APPENDIX A

ATSDR MINIMAL RISK LEVEL AND WORKSHEETS

The Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) [42 U.S.C. 9601 et seq.], as amended by the Superfund Amendments and Reauthorization Act (SARA) [Pub. L. 99–499], requires that the Agency for Toxic Substances and Disease Registry (ATSDR) develop jointly with the U.S. Environmental Protection Agency (EPA), in order of priority, a list of hazardous substances most commonly found at facilities on the CERCLA National Priorities List (NPL); prepare toxicological profiles for each substance included on the priority list of hazardous substances; and assure the initiation of a research program to fill identified data needs associated with the substances.

The toxicological profiles include an examination, summary, and interpretation of available toxicological information and epidemiologic evaluations of a hazardous substance. During the development of toxicological profiles, Minimal Risk Levels (MRLs) are derived when reliable and sufficient data exist to identify the target organ(s) of effect or the most sensitive health effect(s) for a specific duration for a given route of exposure. An MRL is an estimate of the daily human exposure to a hazardous substance that is likely to be without appreciable risk of adverse noncancer health effects over a specified duration of exposure. MRLs are based on noncancer health effects only and are not based on a consideration of cancer effects. These substance-specific estimates, which are intended to serve as screening levels, are used by ATSDR health assessors to identify contaminants and potential health effects that may be of concern at hazardous waste sites. It is important to note that MRLs are not intended to define clean-up or action levels.

MRLs are derived for hazardous substances using the no-observed-adverse-effect level/uncertainty factor approach. They are below levels that might cause adverse health effects in the people most sensitive to such chemical-induced effects. MRLs are derived for acute (1–14 days), intermediate (15–364 days), and chronic (365 days and longer) durations and for the oral and inhalation routes of exposure. Currently, MRLs for the dermal route of exposure are not derived because ATSDR has not yet identified a method suitable for this route of exposure. MRLs are generally based on the most sensitive chemical-induced end point considered to be of relevance to humans. Serious health effects (such as irreparable damage to the liver or kidneys, or birth defects) are not used as a basis for establishing MRLs. Exposure to a level above the MRL does not mean that adverse health effects will occur.

MRLs are intended only to serve as a screening tool to help public health professionals decide where to look more closely. They may also be viewed as a mechanism to identify those hazardous waste sites that are not expected to cause adverse health effects. Most MRLs contain a degree of uncertainty because of the lack of precise toxicological information on the people who might be most sensitive (e.g., infants, elderly, nutritionally or immunologically compromised) to the effects of hazardous substances. ATSDR uses a conservative (i.e., protective) approach to address this uncertainty consistent with the public health principle of prevention. Although human data are preferred, MRLs often must be based on animal studies because relevant human studies are lacking. In the absence of evidence to the contrary, ATSDR assumes that humans are more sensitive to the effects of hazardous substance than animals and that certain persons may be particularly sensitive. Thus, the resulting MRL may be as much as a hundredfold below levels that have been shown to be nontoxic in laboratory animals.

Proposed MRLs undergo a rigorous review process: Health Effects/MRL Workgroup reviews within the Division of Toxicology, expert panel peer reviews, and agencywide MRL Workgroup reviews, with participation from other federal agencies and comments from the public. They are subject to change as new information becomes available concomitant with updating the toxicological profiles. Thus, MRLs in the most recent toxicological profiles supersede previously published levels. For additional information regarding MRLs, please contact the Division of Toxicology, Agency for Toxic Substances and Disease Registry, 1600 Clifton Road, Mailstop E-29, Atlanta, Georgia 30333.

APPENDIX A

MINIMAL RISK LEVEL (MRL) WORKSHEET

Chemical Name: Mercury (metallic, vapor)
CAS Number: 7439-97-6
Date: June 15, 2001
Profile Status: Final Draft
Route: [X] Inhalation [ ] Oral
Duration: [ ] Acute [ ] Intermediate [X] Chronic
Key to figure: 21
Species: Human

Minimal Risk Level: 0.0002 [ ] mg/kg/day [X] mg/m^3

Reference: Fawer RF, de Ribaupierre Y, Guillemin MP, et al. 1983. Measurement of hand tremor induced by industrial exposure to metallic mercury. British Journal of Industrial Medicine 40:204-208.

Experimental design. Hand tremors were measured in 26 male workers exposed to metallic mercury and 25 control males working in the same facilities, but not exposed to mercury. Workers had been exposed to mercury through the manufacture of fluorescent tubes, chloralkali, or acetaldehyde. Mercury-exposed workers had a duration of exposure of 15.3±2.6 years, blood mercury of 41.3±3.5 micromoles Hg/L, and urinary mercury of 11.3±1.2 micromoles Hg/mole of creatinine. The mean mercury level measured using personal air monitors was 0.026±0.004 mg/m^3 (3 subjects were exposed to greater than 0.05 mg/m^3). Hand tremors were measured in the subjects using an accelerometer attached to the dorsum of the hand both at rest and while holding 1,250 grams. The highest peak frequency of the acceleration was determined.

Effects noted in study and corresponding doses: The highest peak frequency of the tremor was greater in exposed men than in controls. The highest peak frequency corresponded significantly to duration of exposure and age. Comparison of tremors using an index of the entire spectrum of the tremor showed no differences between exposed men and controls at rest, but the changes observed between rest and load were higher in the exposed men. These changes correlated with the duration of exposure and biological indices of exposure (blood and mercury levels), but not with age.

Dose and end point used for MRL derivation: 0.026 mg/m^3; increased frequency of tremors.

[ ] NOAEL [X] LOAEL

Uncertainty and Modifying Factors used in MRL derivation: 30

[ ] 1 [X] 3 [ ] 10 (for use of a minimal LOAEL)
[X] 1 [ ] 3 [ ] 10 (for extrapolation from animals to humans)
[ ] 1 [ ] 3 [X] 10 (for human variability)

Was a conversion factor used from ppm in food or water to a mg/body weight dose?
If so explain: No.

Was a conversion used from intermittent to continuous exposure?
If so, explain: Yes. To estimate an equivalent continuous exposure concentration, the average concentration assumed for the 8 hour/day exposures was multiplied by 8/24 and 5/7 (0.026 mg/m^3 x 8/24 hours/day x 5/7 days/week = 0.0062 mg/m^3). Uncertainty factors of 10 for variability in sensitivity to mercury within the human population and 3 for use of a minimal effect LOAEL in MRL derivation were then applied to the calculated 0.0062 mg/m^3 value, yielding a chronic inhalation MRL of 0.2 $\mu g/m^3$. It should be noted that this MRL, although based upon an adult working population, is considered also to be sufficiently protective of neurodevelopmental effects in developing embryos/fetuses and children, the most sensitive subgroups for metallic mercury toxicity.

$LOAEL_{(ADJ)}$ = 0.026 mg/m^3 x (8 hr/24 hr) x (5 days/7 days)
= 0.0062 mg/m^3

$MRL = LOAEL_{(ADJ)} \div UF = 0.0062\ mg/m^3 \div 30 = 0.0002\ mg/m^3$

If an inhalation study in animals, list the conversion factors used in determining human equivalent concentration (HEC): No.

Additional studies or pertinent information which lend support to this MRL: Inhaled metallic mercury is quickly absorbed through the lungs into the blood. Its biologic half-life in humans is approximately 60 days, with the half-life varying with the physiological compartment (e.g., 21 days in the head, versus 64 days in the kidneys; Cherian et al. 1978). Since the duration of exposure does influence the level of mercury in the body, the exposure level reported in the Fawer et al. (1983) occupational study was extrapolated from an 8-hour/day, 40-hour/workweek exposure to a level equivalent to a continuous 24 hour/day, 7 days/week exposure as might be encountered near a hazardous waste site containing metallic mercury.

