were no direct measurements of acrylamide in these products. Worst case estimates with unrealistic estimates of surface coverage (total body) and absorption (100%) resulted in small uptake, ~1 μg/kg bw/day.

Occupational Exposures

Historically, occupational inhalation and dermal exposures have been substantial in the production and industrial use of acrylamide. The most recent data on these airborne exposure scenarios include production of the acrylamide monomer (geometric means 0.09–0.13 mg/m^3) and polymer (geometric means 0.01–0.02 mg/m^3), and in the use of acrylamide grout as a waste-water system sealant

(geometric means 0.01–0.03 mg/m^3). Inhalation doses from these estimated geometric means will range from 1.4 μg/kg bw/day to 18.6 μg/kg bw/day. The amount of exposure from skin exposure and uptake is unknown and difficult to measure or estimate.

5.4 Overall Conclusions

There are no human data available on developmental toxicity of acrylamide. Available experimental data are sufficient to conclude that acrylamide can produce developmental toxicity in rats and mice. These rodent data are assumed to be relevant for humans. Accordingly, dose levels were identified from animal studies for use in this evaluation.

- A LOAEL of 4–5 mg/kg bw/day (4,000–5,000 μg/kg bw/day) for developmental toxicity based on marginal decreases in pup weights during the postnatal period was identified in rats, with maternal drinking water or gavage exposures.
- A LOAEL of 15 mg/kg bw/day (15,000 μg/kg bw/day) for developmental neurotoxicity based on alterations in activity patterns and decreased auditory startle amplitude was identified in rats, with maternal gavage exposures. This dose also produced signs of maternal neurotoxicity.
- A LOAEL of 45 mg/kg bw/day (45,000 μg/kg bw/day) for developmental toxicity based on decreased fetal body weight was identified in mice, with maternal gavage exposures.

The Expert Panel was not able to separate developmental effects of acrylamide on rat or mouse offspring from effects that may be due to maternal toxicity at exposure levels ≥ 10 mg/kg bw/day (10,000 μg/kg bw/day), or to determine whether maternal gestational or lactational exposure, or both, was critical for producing developmental toxicity.

There are no human data available on reproductive toxicity of acrylamide. The data are sufficient to conclude that acrylamide is a reproductive toxicant in male rats and mice bred to untreated females. These rodent data are assumed relevant to humans.

- A LOAEL of 5–8 mg/kg bw/day (5,000–8,000 μg/kg bw/day) for male reproductive toxicity in rats was identified with drinking water exposure; toxicity was manifested as impaired delivery of sperm to the female genital tract and reduction of litter size due to increased post implantation loss.
- A LOAEL of 7–14 mg/kg bw/day (7,000–14,000 μg/kg bw/day) for male reproductive toxicity in mice was identified with drinking water exposure; toxicity was manifested as a decrease in litter size and increased post implantation loss.

The data suggest that acrylamide has no effect on female reproductive function in rats or mice at these exposure levels (5–14 mg/kg bw/day; 5000–14,000 μg/kg bw/day). The Expert Panel found the data to indicate that the male reproductive toxicity of acrylamide in rodents is due to multiple effects, including impairment of mating ability and post implantation loss at these doses, and at higher doses, alterations in sperm functions.

In addition, there are sufficient data to conclude that acrylamide induces transmissible genetic damage in male germ cells of mice in the form of reciprocal translocations and gene mutations. Such effects can lead to genetic disorders and infertility in subsequent generations. Such risks were not considered by the Expert Panel in their evaluation of LOAELs because of the lack of testing at low dose levels where reproductive and developmental toxic effects are observed. However, considering

the magnitude of the response detected for heritable translocations at the lowest dose level tested (40 mg/kg bw/day [40,000 µg/kg bw/day] × 5 days or 50 mg/kg bw (50,000 µg/kg bw] as a single dose), it is likely that such effects would occur at lower dose levels.

Measurements of internal acrylamide concentrations were not carried out in the context of the reproductive and developmental toxicity studies. Consequently, doses administered in these animal studies must be used for direct comparisons to estimates of human exposure levels (Table 37) to ascertain levels of concern. It should be noted that several different routes of dosing and durations of exposure were used in the animal experiments, and there was no correction for the likely differences in the amount of acrylamide entering the test animals, which makes the comparisons across µg/kg bw/day less certain than they might appear. Similar concerns are present for the estimates of human doses received by inhalation, ingestion and dermal uptake.

Expert Panel Conclusions

1. Considering the low level of estimated human exposure to acrylamide derived from a variety of sources, the Expert Panel expressed negligible concern for adverse reproductive and developmental effects for exposures in the general population.

2. The Expert Panel expressed minimal concern for acrylamide-induced heritable effects in the general population. The Expert Panel recognizes that dose-response information for these effects is limited.[1]

3. Recognizing the broad range of occupational exposure estimates for acrylamide, the occurrence of neurotoxicity in some occupational settings, and the concurrent expression of neurotoxicity and reproductive toxicity in some experimental animal studies, the Expert Panel expressed some concern for adverse reproductive and developmental effects, including heritable effects, for exposures in occupational settings.

5.5 Critical Data Needs

Critical data needs are defined as tests or measurements that could provide information to substantially improve an assessment of human reproductive and developmental risks. The items listed below under exposure and effects are considered by the Panel as critical data needs:

Section 1: Chemistry, Use and Human Exposure

- Occupational exposures need to be better defined, especially for high-exposure groups.
- The linkage between external exposure and hemoglobin and sperm adduct concentrations needs to be carefully assessed in humans. Research is needed to reconcile the discrepancy

[1] Drs. Dale Hattis and John Favor did not concur with the Expert Panel's "minimal concern" for heritable effects in the general population. Drs. Hattis and Favor concluded that a higher level of concern, i.e., some concern, was justified based on the expectation that a portion of the acrylamide-induced genetic damage in germ cells could exhibit a linear dose-response relationship at low exposure levels. Because of ubiquitous acrylamide exposure to the general population, such a linear component of the dose response could, in their judgment, produce appreciable numbers of adverse effects.

between estimates of exposure based on adducts in the general smoking and non smoking population and estimates of exposure based on dietary exposures.
- Subpopulation differences in exposures need to be characterized, especially ingestion of high contamination foods by young adults.
- Research is needed to explore susceptible subpopulations based on metabolic genotypes for enzymes involved in the metabolism of acrylamide.

Section 2: Developmental Toxicity

- There are no critical data needs for developmental toxicity. Acrylamide has been examined in two species using multiple routes of administration, and no further studies are recommended.

Section 3: Reproductive Toxicity

- A study to identify biologically relevant adducts and their relationship to reproductive toxicity by techniques such as the use of knock-out mice for CYP2E1 is needed to determine the role of acrylamide metabolism in genetic damage.
- A study is needed to define dose-response relationships for heritable alterations in male germ cells; direct assays of germ cells are preferable to breeding studies.
- A reproductive epidemiology study in occupationally exposed male workers to determine the relationship between external exposure and internal biomarkers of exposure, male reproductive health, including direct assays of sperm integrity, and neurobehavioral effects.

6.0 REFERENCES

1. Chemfinder. Acrylamide. Available at: <*http://chemfinder.cambridgesoft.com/result.asp*> 2003.

2. HSDB. Acrylamide. 2003.

3. IPCS. Acrylamide Environmental Health Criteria 49 <*http://www.inchem.org/documents/ehc/ehc/ehc49.htm*>. 1985.

4. Molak, V. NIOH and NIOSH Basis for an Occupational Health Standard. Acrylamide: A Review of the Literature. Atlanta, Georgia: U.S. Department of Health and Human Services; 1991.

5. European-Union. European Union Risk Assessment Report: Acrylamide. Institute for Health and Consumer Protection; 2002.

6. Mallinckrodt. Acrylamide Material Safety Data Sheet. Mallinckrodt Science Product Division. 1987.

7. IPCS. Poisons Information Monograph 652: Acrylamide <*http://www.inchem.org/documents/pims/chemical/pim652.htm*> 1996.

8. IARC. Acrylamide. TA:IARC Monographs on the evaluation of the carcinogenic risk of chemicals to humans PG 1994; 60.

9. NTP. Report on Carcinogens, Tenth Edition. ed. US Department of Health and Human Services, Public Health Service; 2002.

10. EPA. Chemical summary for acrylamide. Office of Pollution Prevention and Toxics; 1994.

11. Friedman, M. Chemistry, Biochemistry, and Safety of Acrylamide. A Review. J Agric Food Chem 2003; 51: 4504-26.

12. FDA. Acrylamide: Questions & Answers. Center for Food Safety and Applied Nutrition. 2003.

13. NLM. Household Products Database: Polyacrylamide. NIH National Library of Medicine Specialized Information Services. 2001.

14. FAO/WHO. Health implications of acrylamide in food <*http://www.who.int/fsf/Acrylamide/Acrylamide_index.htm*> Geneva, Switzerland: 2002.

15. FDA. FDA draft action plan for acrylamide in food - February 24, 2003 Update. Center for Food Safety and Applied Nutrition, Office of Plant & Dairy Foods & Beverages. 2003.

16. JIFSAN/NCFST. Exposure and biomarkers white paper. In: Acrylamide in food workshop:

scientific issues, uncertainties, and research strategies. ed. 2002:

17. FDA. Exploratory data on acrylamide in food. FY 2003 total diet study results. Available at <*http://www.cfsan.fda.gov/~dms/acrydat2.html*> FDA CFSAN/Office of Plant &Dairy Foods; 2004.

18. FDA. Exploratory data on acrylamide in food. Available at <*http://www.cfsan.fda.gov/~dms/acrydata.html#last*> FDA CFSAN/Office of Plant & Dairy Foods; 2004.

19. JIFSAN/NCFST. Mechanisms of formation of acrylamide in food summary report. In: ed.^eds. Acrylamide in food workshop: scientific issues, uncertainties, and research strategies. ed. 2002:

20. EPA. National primary drinking water regulations: Treatment techniques for acrylamide and epichlorohydrin. 2002.

21. EPA. Consumer Factsheet on: Acrylamide. 2002.

22. Smith, C. J., Perfetti, T. A., Rumple, M. A., Rodgman, A. and Doolittle, D. J. "IARC group 2A Carcinogens" reported in cigarette mainstream smoke. Food Chem Toxicol 2000; 38: 371-83.

23. EPA. TRI Calculation Results. 2000.

24. Cosmetic_Ingredient_Review. Amended Report of the Cosmetic Ingredient Review Expert Panel: Safety Assessment of Polyacrylamide. Washington, DC: 2003.

25. European_Commision. Opinion of the scientific committee on food on new findings regarding the presence of acrylamide in food. <*http://europa.eu.int/comm/food/fs/sc/scf/out131_en.pdf*> Brussels, Belgium: 2002.

26. DiNovi, M. and Howard, D. The Updated Exposure Assessment for Acrylamide. Available at <*http://www.jifsan.umd.edu/acrylamide2004.htm*. FDA/CFSAN; 2004.

27. Sorgel, F., Weissenbacher, R., Kinzig-Schippers, M., Hofmann, A., Illauer, M., Skott, A. and Landersdorfer, C. Acrylamide: increased concentrations in homemade food and first evidence of its variable absorption from food, variable metabolism and placental and breast milk transfer in humans. Chemotherapy 2002; 48: 267-74.

28. Calleman, C. J. The metabolism and pharmacokinetics of acrylamide: implications for mechanisms of toxicity and human risk estimation. Drug Metab Rev 1996; 28: 527-90.

29. NIOSH. National Occupational Exposure Survey (1981-1983). 2003.

30. ACGIH. Acrylamide. TA:ACGIH. Documentation of the threshold limit values and biological exposure indices PG 2001; 3:

31. ACGIH. Acrylamide. Documentation of the threshold limit values and biological exposure indices 2003; 12.

32. NIOSH. Acrylamide: NIOSH Pocket Guide. 2003.

33. OSHA. Air contaminants. 29 CFR 1910.1000 2001;

34. Pantusa, V. P., Stock, T. H., Morandi, M. T., Harrist, R. B. and Afshar, M. Inhalation exposures to acrylamide in biomedical laboratories. AIHA J (Fairfax, Va) 2002; 63: 468-73.

35. Schettgen, T., Broding, H. C., Angerer, J. and Drexler, H. Hemoglobin adducts of ethylene oxide, propylene oxide, acrylonitrile and acrylamide-biomarkers in occupational and environmental medicine. Toxicol Lett 2002; 134: 65-70.

36. Schettgen, T., Weiss, T., Drexler, H. and Angerer, J. A first approach to estimate the internal exposure to acrylamide in smoking and non-smoking adults from Germany. Int J Hyg Environ Health 2003; 206: 9-14.

37. Fennell, T. R., MacNeela, J. P., Morris, R. W., Watson, M., Thompson, C. L. and Bell, D. A. Hemoglobin adducts from acrylonitrile and ethylene oxide in cigarette smokers: effects of glutathione S-transferase T1-null and M1-null genotypes. Cancer Epidemiol Biomarkers Prev 2000; 9: 705-12.

38. Hagmar, L., Tornqvist, M., Nordander, C., Rosen, I., Bruze, M., Kautiainen, A., Magnusson, A. L., Malmberg, B., Aprea, P., Granath, F. and Axmon, A. Health effects of occupational exposure to acrylamide using hemoglobin adducts as biomarkers of internal dose. Scand J Work Environ Health 2001; 27: 219-26.

39. JIFSAN/NCFST. Overview of acrylamide toxicity and metabolism. In: ed.^eds. Acrylamide in food workshop: scientific issues, uncertainties, and research strategies. ed. 2002:

40. Sumner, S. C., Williams, C. C., Snyder, R. W., Krol, W. L., Asgharian, B. and Fennell, T. R. Acrylamide: a comparison of metabolism and hemoglobin adducts in rodents following dermal, intraperitoneal, oral, or inhalation exposure. Toxicol Sci 2003; 75: 260-70.

41. Barber, D. S., Hunt, J. R., Ehrich, M. F., Lehning, E. J. and LoPachin, R. M. Metabolism, toxicokinetics and hemoglobin adduct formation in rats following subacute and subchronic acrylamide dosing. Neurotoxicology 2001; 22: 341-53.

42. Miller, M. J., Carter, D. E. and Sipes, I. G. Pharmacokinetics of Acrylamide in Fisher-334 Rats. Toxicol Appl Pharmacol 1982; 63: 36-44.

43. Schettgen, T., Kutting, B., Hornig, M., Beckmann, M. W., Weiss, T., Drexler, H. and Angerer, J. Trans-placental exposure of neonates to acrylamide-a pilot study. Int Arch Occup Environ Health 2004; 74:

44. Edwards, P. M. The insensitivity of the developing rat foetus to the toxic effects of acrylamide. Chem Biol Interact 1976; 12: 13-18.

45. Marlowe, C., Clark, M. J., Mast, R. W., Friedman, M. A. and Waddell, W. J. The distribution of [14C]acrylamide in male and pregnant Swiss-Webster mice studied by whole-body autoradiography. Toxicol Appl Pharmacol 1986; 86: 457-65.

46. Ikeda, G. J., Miller, E., Sapienza, P. P., Michel, T. C., King, M. T. and Sager, A. O. Maternal-foetal distribution studies in late pregnancy. II. Distribution of [1-14C]acrylamide in tissues of beagle dogs and miniature pigs. Food Chem Toxicol 1985; 23: 757-61.

47. Ikeda, G. J., Miller, E., Sapienza, P. P., Michel, T. C., King, M. T., Turner, V. A., Blumenthal, H., Jackson, W. E., 3rd and Levin, S. Distribution of 14C-labelled acrylamide and betaine in foetuses of rats, rabbits, beagle dogs and miniature pigs. Food Chem Toxicol 1983; 21: 49-58.

48. Kirman, C. R., Gargas, M. L., Deskin, R., Tonner-Navarro, L. and Andersen, M. E. A physiologically based pharmacokinetic model for acrylamide and its metabolite, glycidamide, in the rat. J Toxicol Environ Health A 2003; 66: 253-74.

49. Sumner, S. C., Fennell, T. R., Moore, T. A., Chanas, B., Gonzalez, F. and Ghanayem, B. I. Role of cytochrome P450 2E1 in the metabolism of acrylamide and acrylonitrile in mice. Chemical Research In Toxicology 1999; 12: 1110-1116.

50. Bergmark, E., Calleman, C. J. and Costa, L. G. Formation of hemoglobin adducts of acrylamide and its epoxide metabolite glycidamide in the rat. Toxicol Appl Pharmacol 1991; 111: 352-363.

51. Igisu, H., Goto, I., Kawamura, Y., Kato, M. and Izumi, K. Acrylamide encephaloneuropathy due to well water pollution. J Neurol Neurosurg Psychiatry 1975; 38: 581-4.

52. NICNAS. Acrylamide: Priority existing chemical assessment report No. 23. 2002.

53. He, F. S., Zhang, S. L., Wang, H. L., Li, G., Zhang, Z. M., Li, F. L., Dong, X. M. and Hu, F. R. Neurological and electroneuromyographic assessment of the adverse effects of acrylamide on occupationally exposed workers. Scand J Work Environ Health 1989; 15: 125-9.

54. NTP. NTP Chemical Repository: Acrylamide. 2001.

55. Burek, J. D., Albee, R. R., Beyer, J. E., Bell, T. J., Carreon, R. M., Morden, D. C., Wade, C. E., Hermann, E. A. and Gorzinski, S. J. Subchronic toxicity of acrylamide administered to rats in the drinking water followed by up to 144 days of recovery. J Environ Pathol Toxicol 1980; 4: 157-82.

56. EPA. IRIS Acrylamide File. 2001.

57. Johnson, K. A., Gorzinski, S. J., Bodner, K. M., Campbell, R. A., Wolf, C. H., Friedman, M. A. and Mast, R. W. Chronic toxicity and oncogenicity study on acrylamide incorporated in the

drinking water of Fischer 344 rats. Toxicol Appl Pharmacol 1986; 85: 154-68.

58. Dearfield, K. L., Douglas, G. R., Ehling, U. H., Moore, M. M., Sega, G. A. and Brusick, D. J. Acrylamide: a review of its genotoxicity and an assessment of heritable genetic risk. Mutat Res 1995; 330: 71-99.

59. Besaratinia, A. and Pfeifer, G. P. Weak yet distinct mutagenicity of acrylamide in mammalian cells. J Natl Cancer Inst 2003; 95: 889-96.

60. Abramsson-Zetterberg, L. The dose-response relationship at very low doses of acrylamide is linear in the flow cytometer-based mouse micronucleus assay. Mutat Res 2003; 535: 215-22.

61. Neuhauser-Klaus, A. and Schmahl, W. Mutagenic and teratogenic effects of acrylamide in the mammalian spot test. Mutat Res 1989; 226: 157-62.

62. Shiraishi, Y. Chromosome aberrations induced by monomeric acrylamide in bone marrow and germ cells of mice. Mutat Res 1978; 57: 313-24.

63. Xiao, Y. and Tates, A. D. Increased frequencies of micronuclei in early spermatids of rats following exposure of young primary spermatocytes to acrylamide. Mutat Res 1994; 309: 245-53.

64. Dobrzynska, M. M. and Gajewski, A. K. Induction of micronuclei in bone marrow and sperm head abnormalities after combined exposure of mice to low doses of X-rays and acrylamide. Teratog Carcinog Mutagen 2000; 20: 133-40.

65. Backer, L. C., Dearfield, K. L., Erexson, G. L., Campbell, J. A., Westbrook-Collins, B. and Allen, J. W. The effects of acrylamide on mouse germ-line and somatic cell chromosomes. Environ Mol Mutagen 1989; 13: 218-26.

66. Adler, I. D. Clastogenic Effects of Acrylamide in Different Germ-Cell Stages of Male Mice. Banbury Report 1990; 34: 115-131.