The ability of long-term, low level exposure to metallic mercury to produce a degradation in neurological performance was also demonstrated in other studies. One such study (Ngim et al. 1992) attributed adverse neurological effects to a lower average level of exposure than did the Fawer et al. (1983) study; however, this study was not used in deriving a chronic inhalation MRL due to uncertainties concerning the study protocol, including methodological and reporting deficiencies. In the Ngim et al. (1992) study, dentists with an average of 5.5 years of exposure to low levels of metallic mercury were reported to have demonstrated impaired performance on several neurobehavioral tests. Exposure levels measured at the time of the study ranged from 0.0007 to 0.042 mg/m^3, with an average of 0.014 mg/m^3. Mean blood mercury levels among the dentists ranged from 0.6 to 57 $\mu g/L$, with a geometric mean of 9.8 $\mu g/L$. The performance of the dentists on finger tapping (motor speed measure), trail making (visual scanning measure), digit symbol (measure of visuomotor coordination and concentration), digit span, logical memory delayed recall (measure of visual memory), and Bender-Gestalt time (measures visuomotor coordination) were significantly poorer than controls. The exposed dentists also showed higher aggression than did controls. Furthermore, within the group of exposed dentists, significant differences were reported to have been observed between a subgroup with high mercury exposure compared to a subgroup with lower exposure. These exposure severity subgroups were not compared to controls, and average exposure levels for the subgroups were not reported. The design and reporting of this study limit its usefulness in deriving an MRL for metallic mercury. The exposure status of the subjects was known to the investigator during testing, mercury levels were not reported for controls, and methods used to correct for confounders (especially the common use in this population of traditional medicines containing mercury) were not reported. It was also unclear whether the results for the mercury exposure group were inordinately influenced or skewed by the individual dentists with the highest exposures and/or blood levels. These confounding factors precluded the use of the Ngim et al. (1992) study for the derivation of an MRL, but the study does provide support for both the premise that

low-dose chronic exposure to metallic mercury can result in adverse health sequelae and the chronic inhalation MRL that is based upon the Fawer et al. (1983) study of occupationally exposed individuals.

Other occupational studies further support the ability of metallic mercury to induce neurologic deficits. Several studies have reported significant effects on tremor or cognitive skills among groups exposed occupationally to comparable or slightly higher (up to 0.076 mg/m^3) levels (Ehrenberg et al. 1991; Piikivi et al. 1984; Roels et al. 1982). Difficulty with heel-to-toe gait was observed in thermometer plant workers subjected to mean personal breathing zone air concentrations of 0.076 mg/m^3 (range of 0.026–0.27 mg/m^3 (Ehrenberg et al. 1991).

Tremors have also been reported in occupationally exposed workers with urinary mercury concentrations of 50–100 µg/g creatinine, and blood levels of 10–20 µg/L (Roels et al. 1982). By comparison, blood mercury levels in the Fawer et al. (1983) study averaged 41.3 and 16.6 µmol Hg/L for the exposed and control groups, respectively. Urinary mercury levels for the exposed workers in the Fawer et al. (1983) study averaged 11.3 µmol Hg/mol creatinine (about 20 µg/g creatinine), compared with 3.4 µmol/mol creatinine in the controls. In another study (Piikivi et al. 1984), decreases in performance on tests that measured intelligence (similarities) and memory (digit span and visual reproduction) were observed in chloralkali workers exposed for an average of 16.9 years (range, 10–37 years) to low levels of mercury when compared to an age-matched control group. In this study, significant differences from controls were observed on these tests among 16 workers with blood levels ranging from 75 to 344 nmol/L and urine levels ranging from 280 (about 56 µg/L) to 663 nmol/L. Abnormal nerve conduction velocities have also been observed in chloralkali plant workers at a mean urine concentration of 450 µg/L (Levine et al.1982). These workers also experienced weakness, paresthesias, and muscle cramps. Prolongation of brainstem auditory evoked potentials was observed in workers with urinary mercury levels of 325 µg/g creatinine (Discalzi et al. 1993). Prolonged somatosensory evoked potentials were found in 28 subjects exposed to airborne mercury concentrations of 20–96 mg/m^3 (Langauer-Lewowicka and Kazibutowska 1989).

Agency Contact (Chemical Manager): John Risher

APPENDIX A

MINIMAL RISK LEVEL (MRL) WORKSHEET

Chemical Name: Mercury inorganic
CAS Number: 7439-97-6
Date: June 15, 2001
Profile Status: Final Draft
Route: [ ] Inhalation [X] Oral
Duration: [X] Acute [ ] Intermediate [ ] Chronic
Key to figure: 7
Species: Rat

Minimal Risk Level: 0.007 [X] mg/kg/day [ ] mg/m^3

Reference: NTP. 1993. NTP technical report on the toxicology and carcinogenesis studies of mercuric chloride (CAS no. 7487-94-7) in F344/N rats and $B6C3F_1$ mice (gavage studies). NTP TR408.

Experimental design: Fischer 344 rats (5/sex/group) were administered 0, 0.93, 1.9, 3.7, 7.4, or 14.8 mg Hg/kg/day as mercuric chloride once daily for 14 days, excluding weekends. The mercuric chloride was administered in deionized water via gavage. Body weights were measured and a complete necropsy was performed. Organ weights were obtained for the brain, heart, kidney, liver, lung, and thymus.

Effects noted in study and corresponding doses: The relative and absolute kidney weights were significantly increased for males exposed to at least 1.9 mg Hg/kg/day and for females exposed to at least 3.7 mg Hg/kg/day. An increased incidence of renal tubular necrosis (graded minimal in severity) was observed in 3 of 5 males and 1 of 5 females at the 3.7 mg Hg/kg/day dose level. At 7.4 mg Hg/kg/day, 5/5 males and 3/5 females had minimal-to-mild effects, and at 14.8 mg Hg/kg/day all animals exhibited mild-to-moderate effects.

Dose and end point used for MRL derivation: 0.93 mg Hg/kg/day; no renal effects.

[X] NOAEL [ ] LOAEL

Uncertainty Factors used in MRL derivation: 100

[ ] 1 [ ] 3 [ ] 10 (for use of a LOAEL)
[ ] 1 [ ] 3 [X] 10 (for extrapolation from animals to humans)
[ ] 1 [ ] 3 [X] 10 (for human variability)

Was a conversion factor used from ppm in food or water to a mg/body weight dose?
If so explain: No.

Was a conversion used from intermittent to continuous exposure?
If so, explain: Yes. To estimate an equivalent continuous exposure concentration, the average concentration was multiplied by 5 days/7 days.

$NOAEL_{(ADJ)}$ = 0.93 mg/kg/day x (5 days/7 days)
= 0.66 mg/kg/day

MRL = $NOAEL_{(ADJ)}$ ÷ UF = 0.66 mg/kg/day ÷ 100 = 0.007 mg/kg/day

If an inhalation study in animals, list the conversion factors used in determining human equivalent concentration (HEC): None.

Additional studies or pertinent information which lend support to this MRL: Several other studies examining the effects of oral exposure to inorganic mercury salts have also shown renal toxicity in humans as a result of acute oral exposures. Kidney effects (i.e., heavy albuminuria, hypoalbuminemia, edema, and hypercholesterolemia) have been reported after therapeutic administration of inorganic mercury (Kazantzis et al. 1962). Acute renal failure has been observed in a number of case studies in which mercuric chloride has been ingested (Afonso and deAlvarez 1960; Murphy et al. 1979; Samuels et al. 1982). Autopsy of a 35-year-old man who ingested a lethal dose of mercuric chloride and exhibited acute renal failure showed pale and swollen kidneys (Murphy et al. 1979). A case study reported acute renal failure characterized by oliguria, proteinuria, hematuria, and granular casts in a woman who ingested 30 mg mercury/kg as mercuric chloride (Afonso and deAlvarez 1960). Another case study reported a dramatic increase in urinary protein secretion by a patient who ingested a single dose of 15.8 mg mercury/kg as mercuric chloride (assuming a body weight of 70 kg) (Pesce et al. 1977). The authors of the report surmised that the increased excretion of both albumin and β_2-microglobulin were indicative of mercury-induced tubular and glomerular pathology. Acute renal failure that persisted for 10 days was also observed in a 19-month-old child who ingested an unknown amount of powdered mercuric chloride (Samuels et al. 1982). Decreased urine was also observed in a 22-year-old who attempted suicide by ingesting approximately 20 mg mercury/kg (Chugh et al. 1978).

Agency Contact (Chemical Manager): John Risher

APPENDIX A

MINIMAL RISK LEVEL (MRL) WORKSHEET

Chemical name(s): Mercury (inorganic)
CAS number(s): 7439-97-6
Date: June 15, 2001
Profile status: Final Draft
Route: [ ] Inhalation [X] Oral
Duration: [ ] Acute [X] Intermediate [ ] Chronic
Key to figure: 17
Species: Rat

Minimal Risk Level: 0.002 [X] mg/kg/day [ ] ppm

Reference: NTP. 1993. NTP technical report on the toxicology and carcinogenesis studies of mercuric chloride (CAS no. 7487-94-7) in F344/N rats and B6C3F$_1$ mice (gavage studies). NTP TR408.

Experimental design: Fischer 344 rats (10/sex/group) were administered 0, 0.23, 0.46, 0.93, 1.9, or 3.7 mg Hg/kg/day as mercuric chloride in deionized water by oral gavage once daily 5 days per week for 26 weeks. Body weights were recorded weekly. Surviving animals were sacrificed and necropsied. Organ weights were determined for the brain, heart, liver, lung, kidney, thymus, and testes. Histopathological examinations were performed.

Effects noted in study and corresponding doses: The relative and absolute kidney weights were significantly increased for dosed males and for females exposed to at least 0.46 mg/kg/day. At the two low-dose groups and the control group, minimal nephropathy was observed in nearly all the males. At 0.93 mg/kg/day level, renal tubule necrosis became more severe (moderate) and was statistically significant and remained at this severity at the higher dose groups. The female rats had a significant increased incidence at the high dose only, and severity was minimal. Nephropathy was characterized by foci of tubular regeneration, thickened tubular basement membrane, and scattered dilated tubules containing hyaline casts. Macroscopic changes included granular kidneys in dosed males. After 4 months of exposure, urinary levels of alkaline phosphatase, aspartate aminotransferase, lactate dehydrogenase, and gamma-glutamyl transferase were significantly elevated in both sexes at 3.7 mg Hg/kg/day, but at 6 months control levels had increased such that enzyme levels in males were no longer statistically significant and only levels of alkaline phosphatase and gamma-glutamyl transferase were significantly elevated in females.

Dose end point used for MRL derivation: 0.23 mg Hg/kg/day; no renal effects
[X] NOAEL [ ]LOAEL

Uncertainty and modifying factors used in MRL derivation: 100

[ ] 1 [ ] 3 [ ] 10 (for use of a LOAEL)
[ ] 1 [ ] 3 [X] 10 (for extrapolation from animals to humans)
[ ] 1 [ ] 3 [X] 10 (for human variability)

Was a conversion factor used from ppm in food or water to a mg/body weight dose?
If so explain: No conversion factor used.

Was a conversion used from intermittent to continuous exposure?

If so, explain: Yes. The dose was adjusted for a continuous exposure by multiplying the NOAEL (0.23 mg/kg/day) by a conversion factor of 5/7:

$NOAEL_{(ADJ)}$ = 0.23 mg/kg/day x (5 days/7 days)
= 0.16 mg/kg/day

$MRL = NOAEL_{(ADJ)} \div UF = 0.16 \text{ mg/kg/day} \div 100 = 0.002 \text{ mg/kg/day}$

If an inhalation study in animals, list conversion factors used in determining human equivalent dose: Not applicable.

Additional studies or pertinent information that lend support to this MRL: Renal toxicity has been observed in other intermediate-duration oral studies on rats and mice exposed to inorganic mercury (Carmignani et al. 1992; Jonker et al. 1993a; NTP 1993), as well as case reports on humans ingesting inorganic mercury for acute and chronic durations (Afonso and deAlvarez 1960; Davis et al. 1974; Kang-Yum and Oransky 1992; Nielsen et al. 1991; Pesce et al. 1977).

Agency Contact (Chemical Manager): John Risher

APPENDIX A

MINIMAL RISK LEVEL (MRL) WORKSHEET

Chemical Name: Methylmercury
CAS Number: 22967-92-6
Date: June 15, 2001
Profile Status: Final Draft
Route: [ ] Inhalation [X] Oral
Duration: [ ] Acute [ ] Intermediate [X] Chronic
Key to figure: 88
Species: Human

Minimal Risk Level: 0.0003 [X] mg/kg/day [ ] mg/m^3

Reference: Davidson et al. 1998. Effects of prenatal and postnatal methylmercury exposure from fish consumption on neurodevelopment: Outcomes at 66 months of age in the Seychelles Child Development Study. JAMA 280(8):701-707.

Experimental design. This MRL is based on the results of the Seychelles Child Development Study (SCDS), a series of evaluations on a population in the Seychelles Islands. The chronic oral MRL for methylmercury is based upon the Seychelles Child Development Study (SCDS), in which over 700 mother-infant pairs have, to date, been followed and tested from parturition through 66 months of age (Davidson et al. 1998). The SCDS was conducted as a double-blind study and used maternal hair mercury as the index of fetal exposure. Enrollees were recruited by the head nurse/hospital midwife by asking the mothers if they wished to participate in the study when they arrived at the hospital for delivery. The first 779 who did not decline participation became the mothers in the study cohort. Of the initial 779 mothers enrolled in the study at parturition, 740 remained at the predetermined child testing age of 6.5 months, 738 remained in the 19-month cohort, 736 remained at 29 months, and 711 remained for the 66-month neurobehavioral and developmental examinations.

The Seychellois were chosen as a study population for a number of reasons. (1) All fish contain some level of methylmercury (Davidson et al. 1998); and the Seychellois regularly consume a large quantity and variety of ocean fish, with 12 fish meals per week representing a typical methylmercury exposure. (2) The median total mercury concentration in 350 fish sampled from 25 species consumed by the Seychellois was <1 ppm (range, 0.004–0.75 ppm), comparable to that consumed by the U.S. population; thus, the methyl-mercury levels in the Seychellois population are 10–20 times those in the United States, not because they consume more highly contaminated fish than do Americans, but rather because they consume more fish than the U.S. population. (3) The Seychelles represent a relatively pristine environment, with no local industry for pollution, and are situated more than 1,000 miles from any continent or large population center. (4) The population is highly literate, cooperative, and has minimal immigration and emigration. (5) The Seychellois constitute a generally healthy population, with low maternal alcohol consumption and tobacco use (<2%). (6) In the 66-month study cohort, the mean maternal hair level of total mercury during pregnancy was 6.8 ppm (range, 0.5–26.7 ppm).

Effects noted in study and corresponding doses: The results of the 66-month testing in the SCDS revealed no evidence of adverse effects attributable to chronic ingestion of low levels of methylmercury in fish (Davidson et al. 1998). In this study, developing fetuses were exposed *in utero* through maternal fish ingestion before and during pregnancy (Davidson et al. 1998). Neonates continued to be exposed to maternal mercury during breastfeeding (i.e., some mercury is secreted in breast milk), and methylmercury

exposure from the regular diet continued after the gradual post-weaning shift to a fish diet. In the 66-month study cohort, the mean maternal hair level of total mercury during pregnancy was 6.8 ppm (range, 0.5–26.7 ppm; n = 711), and the mean child hair level at the 66-month testing interval was 6.5 ppm (range, 0.9–25.8 ppm; n = 708). The 66-month test battery, which was designed to test multiple developmental domains, included as primary measures the following: (1) General Cognitive Index (GCI) of the McCarthy Scales of Children's Abilities (to estimate cognitive ability); (2) the Preschool Language Scale (PLS) total score (to measure both expressive and receptive language ability); (3) the Letter and Word Recognition and (4) Applied Problems subtests of the Woodcock-Johnson (W-J) Tests of Achievement (to measure reading and arithmetic achievement); (5) the Bender-Gestalt test (to measure visual-spatial ability); and (6) the total T score from the Child Behavior Checklist (CBCL) (to measure the child's social and adaptive behavior). Serum sampling revealed no detectable levels of PCBs (detection limit = 0.2 ng/mL).

None of the tests indicated an adverse effect of methylmercury exposure. In contrast, four of the six measures showed better scores in the highest MeHg-exposed groups, compared with lower exposure groups for both prenatal and postnatal exposure (the four test were the (1) General Cognitive Index (GCI) of the McCarthy Scales of Children's Abilities (to estimate cognitive ability); (2) the Preschool Language Scale (PLS) total score (to measure both expressive and receptive language ability); (3) the Letter and Word Recognition and (4) Applied Problems subtests of the Woodcock-Johnson (W-J) Tests of Achievement (to measure reading and arithmetic achievement). While the positive outcomes are not considered to indicate any beneficial effect of methylmercury on neurological development or behavior, they might be more appropriately attributed to the beneficial effects of omega-3 fatty acids or other constituents present in fish tissue, since the methylmercury levels in hair are known to correlate closely with fish intake. The slight decreases in the subjectively reported activity level of boys reported in the 29-month observations were not seen during the 66-month tests. The mean maternal hair level of 15.3 ppm in the group with the highest exposure in the 66-month test cohort is, therefore, considered a NOAEL for SCDS, and is used by ATSDR as the basis for derivation of a chronic oral MRL for methylmercury. A related study (Myers et al. 1997) by the same team of researchers from the University of Rochester examined the Seychellois children for attainment of the same developmental milestones reported to have been delayed in the Iraqi poisoning incident in the early 1970s (Cox et al. 1989) and found no such delays in the Seychellois children exposed in utero. Since the children had been exposed *in utero*, they represent the most sensitive subpopulation.