67. Collins, B. W., Howard, D. R. and Allen, J. W. Kinetochore-staining of spermatid micronuclei: studies of mice treated with X-radiation or acrylamide. Mutat Res 1992; 281: 287-94.

68. Russo, A., Gabbani, G. and Simoncini, B. Weak genotoxicity of acrylamide on premeiotic and somatic cells of the mouse. Mutat Res 1994; 309: 263-72.

69. Lahdetie, J., Suutari, A. and Sjoblom, T. The spermatid micronucleus test with the dissection technique detects the germ cell mutagenicity of acrylamide in rat meiotic cells. Mutation Research 1994; 309: 255-262.

70. Gassner, P. and Adler, I. D. Induction of hypoploidy and cell cycle delay by acrylamide in somatic and germinal cells of male mice. Mutation Research 1996; 367: 195-202.

71. Bjorge, C., Brunborg, G., Wiger, R., Holme, J. A., Scholz, T., Dybing, E. and Soderlund, E. J. A comparative study of chemically induced DNA damage in isolated human and rat testicular cells. Reprod Toxicol 1996; 10: 509-19.

72. Schmid, T. E., Xu, W. and Adler, I. D. Detection of aneuploidy by multicolor FISH in mouse sperm after *in vivo* treatment with acrylamide, colchicine, diazepam or thiabendazole. Mutagenesis 1999; 14: 173-179.

73. Gassner, P. and Adler, I. D. Analysis of chemically induced spindle aberrations in male mouse germ cells: comparison of differential and immunofluorescent staining procedures. Mutagenesis 1995; 10: 243-52.

74. Smith, M. K., Zenick, H., Preston, R. J., George, E. L. and Lon, R. E. Dominant Lethal Effects Of Subchronic Acrylamide Administration In The Male Long-Evans Rat. Mutation Research 1986; 173: 273-277.

75. Sublet, V. H., Zenick, H. and Smith, M. K. Factors associated with reduced fertility and implantation rates in females mated to acrylamide-treated rats. Toxicology 1989; 55: 53-67.

76. Ehling, U. H. and Neuhaeuser-Klaus, A. Reevaluation of the induction of specific-locus mutations in spermatogonia of the mouse by acrylamide. Mutat Res 1992; 283: 185-191.

77. Gutierrez-Espeleta, G. A., Hughes, L. A., Piegorsch, W. W., Shelby, M. D. and Generoso, W. M. Acrylamide: dermal exposure produces genetic damage in male mouse germ cells. Fundam Appl Toxicol 1992; 18: 189-92.

78. NTP. Final report on the reproductive toxicity of acrylamide (ACRL) (CAS no. 79-06-1) in CD-1 Swiss mice. NTIS Technical Report 1993;

79. Adler, I. D., Baumgartner, A., Gonda, H., Friedman, M. A. and Skerhut, M. 1-Aminobenzotriazole inhibits acrylamide-induced dominant lethal effects in spermatids of male mice. Mutagenesis 2000; 15: 133-6.

80. Shelby, M. D., Cain, K. T., Hughes, L. A., Braden, P. W. and Generoso, W. M. Dominant lethal effects of acrylamide in male mice. Mutat Res 1986; 173: 35-40.

81. Zenick, H., Hope, E. and Smith, M. K. Reproductive toxicity associated with acrylamide treatment in male and female rats. J Toxicol Environ Health 1986; 17: 457-72.

82. Working, P. K., Bentley, K. S., Hurtt, M. E. and Mohr, K. L. Comparison of the dominant lethal effects of acrylonitrile and acrylamide in male Fischer 344 rats. Mutagenesis 1987; 2: 215-20.

83. Shelby, M. D., Cain, K. T., Cornett, C. V. and Generoso, W. M. Acrylamide: induction of heritable translocation in male mice. Environ Mutagen 1987; 9: 363-8.

84. Dobrzynska, M., Lenarczyk, M. and Gajewski, A. K. Induction of dominant lethal mutations by combined X-ray-acrylamide treatment in male mice. Mutat Res 1990; 232: 209-15.

85. Nagao, T. Developmental abnormalities due to exposure of mouse paternal germ cells, preimplantation embryos, and organogenic embryos to acrylamide. Congenital Anomalies 1994; 34: 35-46.

86. Holland, N., Ahlborn, T., Turteltaub, K., Markee, C., Moore, D., 2nd, Wyrobek, A. J. and Smith, M. T. Acrylamide causes preimplantation abnormalities in embryos and induces chromatin-adducts in male germ cells of mice. Reprod Toxicol 1999; 13: 167-78.

87. Tyl, R. W., Friedman, M. A., Losco, P. E., Fisher, L. C., Johnson, K. A., Strother, D. E. and Wolf, C. H. Rat two-generation reproduction and dominant lethal study of acrylamide in drinking water. Reprod Toxicol 2000; 14: 385-401.

88. Pacchierotti, F., Tiveron, C., D'Archivio, M., Bassani, B., Cordelli, E., Leter, G. and Spano, M. Acrylamide-induced chromosomal damage in male mouse germ cells detected by cytogenetic analysis of one-cell zygotes. Mutat Res 1994; 309: 273-84.

89. Marchetti, F., Lowe, X., Bishop, J. and Wyrobek, A. J. Induction of chromosomal aberrations in mouse zygotes by acrylamide treatment of male germ cells and their correlation with dominant lethality and heritable translocations. Environmental And Molecular Mutagenesis 1997; 30: 410-417.

90. Titenko-Holland, N., Ahlborn, T., Lowe, X., Shang, N., Smith, M. T. and Wyrobek, A. J. Micronuclei and developmental abnormalities in 4-day mouse embryos after paternal treatment with acrylamide. Environmental And Molecular Mutagenesis 1998; 31: 206-217.

91. Adler, I. D., Reitmeir, P., Schmoller, R. and Schriever-Schwemmer, G. Dose response for heritable translocations induced by acrylamide in spermatids of mice. Mutat Res 1994; 309: 285-91.

92. Russell, L. B., Hunsicker, P. R., Cacheiro, N. L. and Generoso, W. M. Induction of specific-locus mutations in male germ cells of the mouse by acrylamide monomer. Mutat Res 1991; 262: 101-107.

93. Sega, G. A., Alcota, R. P. V., Tancongco, C. P. and Brimer, P. A. Acrylamide binding to the DNA and protamine of spermiogenic stages in the mouse and its relationship to genetic damage. Mutat Res 1989; 216: 221-230.

94. Sega, G. A. Adducts in sperm protamine and DNA vs. mutation frequency. Prog Clin Biol Res 1991; 372: 521-30.

95. Sega, G. A. and Generoso, E. E. Measurement of DNA breakage in specific germ-cell stages of male mice exposed to acrylamide, using an alkaline-elution procedure. Mutat Res 1990; 242; 79-87.

96. Sega, G. A., Generoso, E. E. and Brimer, P. A. Acrylamide exposure induces a delayed unscheduled DNA synthesis in germ cells of male mice that is correlated with the temporal pattern of adduct formation in testis DNA. Environ Mol Mutagen 1990; 16: 137-142.

97. Generoso, W. M., Sega, G. A., Lockhart, A. M., Hughes, L. A., Cain, K. T., Cacheiro, N. L. A. and Shelby, M. D. Dominant Lethal Mutations, Heritable Translocations, and Unscheduled DNA Synthesis Induced in Male Mouse Germ Cells by Glycidamide, a Metabolite of Acrylamide. Mutation Research 1996; 3: 175-183.

98. Collins, J. J., Swaen, G. M., Marsh, G. M., Utidjian, H. M., Caporossi, J. C. and Lucas, L. J. Mortality patterns among workers exposed to acrylamide. J Occup Med 1989; 31: 614-7.

99. Sobel, W., Bond, G. G., Parsons, T. W. and Brenner, F. E. Acrylamide cohort mortality study. Br J Ind Med 1986; 43: 785-8.

100. Marsh, G. M., Lucas, L. J., Youk, A. O. and Schall, L. C. Mortality patterns among workers exposed to acrylamide: 1994 follow up. Occupational And Environmental Medicine 1999; 56: 181-190.

101. Pelucchi, C., Franceschi, S., Levi, F., Trichopoulos, D., Bosetti, C., Negri, E. and La Vecchia, C. Fried potatoes and human cancer. Int J Cancer 2003; 105: 558-60.

102. Mucci, L. A., Dickman, P. W., Steineck, G., Adami, H. O. and Augustsson, K. Dietary acrylamide and cancer of the large bowel, kidney, and bladder: absence of an association in a population-based study in Sweden. Br J Cancer 2003; 88: 84-9.

103. Friedman, M. A., Dulak, L. H. and Stedham, M. A. A lifetime oncogenicity study in rats with acrylamide. Fundam Appl Toxicol 1995; 27: 95-105.

104. Damjanov, I. and Friedman, M. A. Mesotheliomas of tunica vaginalis testis of Fischer 344 (F344) rats treated with acrylamide: a light and electron microscopy study. *In Vivo* 1998; 12: 495-502.

105. Fullerton, P. M. and Barnes, J. M. Peripheral neuropathy in rats produced by acrylamide. Br J Ind Med 1966; 23: 210-21.

106. Kaplan, M. L. and Murphy, S. D. Effect of acrylamide on rotarod performance and sciatic nerve beta-glucuronidase activity of rats. Toxicol Appl Pharmacol 1972; 22: 259-68.

107. Suzuki, K. and Pfaff, L. D. Acrylamide neuropathy in rats. An electron microscopic study of degeneration and regeneration. Acta Neuropathol (Berl) 1973; 24: 197-213.

108. Ko, M. H., Chen, W. P., Lin-Shiau, S. Y. and Hsieh, S. T. Age-dependent acrylamide neurotoxicity in mice: morphology, physiology, and function. Exp Neurol 1999; 158: 37-46.

109. Husain, R., Dixit, R., Das, M. and Seth, P. K. Neurotoxicity of acrylamide in developing rat brain: changes in the levels of brain biogenic amines and activities of monoamine oxidase and acetylcholine esterase. Ind Health 1987; 25: 19-28.

110. Dixit, R., Husain, R., Mukhtar, H. and Seth, P. K. Acrylamide induced inhibition of hepatic glutathione-S-transferase activity in rats. Toxicol Lett 1981; 7: 207-10.

111. McCarver, D. G. and Hines, R. N. The ontogeny of human drug-metabolizing enzymes: phase II conjugation enzymes and regulatory mechanisms. J Pharmacol Exp Ther 2002; 300: 361-6.

112. Hayes, J. D. and Pulford, D. J. The glutathione S-transferase supergene family: regulation of GST and the contribution of the isoenzymes to cancer chemoprotection and drug resistance. Crit Rev Biochem Mol Biol 1995; 30: 445-600.

113. Hines, R. N. and McCarver, D. G. The ontogeny of human drug-metabolizing enzymes: phase I oxidative enzymes. J Pharmacol Exp Ther 2002; 300: 355-60.

114. Anzenbacher, P. and Anzenbacherova, E. Cytochromes P450 and metabolism of xenobiotics. Cell Mol Life Sci 2001; 58: 737-47.

115. BIO/DYNAMICS-INC. A Fetal Toxicity Study of Acrylamide in Rats. EPA/OTS; Doc #878211679; NTIS/OTS0206055 1979;

116. ALBERT-EINSTEIN-CLG-OF-MEDICIN. A Fetal Toxicity Study of Acrylamide in Rats. Wayne, NJ: 1980.

117. Walden, R., Squibb, R. E. and Schiller, C. M. Effects of prenatal and lactational exposure to acrylamide on the development of intestinal enzymes in the rat. Toxicol Appl Pharmacol 1981; 58: 363-9.

118. Field, E. A., Price, C. J., Sleet, R. B., Marr, M. C., Schwetz, B. A. and Morrissey, R. E. Developmental toxicity evaluation of acrylamide in rats and mice. Fundam Appl Toxicol 1990; 14: 502-12.

119. Rutledge, J. C., Generoso, W. M., Shourbaji, A., Cain, K. T., Gans, M. and Oliva, J. Developmental anomalies derived from exposure of zygotes and first-cleavage embryos to mutagens. Mutat Res 1992; 296: 167-177.

120. Agrawal, A. K. and Squibb, R. E. Effects of acrylamide given during gestation on dopamine receptor binding in rat pups. Toxicol Lett 1981; 7: 233-8.

121. Wise, L. D., Gordon, L. R., Soper, K. A., Duchai, D. M. and Morrissey, R. E. Developmental neurotoxicity evaluation of acrylamide in Sprague-Dawley rats. Neurotoxicology And Teratology 1995; 17: 189-198.

National Toxicology Program
U.S. Department of Health and Human Services

Center For The Evaluation Of Risks To Human Reproduction

PUBLIC COMMENTS ON THE EXPERT PANEL REPORT ON ACRYLAMIDE

Appendix III

NORTH AMERICAN POLYELECTROLYTE PRODUCERS ASSOCIATION

1250 Connecticut Avenue, N.W. • Suite 700 • Washington, D.C. 20036
Phone: 202-419-1500 • Fax: 202-659-8037

August 18, 2004

Dr. Michael Shelby, Director
Center for the Evaluation of Risks to Human Reproduction (CERHR)
National Institute of Environmental Health Sciences (NIEHS)
P.O. Box 12233, MD EC–32
Research Triangle Park, NC 27709
Via E-mail: shelby@niehs.nih.gov

Re: Comments on CERHR Expert Panel Report on Acrylamide

Dear Dr. Shelby:

The North American Polyelectrolyte Producers Association (NAPPA) welcomes the opportunity to comment on the NTP-CERHR Expert Panel Report on the Reproductive and Developmental Toxicity of Acrylamide dated June 2004 (NTP-CERHR-Acrylamide-04) as announced in the *Federal Register* on June 21, 2004 (69 *Fed. Reg.* 34382). NAPPA represents the major manufacturers and importers of synthetically produced coagulants and flocculants, which are generically referred to as polyelectrolytes. A major class of these polyelectrolytes is polyacrylamides. Some of NAPPA's members not only produce these polyacrylamides, but they are also manufacturers of the acrylamide monomer. For this reason, NAPPA members have a unique interest in this report and as such have been actively involved in this proceeding.

Generally, the summaries of the results of individual toxicity studies are accurate. However, the conclusions require comment particularly relating to the issues of occurrence of neurotoxicity in the workplace and industrial exposure. The Report states that:

> *Recognizing the broad range of occupational exposure estimates for acrylamide, the occurrence of neurotoxicity in some occupational settings, and the concurrent expression of neurotoxicity and reproductive toxicity in some experimental animal studies, the Expert Panel expressed some concern for adverse reproductive and developmental effects, including heritable effects, for exposures in occupational settings.*

Briefly, there have been no reported cases of neurotoxicity due to workplace exposure to acrylamide in the United States in the past two decades. Exposure is overestimated in the report by more than a factor of 10, the LOAEL in the rodent developmental study was 2.5-fold lower than the reproductive LOAEL (*i.e.*, there were no reproductive effects observed at doses which did not also induce maternal toxicity)

and neurotoxicity is a more sensitive endpoint than reproductive toxicity. Each of these issues is briefly described below.

Industrial Exposure

In Table 37 of the Report, the upper 90th percentile for industrial exposure is given as 45-52 µg/kg bw/day. We are unable to ascertain the source of this value. Within the United States, the OSHA PEL is 0.3 mg/m^3. Consequently, air concentrations of acrylamide do not exceed this value. Facilities are designed to operate substantially below 0.3 mg/m^3 to comply with the workplace regulations. In order to permanently operate within the regulations, the mean value must be maintained at or around 0.1 mg/m^3. The ACGIH TLV is even lower at 0.03 mg/m^3. The majority of states within the US utilize this TLV as a standard. It is also recognized internationally.

To attain the body burden exposure level of 45 µg/kg bw/day cited above, employees would necessarily be exposed to air levels of greater than 0.3 mg/m^3:

$$(45\text{-}52\ \mu g\ AM/kg\ bw/day) \times (70\ kg\ bw) = 3{,}150\text{-}3{,}650\ \mu g/day.$$

At a working inhalation rate of 10 m^3 for an 8-hour shift, this would result in air concentrations between 0.32 to 0.36 mg/m^3.

Internal Dose

Since acrylamide is absorbed at 50% or less by the inhalation route[1] and at 5% or less by the dermal route[2], the air concentrations required to attain the exposure given in Table 37 would exceed the OSHA PEL by a factor of 2, *i.e.*, 0.65 to 0.7 µg/m^3.

Additionally, since there are only 200 workdays per year, the value would be even higher at 1.19 to 1.28 µg/m^3. Based on the workplace exposure value given in the final report, more than 10% of the workforce is exposed to air concentrations that are four times higher than the OSHA standard and are in violation of the Occupational Safety and Health Act, not to mention the ACGIH TLV of 0.03 mg/m3. This estimate is flawed and needs revision. Additionally, the estimates of the upper 90th percentile are too high. Based on current, industry-wide practices, air levels approximating 0.09 mg/m^3 are more representative of the upper 90 percentile. This value is in agreement with the geometric mean reported in the EU Risk Assessment for UK where the MEL is 0.3 mg/m^3. The value for Germany was much lower and that for the Netherlands included the values for the manufacture of solid grade acrylamide. The manufacture of solid grade acrylamide,

[1] Sumner, S.C.J., Asgharian, B., Williams, C.C. and Fennell, T.R. (2001) Acrylamide: Metabolism, Distribution, and Hemoglobin Adducts in Male F344 Rats and B6C3F1 Mice Following Inhalation Exposure and Distribution and Hemoglobin Adducts Following Dermal Application to F344 Rats. CIIT report to Polyelectrolyte Producers Group (PPG).

[2] Fennell, T., Sumner, S.J., Snyder, R.W., Burgess, J., Spicer, R., Bridson, W.E. and Friedman, M.A. (In Press) Metabolism and Hemoglobin Adduct Formation of Acrylamide in Humans. *Tox. Sci.*

which produces air levels far higher than are generated from liquid acrylamide, does not take place in United States.

With regard to dermal absorption, I am enclosing a manuscript describing the research from which the Cosmetic Ingredient Review (CIR) Expert Panel generated their value for dermal absorption. Briefly stated, humans absorb approximately 5% of applied dose over a 24-hour period of continuous exposure. Over an 8-hour workday this would result in (5% × 8) / 24 = 1.67% of any acrylamide contacted dermally being absorbed. The Report's worst-case calculations are based on assumed dermal and inhalation absorption of 100%. We encourage CERHR to rely on the experimental data.

The Report expresses some confusion over the estimates of exposure from the Sumner papers. These are semantic difficulties. In the case of Dr. Sumner's higher estimate (22%), she evaluated material that was not recoverable from the dosing solution. In the case of her lower estimate (2%), she measured the systemically available dose. We believe that systemic dose should be the relevant metric.

Grouting has historically been an area of concern. There are recent data that bear on the issue of exposure among grout workers. We are providing a copy of a recent study conducted by Dr. Leonard Vance of Virginia Commonwealth University. In this study, he evaluates acrylamide exposure among grout workers in Maryland. He finds virtually no exposure among these workers. There are two reasons for this: there is an increased awareness of the potential adverse health effects of acrylamide; and, a different physical form of acrylamide was supplied, which results in lower exposure. There has been no reported neurotoxicity as a result of grout use in the US in the last two decades.

With regard to exposures in developing countries, technology has improved also. The toxicological properties of acrylamide have been disseminated and there are no documented overexposures as identified in the reports from Dr. Costa's group in China.

Developmental Effects

The Report describes a large number of negative developmental toxicity studies. There were some studies where clear maternal toxicity was accompanied by lower body weights in the pups, which is not unexpected due to effects on water consumption and behavioral parameters. However, the document should conclude that at doses where there is no maternal toxicity, there are no developmental effects. The cause of these developmental effects is not relevant as maternal toxicity would be present. While of academic interest, developmental effects do not impact on the thrust of the document.