Sensitivity of Neurobehavioral Measures /Reliability of Tests Used in Critical Study

The neurobehavioral test battery used in the 66-month Seychelles study was designed to assess multiple developmental domains (Davidson et al. 1998). The tests were considered to be sufficiently sensitive and accurate to detect neurotoxicity in the presence of a number of confounding factors. On-site test administration reliability was assessed by an independent scorer, and mean interclass correlations for interscorer reliability were 0.96–0.97 (Davidson et al. 1998). The sample size was determined to be sufficient to detect a 5.7 point difference on any test with a mean (SD) of 100 (16) between low (0–3 ppm) and high >12 ppm) hair mercury concentration groups for a 2-sided test (A = 0.05 at 80% power).

Converting blood concentration to daily intake.

The concentration of mercury in the blood may be converted to a daily intake by using the following equation from WHO (1990):

$$C = \frac{f(d}{b(V} \cdot \frac{A_D(A_B(d}{b(V}$$

Where:

C	=	concentration in blood
f	=	fraction of the daily intake taken up by the blood
d	=	daily dietary intake
b	=	elimination constant
A_D	=	percent of mercury intake in diet that is absorbed
A_B	=	percent of the absorbed amount that enters the blood
V	=	volume of blood in the body

Hair to Blood Concentration Ratio.

The hair:blood concentration ratio for total mercury is frequently cited as 250. However, a precise basis for this particular value is unclear. Ratios reported in the literature range from 140 to 370, a difference of more than a factor of 2.5 (see Table 2-9). Differences in the location of hair sampled (head versus chest, distance of sample from head or skin) may contribute to differences in observed ratios between studies. For example, as much as a 3-fold seasonal variation in mercury levels was observed in average hair levels for a group of individuals with moderate-to-high fish consumption rates, with yearly highs occurring in the fall and early winter (Phelps et al. 1980; Suzuki et al. 1992). Thus, it is important to obtain hair samples as close to the follicle as possible to obtain an estimate of recent blood levels. Large errors (the direction of which depends on whether samples were taken while blood levels were falling or rising) could result if hair samples are not taken close to the scalp. Several studies did not report the distance to the scalp for the hair samples taken. The high slope reported by Tsubaki (1971a) may have reflected the fact that mercury levels were declining at the time of sampling (Berglund et al. 1971), so the hair levels may reflect earlier, higher blood levels. Hair taken from different parts of the body also may yield different ratios. In 26 subjects with moderate-to-high fish consumption, axillary hair (i.e., from the armpit area) was found to contain an average of 23% less mercury than head hair (Skerfving et al. 1974).

Phelps et al. (1980) obtained multiple blood samples and sequentially analyzed lengths of hair from 339 individuals in Northwestern Ontario. The large sample size and the attention to sampling and analysis with regard to the hair:blood relationship make this study the most appropriate to use for estimating the mercury blood levels of the Seychellois women during pregnancy. The actual ratio Phelps et al. (1980) observed between the total mercury concentration in hair taken close to the scalp and simultaneous blood sampling for this group was 296. To estimate the actual ratio, the authors assumed that blood and hair samples were taken following complete cessation of methylmercury intake. They also assumed a half-life of methylmercury in blood of 52 days and a lag of 4 weeks for appearance of the relevant level in hair at the scalp. Based on these assumptions, they calculated that if the actual hair:blood ratio were 200, they would have observed a ratio of 290 (i.e., essentially equivalent to the observed value of 296). Based on these and other considerations, Phelps et al. (1980) state that the actual ratio is "probably higher than 200, but less than the observed value of 296." As the authors point out, two-thirds of the study population were sampled

during the falling phase of the seasonal variation and one-third or less in the rising phase. This fact would tend to result in a lower observed ratio; therefore, the actual average value is likely to be >200.
Phelps et al. (1980) also provide estimates assuming a 2-week lag for the appearance of the relevant level of mercury in the centimeter of hair nearest the scalp. For a 2-week lag time, an actual ratio of 250 would have resulted in an observed ratio of 301 (again, essentially identical to the observed value of 296). A study of ingestion of a large dose of mercuric chloride in one individual suggests that the lag time is longer than 2 weeks (Suzuki et al. 1992). Hair samples were taken at 41 and 95 days following ingestion of the mercuric chloride. In the 41-day hair sample, a large mercury peak occurred in the centimeter of hair closest to the scalp, with no elevation in mercury in the second centimeter of hair. Head hair grows at a rate of about 1.1 cm a month (Al-Shahristani and Shihab 1974; Cox et al. 1989). If emergence had occurred so that the elevation in mercury could be measured in the first centimeter of hair by 2 weeks after exposure, then by day 41 after exposure the peak should have moved into the second centimeter of hair, at least enough to raise the mercury level slightly in the second centimeter. Because no elevation was seen in the second centimeter of hair at 41 days, it would appear that emergence occurred at a lag of >2 weeks. In the hair sample taken at 95 days, the leading edge of the mercury peak occurred in the third centimeter of hair.

Based on the data presented in Phelps et al. (1980) and the lag time indicated in the individual studied by Suzuki et al. (1992), the actual average value is likely to be somewhere between 200 and 250. Because the data do not allow a more accurate determination of an average ratio, the value 250 is acceptable for the purpose of estimating average blood levels in the Seychellois population. Using 250 rather than a lower number results in a lower MRL. It should be noted that a wide range in hair:blood ratios has been reported for individuals in various studies: 137–342 in Soria et al. (1992), 171–270 in Phelps et al. (1980), and 137–585 in Birke et al. (1972). Therefore, this ratio (250) should not be used as the sole basis for determining levels of exposure and potential effect for individuals.

Calculation of dietary intake from blood concentration.

Fraction of mercury in diet that is absorbed (A_D). Radiolabeled methyl-mercuric nitrate was administered in water to three healthy volunteers (Aberg et al. 1969). The uptake was >95%. Miettinen et al. (1971) incubated fish liver homogenate with radiolabeled $MeHgNO_3$ to yield a methylmercury proteinate. The proteinate was then fed to fish that were killed after a week, cooked, and fed to volunteers after confirmation of the methylmercury in the fish. Mean uptake exceeded 94%. For the derivation of an MRL, an absorption factor of 0.95 is used.

Fraction of the absorbed dose that is found in the blood (A_B). The value 0.05 has been used for this parameter in the past (Berglund et al. 1971; WHO 1990). Three studies report observations of the fraction of the absorbed methylmercury dose distributed to blood volume in humans. Kershaw et al. (1980) report an average fraction of 0.059 of the absorbed dose in the total blood volume, based on a study of 5 adult male subjects who ingested methylmercury-contaminated tuna. In a group of 9 male and 6 female volunteers who had received ^{203}Hg-methylmercury in fish, approximately 10% of the total body burden was present in 1 L of blood in the first few days after exposure, dropping to approximately 5% over the first 100 days (Miettinen et al. 1971). In another study, an average value of 1.14% for the percentage of absorbed dose in 1 kg of blood was derived from subjects who consumed a known amount of methylmercury in fish over a period of 3 months (Sherlock et al. 1984). Average daily intake for the 4 groups observed in the study ranged from 43 to 233 µg/day. The authors report a dose-related effect on the estimated percentage of the absorbed dose in 1 kg of blood, with 1.26% of the absorbed dose in 1 kg of blood at an average daily intake of 43 µg/day and 1.03% of the absorbed dose in 1 kg of blood at an average daily intake of 233 µg/day. The average for all subjects in the study was 1.14%. When individual values for distribution to one kilogram of blood reported in the study are converted into the percentage of the absorbed

dose in the total blood volume (assuming that blood is 7% of body weight [Best 1961] and using body weights reported for individuals in the study), the average value for A_B for all individuals is 0.056 (0.057 using the values for percentage in 1 kg normalized for body weight as reported in the study). The average value for A_B for 6 women as reported in Sherlock et al. (1984) is 0.048 (0.047 using values normalized for body weight). The average for 14 men is 0.059 (0.061 using values normalized for body weight).

The average values for A_B for all studies ranged from 0.047 to 0.061 (the values for women and men reported in Sherlock et al. [1984]). The data suggest that the average value of A_B for women may be lower than that for men, and they further suggest that 0.05 may be appropriate for modeling intake in a group of women (Sherlock et al. 1984). Based on these studies, the best estimate of A_B based on the available data is 0.05. Use of a higher value (i.e., 0.06 instead of 0.05) for this parameter would result in a lower MR, but the sensitive populations are pregnant women and developing fetuses, making the 0.5 value more appropriate for the Seychelles study population.