Reproductive Toxicity versus Neurotoxicity

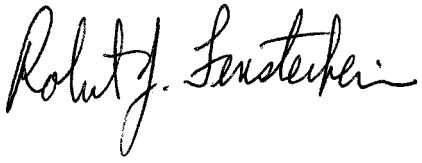
The LOAEL for reproductive toxicity, cited in the report, is 5 to 8 mg/kg/day (the basis for citing 8 mg/kg/day is unclear as this dose level was not used in the study. In this study, neurotoxicity (leg splay) was observed at the 2.0 and 5.0 mg/kg/day groups in parental and F_1 generations in this reproduction study with LOAEL of 0.5 mg/kg/day. The LOAEL for neurotoxicity in a 13-week study was 1 mg/kg/day with a NOAEL of 0.2 mg/kg/day. Neurotoxicity is clearly a more sensitive endpoint. The statement that the neurotoxic and reproductive effects occur concurrently refers to highly neurotoxic doses. Relevant arguments can be made mechanistically to support this contention, but these mechanistic arguments take away from the toxicological data sited in the report.

Conclusion

Industrial exposure has been overstated in the CERHR Expert Panel Report. Moreover, the conclusions are based on the concurrent observation of neurotoxicity and reproductive effects, which are not relevant to the relative potency. Based on an air level of 0.09 mg/m^3, the annualized daily exposure would be 0.49 mg/person/day (0.09 mg/m^3 $\times$ 10 m^3/day $\times$ 200 days worked/365 days per year) or 0.007 mg/kg bw/day. This is approximately 1,000-fold less than the LOAEL and 350 fold lower than the NOAEL. It is also 71 fold lower than the NOAEL for neurotoxicity. The exposure of 0.007 mg/kg/day is approximately 10 fold higher than the exposure from food. However, Erdreich[3] demonstrated that lifetime exposure from food was equivalent to lifetime industrial exposure as measured by Marsh *et al.*[4]

Based on the above cited data, we recommend that the CERHR conclusion mirror the EU conclusion that "an adequate margin of safety exists for the protection of workers from the reproductive effects of acrylamide."

Sincerely,



Robert J. Fensterheim
Executive Director

[3] Erdreich, L.S. and Friedman, M.A. (2004) Epidemiologic Evidence for Assessing the Carcinogenicity of Acrylamide. *Regul. Toxicol. Pharmacol.* 39(2): 150-157.

[4] Marsh, G.M., Lucas, L.J., Youk, A.O. and Schall, L.C. (1999) Mortality Patterns Among Workers Exposed to Acrylamide: 1994 Follow Up. *Occupational and Environmental Medicine* 56: 181-190.

Metabolism and Hemoglobin Adduct Formation of Acrylamide in Humans

Timothy R. Fennell[1], Susan C.J. Sumner[2], Rodney W. Snyder[1], Jason Burgess[1], Rebecca Spicer[3], William E. Bridson[3], and Marvin A. Friedman[4]

[1]Research Triangle Institute, Research Triangle Park, NC.

[2]Paradigm Genetics, Inc., Research Triangle Park, NC.

[3]Covance Clinical Research Unit, Inc, Madison WI

[4]UMDNJ, Newark, NJ.

Address Correspondence to
Timothy R. Fennell
Research Triangle Institute
P.O. Box 12190
3040 Cornwallis Road,
Research Triangle Park
NC 27709
(919) 485-2781
Fennell@RTI.org

Appendix III

Running Title: Metabolism and Adducts of Acrylamide in Humans

Abstract

Acrylamide, used in the manufacture of polyacrylamide and grouting agents, is produced during the cooking of foods. Workplace exposure to acrylamide can occur through the dermal and inhalation routes. The objectives of this study were to evaluate the metabolism of acrylamide in humans following oral administration, to compare hemoglobin adduct formation on oral and dermal administration, to measure hormone levels, and to monitor the safety of acrylamide in people exposed under controlled conditions. Prior to conducting exposures in humans, a low-dose study was conducted in rats administered 3 mg/kg 1,2,3-$^{13}C_3$ acrylamide by gavage. The study protocol was reviewed and approved by Institute Review Boards both at RTI which performed the sample analysis, and the clinical research center conducting the study. 1,2,3-$^{13}C_3$ Acrylamide (AM) was administered in an aqueous solution orally (single dose of 0.5, 1.0, or 3.0 mg/kg) or dermally (3 daily doses of 3.0 mg/kg) to sterile male volunteers. Urine samples (3 mg/kg oral dose) were analyzed for AM metabolites using ^{13}C NMR spectroscopy. Approximately 86 % of the urinary metabolites were derived from GSH conjugation, and excreted as *N*-acetyl-*S*-(3-amino-3-oxopropyl)cysteine and its *S*-oxide. Glycidamide, glyceramide, and low levels of *N*-acetyl-*S*-(3-amino-2-hydroxy-3-oxopropyl)cysteine were detected in urine. On oral administration, a linear dose response was observed for *N*-(2-carbamoylethyl)valine (AAVal) and *N*-(2-carbamoyl-2-hydroxyethyl)valine (GAVal) in hemoglobin. Dermal administration resulted in lower levels of AAVal and GAVal. This study indicated that humans metabolize acrylamide via glycidamide to a lesser extent than rodents, and dermal uptake was approximately 5% of that observed with oral uptake.

Acrylamide is used in the manufacture of water- soluble polymers (European Union, 2002). These polymers are then used for wastewater and sludge treatment, paper manufacture, soil stabilization, mining and many other uses (European Union, 2002). Acrylamide is also a chemical intermediate in the manufacture of other monomeric chemicals and used for grouting and preparation of laboratory gels for electrophoresis. Human exposure through these applications is very small (European Union, 2002). Previously, it has been postulated that dermal absorption was the major route of human exposure to acrylamide (European Union, 2002). The magnitude of this dermal absorption is highly relevant as one of the uses of acrylamide based polymers is in the formulation of skin creams (European Union, 2002). Estimates of dermal absorption based on in vitro and rodent studies have ranged from 3% to 100 (European Union, 2002). Recently, exposure to acrylamide in a variety of cooked foods has been described (Rosen and Hellenas, 2002; Tareke *et al.*, 2002). Human exposure via this route is substantial, with estimated exposures as high as 70 µg per day proposed (Tareke *et al.*, 2002).

Acrylamide is metabolized by two main pathways: glutathione conjugation (Dixit *et al.*, 1982; Edwards, 1975; Hashimoto and Aldridge, 1970; Miller *et al.*, 1982; Sumner *et al.*, 1992), and oxidation to glycidamide (Calleman *et al.*, 1990; Sumner *et al.*, 1992). The metabolism of acrylamide in vivo results in the formation of a number of metabolites. These metabolism of acrylamide in vivo has been investigated by administration of 1,2,3-$^{13}C_3$ acrylamide to rodents, with the detection and quantitation of metabolites by ^{13}C NMR spectroscopy (Sumner *et al.*, 1999; Sumner *et al.*, 1992; Sumner *et al.*, 2003). The

oxidation reaction to glycidamide is catalyzed by cytochrome P450 2E1 in rodents (Sumner *et al.*, 1999). Both acrylamide and glycidamide react with hemoglobin producing a stable adduct which can be measured as an indicator of exposure. Correlations have been made with hemoglobin adducts and neurotoxicity, but there has been no systematic standardization of hemoglobin adducts with dose. Glycidamide is weakly mutagenic in the Salmonella test (Hashimoto and Tanii, 1985). It can react with DNA in vitro to produce a guanine derivative N7-(2-carbamoyl-2-hydroxyethyl)guanine (Gamboa da Costa *et al.*, 2003; Segerback *et al.*, 1995). In vivo, administration of acrylamide to rats and mice produces low levels of N7-(2-carbamoyl-2-hydroxyethyl)guanine (Gamboa da Costa *et al.*, 2003; Segerback *et al.*, 1995).

Acrylamide induces a characteristic peripheral neurotoxicity in animals and man (Spencer and Schaumburg, 1974a, b, 1975). This toxicity manifests itself as a distal to proximal loss of nerve function and dying back of cells. Acrylamide also effects rodent reproduction, namely smaller litter size. At elevated acrylamide doses other reproductive effects are seen, likely as a consequence of the neurotoxicity.

Acrylamide is carcinogenic in drinking water studies in laboratory rats (Friedman *et al.*, 1995; Johnson *et al.*, 1986). In male rats, it induces tumors of the tunica vaginalis testes and the thyroid, while in females, it induces mammary fibroadenomas and thyroid tumors (Friedman *et al.*, 1995). The mechanism for this tumorigenicity is unclear, although interaction with the dopamine receptor has been postulated as well as genotoxicity (Tyl and Friedman, 2003). If the mechanism were genotoxicity, then conversion of

acrylamide to glycidamide is directly proportional to carcinogenic activity. Understanding the mechanism of tumorigenicity is important, since conventional risk assessment techniques place the order of magnitude of the risk at approximately 10^{-3} with exposures of 70 µg/ day.

The relative contributions of acrylamide and glycidamide in the mode of action of acrylamide are the subject of debate and current research. Understanding the conversion of acrylamide to glycidamide and differences that may occur between species, exposure route, and dose are important considerations in assessing the risk of the possible effects of acrylamide exposures in the diet, in consumer products, and in the workplace.

The primary objectives of this study were to evaluate the conversion of acrylamide to glycidamide in people exposed to acrylamide, and to evaluate the extent of uptake following dermal administration. This was conducted by administering a low dose of ^{13}C labeled acrylamide to volunteers orally or dermally, and by measuring urinary metabolites or hemoglobin adducts derived from the glycidamide pathway and comparing them to metabolites and hemoglobin adducts derived from acrylamide directly. More specifically, we intended to evaluate urinary metabolites and hemoglobin adducts, and to measure hormone levels after exposure to a known dose of acrylamide. As a secondary and no less important objective, we intended to monitor the safety of acrylamide in people exposed under controlled conditions.

MATERIALS AND METHODS

Chemicals

1,2,3-$^{13}C_3$ Acrylamide (CLM-813, lot number 11085) was obtained from Cambridge Isotopes Limited. Identity and purity were confirmed by ^{1}H and ^{13}C NMR spectroscopy. Glycidamide was synthesized by H_2O_2 oxidation of acrylonitrile (Payne and Williams, 1961), and stored at –20 ^{o}C. *N*-(2-Carbamoylethyl)valine (AAVal), *N*-(2-carbamoylethyl)valine -$^{13}C_5$ (AAVal-$^{13}C_5$), *N*-(2-Carbamoyl-2-hydroxyethyl)valine (GAVal) and *N*-(2-carbamoyl-2-hydroxyethyl)valine -$^{13}C_5$ (GAVal-$^{13}C_5$) were synthesized and purified as described previously by Fennell et al. (2003). The AAVal phenylthiohydantoin derivative (AAVal PTH), the corresponding ^{13}C labeled standard AAVal-$^{13}C_5$, GAVal PTH and ^{13}C GAVal PTH standards were prepared as described by Fennell et al. (2003). AAVal-leu-anilide was obtained from Bachem Bioscience Inc. (King of Prussia, PA).

Human Study

Institutional Review Board Approval.

This study was conducted in accordance with the CFRs governing Protection of Human Subjects (21 CFR 50), IRB (21 CFR 56), retention of data (21 CFR 312) as applicable and consistent with the Declaration of Helsinki. The administration of ^{13}C acrylamide to the study subjects was conducted at Covance Clinical Laboratories. Institutional Review Board approval of the protocol and the consent form was obtained at Covance Clinical

Laboratories. Institutional Review Board approval was also obtained at RTI, where the analysis of the samples was conducted.

Acrylamide Exposure

Twenty-four volunteers participated in this study. They were all male Caucasians (with the exception of one Native American) weighing between 71 and 101 kg and between 26 and 68 years of age. All volunteers were aspermic and had not used tobacco products for the past 6 months. They passed a drug screen and had not taken prescription drugs or caffeinated products over the previous 3 days. Each experimental group consisted of 6 individuals of which 1 was a placebo. There were 2 phases to this study: an oral phase and a dermal phase.

A comprehensive physical exam was conducted on each individual upon check-in to the clinic, at 24 hours after compound administration, and 7 days after check out. This exam included medical history, demographic data, neurological examination, 12-lead ECG, vital signs (including oral temperature, respiratory rate and automated seated pulse and blood pressure), clinical laboratory evaluation (including clinical chemistry, hematology, and complete urinalysis). Each individual also had screens for HIV, hepatitis, and selected drugs of abuse, and provided a semen sample to confirm aspermia.

In the oral phase, three groups of six people were administered 0.5, 1.0 or 3.0 mg/kg $^{13}C_3$ acrylamide. Individuals were presented with test substance at approximately 9:00 in the morning to initiate the study. Urine was collected at 0-2, 2-4, 4-8, 8-16 and 16-24 hours. Blood was collected immediately prior to compound administration and 24 hours later.

Hormone blood samples (testosterone, LH, and prolactin levels) were drawn immediately prior to compound administration, 24 hours later and on the follow up visit on day 8.

In the dermal phase, a 50% solution of $^{13}C_3$ acrylamide was applied directly on the skin to a clean, dry, marked off, 24 cm^2 (3 cm x 8 cm) area on the volar forearm. After applying the appropriate amount of material, the liquid was evaporated to dryness using a commercial hair dryer and covered with a sterile gauze pad. Dermal applications alternated between left and right arms, starting with the subject's dominant arm. Removal of dermal application consisted of washing with 1000 mL of water and an appropriate number of additional pieces of gauze. Blood was collected immediately prior to compound administration and 24, 48, 72 and 96 hours later (immediately prior to administration of the second and third doses, after gauze removal and prior to leaving the clinic). Hormone blood samples were drawn immediately prior to compound administration, after 24 hours and on day 5 when the volunteers left the clinic.

Urine and blood samples were obtained from sterile male volunteers who were exposed to 0.5 (low), 1.0 (mid) or 3.0 mg/kg (high) 1,2,3-$^{13}C_3$ acrylamide by a single oral dose, or 3 x 3.0 mg/kg 1,2,3-$^{13}C_3$ acrylamide administered dermally. Each exposure group contained 6 volunteers. Of the 6 volunteers in each group, 5 received the designated amount of acrylamide, and one received no acrylamide. For the groups administered acrylamide orally, a blood sample was collected immediately before acrylamide administration, and a second sample was collected at 24 h following the administration. For the group administered acrylamide dermally, blood samples were collected immediately before administration. Acrylamide was applied to the skin for 24 hours on

one forearm, and a blood sample was collected at 24 hours following the first administration. This was repeated on the following two days, with acrylamide applied on alternating arms, for a total of three dermal doses of acrylamide at 24 h intervals. A total of 5 blood samples was collected from each volunteer administered acrylamide dermally, on day 1 (prior to the first dose), day 2, day 3, day 4, and day 5. The sample obtained on day 5 was at 24 hours following removal of the occlusion at the site of application.

Blood samples were processed for storage and shipment at the Covance Clinical Research Unit as follows: the blood samples were centrifuged and plasma was removed, an equal volume of isotonic saline was added to the red cell pellets, the remaining washed red blood cells were washed by centrifugation with isotonic saline. The washing procedure was repeated a total of three times. The samples were stored frozen until shipped to RTI.

Urine samples were collected at intervals of 0-2, 2-4, 4-8, 8-16 and 16-24 hr following administration of acrylamide. The volume of urine in each sample was recorded, and sample aliquots were transferred to sample vials for storage.

Samples of urine and washed red blood cells were shipped to RTI from Covance Clinical Laboratories on dry ice, and were stored at –20 ^{o}C until processed for analysis.

Acrylamide Analysis

The dose solutions, dermal dam solutions, and wash solutions provided by the Covance Clinical Research Unit were analyzed for the concentration of acrylamide using a

reversed phase HPLC method. A calibration curve was prepared with acrylamide over a concentration range of 5–200 µg/mL. Analysis was conducted with a Waters HPLC system consisting of two 515 pumps, a 717 autosampler, and an Applied Biosystems 759A UV detector. Data was recorded with a Waters Millennium data system. Chromatography was conducted on a Beckman Ultrasphere ODS column (4.5 mm x 25 cm) eluted at a flow rate of 1 mL/min with 100% water. Elution was monitored by measuring UV absorbance at 195 nm. The measurements of acrylamide concentration in dose solutions were used to confirm the amount of acrylamide administered in oral dose solutions, and in the dose solution used for dermal applications. The amount of acrylamide recovered from dermal application in both the dermal dam, which was used to outline the skin area for application, and the skin washings following removal of the gauze covering the application site were also measured. The total amount of acrylamide recovered following dermal application was used to calculate the maximum amount of acrylamide that was available for absorption (total dose applied – amount recovered in the dermal dam and washing solutions).

Urinary Metabolite Analysis

Metabolites of 1,2,3-$^{13}C_3$ acrylamide in urine were analyzed from the group of volunteers exposed to 3 mg/kg AM orally by ^{13}C NMR spectroscopy, essentially as described by Sumner et al. (1991). No analyses were conducted on the samples from the volunteers administered 0.5, or 1.0 mg/kg orally , or those administered acrylamide dermally, due to the sensitivity of the methodology. Samples were prepared for all urine samples from subject 016 (3 mg/kg). Composite urine samples were prepared for analysis of each

subject administered 3.0 mg/kg orally. Aliquots of each sample were combined in the appropriate proportion to make a total of 10 mL. Samples were concentrated by mixing 5.0 mL of urine with 10 mL of methanol, centrifuging at 5000 g for 10 min. The supernatant was reduced in volume under a stream of nitrogen in a preweighed tube to approximately 300 – 600 µL. The weight of the concentrated urine was recorded. Water was added to make a total volume of 600 µL, and a solution of dioxane in D2O was added (200 µL).

NMR Analysis of Urinary Metabolites

Initial analysis of urine samples was conducted on a Bruker 500 MHz NMR spectrometer operating a 125 MHz for ^{13}C. Quantitative analysis of metabolites was conducted on a Varian 500 MHz NMR spectrometer operating at 125 MHz. Samples were prepared by adding D_2O, or D_2O containing dioxane at a known concentration (200 µl) to an aliquot of a urine sample, a composite urine sample, or a concentrated composite urine sample (800 µl). Carbon-Carbon connectivity was established using two-dimensional incredible natural abundance double quantum transfer spectra (INADEQUATE) using the Varian pulse sequence.

LC-MS/MS Analysis of Hemoglobin Adducts

Initial LC-MS/MS analyses of hemoglobin adducts were conducted using an API-3000 LC/MS/MS system with a heated nebuliser source coupled to an Agilent 1100 HPLC system. Data was processed using Analyst version 1.1 software. The HPLC system was composed of a binary HPLC pump, a refrigerated vial/96 well plate autosampler, a photodiodearray detector and a column heater. Direct infusion experiments were

conducted with an infusion rate of 10 µl/min, source temperature of 100°C, an ionspray voltage of 5000 V, curtain gas flow rate of 8, nebuliser gas flow rate of 5, and collision gas flow rate of 4. Nitrogen was used as the curtain gas, nebuliser gas, and collision gas.

Final quantitative analysis of all of the human globin samples was conducted using an API-4000 LC/MS/MS system with a heated nebuliser source coupled to an Agilent 1100 HPLC system. Data was processed using Analyst version 1.3 software. The HPLC system was composed of a binary HPLC pump, a refrigerated vial/96 well plate autosampler, a photodiodearray detector and a column heater.

Hemoglobin Adduct Analysis

N-(2-carbamoylethyl)valine (AAVal) and *N*-(2-carbamoyl-2-hydroxyethyl)valine (GAVal), formed by reaction of acrylamide and glycidamide, respectively, with the N-terminal valine residue in hemoglobin, were measured by an LC-MS/MS method. Globin was isolated from washed red cells (Mowrer et al., 1986). Samples were derivatized with phenylisothiocyanate in formamide to form adduct phenylthiohydantoin derivatives in a manner analogous to the modified Edman degradation (Tornqvist et al., 1986; Bergmark, 1997; Perez et al., 1999). Internal standards, AAValPTH-$^{13}C_5$ and GAVal PTH-$^{13}C_5$ were added, and the samples were extracted using a Waters Oasis HLB 3 cc (60 mg) extraction cartridge (Milford, MA). The samples were eluted with methanol, dried, and reconstituted in 100µl of 50:50 MeOH:H2O (containing 0.1% formic acid). Analysis was conducted using an HP 1100 HPLC system interfaced to a PE Sciex API 4000 LC-MS with a Turboionspray interface. Chromatography was conducted on a Phenomenex Luna Phenyl-Hexyl Column (50 mm × 2 mm, 3 µm) eluted with 0.1% acetic acid in

water and methanol at a flow rate of 350 µl/min, with a gradient of 45-55% methanol in 2.1 min. The elution of adducts was monitored by Multiple Reaction Monitoring (MRM) in the negative ion mode for the following ions:

Natural Abundance Analytes

AAVal-PTH: m/z 304 → 233 ($M\text{-}H^- \rightarrow M\text{-}H^- - CH_2\text{-}CH_2\text{-}CONH_2$)
GAVal-PTH: m/z 320 → 233 ($M\text{-}H^- \rightarrow M\text{-}H^- - CH_2\text{-}CHOH\text{-}CONH_2$)

Adducts Derived from 1,2,3-^{13}C Acrylamide

$^{13}C_3$-AAVal-PTH: m/z 307 → 233 ($M\text{-}H^- \rightarrow M\text{-}H^- - {}^{13}CH_2\text{-}{}^{13}CH_2\text{-}{}^{13}CONH_2$)
$^{13}C_3$-GAVal-PTH: m/z 323 → 233 ($M\text{-}H^- \rightarrow M\text{-}H^- - {}^{13}CH_2\text{-}{}^{13}CHOH\text{-}{}^{13}CONH_2$)

Internal Standards

AAVal-PTH-$^{13}C_5$: m/z 309 → 238 ($M\text{-}H^- \rightarrow M\text{-}H^- - CH_2\text{-}CH_2\text{-}CONH_2$)
GAVal-PTH-$^{13}C_5$: m/z 325 → 238 ($M\text{-}H^- \rightarrow M\text{-}H^- - CH_2\text{-}CHOH\text{-}CONH_2$)

Quantitation of AAVal was conducted using the ratio of analyte to internal standard, with a calibration curve generated using AAVal-leu-anilide. Quantitation of GAVal was conducted using the ratio of analyte to internal standard.

Rat Study

Prior to conducting the study in humans, male Fischer 344 rats were administered [1,2,3-^{13}C] acrylamide at a dose of 3 mg/kg by gavage in distilled water. This component of the study was conducted in parallel with administration of 50 mg [1,2,3-^{13}C] AM/kg to rats by gavage described in detail previously (Sumner *et al.*, 2003). The rats were placed in metabolism cages for 24 hours following dosing for collection of urine. After 24 hours, the rats were euthanized, and blood samples were collected by cardiac puncture. Washed

red blood cells were prepared by centrifugation, and globin was isolated by the method of Mowrer et al. (1986). Globin samples were analyzed by LC-MS/MS for AAVal, $^{13}C_3$-AAVal, GAVal and $^{13}C_3$-GAVal as described in (Sumner *et al.*, 2003). Urine samples were analyzed by ^{13}C NMR spectroscopy for metabolites of acrylamide (Sumner *et al.*, 2003). For quantitation of metabolites, samples were concentrated by addition of methanol to a 3 mL sample of urine, centrifugation, and evaporation under a stream of nitrogen. D_2O and dioxane were added.

In Vitro Reaction Rate Constants

Washed red cells from male F-344 rats, or from human blood were lysed with an equal volume of distilled water, and incubated with acrylamide or glycidamide at a concentration of 100 mM. Samples were removed at 0, 2, 5, 10, 15, 30 and 60 minutes, and the reactions were terminated by placing the tubes on ice and immediately adding 3 ml of 50 mM HCl in isopropanol. Globin was then isolated as described by Mowrer et al. (1986).

RESULTS

Rat Study

Analysis of Urinary Metabolites

Prior to conducting the administration of acrylamide in humans, the ability of the methods used to detect urinary metabolites and hemoglobin adducts was evaluated with a single dose of 3 mg/kg $^{13}C_3$ acrylamide administered by gavage in rats. The analysis of urinary metabolites was conducted as described previously (Sumner *et al.*, 2003). The

metabolites could be detected in urine samples. However, for quantitation of urinary metabolites, concentration of urine samples was required. The results of the quantitative analysis are shown in Table 1. Conjugation with GSH to form metabolite 1 accounted for 59% of the total metabolites. Metabolites 2,2' and 3,3', produced by GSH conjugation of glycidamide accounted for 25 and 16% of the urinary metabolites, respectively. Glycidamide was detected in urine samples from 2 of the rats prior to concentration, but was below the limit of quantitation in the concentrated samples. Metabolism via oxidation to glycidamide (2,2'-5, Table 1) accounted for approximately 41% of the urinary metabolites.

Analysis of the hemoglobin adducts from rats administered 3 mg/kg $^{13}C_3$ acrylamide is shown in Table 2. $^{13}C_3$-AAVal and $^{13}C_3$-GAVal were both increased by administration of acrylamide. The ratio of $^{13}C_3$-GAVal: $^{13}C_3$-AAVal was 0.84 ± 0.07.

Human Study

Clinical Findings

No adverse events were reported in the oral phase of the study. With the dermal administration, one individual appeared to have a mild contact dermatitis which is a known response to acrylamide and was part of the informed consent. This individual was seen by a dermatologist who performed a skin biopsy which was consistent with a delayed hypersensitivity reaction. The skin reaction resolved 39 days after the first application of acrylamide and 23 days after the reaction was manifested. Thus, the acrylamide caused a delayed hypersensitivity reaction when placed on the skin, a reaction

that took more than three weeks to resolve completely. An increase in the liver enzyme alanine aminotransferase (ALT) was observed above the upper limit of the reference range (normal) in 4 of the 5 individuals who received acrylamide by dermal application, one of whom had a preexisting elevation of this enzyme prior to receiving the dose (not shown). One individual who received dermal acrylamide also had an elevation in serum aspartate transaminase (not shown). The elevated liver function tests returned to within or near the reference range at subsequent determinations and were judged to be not clinically significant. When administered to the skin, acrylamide may cause a moderate increase in ALT levels. Serum prolactin, testosterone, and luteinizing hormone did not differ between subjects who received acrylamide and those who received placebo (not shown). All blood parameters and hormone levels were within the normal range. There were no neurological or cardiovascular findings among these individuals.

Dose Administered

For oral administration, acrylamide was administered in a constant volume of 200 mL to give the appropriate dose of 0.5, 1.0, or 3.0 mg/kg. The actual amount of acrylamide administered was verified by analysis of aliquots of the dose solution with calculation of the amount of acrylamide in 200 mL for each subject and the amount of acrylamide administered per kg body weight. One individual from each dose group did not receive acrylamide and this was verified by analysis of the administered dose. The mean doses calculated were 0.43 ± 0.01, 0.89 ± 0.01, and 2.75 ± 0.03 mg/kg, and were 86, 89, and 92% of the nominal dose at 0.5, 1.0, and 3.0 mg/kg, respectively.

With dermal administration, the appropriate volume of a 50% solution of acrylamide was applied to the skin. The dose applied each day based on HPLC analysis was calculated as 2.48 mg/kg, and was 83% of the nominal dose.

After drying the acrylamide solution, the tape which had been used to demark the area of application was removed and placed in a vial containing 20 mL of water. The water (dermal dam solution) was analyzed for acrylamide by HPLC and was found to contain between 9 and 54 mg of acrylamide (Table 3). The site of application was covered with gauze for 24 h at which time the gauze was removed and the area was washed with 1000 mL of water. The recovered wash water was analyzed by HPLC for acrylamide. The amount of acrylamide recovered ranged between 62 and 154 mg. The total acrylamide per day recovered in dermal dam and wash solutions ranged between 85 and 190 mg and accounted for 36–86% of the applied acrylamide. While considerable variability was observed in the recovery of acrylamide, the mean recovery in dam and washes ranged between 65 and 71% of the total acrylamide applied. The acrylamide recovered in the dermal dam and wash solutions would not be available systemically. The amount of dose that could have been taken up was calculated as:

$$\text{Absorbed dose} = \frac{\text{Total Dose Administered} - (\text{Dermal Dam} + \text{Wash})}{\text{Body Weight}} \qquad (1)$$

The mean absorbed dose ranged from 0.73 to 0.86 mg/kg/day (Table 3). The cumulative absorbed dose (over the three days of administration) was 2.35 ± 0.50 mg/kg (Table 3). This value includes material that could be retained at the site of application, and probably represents the maximum that could be absorbed rather than the actual amount absorbed.

Analysis of Urinary Metabolites

Urine samples from a single individual administered 3 mg/kg orally were evaluated qualitatively by ^{13}C NMR spectroscopy prior to quantitative analysis. A sample of each time point collection was analyzed from subject 15. The majority of the metabolite signals were found in the 2–4, 4–8, and 8–16 h samples. No signals indicative of the presence of $^{13}C_3$ acrylamide or its metabolites were found in the predose urine.

To achieve the necessary signal to noise ratio for quantitative analysis, and to collect data that were similar to those obtained from studies in rodents, aliquots of the urine samples from individuals were combined in the appropriate proportions to make a 24-h composite sample, which was then concentrated. Dioxane was added as an internal standard for quantitation of the metabolites.

The ^{13}C NMR spectrum of a composite urine sample obtained from a volunteer who did not receive acrylamide is shown in Figure 2. A number of signals from endogenous metabolites, including urea at 162.5 ppm can be seen. In the samples of urine from volunteers administered 3.0 mg/kg 1,2,3-$^{13}C_3$ acrylamide, there are additional signals arising from acrylamide and its metabolites (Figure 3). These signals show characteristic multiplets arising from coupling with adjacent labeled carbon atoms. Many but not all of the signals present in urine samples from rats and mice administered 1,2,3-$^{13}C_3$ acrylamide were present in the human urine samples. Some additional signals that had not been previously observed were also present. These signals are presented in Table 4. The nomenclature used previously (Sumner *et al.*, 1992; Sumner *et al.*, 1997; Sumner *et al.*, 2003) is also used to describe the metabolites in this report. The major metabolites present in all of the composite urine samples were derived from direct glutathione

conjugation of acrylamide (Sumner *et al.*, 1992; Sumner *et al.*, 1997; Sumner *et al.*, 2003).

The major metabolites, 1 and 1', corresponding to *N*-acetyl-*S*-(3-amino-3-oxopropyl)cysteine and *S*-(3-amino-3-oxopropyl)cysteine, showed signals at 27 ppm (doublet), 34.7 ppm (2 doublets of doublets, Figure 3), and at 177 ppm (2 doublets, Figure 3). An additional set of signals has been tentatively assigned as 1'' at 27.8 ppm. Signals associated with glycidamide, metabolite 4, were observed at 46.9 ppm (4a, Figure 3), and at 48.5 ppm (4b). Signals from the hydrolysis product of glycidamide (2,3-dihydroxypropionamide) were observed at 62.99 ppm (5a, doublet), at 72 ppm (5,5'b, doublet of doublets, Figure 3), and at 175.5 ppm (5,5'c, doublet). Low intensity signals that may be due to metabolite 2 (*N*-acetyl-*S*-(3-amino-2-hydroxy-3-oxopropyl)cysteine) were observed at 35.8 ppm and at 70.2 ppm. Signals that are associated with metabolite 3 (*N*-acetyl-*S*-(1-carbamoyl-2-hydroxyethyl)cysteine) were not observed. A metabolite that had not been previously observed in rats and mice gave a signal at 46.47 ppm (doublet, J = 37 Hz). An INADEQUATE spectrum was used to establish the carbon-carbon connectivity of the main signals of metabolite 1, glycdamide and glyceramide. In addition, the connectivity of the doublet at 46.47 ppm was established with a complex doublet of doublets at 27.60 ppm, and a doublet at 175.4 ppm. These signals have been assigned to the labeled carbon atoms of *N*-acetyl-*S*-(3-amino-3-oxopropyl)cysteine-S-oxide, based on the comparison with a synthesized standard (to be reported in an additional publication).

Quantitation of the metabolites present was conducted using the integral of the metabolite signals and dioxane added as internal standard. Spectra for quantitation were acquired

with decoupling only during acquisition to ensure that nuclear Overhauser enhancement was minimized so that accurate quantitation could be conducted. This resulted in the decrease in intensity of some of the low intensity signals to the point were quantitation was not readily possible, e.g. with metabolite 2. Although signals for acrylamide were readily apparent, these were not quantitated because of the long relaxation time for the signals of acrylamide. A summary of the quantitative information for urinary metabolites is presented in Table 5. Approximately 34% of the administered dose of acrylamide was recovered in the total urinary metabolites within 24 h of administration. Metabolite 1 accounted for approximately 72% of the metabolites excreted. The sulfoxide derived from metabolite 1 accounted for approximately 14% of the metabolites measured. Metabolites that are known to be derived from glycidamide (4 and 5) represented approximately 14% of the metabolites.

Analysis of Hemoglobin Adducts

Analysis of AAVal and GAVal was set up and validated as described previously (Fennell et al., 2003). A standard curve was developed with AAVal-leu-anilide standard and $^{13}C_5$-AAVal PTH. GAVal was measured based on the ratio of analyte to added $^{13}C_5$ GAVal PTH. In each of the samples obtained prior to administration of 1,2,3-$^{13}C_3$ acrylamide, measureable adduct backgrounds for AAVal and GAVal were detected.

Typical chromatograms for AAVal and GAVal from a volunteer administered $^{13}C_3$ acrylamide orally (0.5 mg/kg) are shown in Figure 4 (before administration) and Figure 5 (following administration). The administration of 1,2,3-^{13}C acrylamide resulted in an

increase in the peak height and area for $^{13}C_3$-AAVal and $^{13}C_3$-GAVal in the Figure 5 B and E. The mean values for hemoglobin adduct levels from the various groups administered acrylamide orally are presented in Table 6. AAVal, GAVal, $^{13}C_3$-AAVal and $^{13}C_3$-GAVal were measured for each individual prior to exposure to $^{13}C_3$ acrylamide, and at 24 hours following administration. The majority of the individual values (not shown) for AAVal prior to exposure were in the range of 40 – 200 fmol/mg globin. Most of the values for AAVal measured before and after exposure were similar. One exception to this was noted. One volunteer had high levels of AAVal in the first sample (986 fmol/mg), which dropped in the second sample (43 fmol/mg). The reason for this discrepancy can not be explained, and the value for the pre exposure sample has been excluded from calculations of statistical parameters. Prior to administration of acrylamide, the levels of GAVal were in the range of 16 – 67 fmol/mg globin and peaks associated with $^{13}C_3$-AAVal and $^{13}C_3$-GAVal were not detected. Following administration of acrylamide, $^{13}C_3$-AAVal and $^{13}C_3$-GAVal adduct levels increased in 5 out of the 6 members of each group. The subjects who received no 1,2,3-$^{13}C_3$ acrylamide were readily identified by a lack of detectable $^{13}C_3$-AAVal and $^{13}C_3$-GAVal.

On oral administration of 1,2,3-$^{13}C_3$ acrylamide, levels of $^{13}C_3$-AAVal increased in a dose-dependent manner (Table 6). A plot of $^{13}C_3$-AAVal vs. the nominal dose administered was linear (Figure 6). Similarly, on oral administration of 1,2,3-$^{13}C_3$ acrylamide, levels of $^{13}C_3$-GAVal increased in a dose-dependent manner (Table 6). A plot of $^{13}C_3$-GAVal vs. the nominal dose administered was also linear (Figure 6). The levels of $^{13}C_3$-GAVal formed were considerably lower than those of $^{13}C_3$-AAVal, with a ratio of $^{13}C_3$-GAVal: $^{13}C_3$-AAVal of ranging from 0.36 – 0.44 (Table 6).

Following dermal administration of acrylamide (days 1, 2, and 3), both AAVal and GAVal increased in a linear manner after each dose, on days 2, 3, and 4 (Table 6). Little change was noted between days 4 and 5 when no administration took place. A graph of $^{13}C_3$-AAVal and $^{13}C_3$-GAVal vs. the cumulative nominal dose administered produced a straight line (Figure 7). However, the initial point for both $^{13}C_3$-AAVal and $^{13}C_3$-GAVal were below the line in each case. The ratio of $^{13}C_3$-GAVal:$^{13}C_3$-AAVal ranged from 0.48 – 0.68.

To enable the comparison of dose groups, the data for hemoglobin adducts have been normalized by the nominal dose of acrylamide administered (Table 7), and by the actual dose estimated from analysis of acrylamide administered and recovered (Table 8). Comparison of the hemoglobin adducts formed in humans on oral administration with those formed in rats on gavage administration is presented in Table 9. Adduct levels normalized for dose are approximately 3-fold higher in humans for AAVal and 1.7 fold higher for GAVal in humans. The ratio of GAVal:AAVal in humans on oral administration was similar to that previously reported (Fennell *et al.*, 2003) for rats administered acrylamide by gavage at 50 mg/kg (Table 9). On dermal administration in humans, the ratio of GAVal:AAVal was slightly increased compared with oral administration (0.57 vs 0.39), the magnitude of the increase was much less than that observed in rats (1.7 vs 0.38).

Hemoglobin adducts can be used to calculate the internal dose or area under the curve in blood, using the reaction rate constant measured in vitro (Osterman-Golkar *et al.*, 1976), using the relationship:

$$\text{AUC} = \text{Adduct concentration/reaction rate constant} \qquad (2)$$

where the second order reaction rate constant is expressed in units of l/g globin/hr and adduct concentration is the amount of adduct per g globin. In Table 9, the rate constants measured in this laboratory are presented. These are similar in magnitude to those reported previously by Bergmark et al. (1993). For the human AAVal rate constant, our value of 4.24×10^{-6} agrees well with the previously reported value of 4.4×10^{-6}. However, our values for glycidamide reaction with rat and human hemoglobin are approximately half of those reported previously. Calculated values for AAVal and GAVal normalized for administered or absorbed dose are shown in Table 10. These values converted to AUC normalized for administered or absorbed dose are shown in Table 11. Compared with the AUC calculated for acrylamide in rats administered 3 mg/kg, the AUC in humans ranged from 2.75 to 3.7 fold higher. In contrast, the AUC for glycidamide in humans was similar to that in the rat, ranging from approximately 1.2 – 1.4 times that of rat.

DISCUSSION

The administration of a low dose (3 mg/kg) of acrylamide by gavage to rats resulted in a greater amount of metabolism via glycidamide (41 % of the urinary metabolites) compared with a higher dose of 59 mg/kg (28% of the urinary metabolites, (Sumner *et*

al., 2003)). The fate of glycidamide was primarily conjugation with GSH, resulting in the excretion of two mercapturic acids (metabolites 2 and 3).

The ratio of GAVal:AAVal has been observed to differ with route of exposure, and reflects the relative AUCs for acrylamide and glycidamide in blood. At a dose of 3 mg/kg in rats, GAVal:AAVal was lower (1.2) than that observed at 50 mg/kg (2.6, (Sumner *et al.*, 2003)). Both this observation and the larger percentage of metabolites in urine derived from glycidamide at the lower dose are consistent with saturation of the oxidation of acrylamide at the higher dose administered (Calleman *et al.*, 1992).