Elimination constant (b). Reported clearance half-times for methylmercury from blood or hair range from 48 to 65 days (Table 2-5). The average elimination constant based on the 6 studies listed in Table 2.5 is 0.014. The average of the individual values for *b* reported for 20 volunteers ingesting from 42 to 233 µg Hg/day in fish for 3 months (Sherlock et al. 1984) is also 0.014. Use of the value 0.014 for this parameter, rather than 0.01 (as used by WHO 1990), results in a higher MRL.

Volume of blood in body (V), and body weight. Blood volume is assumed to be 7% of body weight, with an increase to about 9% during pregnancy (Best 1961). Data for the body weight of the Seychelles Islands women were not found. Assuming an average body weight of 60 kg for women, the blood volume is 4.2 L (60 kg x 0.07 L/kg).

Calculation of Exposure Dose

The concentration of mercury in hair is assumed to be 250 times the concentration in blood. Using the mean total mercury level of 15.3 ppm in maternal hair taken at parturition to represent a NOAEL in the 66-month Seychelles testing (Davidson et al. 1998), the corresponding methylmercury concentration in blood would be: 1/250 x 15.3 µg/g x 1 mg/1,000 µg x 1,000 g/L = 0.061 mg/L.

Calculation of Daily Intake from Blood Concentration

$$C = \frac{f(d}{b(V} \cdot \frac{A_D(A_B(d}{b(V}$$

Using the above equation to relate the concentration in blood (C, in µg/L) to daily intake (d, in µg/day): where C = (percent of ingested dose absorbed through the GI tract x percent of that dose absorbed into the blood x the daily amount ingested) divided by (elimination constant x blood volume in a 60 kg female)

that is,

C = (0.95 x 0.05 x d)/(0.014 x 4.2)
C = 0.81 d
0.061 mg/L = 0.81 d
d = 0.075 mg/day

Using the assumed body weight of 60 kg for women, the estimated dose that would result in a hair level of 15.3 ppm is 0.075/60 kg = 0.0013 mg/kg/day. Therefore, the NOAEL derived from the highest exposure group (n = 95) at 66 months is 0.0013 mg/kg/day.

Dose and end point used for MRL derivation: 0.0013 mg/kg/day NOAEL

[X] NOAEL [ ] LOAEL

Uncertainty and Modifying Factors used in MRL derivation:

[ ] 1 [ ] 3 [ ] 10 (for use of a minimal LOAEL)
[ ] 1 [ ] 3 [ ] 10 (for extrapolation from animals to humans)
[ ] 1 [X] 3 [ ] 10 (for human pharmacokinetic and pharmacodynamic variability)
[X] 1.5 [ ] 3 [ ] 10 (Modifying factor to account for domain-specific findings in Faroe study)

Consideration of Uncertainty

The standard/traditional areas of uncertainty addressed in any duration-specific MRL are: (1) interspecies variability (i.e., cross-species extrapolation of a NOAEL or LOAEL); (2) intra-human variability (i.e., differences in susceptibility to a substance or effect within the human population); (3) use of an LOAEL for MRL derivation when an NOAEL for the critical effect is not available; and (4) extrapolation from subchronic to chronic duration. In addition, a modifying factor may also be used when special circumstances exist that may contribute to, or introduce, uncertainty into the calculated health guidance value (MRL) in an area not typically covered by the traditional uncertainty factor approach.

The NOAEL of 15.3 ppm mercury in maternal hair from Davidson et al. (1998) used as the starting point for MRL derivation was based upon an unusually large study cohort of the population considered most sensitive to the neurodevelopmental effects of methylmercury, i.e., pregnant women and their developing fetuses. The negative results of this study are strongly supported by the BMD NOAEL range of 13 to 21 ppm calculated for the New Zealand cohort of 237 mother-child pairs (Crump et al. 1998). Consequently, much of the uncertainty normally present in the MRL derivation process does not exist in the case of methylmercury. Nonetheless, in view of the nature of the most susceptible group (developing fetuses) and some questions raised in the vast human data base for this chemical, an aggregate value of 4.5 was employed.

This value (4.5) was based upon three separate components, two of which are interrelated and the other independent. For the Seychelles data, a value of 1.5 was used to address the variability in hair-to-blood ratios among women and fetuses in the U.S. population, as determined by pharmacokinetic modeling of actual data by Clewell et al. (1998); a second value of 1.5 was applied to address the remainder of any inter-individual variability (i.e., pharmacodynamics) in the U.S. population. A third, and independent, factor of 1.5 was employed to account for the possibility that the domain-specific tests, as employed extensively in the Faroe Islands, but not the Seychelles (which used primarily neurobehavioral tests of global function) might be able to detect very subtle neurological effects not tested for in the 66-month Seychelles cohort.

The World Health Organization (WHO, 1993, 1996) has defined the -kinetic and -dynamic components of intrahuman variability as being equal contributors to, and collectively constituting the total of, human variability. In order to ensure a conservative approach, these two interdependent components were added to give a composite uncertainty factor of three (i.e., 1.5 + 1.5 = 3) to account for the full range of variability attributable to mercury in the Seychelles study. A modifying factor of 1.5 was also used to account for the

possibility of domain-specific effects, as were seen in the Faroe study, being attributable to mercury. Since these effects were considered to be entirely separate or "independent" events, this modifying factor of 1.5 was multiplied by the uncertainty factor of 3.0 (for uncertainty attributable solely to the Seychelles study) to yield an aggregate uncertainty of 4.5 for chronic oral exposure to methylmercury.

While domain-specific tests from the Seychelles were reviewed at the North Carolina meeting in November 1998 and the results failed to demonstrate effects, the tests do not represent the full range of domain-specific tests that were administered in the Faroe Islands. For these reasons, and based on our consultation with our Board of Scientific Counselors about concerns for "missing" data sets (i.e., in relation to the Executive Order of children's health and the agency's efforts to protect the health of children, including the developing fetus), ATSDR determined that an additional factor of 1.5 should be used since the full range of domain-specific neuropsychological test results from the Seychelles are not yet available. When these results become available and if they fail to show domain-specific effects, this additional factor of 1.5 would no longer be needed. At that time ATSDR will re-evaluate its MRL, as well as all other relevant data, in compliance with the agency's mandates and authorities.

Therefore, in the calculation of the chronic oral MRL for methylmercury, the NOAEL of 0.0013 mg/kg/day from the 66-month study (Davidson et al. 1998) is divided by 4.5, giving a chronic oral MRL for methylmercury of 0.0003 mg/kg/day [0.0013 mg/kg/day / 4.5 (UF) = 0.0003 mg/kg/day].

If an inhalation study in animals, list the conversion factors used in determining human equivalent concentration (HEC): Not applicable.

Additional studies or pertinent information which lend support to this MRL:

Crump et al. (1998) conducted benchmark dose (BMD) calculations and additional regression analyses of data collected in a study in which a series of scholastic and psychological tests were administered to children whose mothers had been exposed to methylmercury during pregnancy. Hair samples were collected from 10,970 new mothers in New Zealand in 1977 and 1978. High hair mercury levels were considered to be those over 6 ppm, which was the hair level predicted to result at steady state from consumption of mercury at the WHO/FAO Provisional Tolerable Weekly Intake of 0.3 mg total mercury/week and 0.2 mg methylmercury/week. By this criterion, 73 of approximately 1,000 mothers who had consumed fish more than three times/week during pregnancy were determined to have high hair mercury levels. In 1985, when the children were 6 to 7 years of age, 61 children (1 set of twins) of the 73 mothers in the high hair mercury group were located, and constituted the high exposure group, which was matched with three control groups (one with 3-6 ppm maternal hair mercury levels, one with 0-3 ppm whose mothers had been high fish consumers, and one with 0-3 ppm whose mothers had not been high fish consumers). The entire study cohort consisted of 237 children. A battery of 26 psychological and scholastic tests were administered to the children at school during the year 1985. Mothers were interviewed at the time of test administration to obtain additional data on social and environmental factors. In the high exposure group of children, one boy's mother had a hair mercury level of 86 ppm, which was more than four times higher than the next highest hair mercury level of 20 ppm. BMDs (10% response rate) calculated from five tests ranged from 32 to 73 ppm, when the 86 ppm mother's child was included. This corresponded to a BMDL range of 17 to 24 ppm. Although none of the 86 ppm child's test scores was an outlier according to the definition used in the analyses, his scores were significantly influential in the analyses. When this child was omitted from the analyses, BMDs ranged from 13 to 21, with corresponding BMDLs of 7.4 to 10 ppm.