The urinary metabolites of acrylamide in humans showed similarities and differences with data obtained previously in the rat and mouse. The main pathway of metabolism in humans was via direct glutathione conjugation, forming *N*-acetyl-*S*-(3-amino-3-oxopropyl)cysteine, as observed in the rat and mouse, and its *S*-oxide, which has not been reported previously. Oxidation to glycidamide was the other important pathway, with glyceramide formed as a major metabolite in humans. Glycidamide was detected in low amounts. The glutathione conjugation of glycidamide, which is a major pathway in rodents, appeared to occur at very low levels in humans, with metabolite 2 detected, but not quantitated, and metabolite 3 not detected. Metabolism via glycidamide (derived from glycidamide and glyceramide) in humans was approximately 12% of the total urinary metabolites. This is considerably lower than the amount of glycidamide derived metabolites reported for oral administration of acrylamide in rats (28% at 50 mg/kg, (Sumner *et al.*, 2003) and in mice (59% at 50 mg/kg, (Sumner *et al.*, 1992)).

This study has provided data on the amount of hemoglobin adducts derived from acrylamide and glycidamide following administration of a defined dose of acrylamide to people. Both AAVal and GAVal increased linearly with increasing dose of acrylamide administered orally, suggesting that over the range of 0.5–3.0 mg/kg, there is no saturation of metabolism of acrylamide to glycidamide. The ratio of GAVal:AAVal produced by administration of acrylamide was similar to the ratio of the background adducts prior to exposure. Compared with the equivalent oral administration in rats (3 mg/kg), the ratio of $^{13}C_3$-GAVal: $^{13}C_3$-AAVal in humans was lower (0.44 ± 0.06) than in rats (0.84 ± 0.07), and the absolute amount of $^{13}C_3$-AAVal formed in humans was approximately 2.7 fold higher than in the rat. The absolute amount of $^{13}C_3$-GAVal was approximately 1.4 fold higher than that formed in the rat.

The extrapolation of dose between species is generally conducted using a scaling factor of body weight$^{3/4}$. For extrapolation from rats to humans, a scaling factor of 4.5 would be used. For effects that are mediated via the action of acrylamide, based on the AAVal comparison between rats and humans, a factor of 2.7 would appear appropriate, whereas for effects mediated by glycidamide, a factor of 1.4 would appear appropriate.

Dermal administration of acrylamide resulted in much lower levels of AAVal and GAVal formed compared with an equivalent dose by the oral route. Comparing AAVal after dermal and oral administration indicated approximately 5.6% of the dermally administered dose was taken up, assuming 100% oral absorption. Dermal administration also resulted in much lower formation of GAVal (8.6% of that formed on oral administration). Approximately 66% of the administered dose of acrylamide was recovered in dam solutions and the wash solutions, and thus was not systemically

absorbed on dermal administration. This suggests that only approximately 33% of the dermally applied dose could have been absorbed. If AAVal formed on oral and dermal administration is normalized with the absorbed dose, 16.4% of the absorbed dose (Equation 1) would have been systemically available (Table 8, 172 fmol/mg globin/mg acrylamide/kg for dermal vs. 1047 fmol/mg globin/mg acrylamide/kg for oral). This may indicate that 80% of the acrylamide that penetrated the skin was not available systemically. GAVal on dermal administration normalized for the actual dose in a similar manner was 24.4% of that formed on oral administration (Table 8, 99 fmol/mg globin/mg acrylamide/kg for dermal vs. 405 fmol/mg globin/mg acrylamide/kg for oral). An alternative explanation is that the acrylamide and glycidamide may be more rapidly metabolized on dermal exposure, resulting in a lower AUC and lower adduct formation per mg/kg.

The normalized formation of AAVal per unit dose, averaged for all of the oral dose groups, was calculated as 924 fmol/mg globin/mg acrylamide/kg. Using this value, the amount of acrylamide exposure that would be expected in a human from the diet can be calculated. In this study, the average pre-exposure AAVal level was 79 ± 49 fmol/mg globin (excluding subject 13). Hagmar *et al.* (2001) reported a range of 0.02–0.07 nmol AAVal/g globin (equivalent to 20–70 fmol AAVal/mg globin) in unexposed individuals. The steady state adduct level from continuous exposure is calculated to be $a.t_{er}/2$, where a is the daily adduct increment, and t_{er} is the erythrocyte lifespan, which in humans is approximately 120 days. The amount of adduct formed per day, assuming similar exposure per day over the erythrocyte lifespan, would be $1/60^{th}$ of the daily adduct increment. For the average level of 80 fmol/mg:

Daily adduct increment = 2*80 fmol/mg globin/120 days = 1.33 fmol/mg globin/day

The amount of acrylamide taken in can be estimated by:

$$\text{Acrylamide intake} = \frac{\text{1.33 fmol/mg globin/day}}{\text{924 fmol/mg globin/mg acrylamide/kg body wt.}} \quad (3)$$

= 1.44 μg/kg/day.

Similarly for the lower level of 20 fmol/mg, the daily adduct increment is 0.33 fmol/mg globin/day, and acrylamide intake is 0.36 μg/kg/day.

These estimates suggest a daily intake in the range of 25 – 101 μg for an average 70-kg person, and can be compared with a variety of estimates that have been produced for the average daily intake of acrylamide. The World Health Organization consultation (2002) estimated a daily intake of 0.8 μg acrylamide/kg/day for the average consumer, based on acrylamide levels in foods. Similarly, Svennson *et al.* (2003) estimated a mean daily intake of 31 μg/day based on food consumption data, which corresponds to 0.44 μg/kg/day for a 70-kg person. Törnqvist *et al.* (1998) have estimated a daily intake of approximately 100 μg per person based on hemoglobin adduct measurements of 30 fmol/mg globin, reported in Tareke et al. (2002). These calculations are based on a complex equation that relates the estimated dose to adduct level accumulated over the erythrocyte lifespan, rate of elimination (k), the reaction rate constant for adduct formation, the volume of distribution, and the erythrocyte lifespan (t_{er}).

Uptake (g/kg/day) =

$$\frac{\text{Adduct level } (30 \times 10^{-12} \text{ mol/g globin}) \times k\ (0.15\ \text{hr}^{-1}) \times 71\ \text{g/mol} \times \text{VD } (1\ \text{L/kg})}{[\text{Erythrocyte lifespan} \times 0.5\ (63\ \text{days})] \times \text{reaction rate constant } (4.4 \times 10^{-6}\ \text{L/g globin/hr})} \quad (4)$$

$$= 1.1\ \mu\text{g/kg/day}.$$

Of the parameters in this equation, two are estimated: the elimination rate constant in humans, and the volume of distribution (Calleman, 1996). Using the data obtained in this study for a single exposure in a modified equation enables the estimation of possible values for the elimination rate constant and volume of distribution.

Dose Administered (1 mg/kg) =

$$\frac{\text{Adduct level } (924 \times 10^{-12} \text{ mol/g globin}) \times k\ (0.15\ \text{hr}^{-1}) \times 71\ \text{g/mol} \times \text{VD (L/kg)}}{\text{Reaction rate contant } (4.24 \times 10^{-6}\ \text{L/g globin/hr})} \quad (5)$$

Rearranging and solving for VD yields a value of 0.44 L/kg, or distribution into 31 liters in a 70 kg person. This is approximately 73% of the estimated 42 liters of total body water. Using the value for VD of 0.44 L/kg and an adduct level of 30 pmol adduct/g globin, an uptake of acrylamide of 0.46 µg/kg/day is calculated, or 32 µg /day for a 70 kg person. This estimated uptake is more in line with the estimates of acrylamide exposure based on food consumption.

In summary, this study has examined the metabolism of acrylamide in people, and compared the internal dose of acrylamide and glycidamide in people with that observed in rats. The data reported are consistent with slower elimination of acrylamide in humans, and slower metabolism of acrylamide to glycidamide in humans. The hemoglobin adduct measurements obtained will provide a calibration for estimates of

exposure from diet, lifestyle, and the workplace.

ACKNOWLEDGEMENTS

The authors would like to acknowledge CIIT Centers for Health Research, Research Triangle Park, NC, where the administration of acrylamide to rats and analyses of rat urine and globin were conducted. This study was funded by SNF SA.

REFERENCES

Bergmark, E., Calleman, C. J., He, F., and Costa, L. G. (1993). Determination of hemoglobin adducts in humans occupationally exposed to acrylamide. *Toxicol. Appl. Pharmacol.* **120**, 45-54.

Calleman, C. J. (1996). The metabolism and pharmacokinetics of acrylamide: implications for mechanisms of toxicity and human risk estimation. *Drug Metab. Rev.* **28**, 527-590.

Calleman, C. J., Bergmark, E., and Costa, L. G. (1990). Acrylamide is metabolized to glycidamide in the rat: evidence from hemoglobin adduct formation. *Chem. Res. Toxicol.* **3**, 406-412.

Calleman, C. J., Stern, L. G., Bergmark, E., and Costa, L. G. (1992). Linear versus nonlinear models for hemoglobin adduct formation by acrylamide and its metabolite glycidamide: implications for risk estimation. *Cancer Epidemiol. Biomarkers Prev.* **1**, 361-368.

Dixit, R., Seth, P. K., and Mukjtar, H. (1982). Metabolism of acrylamide into urinary mercapturic acid and cysteine conjugates in rats. *Drug Metab Dispos* **10**, 196-197.

Edwards, P. M. (1975). The distribution and metabolism of acrylamide and its neurotoxic analogues in rats. *Biochem. Pharmacol.* **24**, 1277-1282.

European Union (2002). European Union Risk Assessment Report

Acrylamide, p. 210 pp, Luxembourg.

Fennell, T. R., Snyder, R. W., Krol, W. L., and Sumner, S. C. (2003). Comparison of the hemoglobin adducts formed by administration of N-methylolacrylamide and acrylamide to rats. *Toxicol Sci* **71**, 164-175.

Friedman, M. A., Dulak, L. H., and Stedham, M. A. (1995). A lifetime oncogenicity study in rats with acrylamide. *Fundam. Appl. Toxicol.* **27**, 95-105.

Gamboa da Costa, G., Churchwell, M. I., Hamilton, L. P., Von Tungeln, L. S., Beland, F. A., Marques, M. M., and Doerge, D. R. (2003). DNA adduct formation from acrylamide via conversion to glycidamide in adult and neonatal mice. *Chem Res Toxicol* **16**, 1328-1337.

Hagmar, L., Törnqvist, M., Nordander, C., Rosen, I., Bruze, M., Kautiainen, A., Magnusson, A. L., Malmberg, B., Aprea, P., Granath, F., and Axmon, A. (2001). Health effects of occupational exposure to acrylamide using hemoglobin adducts as biomarkers of internal dose. *Scand. J. Work Environ. Health* **27**, 219-226.

Hashimoto, K., and Aldridge, W. N. (1970). Biochemical studies on acrylamide, a neurotoxic agent. *Biochem. Pharmacol.* **19**, 2591-2604.

Hashimoto, K., and Tanii, H. (1985). Mutagenicity of acrylamide and its analogues in Salmonella typhimurium. *Mutat. Res.* **158**, 129-133.

Johnson, K. A., Gorzinski, S. J., Bodner, K. M., Campbell, R. A., Wolf, C. H., Friedman, M. A., and Mast, R. W. (1986). Chronic toxicity and oncogenicity study on acrylamide incorporated in the drinking water of Fischer 344 rats. *Toxicol. Appl. Pharmacol.* **85**, 154-168.

Miller, M. J., Carter, D. E., and Sipes, I. G. (1982). Pharmacokinetics of acrylamide in Fisher-344 rats. *Toxicol. Appl. Pharmacol.* **63**, 36-44.

Mowrer, J., Törnqvist, M., Jensen, S., and Ehrenberg, L. (1986). Modified Edman Degradation applied to hemoglobin for monitoring occupational exposure to alkylating agents. *Toxicol. Env. Chem.* **11**, 215-231.

Osterman-Golkar, S., Ehrenberg, L., Segerbäck, D., and Hallstrom, I. (1976). Evaluation of genetic risks of alkylating agents. II. Haemoglobin as a dose monitor. *Mutat. Res.* **34**, 1-10.

Payne, G. B., and Williams, P. H. (1961). Reactions of Hydrogen Peroxide. VI. Alkaline epoxidation of acrylonitrile. *J. Org. Chem.* **26**, 651-659.

Rosen, J., and Hellenas, K. E. (2002). Analysis of acrylamide in cooked foods by liquid chromatography tandem mass spectrometry. *Analyst* **127**, 880-882.

Segerback, D., Calleman, C. J., Schroeder, J. L., Costa, L. G., and Faustman, E. M. (1995). Formation of N-7-(2-carbamoyl-2-hydroxyethyl)guanine in DNA of the mouse and the rat following intraperitoneal administration of [14C]acrylamide. *Carcinogenesis* **16**, 1161-1165.

Spencer, P. S., and Schaumburg, H. H. (1974a). A review of acrylamide neurotoxicity. Part I. Properties, uses and human exposure. *Can J Neurol Sci* **1**, 143-150.

Spencer, P. S., and Schaumburg, H. H. (1974b). A review of acrylamide neurotoxicity. Part II. Experimental animal neurotoxicity and pathologic mechanisms. *Can J Neurol Sci* **1**, 152-169.

Spencer, P. S., and Schaumburg, H. H. (1975). Nervous system degeneration produced by acrylamide monomer. *Environ Health Perspect* **11**, 129-133.

Sumner, S. C., Fennell, T. R., Moore, T. A., Chanas, B., Gonzalez, F., and Ghanayem, B. I. (1999). Role of cytochrome P450 2E1 in the metabolism of acrylamide and acrylonitrile in mice. *Chem. Res. Toxicol.* **12**, 1110-1116.

Sumner, S. C., MacNeela, J. P., and Fennell, T. R. (1992). Characterization and quantitation of urinary metabolites of [1,2,3-^{13}C]acrylamide in rats and mice using ^{13}C nuclear magnetic resonance spectroscopy. *Chem. Res. Toxicol.* **5**, 81-89.

Sumner, S. C., Selvaraj, L., Nauhaus, S. K., and Fennell, T. R. (1997). Urinary metabolites from F344 rats and B6C3F1 mice coadministered acrylamide and acrylonitrile for 1 or 5 days. *Chem. Res. Toxicol.* **10**, 1152-1160.

Sumner, S. C., Williams, C. C., Snyder, R. W., Krol, W. L., Asgharian, B., and Fennell, T. R. (2003). Acrylamide: a comparison of metabolism and hemoglobin adducts in rodents following dermal, intraperitoneal, oral, or inhalation exposure. *Toxicol Sci* **75**, 260-270.

Svensson, K., Abramsson, L., Becker, W., Glynn, A., Hellenas, K. E., Lind, Y., and Rosen, J. (2003). Dietary intake of acrylamide in Sweden. *Food Chem Toxicol* **41**, 1581-1586.

Tareke, E., Rydberg, P., Karlsson, P., Eriksson, S., and Tornqvist, M. (2002). Analysis of acrylamide, a carcinogen formed in heated foodstuffs. *J Agric Food Chem* **50**, 4998-5006.

Törnqvist, M., Bergmark, E., Ehrenberg, L., and Granath, F. (1998). Risk Assessment of Acrylamide. Swedish Chemicals Inspectorate, Solna, Sweden.

Tyl, R. W., and Friedman, M. A. (2003). Effects of acrylamide on rodent reproductive performance. *Reprod Toxicol* **17**, 1-13.

WHO (2002). Joint FAO/WHO Consultation on Health Implication of Acrylamide in Food., p. 33 pp. World Health Organization, Geneva, Switzerland.

Table 1. Quantitation of urinary metabolites by NMR spectroscopy in rats administered 3 mg 1,2,3-^{13}C acrylamide/kg body wt.

	3 mg/kg [^{13}C]Acrylamide (8.7 ± 0.46 µmol)[a]				
Metabolite	% of Total	mM	µmol	µmol/kg bw	% of Dose
1,1'	59 ± 1.5	0.31 ± 0.061	2.6 ± 0.31	12 ± 1.6	29 ± 4.5
2,2'	25 ± 0.19	0.14 ± 0.028	1.1 ± 0.15	5.3 ± 0.73	13 ± 2.1
3,3'	16 ± 1.7	0.085 ± 0.026	0.69 ± 0.17	3.3 ± 0.82	8.0 ± 2.1
4	BDG[b]	BDG	BDG	BDG	BDG
5,5'	BD[c]	BD	BD	BD	BD
2,2'-5	41 ± 1.5	0.22 ± 0.053	1.8 ± 0.32	8.6 ± 1.5	21 ± 4.2
Total	100 ± 0	0.53 ± 0.11	4.3 ± 0.63	21 ± 3.0	50 ± 8.6

[a] N = 4, (Average ± Standard Deviation of dose in µmols). Urine samples were concentrated.

[b] BDG = Below detection limit in concentrated urine samples. Metabolite 4 (Glycidamide) constitutes 0.76-3.5 % of total measured excreted metabolites in 2 rats prior to concentration of urine. Following concentration, Glycidamide signals are not observed.

[c] BD = Below detection limit.

Table 2. Mean AAVal and GAVal levels following administration of 3 mg/kg 1,2,3-$^{13}C_3$ acrylamide to male rats by gavage.

	AAVal (fmol/mg globin)	GAVal (fmol/mg globin)	$^{13}C_3$-AAVal (fmol/mg globin)	$^{13}C_3$-GAVal (fmol/mg globin)
Control	156 ± 9	117 ± 16	19 ± 2	ND
3 mg/kg gavage	224 ± 100	111 ± 19	907 ± 176	752 ± 106

Table 3. Dermal dose delivered.

Subject	Body Wt (kg)	Dose Administered (mg)	Dermal Dam Total Acrylamide (mg)	Total Acrylamide in Wash (mg)	Total Acrylamide Recovered (mg)	Total Dose - (Dam + Wash) (mg)	Actual Dose (mg/kg)
Day 1	85.8 ± 9.1	212.4 ± 21.7	38.8 ± 11.5	100.2 ± 23.0	139.0 ± 18.4	73.4 ± 15.4	0.86 ± 0.14
Day 2	85.8 ± 9.1	212.4 ± 21.7	36.5 ± 19.2	113.3 ± 19.0	149.8 ± 23.6	62.6 ± 19.1	0.73 ± 0.2
Day 3	85.8 ± 9.1	212.4 ± 21.7	29.5 ± 9.0	115.2 ± 35.7	144.6 ± 37.8	67.7 ± 47.7	0.77 ± 0.48
Total	85.8 ± 9.1	637.1 ± 65.1	104.7 ± 22.1	328.7 ± 30.5	433.4 ± 42.4	203.7 ± 58.8	2.35 ± 0.5

Table 4. Chemical shift and coupling constants of metabolites in human urine derived from 1,2,3-$^{13}C_3$ acrylamide

Metabolite Identification[a]	Chemical Shift (ppm)[b]	Carbon-carbon Coupling (J_{cc}, Hz)	Observed in This Study
1a	26.97	35	Yes
1b	34.72	35, 48	Yes
1'b	34.68	35, 48	Yes
1c	177.14	48	Yes
1'c	177.08	48	Yes
2a	35.96	38	Yes
2'a	35.76	38	Yes
2b	70.22	38,52	Yes
2'b	70.09	38,52	Yes
2c	177.61	52	No
3a	61.45	37	No
3'a	61.48	37	No
3b	49.69	38,50	No
3'b	49.63	38,50	No
3c	175.54	50	No
4a	46.81	26	Yes
4b	48.45	26,63	Yes
4c	173.84	63	No
5a	62.99	40	Yes
5b	72.00	40,50	Yes
5c	175.46	50	Yes
6b	27.60	37,51	Yes
6a	46.47	37	Yes
6c	175.4	51	Yes

[a] Signals for metabolites are labeled according to the letter designating the carbon derived from acrylamide ($_aCH_2 =_bCH-_cCONH_2$). Derivation of metabolites given in Sumner et al. (1992, 1997, 2003).

[b] Chemical shift for center of multiplet pattern.

Table 5. Quantitation of urinary metabolites by NMR spectroscopy in humans administered 3 mg 1,2,3-^{13}C acrylamide/kg body wt orally.

		3 mg/kg [^{13}C]Acrylamide			
Metabolite		% of Total	mM	µmol	% of Dose
1,1'		72 ± 6.5	0.33 ± 0.09	679 ± 162	22 ± 5.3
6		14.1 ± 3.9	0.06 ± 0.01	130 ± 35	4.2 ± 1.1
2,2’		BD	BD	BD	BD
3,3'		BD	BD	BD	BD
4		2.6 ± 0.57	0.01± 0.00	25 ± 7.9	0.79 ± 0.24
5,5'		11.0 ± 3.7	0.05 ± 0.02	102 ± 40	3.3 ± 1.1
2,2'-5		13.5 ± 3.9		126 ± 44	4.1 ± 1.2
Total		100 ± 0		1056 ± 183	34 ± 5.7

Table 6. Mean AAVal and GAVal levels prior to and following administration of 1,2,3-$^{13}C_3$ acrylamide orally and dermally.

	AAVal (fmol/mg globin)	GAVal (fmol/mg globin)	$^{13}C_3$-AAVal (fmol/mg globin)	$^{13}C_3$-GAVal (fmol/mg globin)	$^{13}C_3$-GAVal/ $^{13}C_3$-AAVal
Pre-Dose Oral Group A1 (0.5 mg/kg)	89 ± 52	32 ± 17	ND [a]	ND	-
Pre-Dose Oral Group A2 (1 mg/kg)	63 ± 29	26 ± 5	ND	ND	-
Pre-Dose Oral Group A3 (3 mg/kg)	271 ± 354 [b]	288 ± 5	ND	ND	-
Oral Group A1 (0.5 mg/kg)	81 ± 41	34 ± 12	514 ± 49	186 ± 47	0.36 ± 0.06
Oral Group A2 (1 mg/kg)	66 ± 21	26 ± 6	914 ± 125	344 ± 52	0.38 ± 0.03
Oral Group A3 (3 mg/kg)	64 ± 26	35 ± 7	2479 ± 685	1076 ± 237	0.44 ± 0.06
Pre-Dose Dermal Group B (3 mg/kg)	167 ± 307 [c]	24 ± 6	ND	ND	-
Dermal Day 2	45 ± 11	27 ± 8	116 ± 15	55 ± 12	0.48 ± 0.09
Dermal Day 3	43 ± 9	28 ± 5	292 ± 78	167 ± 55	0.57 ± 0.11
Dermal Day 4	41 ± 5	27 ± 6	440 ± 101	292 ± 95	0.66 ± 0.11
Dermal Day 5	48 ± 14	30 ± 6	464 ± 62	316 ± 67	0.68 ± 0.11

[a] ND = not detected
[b] Recalculation with 13 removed: 128 ± 56
[c] Recalculation with 19 removed: 42.0 ± 12.1

Table 7. Hemoglobin adducts in humans normalized by nominal dose of 1,2,3-13C3 acrylamide (mg/kg).

Dose (Route) (mg/kg)	$^{13}C_3$-AAVal [a] (fmol/mg globin/ mg acrylamide/kg)	$^{13}C_3$-GAVal (fmol/mg globin/ mg acrylamide/kg)
0.5 (Oral)	1027 ± 98	372 ± 95
1 (Oral)	914 ± 125	344 ± 53
3 (Oral)	829 ± 228	359 ± 99
Combined (Oral)	924 ± 171	358 ± 73
1 x 3 (Dermal)	39 ± 5	18 ± 4
2 x 3 (Dermal)	49 ± 13	28 ± 9
3 x 3 (Dermal)	49 ± 11	32 ± 11
Combined (Dermal)	45 ± 11	26 ± 10

[a] Values represent mean ± SD for 5 individuals.

Table 8. Hemoglobin adducts in humans normalized by actual dose of 1,2,3-$^{13}C_3$ acrylamide (mg/kg).

Dose (Route) (mg/kg)	Actual Dose[a] (mg/kg)	$^{13}C_3$-AAVal [b] (fmol/mg globin/ mg acrylamide/kg)	$^{13}C_3$-GAVal (fmol/mg globin/ mg acrylamide/kg)
0.5 (Oral)	0.43 ± 0.01	1206 ± 105	436 ± 107
1 (Oral)	0.89 ± 0.01	1032 ± 139	389 ± 60
3 (Oral)	2.75 ± 0.03	903 ± 250	391 ± 87
Combined (Oral)		1047 ± 207	405 ± 84
1 x 3 (Dermal)	0.86 ± 0.14	140 ± 34	66 ± 20
2 x 3 (Dermal)	1.58 ± 0.12	183 ± 35	104 ± 27
3 x 3 (Dermal)	2.35 ± 0.50	194 ± 56	128 ± 41
Combined (Dermal)		172 ± 47	99 ± 39

[a] Dose calculated from analysis of dose solutions (oral) or absorbed dose (dermal).

[b] Values represent mean ± SD for 5 individuals.

Table 9. Rate constant for reaction of acrylamide and glycidamide with the *N*-terminal valine residue of hemoglobin.

	AAVal l/g/h	GAVal l/g/h	AAVal/GAVal
Rat	3.82×10^{-6}	4.96×10^{-6}	0.77
Human	4.27×10^{-6}	6.72×10^{-6}	0.64
Rat/human	0.89	0.73	

Table 10. Comparison of hemoglobin adducts normalized by administered or absorbed dose (mmol/kg) in rats and humans.

Dose (Route) (mg/kg)	Actual Dose (mg/kg)	$^{13}C_3$AAVal [a] (nmol/g globin/ mmol acrylamide/kg)	$^{13}C_3$ GAVal (nmol/g globin/ mmol acrylamide/kg)	GAVal: AAVal
Human				
0.5 (Oral)	0.43 ± 0.01	89.2 ± 7.8	33.2 ± 7.9	0.36 ± 0.06
1 (Oral)	0.89 ± 0.01	76.4 ± 10.2	28.8 ± 4.4	0.38 ± 0.03
3 (Oral)	2.75 ± 0.03	66.9 ± 18.5	28.9 ± 6.5	0.44 ± 0.06
Combined		77.4 ± 15.3	30.0 ± 6.2	0.39 ± 0.06
1 x 3 (Dermal)	0.86 ± 0.14	10.3 ± 2.5	4.9 ± 1.5	0.48 ± 0.09
2 x 3 (Dermal)	1.58 ± 0.12	13.5 ± 2.6	7.7 ± 2.0	0.57 ± 0.11
3 x 3 (Dermal)	2.35 ± 0.50	14.4 ± 4.1	9.5 ± 3.0	0.66 ± 0.11
Combined		12.7 ± 3.4	7.3 ± 2.8	0.57 ± 0.12
Rat [b]				
Oral	3	21.8 ± 4.1	18.1 ± 2.7	0.84 ± 0.07
Oral	50	26.4 ± 4.9	9.9 ± 1.6	0.38 ± 0.07
i.p.	50	20.6 ± 1.4	14.4 ± 1.5	0.71 ± 0.03
Dermal (1)	150	0.75 ± 0.3	1.2 ± 0.3	1.7 ± 0.42
Dermal (2)	150	2.8 ± 0.3	4.4 ± 1.4	1.7 ± 0.27
Dermal (2) [c]	150	12.8 ± 3.1	20.8 ± 4.3	

[a] Values represent mean ± SD for 5 individuals.
[b] Values for the rat are from this study, or are published in (Fennell *et al.*, 2003; Sumner *et al.*, 2003).
[c] Calculated based on dose recovered in tissue, excreta, and carcass.

Appendix III

Table 11. Comparison of AUC normalized by actual dose (mmol/kg) in rats and humans.

Dose (Route) (mg/kg)	Actual Dose (mg/kg)	$^{13}C_3$Acrylamide [a] (mM.h/ mmol acrylamide/kg)	$^{13}C_3$ Glycidamide (mM.h/ mmol acrylamide/kg)
Human			
0.5 (Oral)	0.43 ± 0.01	20.9 ± 1.8	4.9 ± 1.8
1 (Oral)	0.89 ± 0.01	17.9 ± 2.4	4.3 ± 0.6
3 (Oral)	2.75 ± 0.03	15.7 ± 1.5	4.3 ± 0.9
Combined		18.1 ± 4.5	4.5 ± 0.9
1 x 3 (Dermal)	0.86 ± 0.14	2.4 ± 0.6	0.73 ± 0.22
2 x 3 (Dermal)	1.58 ± 0.12	3.2 ± 0.6	1.1 ± 0.3
3 x 3 (Dermal)	2.35 ± 0.50	3.4 ± 1.0	1.4 ± 0.45
Combined		3.0 ± 0.8	1.1 ± 0.4
Rat [b]			
Oral	3	5.7 ± 1.1	3.7 ± 0.5
Oral	50	6.9 ± 1.3	2.0 ± 0.3
i.p.	50	5.4 ± 0.4	2.9 ± 0.3
Dermal (1)	150	0.20 ± 0.08	0.24 ± 0.06
Dermal (2)	150	0.73 ± 0.08	0.89 ± 0.28
Dermal (2) [c]	150	3.4 ± 0.8	4.2 ± 0.9

[a] Values represent mean ± SD for 5 individuals.
[b] Values for the rat are from this study, or published previously (Fennell *et al.*, 2003; Sumner *et al.*, 2003).
[c] Calculated based on dose recovered in tissue, excreta, and carcass.

Legends to Figures

Figure 1. Metabolism of acrylamide.

Figure 2. **^{13}C** NMR spectrum of human urine from an unexposed volunteer.

Figure 3. ^{13}C NMR spectrum of a 0-24 h composite human urine sample from a volunteer administered 3 mg/kg 1,2,3-^{13}C acrylamide orally.

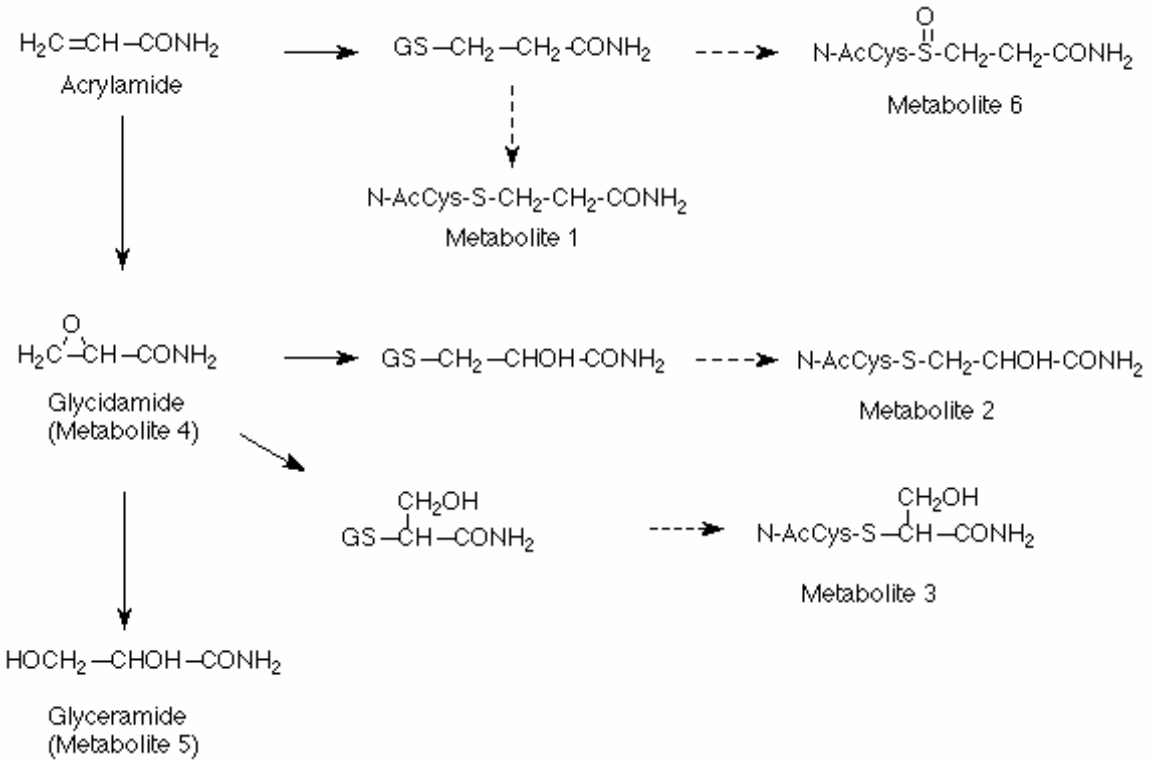
Figure 4. LC-MS/MS analysis of AAVal and GAVal. Adducts were monitored by MRM for (A) AAVal; (B) $^{13}C_3$-AAVal; (C) $^{13}C_5$-AAVal; (D) GAVal; (E) $^{13}C_3$-GAVal; and (F) $^{13}C_5$-GAVal. Globin was obtained from a volunteer prior to administration of acrylamide.

Figure 5. LC-MS/MS analysis of AAVal and GAVal. Adducts were monitored by MRM for (A) AAVal; (B) $^{13}C_3$-AAVal; (C) $^{13}C_5$-AAVal; (D) GAVal; (E) $^{13}C_3$-GAVal; and (F) $^{13}C_5$-GAVal. Globin was obtained from a volunteer 24 h following oral administration of [1,2,3-^{13}C] acrylamide (0.5 mg/kg).

Figure 6. Dose response for $^{13}C_3$-AAVal and $^{13}C_3$-GAVal following oral administration of [1,2,3-^{13}C] acrylamide in humans.

Figure 7. Effect of cumulative dermal dose of [1,2,3-^{13}C] acrylamide on formation of $^{13}C_3$-AAVal and $^{13}C_3$-GAVal in humans.

Figure 1



Appendix III

Figure 2.

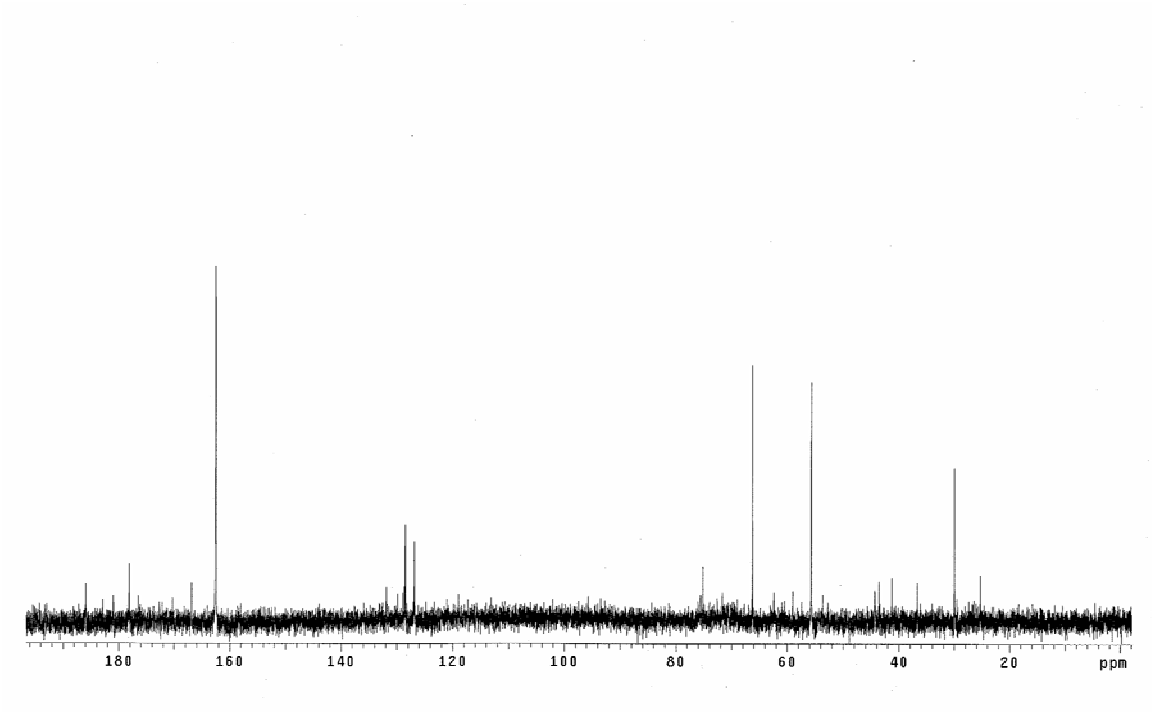
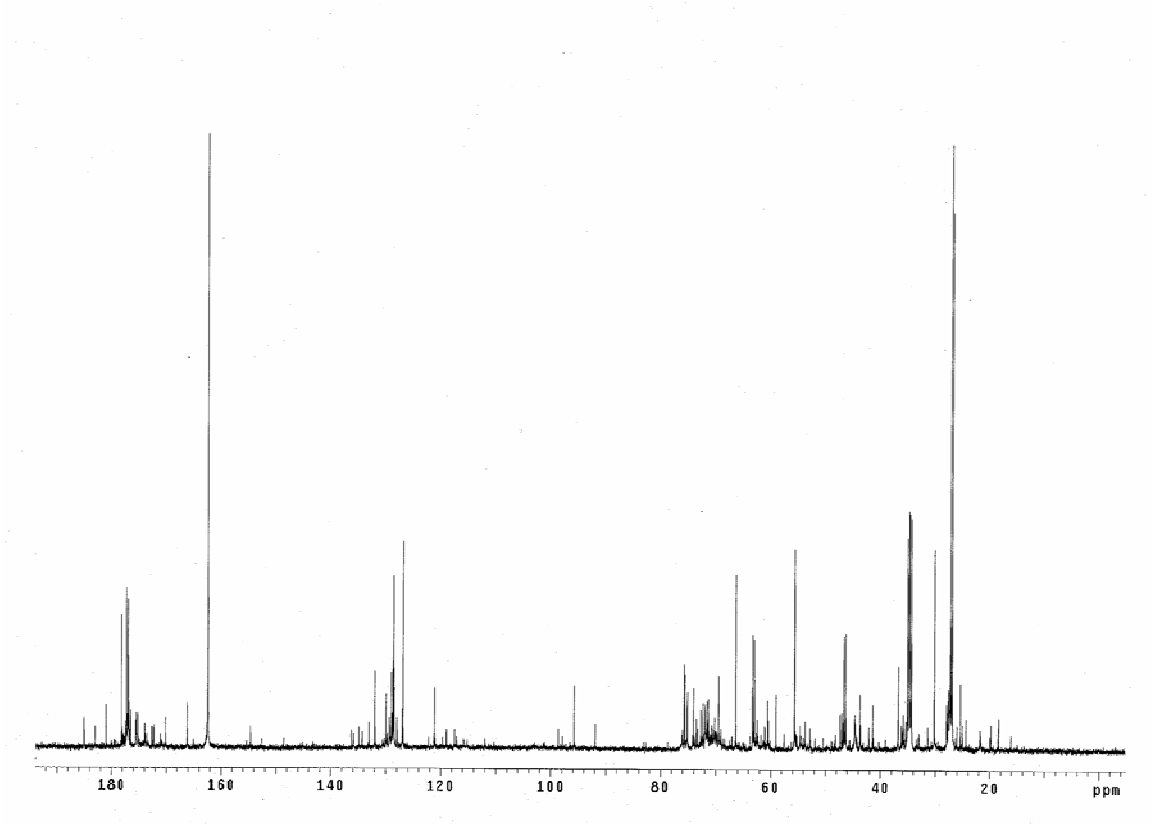
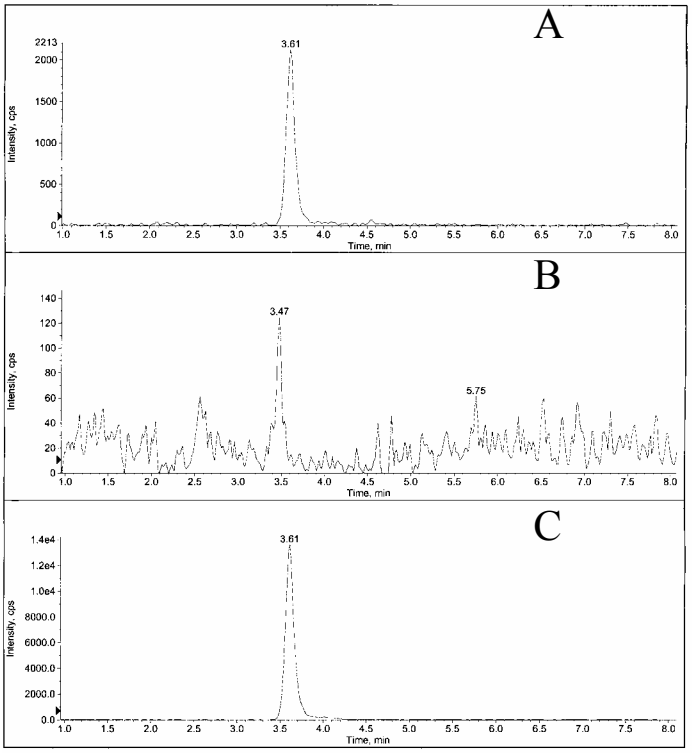