Developing fetuses in the SCDS were exposed through maternal fish ingestion before and during pregnancy. Each child was evaluated at 19 months and again at 29 months (±2 weeks) for infant intelligence (Bayley

Scales of Infant Development [BSID] Mental and Psychomotor Scales), with a modified version of the BSID Infant Behavior Record to measure adaptive behaviors at 29 months (Davidson et al. 1995b). Testing was performed by a team of Seychellois nurses extensively trained in administration of the BSID. Maternal hair concentrations, measured in hair segments that corresponded to pregnancy, ranged from 0.5 to 26.7 ppm, with a median exposure of 5.9 ppm for the entire study group. The mean BSID Mental Scale Indices determined at both 19 and 29 months were found to be comparable to the mean performance of U.S. children. The BSID Psychomotor Scale Indices at both measurement intervals were two standard deviation units above U.S. norms, but were still consistent with previous findings of motor precocity in children reared in African countries. The study found no effect that could be attributed to mercury on the BSID scores obtained at either the 19- or 29-month measurement/testing interval. The 29-month cohort represented 94% of the 779 mother-infant pairs initially enrolled in the study, and approximately 50% of all live births in the Seychelles in 1989.

The only observation in the 29-month testing that might be attributable to prenatal mercury exposure was a slight decrease in the activity level in boys (but not girls) as determined by the Bayley Infant Behavior Record (subjective observation). Whereas this decrease was significant in males ($p = 0.0004$), it was not statistically significant in females ($p = 0.87$). When the subjective activity scores for male and female children were evaluated collectively, no statistically significant or remarkable decrease in activity was apparent outside the >12 ppm maternal hair concentration group. The affect on activity level in boys is not considered an adverse effect by the authors of the study.

Grandjean et al. (1997b, 1998) reported another epidemiological study of methylmercury exposure for a population in the Faroe Islands. Although the Faroese are a fishing culture, the major source of methylmercury exposure for this population is pilot whale meat, which is intermittently consumed as part of the cultural tradition . The initial study cohort consisted of 1,022 singleton births occurring in a 21-month window during 1986-1987. At approximately 7 years of age, neurobehavioral testing was conducted on 917 of the remaining cohort members. No abnormalities attributable to mercury were found during clinical examinations or neurophysiological testing. A neuropsychological test battery was also conducted, which included the following: Finger Tapping; Hand-Eye Coordination; reaction time on a Continuous Performance Test; Wechsler Intelligence Scale for Children - Revised Digit Spans, Similarities, and Block Designs; Bender Visual Motor Gestalt Test; Boston Naming Test; and California Verbal Learning Test (Children). Neuropsychological tests emphasized motor coordination, perceptual-motor performance, and visual acuity. Pattern reversal visual evoked potentials (VEP) with binocular full-field stimulation, brain stem auditory evoked potentials (BAEP), postural sway, and the coefficient of variation for R-R inter-peak intervals (CVRR) on the electrocardiogram were all measured. The neuropsychological testing indicated mercury-related dysfunction in the domains of language, attention, memory, and visuospatial and motor function (to a lesser extent), which the authors considered to remain after the children of women with maternal hair mercury concentrations above 10 μg/g (10 ppm) were excluded. While this study represents a significant contribution to the human database for methylmercury exposure and effects, a number of potentially influential factors not fully considered as possible covariates somewhat cloud the interpretation of the results.

These differences between the neuropsychological effects observed in the Faroe Island cohort and the absence of effects reported in the Seychelles Island cohort might result from a variety of factors. The Faroe Island children were older (7–8 years versus 5.5 in the SCDS). Some of the measurement instruments (i.e., the neuropsychological test administered) were also different. Since the first neuropsychological testing in the Faroe study was not conducted until 7 years of age, it is not known whether the observed effects might have been apparent at an earlier age. Ongoing and planned future testing of the Seychelles population will provide additional information on the progression of any observed effects. Further examination of the

Seychelles population using the neuropsychological test that showed positive results in the Faroe Islands population will also allow a more direct comparison of results.

The diet in the two studies was also considerably different. The majority of the mercury exposure to the Faroe Island population came from whale meat (estimated at about 3 ppm in muscle tissue) with a relatively small portion coming from fish. Some of the mercury in whale meat is in the form of inorganic mercury. In the Seychelles study, all of the mercury came from fish as methylmercury with concentrations of around 0.3 ppm. Whale meat blubber is widely consumed in the Faroe Islands and also contains polychlorinated biphenyls (PCBs). Grandjean et al. (1995b) estimated a daily intake of 200 µg of PCB. This value can be compared to the Tolerable Daily Intake of PCBs established by the FDA, of 60–70 µg/day for an adult. Further statistical analysis of the possible influence of PCBs on the observed study results needs to be conducted (see the discussion below on Peer Panel 1Review of Key Studies for additional comments).

The primary biomarker used to estimate mercury exposure was also different between the two studies. The Faroe Island analysis used cord blood, and the Seychelles study used maternal hair level. The use of mercury in cord blood has the advantage of being a more direct measure of exposure to the fetus, but the levels at term may not reflect exposures at earlier developmental stages. While Grandjean et al. (1997) did report maternal hair mercury levels, the mean hair level for the interquartile range of 2.6–7.7 ppm was reported only as a geometric average (4.27 ppm). In contrast, the Seychellois study reported only an arithmetic mean level for the entire study population (6.8 ppm). While both are valid measures, a direct comparison of "average" values for the two studies is not possible without further statistical analysis of both data sets.

In the case of the Faroe study, there were no data presented in the peer-reviewed publications to address variability of food/whale meat or blubber intake among the Faroe Islanders, making it difficult to evaluate the possibility of peak intake levels during critical development phases. Consumption data was reported only as <1 pilot whale meat meal/month and 1-2 fish meals per week. In contrast, the Seychelles dietary habits provide a relatively stable intake, and a high degree of correlation was found between mean hair levels in samples covering each trimester versus levels in samples for the entire pregnancy (Cernichiari et al. 1995a). Cernichiari et al. (1995b) also report a good correlation between levels of total mercury in neonatal brain and levels in the corresponding maternal hair. While the contribution of continued mercury exposure through breast feeding or post-weaning diet was not fully addressed in the Seychellois study reports (Davidson 1995, 1998), that is not considered a significant drawback with the study, since no effects on neurobahavioral/neuropsychological testing were seen at any maternal hair level. In the Faroese assessment of latent neuropsychological effects from an *in utero* exposure to mercury, however, the role of continuing postnatal exposure to mercury either from breast milk or from ingestion of methylmercury-containing foods (e.g., pilot whale meat) is less clear. Specifically, it is not known what proportion, if any, of the neuropsychological effects reported in the Faroe Island population could be attributed to seven years of postnatal exposure to methylmercury in food. The variability and magnitude of this postnatal exposure should, therefore, be further evaluated.

Peer Panel Review of Key Studies

In addition to the traditional peer review process that precedes publication in most scientific journals, the studies considered by ATSDR for use in estimating a chronic oral MRL for methylmercury underwent two stringent reviews by recognized experts in the environmental health field.

On July 20 and 21, 1998, ATSDR assembled a panel of 18 experts from the scientific and medical communities to review current issues and the relevant literature on mercury and its compounds, including

methylmercury (ATSDR 1999). Several members of each of the respective research teams that conducted the Iraqi, Seychelles, Faroe, and Madeira studies were included among the expert panelists, and provided extensive overviews of their studies. The presentations were followed by an open, wide- ranging scientific discussion of the merits and interpretations of the currently available studies. Topics of significant discussion included the relative merits of the respective study populations, exposure regimens, sensitivity of neurobehavioral measures, and determination of an uncertainty factor. While it was unanimously agreed that the Seychelles and Faroe studies were both excellent studies that provided a significant contribution to the human database for methylmercury exposure and effects, a number of factors that could have contributed to the study results, but were not considered as possible statistical covariates, were discussed. In the case of the Faroe study, the consumption of whale blubber, which is known to be contaminated with PCBs, DDT, and possibly other organochlorines, introduces a potentially significant influence on the study results. Weihe et al. (1996) reported that the PCB and DDT concentrations in blubber of pilot whales taken in Faroese waters are about 30 ppm and 20 ppm, respectively. In contrast, the Seychellois population does not eat marine mammals at all. In addition, the Faroe study did not address other possible statistical covariates, such as the dietary and nutritional status of the study population and the use of tobacco during pregnancy, further complicating the interpretation of the neuropsychological test results.

On November 18–20, 1998, a workshop on Scientific Issues Relevant to the Assessment of Health Effects from Exposure to Methylmercury was conducted in Raleigh, North Carolina. Jointly sponsored by the U.S. Department of Health and Human Services, the National Institute of Environmental Health Sciences (NIEHS), the Centers for Disease Control and Prevention (CDC), the Food and Drug Administration (FDA), the U.S. Environmental Protection Agency (EPA), the National Oceanic and Atmospheric Administration (NOAA), the Office of Science and Technology Policy (OSTP), the Office of Management and Budget (OMB), and ATSDR, the purpose of this workshop was to discuss and evaluate the major epidemiologic studies that associated methylmercury exposure and the results of an array of developmental measures in children. These studies monitored and evaluated exposed populations in Iraq, the Seychelles Islands, the Faroe Islands, and the Amazon River Basin. A number of animal studies were also considered in support of a human health risk assessment. Presentation of these studies by the research team that conducted the study was followed by an expert panel evaluation that examined each study, taking into consideration the exposure data, experimental design and statistical analysis, potential confounders and variables, and neurobehavioral endpoints evaluated. A fifth panel evaluated the results of relevant animal studies. Significant issues that were discussed included the use of umbilical cord blood mercury levels vs. hair mercury concentrations as an index of methylmercury exposure during pregnancy, the patterns of exposure, the dietary/health status of study populations, other potentially relevant exposures, other confounding influences, and the adjustments made for statistical covariates. All five panels at this workshop commended the efforts of the investigators and respective staffs of the Seychelles and Faroe studies for conducting highly sophisticated investigations under difficult conditions. However, specific findings of several of the panels raise issues that, at present, preclude the Faroe data from consideration as a starting point for MRL derivation.

In their addressal of the potential influence of concurrent PCB exposure on the Faroe results, the Confounders and Variables (Epidemiology) panel indicated that with respect to four of the pre-natal outcomes (related primarily to verbal and memory performance), when PCBs were included in the model, only one of these outcomes is specifically related to mercury exposure. Concerning this matter, the panel wrote that "... the most likely explanation is that both (mercury and PCBs)... affect these three outcomes, but their relative contributions cannot be determined given their concurrence in this population." The Neurobehavioral Endpoints Panel also looked at this issue, and noted that "PCB exposure might act as an effect modifier, increasing the susceptibility to MeHg."; however, this panel further indicated that it did not believe that the effects seen in the Faroe Islands were due to uncontrolled confounding by PCBs. A third

panel that addressed the issue of concurrent PCB exposures, the Statistics/Design Panel, noted that only 3 of 208 PCB congeners were measured in the Faroe study, and stated that it "seems likely that mercury was measured more accurately than the biologically relevant PCB exposure. Consequently even if the neurological effects seen in this study were caused entirely by PCBs, it is possible that mercury would still be more highly correlated with these effects than PCBs." The Statistics/Design Panel also said that "the best method to deal with this problem would be to study a population where exposure to PCBs is not an issue." This statement points directly to the Seychelles study as the study most appropriate for MRL derivation.

Another issue raised at Raleigh workshop concerned the taking of hair samples for determining pre-natal exposure. In the Seychelles, hair samples were collected 6 months post-partum, and segments corresponding to pregnancy were selected for analysis. In the case of the Faroese, hair samples were taken at the scalp. Regarding that, the Confounders and Variables (Epidemiology) panel stated that "Given the time it takes the Hg to be excreted into the hair, we can assume that samples collected at parturition do not cover the last 6 weeks of gestation, during which critically important neuronal proliferation and differentiation is taking place."

Regarding both the Seychelles and Faroe studies, the Neurobehavioral Endpoints Panel found "no specific neurobehavioral signature injury from MeHg" in the data from either study (Seychelles or Faroe). The same panel also noted that episodic exposure in the Faroe Islands (1–2 fish meals/week and <1 pilot whale meal/month) "may reduce the likelihood of detecting a consistent 'neurobehavioral signature injury' specific to MeHg and may account for different observations in children with the same average exposure."

Based upon the discussions at the Raleigh workshop and the individual panel findings, as well as the aforementioned Atlanta expert panel review, ATSDR has determined the Seychellois study to represent the most appropriate and reliable data base currently available for calculation of a chronic oral MRL from a population exposed only to methylmercury by a relevant route of exposure for the overall U.S. population.

[It should be emphasized that the Seychelles study and the Faroe study represent credible scientific contributions by widely respected research teams. Similarly, both studies extend our knowledge base well beyond that provided by the Iraqi study and make significant contributions to our understanding of the effects of low-level exposure to methylmercury by an exposure route and vehicle (i.e., food) relevant to U.S. populations. The continuing monitoring and evaluation of the Seychellois and Faroese populations with more comparable neurobehavioral indices should help strengthen our understanding of the effects of low level chronic methylmercury exposure and should reduce the uncertainty regarding the public health implications of exposure.]

Other epidemiology studies were also considered by the workshop panels. Lebel et al. (1997) evaluated a fish-eating populations in the Amazon River Basin with a neurofunctional test battery and clinical manifestations of nervous system dysfunction in relation to hair mercury concentrations. The villagers examined live along the Tapajos River, a tributary of the Amazon. The study population consisted of 91 adult inhabitants 15-31 years of age. Hair mercury levels were below 50 µg/g (ppm). Clinical examinations were essentially normal, although persons displaying disorganized movements on an alternating movement task and those with restricted visual fields generally had higher hair mercury levels. Near visual contrast, sensitivity, and manual dexterity (adjusted for age) were found to decrease significantly with increasing mercury levels, while a tendency for muscular fatigue and decreasing strength were observed in women. The authors suggested that dose-dependent nervous system alterations might be associated with hair mercury levels below 50 ppm. This study, however, also had a number of potentially confounding factors. The impact of parasitic and other diseases endemic to the study area is of primary

concern in the interpretation of the Lebel et al. (1997) results. In addition, the overall nutritional status of the study population was not known or reported, and the use of neuroactive drugs (from local herbs, plants, roots, or mushrooms) was not considered as a potential confounder or covariate. The previous mercury exposure history of the study cohort was also unclear. This is of particular importance because gold mining procedures that use metallic mercury have been commonly practiced along the Amazon Basin for decades. Finally, the endpoints of the Lebel et al. (1977) study evaluated adult toxicity and not effects in the developing fetus or the newborn (i.e., the most sensitive human population).

The panel also reviewed the Iraqi study. Cox et al. (1989) and WHO (1990) reported delayed onset of walking in offspring in Iraqi children whose mothers were exposed to methylmercury through the consumption of seed grain treated with methylmercury as a fungicide (Al-Mufti et al. 1976; Bakir et al. 1973; Cox et al. 1989; Marsh et al. 1981, 1987). Exposure to methylmercury from other sources (e.g., fish or meat) was probably very low or nonexistent (Al-Mufti et al. 1976). It is likely that the children were exposed both prenatally through the placenta and postnatally through the mother's milk. A maternal exposure level of 0.0012 mg/kg/day, corresponding to the hair level of 14 ppm, was estimated using a simple, one-compartment pharmacokinetic model.

Myers et al. (1997) evaluated the population of the SCDS for developmental milestones similar to those determined in Iraq. As part of this ongoing study, cohort children were evaluated at 6.5, 19, 29, and 66 months of age. At 19 months care-givers were asked at what age the child walked (n=720 out of 738) and talked (n=680). Prenatal mercury exposure was determined by atomic absorption analysis of maternal hair segments corresponding to hair growth during the pregnancy. The median mercury level in maternal hair for the cohort in this analysis was 5.8 ppm, with a range of 0.5–26.7 ppm. The mean age (in months) at walking was 10.7 (SD=1.9) for females and 10.6 (SD=2.0) for males. The mean age for talking (in months) was 10.5 (SD=2.6) for females, and 11.0 (SD=2.9) for males. After adjusting for covariates and statistical outliers, no association was found between the age at which Seychellois children walked or talked and prenatal exposure to mercury. The ages for achievement of the developmental milestones were normal for walking and talking in the Seychellois toddlers following prenatal exposure to methylmercury from a maternal fish diet. The 5.8 ppm NOAEL of this study is considerably below the one estimated from the dose-response analysis of the data for the Iraqi methylmercury poisonings (10 ppm).