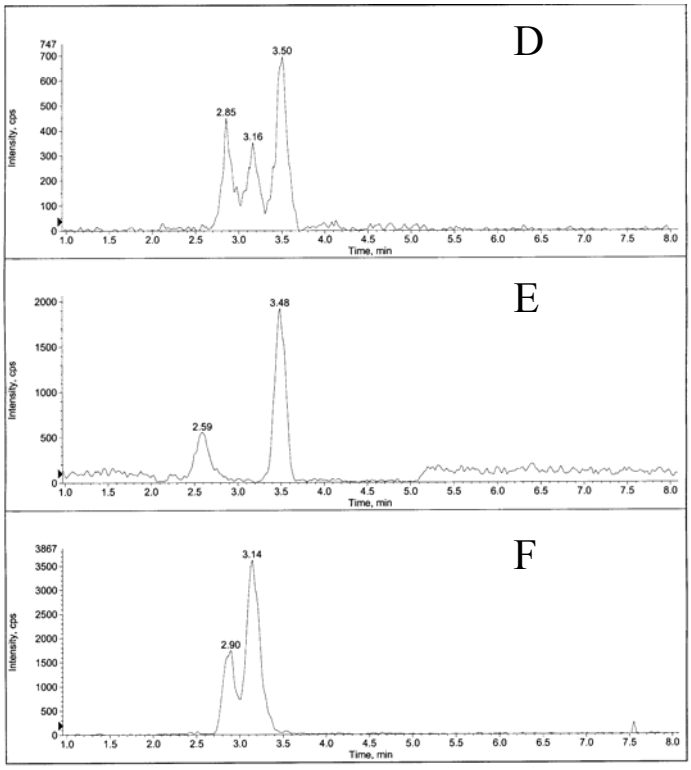
Figure 3.



Appendix III

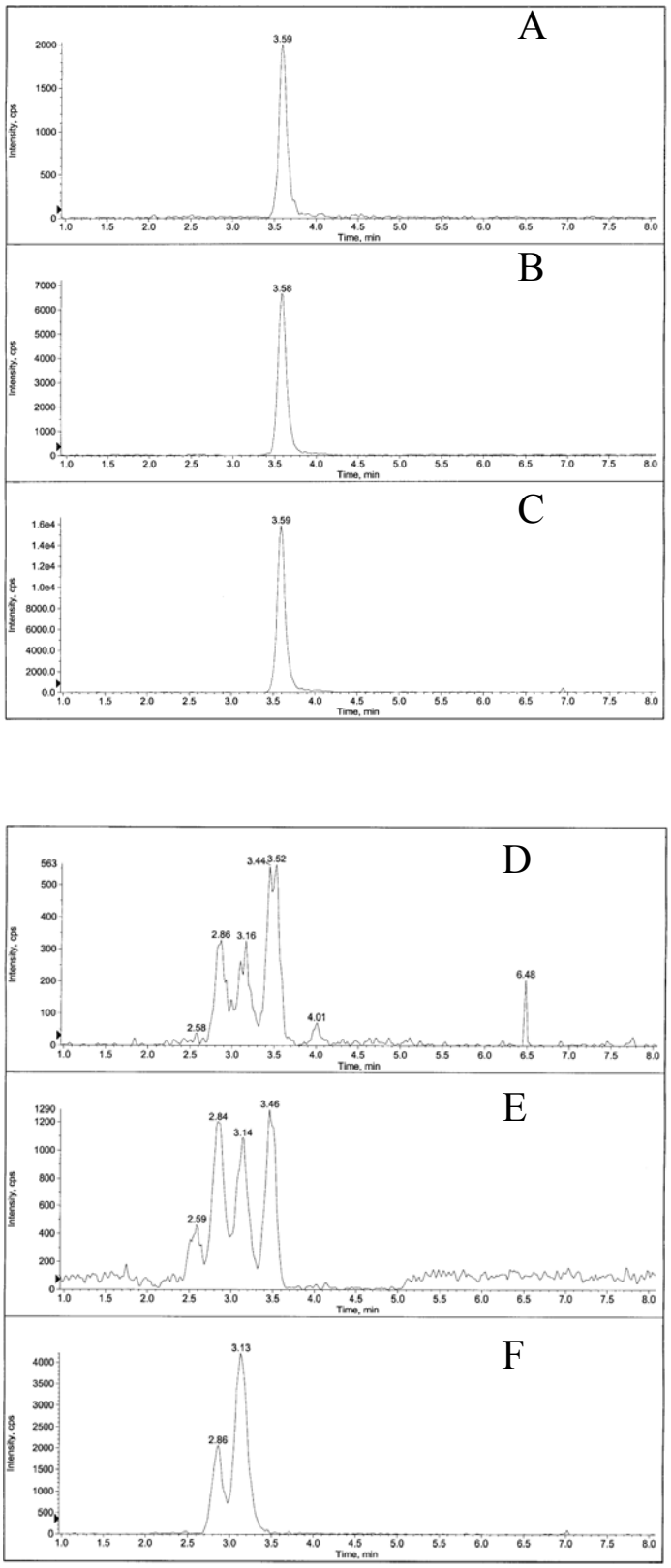
Figure 4.





Appendix III

Figure 5.



Appendix III

Figure 6.

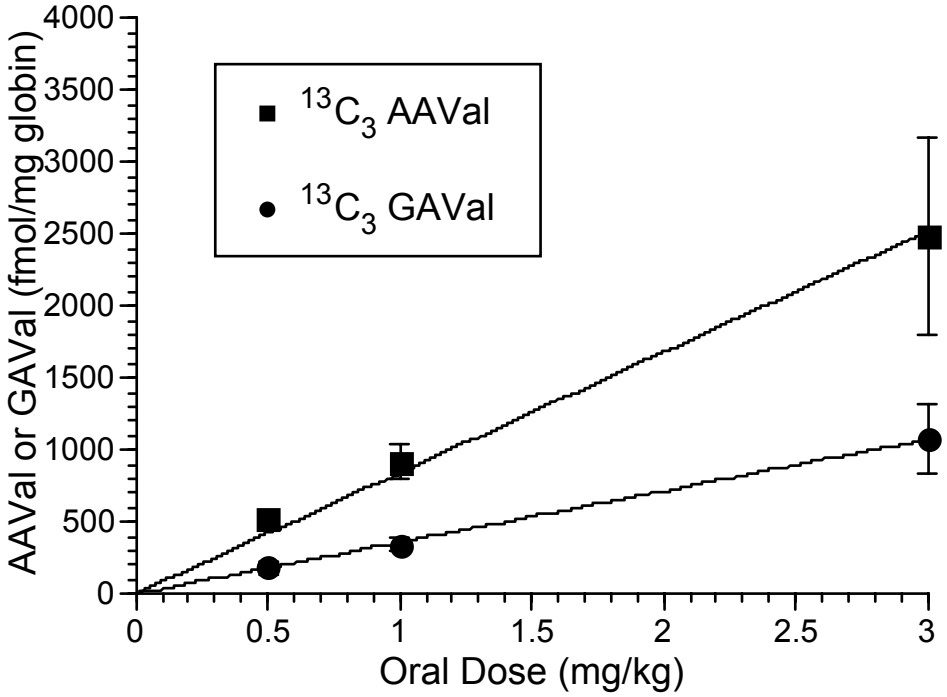
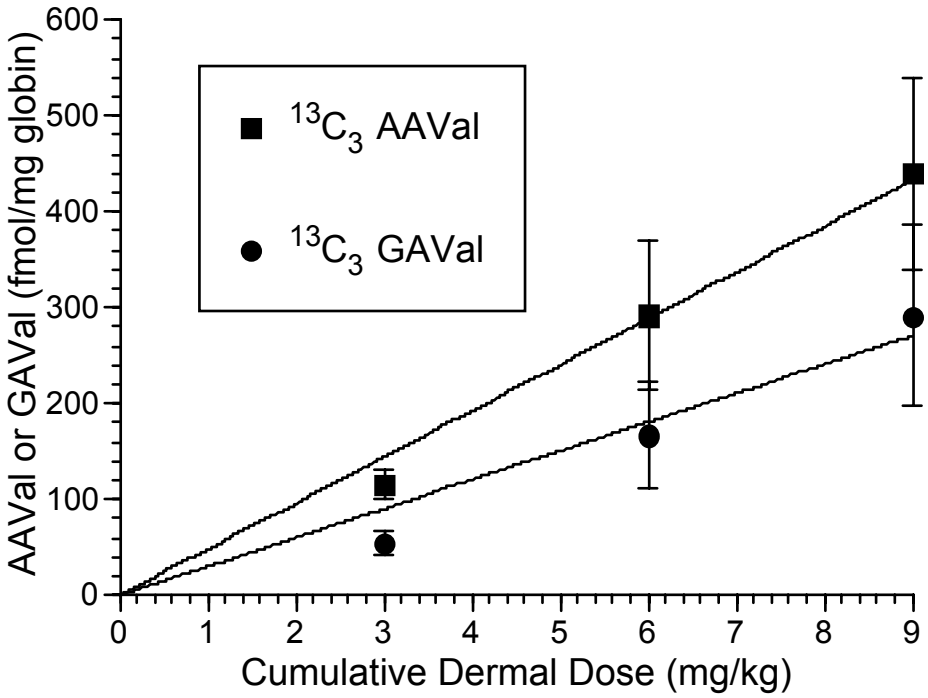

AAVal or GAVal (fmol/mg globin)
4000
3500
3000
2500
2000
1500
1000
500
0
0
0.5
1
1.5
2
2.5
3
Oral Dose (mg/kg)
$^{13}C_3$ AAVal
$^{13}C_3$ GAVal

Figure 7.



Appendix III

VCU
Virginia Commonwealth University

PREVENTIVE MEDICINE AND COMMUNITY HEALTH

GRANT HOUSE
1008 EAST CLAY STREET
P.O. BOX 980212
RICHMOND, VIRGINIA 23298-0212

804 828-9785
FAX: 804 828-9773
TDD: 1-800 828-1120

May 16, 2000

Mr. Dennis Marroni
Director, Product Information & Regulatory Affairs
SNF, S.A.
41 Rue Jean-Huss
42028 Saint-Etienne Cedex
1. France

Re: Acrylamide Grout Industrial Hygiene Monitoring Project

Dear Mr. Marroni:

Attached please find my summary of the results of acrylamide grout industrial hygiene monitoring recently performed on behalf of SNF, SA, pursuant to the agreement between Virginia Commonwealth University and SNF, SA. The purpose of the monitoring study was to determine worker acrylamide exposure levels when aqueous solutions of the monomer, rather than bagged solid acrylamide, are used in grouting operations.

A Maryland company, TRB Specialty Rehabilitation, Gambrills, Md., performed the grouting work. TRB was experienced with acrylamide grouting, having used solid acrylamide in the past. This was, I understand, TRB's first experience using aqueous acrylamide solution

Monitoring was performed on Tuesday, May 2, 2000, by me personally, with the assistance of Mr. Steve Henning and Dr. Marvin Friedman. TRB had three employees present and performing grouting: Mr. Rob Hilton, the crew leader, Mr. John Brady, and Mr. Chucky Hood. The grouting project was performed in storm water sewer lines, Hillmeade Subdivision, Prince Georges County, Maryland.

The protocol used was modeled after that employed by USEPA in its document entitled "Assessment of Airborne Exposure and Dermal Contact to Acrylamide During Chemical Grouting Operations, EPA 560/5-67-009, July, 1987. As EPA did in 1987, we collected four kinds of acrylamide samples: personal air monitoring samples collected in the breathing zone of the employees, dermal exposure samples collected on the bare skin or the protective clothing of each employee, handwash samples at the end of the work shift for each employee, and wipe samples from the equipment used during grouting operations. Thirty-six samples were collected and submitted for analysis.

Our original working hypothesis was that exposure levels encountered by workers using aqueous solutions of acrylamide during grouting would be lower than those

resulting from pouring solid phase acrylamide from bags when performing this work. The preliminary data support this proposition. Exposures to airborne acrylamide were below the limits of detection for all employees. Most dermal exposures were also below the limits of detection of the method. Handwash exposures were generally lower than those collected by EPA.

Of course, the data we have collected are representative of six hours of work on a single day by three employees. EPA collected data from three separate grouting activities: mainline sewer rehabilitation, work in sewer laterals, and work in manholes. Moreover, EPA collected data from four separate sites. It may be appropriate to collect additional data to test the hypothesis further.

The original Schneider Laboratory report sheets are attached. Please let me know if you have any questions or if the University can be of further service to SNF.

Respectfully submitted,

R. Leonard Vance, Ph.D., PE, CIH
Associate Professor

ACRYLAMIDE SAMPLING RESULTS

May 16, 2000

Report prepared by: R. Leonard Vance, Ph.D., PE, CIH; Associate Professor

The tables below set forth the results reported from acrylamide sampling performed by Virginia Commonwealth University on May 2, 2000, in Prince Georges County, Md. The samples were submitted to Schneider Laboratory, Inc., Richmond, Va., for analysis on May 3, 2000.

ACRYLAMIDE WIPE SAMPLES

Wipe Samples - location	Sample number	Analysis Result (mg)
truck dashboard	W-DB	< 0.04
exterior, acrylamide tank	W-AcT	0.054
TV/VCR monitor table	W-MT	< 0.04
steering wheel-truck	W-SW	< 0.04
remote control console	W-RCC	< 0.04
hydraulic hose	W-HH	< 0.04
BA [blank]	W-BA	0.042
duct tape extraction	DT	< 0.04
safety cone in road	W-SC	< 0.04

HANDWASH SAMPLES**

Employee / hand	sample number	Results**
Chucky Hood / left	H-C-L	
Chucky Hood / right	H-C-R	
John Brady / left	H-B-L	
John Brady / right	H-B-R	

* note - sample unavailable from Rob Hilton; ** unavailable as of 5/13/00

AIR SAMPLES [silica gel sorbent tubes plus cassettes]; flow rate: 0.5 /liters/minute

Employee sampled	time sampled	sample no. Cassette*	sample no. Silica gel	Total (mg) acrylamide	8 hr TWA (ppm)
C. Hood	9:00 am-3:30 pm	A-C-1-Tu	A-C-1-Tu sg	< 0.02	<0.029
J. Brady	9:30 am-3:30 pm	A-B-1-Tu	A-B-1-Tu sg	< 0.02	<0.029
R. Hilton	9:35 am-3:30 pm	A-H-1-Tu	A-H-1-Tu sg	< 0.02	<0.029
air blanks	blank	blank	blank	< 0.02	

DERMAL PADS

employee	location	sample number	Total Acrylamide (mg)
Rob Hilton	back	no sample	
Rob Hilton	right shoulder	no sample	
Rob Hilton	left shoulder	D-H-LS-Tu	< 0.100
Rob Hilton	rt knee	D-H-RK-Tu	< 0.100
Rob Hilton	left knee	D-H-LK-Tu	0.325
Rob Hilton	right forearm	D-H-RA-Tu	0.390
Rob Hilton	left forearm	D-H-LA-Tu	< 0.100
blank	blank	blank	< 0.100
Chucky Hood	back	D-C-B-Tu	< 0.100
Chucky Hood	right shoulder	D-C-RS-Tu	< 0.100
Chucky Hood	left shoulder	D-C-LS-Tu	< 0.100
Chucky Hood	rt knee	D-C-RK-Tu	< 0.100
Chucky Hood	left knee	D-C-LK-Tu	< 0.100
Chucky Hood	right forearm	D-C-RA-Tu	< 0.100
Chucky Hood	left forearm	D-C-LA-Tu	< 0.100
John Brady	back	D-B-B-Tu	0.125
John Brady	right shoulder	D-B-RS-Tu	< 0.100
John Brady	left shoulder	D-B-LS-Tu	< 0.100
John Brady	rt knee	no sample	
John Brady	left knee	D-B-LK-Tu	< 0.100
John Brady	right forearm	D-B-RA-Tu	0.295
John Brady	left forearm	D-B-LA-Tu	< 0.100

note: samples chilled until delivery to lab.

HANDWASH SAMPLES [hand rinses in 75 ml deionized water]

Employee / hand	sample number	Concentration ** Acrylamide (μg/ml)	Total acrylamide on hands (μg in 75ml)
Chucky Hood / left	H-C-L	1.71	128
Chucky Hood / right	H-C-R	2.32	167
John Brady / left	H-B-L	1.59	119
John Brady / right	H-B-R	2.48	186

* note - sample unavailable from Rob Hilton

** detection limit: 1.08 (μg/ml)

Comments on
NTP-CERHR Expert Panel Report (June 2004) on the
Reproductive and Developmental Toxicity of Acrylamide

Submitted to
Center for Evaluation of Human Risk to Reproduction (CERHR)
National Toxicology Program
ATTN: Dr. Michael Shelby

by
The Sapphire Group, Inc.[1]
Bethesda, Maryland

On behalf of
Snack Food Association
Alexandria, Virginia

16 August 2004

Appendix

[1]These comments are attributed to Robert G. Tardiff, Ph.D., ATS, and Christopher Kirman, M.S., 3 Bethesda Metro Center, Suite 830, Bethesda, MD 20814.

The National Toxicology Program (NTP) is commended for having prepared a thorough, thoughtful, and sound report of the data on reproductive an developmental toxicity of acrylamide. Furthermore, the process by which this report was prepared, including the public meeting, is a tribute to NTP's commitment to be fair and open in considering the views of many types.

For the final report entitled, "*NTP-CERHR Expert Panel Report on the Reproductive and Developmental Toxicity of Acrylamide*," we ask NTP to consider some additional modifications that, in our view, would be particularly important to those who use the document's contents, particularly for the estimation of risk to the reproductive health of those exposed to acrylamide in the workplace as well as in other walks of life.

Specifically, we recommend some changes to the text in the box found on page 145 of the subject report.

The text of the sentence of lines 15-16 in question states:

> *"Such effects [genetic alterations to male germ cells] can lead to genetic disorders and infertility in subsequent generations."*

First, the verb "can lead" should be changed to "may lead" since such an outcome has not been shown to occur. Furthermore, should such a consequence indeed be manifest, it would likely be dose-dependent, and it may not be operational at all dose rates below those that produced genetic alterations under laboratory conditions. The verb "may lead" conveys a stronger sense that certain conditions would need to be met for the event to occur, and that sense is most fully consistent with not only the data on acrylamide but with the broader understanding the ways in which genotoxic chemicals can be harmful at high doses but be of little or no threat to health at considerably lower doses.

Second, the words "and infertility" should be deleted since the impact of a theoretical heritable change will depend upon which part of the genome is affected, and that this would involve the parts of the genome that are important for fertility is pure speculation at this point.

Third, some further clarification of the sentence noted above should be provided to the reader to convey the full range of understanding. Notably, the issue of acrylamide's potential to produce reproductive effects in subsequent generations and the concept of "genetic risk" needs to consider the mode of action, of which there are at least three: (1) epigenetic (protamine binding & neurotoxicity) which is described in detail by Tyl *et al.* (2003); (2) genetic (*i.e.*, mutations); and (3) genetic (*i.e.*, reciprocal translocations). Each of these modes shares sources of nonlinear kinetics associated with acrylamide metabolism (*e.g.*, saturable

metabolism, sulfhydryl depletion) that while complicating low-dose extrapolation, are also consistent with the presence of biological thresholds.

With respect to these modes of action, agents can be classified into three categories: (1) N-alkylating agents, like glycidamide, that are readily repaired (nonlinear dynamics consistent with biological thresholds); (2) O-alkylating agents, that are repaired slowly, and are, therefore, more potent (not known to be applicable to acrylamide/glycidamide); and (3) agents producing structural changes (which relate to the protamine binding mechanism as described for acrylamide) that generally exhibit a small dose range, only producing effects at toxic or near-toxic dose levels which are also consistent with biological thresholds (Vogel *et al.*, 1998).

The dose-response relationship for heritable translocations induced by acrylamide in mouse spermatids is nonlinear (Adler et al., 1994). By analogy to acrylamide (via glycidamide formation), ethylene oxide produces reciprocal translocations, which by its nature is nonlinear with dose, and risk is likely to diminish by the square of the dose as suggested by the work of Preston *et al.* (1995). Thus, this mode of action, when applied to acrylamide would support a greatly diminished likelihood of producing trans-generational adverse effects via alteration of sperm.

A threshold for heritable tranlocations likely exists, below which the genetic risk is negligible. A NOAEL for dominant lethal mutations was reported by Tyl *et al.*, 2000; this event would likely occur by the same mechanism that would theoretically produce heritable changes, and, therefore, is consistent with a biological threshold for heritable changes.

This information should be incorporated into the subject text to provide the reader with a realization that trans-generational toxicity will not necessarily result at the relatively doses encountered by humans in the general environment.

Furthermore, the sentence on lines 19-21 of this text box on page 145 should be clarified. Presently, the sentence reads:

> *"However, considering the incidence in treated and control animals of the response detected for heritable translocation at the lowest level tested (40 mg/kg bw/day × 5 days), it is likely that such effects would occur at lower dose levels."*

As stated the sentence may be interpreted to mean that these adverse effects will be manifest 20 mg/kg bw/day as well as 20 ng/kg bw/day. While the former may be correct, the latter is not supported by the broader data demonstrating the presence of assorted defense and repair

mechanisms that would reduce considerably the likelihood of any injurious genetic alterations in the first place and of dissemination of unrepaired genetic damage from one generation to the next at a dose rate six orders of magnitude below the observation range.

Further down, the text states,

> *"Such risks were not considered by the Expert Panel in their evaluation of LOAELs because of the lack of testing at low dose levels where reproductive and developmental effects are observed."*

This sentence is internally inconsistent in citing a "lack of testing" where "effects are observed", which at a minimum should be revised to state where "effects may be observed". More importantly, the statement is inconsistent with the one stated on page 33 of the report where the Dearfield *et al*. assessment is described,

> *"The Expert Panel chose to place very little weight on the estimated risks due to the uncertainties associated with the assumptions employed"*

This statement indicates that such risks were considered by the Panel, but were considered to be too uncertain. This concluding section should be revised to be consistent with the earlier statement.

We hope that these suggested modifications will be of value as NTP completes this important document.

Appendix

References

Adler, I.D., Reitmeir, P., Schmoller, R., Schreiver-Schwemmer, G. 1994. Dose response for heritable translocations induced by acrylamide in spermatids of mice. Mutat. Res. 309:285-291.

Favor, J., M. Sund, A. Neuhauser-Klaus, and U. H. Ehling. A dose-response analysis of ethylnitrosourea-induced recessive specific-locus mutations in treated spermatogonia of the mouse. Mutat.Res 231 (1):47-54, 1990.

Preston, R.J., T. R. Fennell, A. P. Leber, R. L. Sielken, Jr., and J. A. Swenberg. Reconsideration of the genetic risk assessment for ethylene oxide exposures. Environ Mol.Mutagen. 26 (3):189-202, 1995.

Sloter, E., J. Nath, B. Eskenazi, and A. J. Wyrobek. Effects of male age on the frequencies of germinal and heritable chromosomal abnormalities in humans and rodents. Fertil.Steril. 81 (4):925-943, 2004.

Tyl, R.W., M. A. Friedman, P. E. Losco, L. C. Fisher, K. A. Johnson, D. E. Strother, and C. H. Wolf. Rat two-generation reproduction and dominant lethal study of acrylamide in drinking water. Reprod Toxicol 14 (5):385-401, 2000.

Tyl, R.W., and M. A. Friedman. Effects of acrylamide on rodent reproductive performance. Reprod Toxicol 17 (1):1-13, 2003.

Vogel, E.W., A. Barbin, M. J. Nivard, H. F. Stack, M. D. Waters, and P. H. Lohman. Heritable and cancer risks of exposures to anticancer drugs: inter-species comparisons of covalent deoxyribonucleic acid-binding agents. Mutat.Res 400 (1-2):509-540, 1998.

*****

Ref: F:\Project\17001\master\report\AMD_NTP-finalComments_081604.wpd

August 16, 2004

NTP-CERHR Expert Panel Report on the Reproductive and Developmental Toxicity of Acrylamide

Comments submitted by:

Kerry L. Dearfield, Ph.D.
U.S. Environmental Protection Agency
Office of the Science Advisor (8105R)
1200 Pennsylvania Ave., NW
Washington, DC 20460
202-564-6486
dearfield.kerry@epa.gov

1. In addition to the reproductive and developmental toxicity posed by a chemical, I believe a major concern for the CERHR is the risk a chemical poses to the induced effects (primarily induced genetic disease) in the offspring of exposed parents ("heritable risk"). When the information is available and the methodologies to evaluate such a heritable risk are available, as for acrylamide, the evaluation of heritable risk is critical in the CERHR report. This acrylamide report details the appropriate germ cell studies, but its conclusion appears to fall short of a logical and robust characterization of potential germ cell risk.

2. "The Expert Panel expressed minimal concern for acrylamide-induced heritable effects in the general population" (p. 151). The Expert Panel further "recognizes that dose-response information for these effects is limited" (p. 151), primarily because of the lack of testing at low dose levels where reproductive and developmental toxic effects are observed (p. 145).

However, the Expert Panel concludes elsewhere (p. 145) "there are sufficient data to conclude that acrylamide induces transmissible genetic damage in male germ cells of mice in the form of reciprocal translocations and gene mutations. Such effects can lead to genetic disorders and infertility in subsequent generations." Further on: "...it is likely that such effects would occur at lower dose levels." I agree that such effects would occur at lower dose levels. However, having qualitatively stated such a conclusion on p. 145, it doesn't seem to connect with the final conclusion on p. 151 with the expression of minimal concern without quantification of risk. The conclusion on p.145 suggests very strongly that acrylamide is a potential human germ-cell mutagen and at least qualitatively suggests that a higher level of concern for heritable effects is warranted.

Unlike reproductive and developmental effects which assume a non-linear dose response, the germ cell data are assumed to follow a linear dose response relationship. You shouldn't use a LOAEL based on reproductive and developmental effects to characterize heritable risk since the LOAEL is not likely to be applicable to the characterization of heritable risk. For example, there

are germ cell effects (e.g., dominant lethal effects (postimplantation loss)) that are seen at similar dose levels as the reproductive and developmental LOAELs. There probably are increased heritable risks at doses below those at the reproductive and developmental LOAELs.

3. I am of the opinion that the issue of heritable risk posed by acrylamide and the heritable risk (germ cell mutagenicity) conclusion needs to be more fully fleshed out and quantified if the Expert Panel provides a judgment about the level of concern for acrylamide. For example, the EPA's Guidelines for Mutagenicity Risk Assessment ("Mutagenicity Guidelines") focus on heritable risk and detail a process for addressing germ cell risk assessment. For acrylamide, the risk assessment would begin with a qualitative discussion about the hazard acrylamide presents to germ cells and would discuss how the evidence is sufficient for acrylamide interaction in the mammalian gonad. The evidence as detailed in the Expert Panel report provides valid, and ample, support that acrylamide is a potential human germ-cell mutagen. It needs to be mentioned that we don't have actual data derived from a human germ cell study to say definitively that acrylamide <u>is</u> a human germ-cell mutagen. But the animal data and other data (including other human data, ADME data) provide the ample evidence that acrylamide is a potential human germ-cell mutagen.

4. The next step for the acrylamide heritable assessment as per the Mutagenicity Guidelines is to quantify the potential germ cell risk. This is outlined as a two step process in the Mutagenicity Guidelines. First, the heritable effect per unit of exposure (dose response) for acrylamide needs to be detailed. This is appropriately done using the data from the heritable translocation studies. The same could be done for the specific locus study, but the data are more complete for the heritable translocation studies and these studies provide reproducibility of the translocation effect as well. Also, the germ cell targets in the mode of action discussion are more consistent with the translocation data (there is probably some contribution from gene mutations a la the specific locus information; this probably needs discussed qualitatively and suggests that the estimates from the heritable translocation data may actually be underestimates of the total germ cell risk). An assumption of linearity is made for the dose response curve for the translocation data. This is the same assumption Drs. Hattis and Favor support and is generally supported by the data. The translocation data demonstrate a linear component and linearity is further supported by the dominant lethal dose response data.

The second step is to determine the relationship between the mutation rate found for acrylamide and disease incidence. The doubling dose approach (discussed in Dearfield et al., 1995) is determined by the experts in mutagenicity risk assessment as appropriate to determine the relationship between acrylamide mutation rate and disease incidence. There is greater uncertainty about the number of disease-associated loci in the other approach (modified direct) discussed in Dearfield et al. in contrast to the greater certainty about the spontaneous rate (for translocations) in humans in the doubling dose approach. Finally, to characterize the quantitative risk in terms of the estimated increase in genetic disease per generation (one of the measures the Mutagenicity Guidelines details for reporting), as expressed per one million offspring, calculations found in Dearfield et al. (1995) are appropriate to apply here.

Below are the appropriate equation and values to use in the equation. I provide a table of the calculated potential germ cell risks expressed as the estimated increase in genetic disease per one million offspring. This table can be inserted into an appropriate section of the report. For exposures, I used representative exposures found in the human exposures summary (pp. 19-20). For the doubling dose, I used two values from the heritable translocation data representing the highest and lowest values found so that a plausible range of germ cell risk can be provided. I rounded the numbers to "whole" numbers (i.e., number of offspring).

Equation (detailed in Dearfield et al., 1995):

new disease in offspring = REF X $Spon_{human}$ X (D/DD) X N

REF	=	risk extrapolation factor (between rodent (mice) and humans) (ICPEMC, 1993); value is 0.2
$Spon_{human}$	=	Overall spontaneous rate (translocations) to dominant disease alleles; value is 1.9 per 1000 newborns (i.e., 0.0019) (Lyon et al., 1983)
D	=	Dose or human exposure (this is from the exposure assessment)
DD	=	doubling dose estimated in the mouse (dose that doubles the spontaneous mutation rate in the mouse); obtained from the dose response data; lowest value from the data = 0.39 mg/kg, highest value from the data = 25 mg/kg
N	=	number of offspring descendent from exposed parent(s); value = one million, so the number of new genetic diseases is expressed per million offspring

From the table (below), for example, with a DD of 0.39 mg/kg, exposure for dermal exposure (assuming 25% absorption) would estimate up to 1 offspring with induced genetic disease per million offspring from exposed parents(s). Likewise, exposure for food ingestion for the general population would estimate up to 4 offspring with induced genetic disease per ten million offspring from exposed parent(s). For 3 kg babies exposed to acrylamide via mother's milk, this exposure would estimate a range of up to 5 offspring per 100 million exposed individuals to 3 offspring per million exposed individuals with induced genetic disease.

Table of estimated values

Endpoint	Mouse dose (mg/kg) (dose schedule)	Doubling Dose (DD) (mg/kg)	Number of induced genetic diseases per million offspring					
			Dermal	Food ingestion (general)	Food ingestion (baby - mother's milk)	Water ingestion	Inhala-tion (mean)	Inhala-tion (upper bound)
			0.0011 (mg/kg bw/day)	0.00043 (mg/kg bw/day)	0.0033 (mg/kg bw/day)	0.000014 (mg/kg bw/day)	0.0014 (mg/kg bw/day)	0.043 (mg/kg bw/day)
Chromosomal alterations	250 [a] (5 X 50)	0.39	1	0.4	3	0.01	1	40
Chromosomal alterations	Combined [a,b] (50 as single combined w/ 250 (5 X 50))	25	0.02	0.007	0.05	0.0002	0.02	0.7

See Dearfield et al., 1995 for details on mouse dose and schedule (data from [a] Adler (1990) and combined from [a] Adler (1990) and [b]Adler et al.(1994))

5. The estimates given above are derived from the translocation data as the endpoint examined. However, there are several caveats that need to be presented in the report discussion and conclusion that indicates that this only presents a portion of the possible heritable risk from acrylamide. These estimates are derived from only one genetic endpoint, translocations. However, we know from the specific locus data, there are also gene mutations being induced in offspring and these can potentially lead to an increase in genetic disease. The translocation data present estimates for *dominant* diseases; however, we know there is risk, potentially more, due to the induction of *recessive* mutations that won't be expressed in the first generation. This aspect is a very important risk factor to future generations that really isn't quantitated here. This needs mentioned.

A major component of the potential risk to acrylamide are the germ cell targets and the timing of the exposure relative to those targets (particularly the time frame when affected sperm are utilized). For example, if exposures are sporadic, then affected sperm (from the post-meiotic germ cell targets affected) may be cleared before reproduction and the risk is lessened. However, if exposure is continuous, there would be a continual risk for affected offspring. If the germ cell target is spermatogonia (as suggested by the specific locus data), then the timing of future exposures isn't as relevant as the risk would remain from the original exposure to the spermatogonia.

All of these caveats suggest that the estimates just from the translocation data may actually be underestimates for the overall heritable risk. We don't know today how to combine the estimates from the translocation and specific locus data as well as combine the estimates for dominant and recessive mutation-related diseases.

6. I agree with Drs. Hattis and Favor that a "higher level of concern" than "minimal concern" for heritable risk be applied to acrylamide. This chemical is a prototypical germ cell mutagen and the exposure to humans is documented - it is a potential human germ-cell mutagen and presents a heritable risk (in the form of potential increased genetic disease) to future generations. This conclusion needs to be more explicitly stated - this seems to be well within the purview of CERHR. In the past, we usually haven't had such data to make this type of conclusion. We do for acrylamide and so this would be a sorely missed opportunity to address the potential heritable risk concern by CERHR. Hopefully I provide enough material to flesh out the heritable risk characterization.

Based on the quantitation presented above, the Expert Panel may rethink its concern level. For the general population, the heritable risk numbers appear low. But for occupational exposures, for example, the risk increases (also see Dearfield et al., 1995). However, with the caveats mentioned above, these risk estimates for offspring from all exposed persons are most likely underestimates. With the Expert Panel conclusion that it is likely that such risks would occur at lower dose levels and now with the estimates quantified (as potential underestimates) for comparison, a case can be made for a higher concern level than minimal for acrylamide heritable risk.

7. To emphasize my point that to make a judgment of minimal concern without quantitation doesn't make sense (especially with the large amount of evidence qualitatively to the contrary), I present a final thought. The Expert Panel states a conclusion that heritable effects would occur at lower dose levels, but does not quantify. The reason for not quantifying is questionable, i.e., absence of low dose-response data. Yet we can extrapolate to these lower doses much like we do for cancer risk estimates at lower doses, particularly with linear dose responses. We have the data for tumors from the 2 year bioassays at "higher" levels, and we have the models for extrapolating to lower doses, so we calculate estimates at the lower doses. Similarly, we have the dose response data for acrylamide germ cell effects at the "higher" animal tested doses, we have the models to estimate induced disease at lower doses (like for most cancers, linearity is assumed), and we have a process about how we can quantify acrylamide heritable risk. Like for cancer risk, we may say at actual exposure levels we might not have a concern, but we still make the qualitative argument that there is greater than a minimal concern for cancer in general. I believe this is a parallel case for acrylamide heritable risk that needs to made in the CERHR report.

8. References I think are not already in the Expert Panel Report:

ICPEMC (International Commission for Protection Against Environmental Mutagens and Carcinogens) (1993) Use of in vivo genetic toxicology data to construct human risk assessments, Final report submitted to Department of Health, Canada, July 1993, Contract No. 3138.

Lyon, M., I.-D. Adler, B. Bridges, L. Ehrenberg, L. Golberg, K. Kilian, S. Kondo, E. Moustacchi, A. Putrament, K. Sankaranarayanan, F. Sobels, R. Sram, G. Streisinger, and K. Sundaram (1983) International Commission for Protection Against Environmental Mutagens and Carcinogens (ICPEMC), Committee 4 Final Report, Estimation of genetic risks and increased incidence of genetic disease due to environmental mutagens, Mutation Research 115: 255-291.

U.S. Environmental Protection Agency (1986) Guidelines for Mutagenicity Risk Assessment, Federal Register 51: 340006-34012.

9. I can be available to discuss this with the Expert Panel should they be interested.

From: liab@slv.se
Sent: Thursday, July 1, 2004 8:07 AM
To: Shelby, Michael (NIH/NIEHS)
Subject: comment on acrylamide report

Dear Prof. Shelby!

I must start to say that I do not know if this is the right address to send my comments to, if not, I hope you can link it to the right person.

I just have some few comments on the "NTP-CERHR expert panel report on the reproductive and developmental toxicity of acrylamide".

1. page 34, the bolded text in the middle: my comment is:

a) Segerbäck et al. 1995, carcinogenesis 16, 1161-65, have clearly shown that it is the metabolite of acrylamide, glycidamide, that binds to DNA.

b) Birgit Paulsson et al. 2002 Mut. Res. 535 15-24 demonstrated that glycidamide is responsible for the induced micronuclei when mice are injected with acrylamide.

My suggestion is to bear this in mind when the conclusion about genotoxicity and acrylamide/glycidamide is written

2. page 34, lower part of the page, the para. starts: Micronucleated erythrocytes scored....: my comment is:

about the article ref. no 60 (Abramsson Zetterberg): The author study the dose response relationship in two intervalls, 0 -30 mg/kg b.w. and 0 - 100 mg/kg b.w. Both these studies point to a stronger response in the low dose regions, although there were not significant differences in the slope. Furthermore, the DNA content disclose a clear clastogenic effect (i.e. not aneugenic) , in the region of 0 to 100 mg/kg b.w. (not 0 -30 mg/kg b.w. written by you.)

Best regards from Lilianne Abramsson Zetterberg

Lilianne Abramsson Zetterberg
Ass. Prof., Fil dr (Ph D)
Livsmedelsverket (National Food Administration)
Toxikologiska enheten (Toxicology Division)
Box 622

SE-75126 Uppsala
tel: 018-17 57 63
fax: 018-10 58 48
e-post: liab@slv.se