Clarkson (1995) raised some interesting issues concerning whether is it reasonable to apply health effects data based on an acute exposure to methylmercury fungicide eaten in homemade bread (in the 1971–1972 Iraq incident) to fish-eating populations having chronic exposure to much lower concentrations of methyl-mercury. Clarkson (1995) addressed two specific issues. The first regards the body's "defense mechanisms" that serve to mitigate the potential damage from mercury. One such mechanism in the case of methylmercury involves an enterohepatic cycling process in which methylmercury from dietary sources absorbed through the intestine is carried to the liver, where substantial quantities are secreted back into the bile and returned to the intestinal tract. During the residence time in the gut, microflora break the carbon-mercury bond, converting methylmercury into inorganic mercury, which in turn is poorly absorbed and is excreted in the feces. This creates an effective detoxification pathway for low-dose dietary exposures to methylmercury, but probably not for acute, high-dose exposures, such as occurred in Iraq. Secondly, the transport of methylmercury into brain tissue is inhibited by the presence of many amino acids, including leucine, methionine, and phenylalanine. Thus, it is possible that the rising plasma concentrations of amino acids from ingestion of fish protein may serve to depress the uptake of methylmercury by the brain.

While both of these issues need further laboratory/clinical investigation, they do raise appropriate questions concerning the relevance of the relatively short-term (i.e., about six weeks), high-level contaminated grain exposure scenario encountered in Iraq to the dietary methylmercury exposure scenarios encountered in many

fish-eating populations (e.g., the Seychelles Islanders, Faroe Islanders, Peruvian villagers, and Inuit native people of Greenland). This position is supported by Cicmanec (1996), who reviewed data from the Iraqi study, as well as data from studies of fish-consuming populations in the Faroe Islands, Seychelles Islands, and Peruvian fishing villages. Cicmanec concluded that the Iraqi population does not represent a sensitive subpopulation within a perinatal group; rather, the relative lower threshold identified in that study was the result of confounders. Crump et al. (1995) reanalyzed the dose-response data from the Cox et al. (1989) report of the Iraqi incident and found the results to be potentially skewed by inadequacies in the study design and data-collection methods. Shortcomings or potentially confounding factors include: (1) the retrospective recall of developmental milestones by mothers and other family members; (2) the lack of precision in the determination of birth and other milestone dates; (3) and the possible biasing of the dose-response analysis by variation in symptom reporting and infant sex composition in the two study subcohorts. Crump et al. (1995) noted that perhaps the most serious limitation of the Iraqi study is the inability to assess the potential effects of low-level chronic-duration exposure to methylmercury, as these particular data are based on very high intake levels over a relatively brief period of time.

No increase in the frequency of neurodevelopmental abnormalities in early childhood was observed in a cohort of 131 infant-mother pairs in Mancora, Peru (Marsh et al. 1995b). The mean concentration of mercury in maternal hair was determined to be 8.3 ppm (range, 1.2–30 ppm), and the source of the mercury was believed to be from consumption of marine fish. Similarly, a study of 583 Faroe Island infants for the first 12 months after birth found no decrease in the age of attainment of sitting, creeping (crawling), and standing developmental milestones (Grandjean et al. 1995a). The age at which a child reached a particular developmental milestone was not only not found to be associated with prenatal mercury exposure, but infants that reached a milestone early were found to have significantly higher mercury concentrations in their hair at 12 months of age. It was also found that early milestone attainment was clearly associated with breast-feeding, which was in turn related to higher infant hair mercury levels. The authors (Grandjean et al. 1995a) concluded that the beneficial effects associated with breast-feeding seemed to overrule, or to compensate for, any neurotoxic effects on milestone development that could be due to the presence of contaminants (e.g., mercury) in human milk.

Additional studies have shown developmental toxicity after oral exposure of humans and animals to organic mercury compounds (Amin-Zaki et al. 1974; Bakir et al. 1973; Bornhausen et al. 1980; Cagiano et al. 1990; Elsner 1991; Engleson and Herner 1952; Fowler and Woods 1977; Guidetti et al. 1992; Harada 1978; Hughes and Annau 1976; Ilback et al. 1991; Inouye and Kajiwara 1988; Khera and Tabacova 1973; Lindstrom et al. 1991; McKeown-Eyssen et al. 1983; Nolen et al. 1972; Olson and Boush 1975; Rice 1992; Rice and Gilbert 1990; Snyder and Seelinger 1976; Stoltenburg-Didinger and Markwort 1990).

The accumulation of mercury is greater in larger fish and in fish higher in the food chain. The tendency for increased mercury concentration with increasing fish body weight is particularly noticeable in carnivorous fish species. Malm et al. (1995) analyzed mercury concentrations in 16 species of carnivorous fish from the Tapajos River basin in Brazil and hair samples from local populations who regularly ate such fish. Mercury levels in the fish averaged 0.55 ppm (range, 0.04–3.77 ppm), and the mercury levels in the hair of the affected fish-eating populations averaged approximately 25 ppm. In one population that consumed higher quantities of large carnivorous fish at the end of the local rainy season, 8 of 29 persons evaluated had hair mercury levels above 40 ppm, and one individual had a hair mercury concentration of 151 ppm. Some villages along the river can have per capita daily fish consumption rates around 200 g or more, which would greatly impact the human body burden and hair levels of mercury in such populations.

Alternative Derivations of the MRL

To ensure a health guidance value based upon the best use of the Seychelles study data (widely considered the most relevant data available), ATSDR evaluated alternate MRL derivation methods for methylmercury.

One such method was a physiologically based pharmacokinetic approach using the mean total mercury level of 6.8 ppm in maternal hair for the entire Seychellois study cohort. Using the same formula as in the previous MRL calculation,

C = (0.95 x 0.05 x d) / (0.014 x 4.2)
C = 0.81 d
(1/250 x 6.8) = 0.027
0.027 mg/L = 0.81 d
d = 0.034 mg/day
0.034 mg/day / 60 kg = 0.0006 mg/kg/day

In consideration of uncertainty factors for this MRL approach, multiple factors also apply. In this case, the mean value of 6.8 ppm for the NOAEL is for the entire study cohort at 66 months (n = 711). An uncertainty factor of 1.5 was used to account for the pharmacokinetically based variability of hair-to-blood ratios (95% confidence level) in pregnant women and fetuses in the U.S. population (Clewell et al. 1998, 1999). The extremely large size of the study population (n=711), in combination with an uncertainty factor of 1.5, is considered adequate to encompass the full range of pharmacokinetic and pharmacodynamic variability within the human population. An independent modifying factor of 1.5 was also used to take into consideration the positive results of the domain-specific tests administered in the Faroe study (Grandjean et al. 1997, 1998). The uncertainty factor of 1.5, multiplied by the modifying factor of 1.5, yields a total aggregate value of 2.25. Applying the factor of 2.25 to the daily intake calculated from the 6.8 ppm NOAEL yields a chronic oral MRL value of 0.0003 mg/kg/day for methylmercury (0.0006 mg/kg/day divided by 2.25 = 0.0003 mg/kg/day).

A third approach to deriving a health guidance value is the use of bench mark dose (BMD) modeling. Clewell et al. (1998) used a benchmark dose analysis to determine a reference dose (RfD, a health guidance value used by the Environmental Protection Agency and, in some ways, the equivalent of ATSDR's chronic oral MRL). Clewell et al. (1998) used the data from the 29-month test in the Seychellois population (Davidson et al. 1995b) for their analysis (i.e., the 66-month study had not been published at the time of their benchmark dose analysis). The BMD is calculated by fitting a mathematical dose-response model to dose-response data. The bench mark dose level (BMDL) is a lower statistical confidence bound on the BMD and replaces the NOAEL in the calculation of a health guidance value. The BMD approach has been proposed as superior to the use of "average" or "grouped" exposure estimates when dose-response information is available, as is the case for the Seychelles study. Clewell et al. (1998) note that the Faroe Islands study reported by Grandjean et al. (1997b) could not be used for dose-response modeling due to inadequate reporting of the data and the confounding influence of co-exposure to PCBs.

For the 29-month Seychelles data, Clewell et al. (1998) used the 95% lower bound on the 10% benchmark dose level (BMDL), which represents a conservative estimate of the traditional NOAEL. The benchmark dose modeling over the entire range of neurological endpoints reported by Davidson et al. (1995b) yielded a lowest $BMDL_{10}$ of 21 ppm methylmercury in maternal hair. This $BMDL_{10}$ was then converted to an expected distribution of daily ingestion rates across a population of U.S. women of child-bearing age by using a Monte Carlo analysis with a physiologically based pharmacokinetic (PBPK) model of methylmercury developed by Gearhart et al. (1995). This analysis addresses the impact of interindividual

pharmacokinetic variability on the relationship between ingestion rate and hair concentration for methyl-mercury. The resulting distribution had a geometric mean value of 0.00160 mg/kg/day (S.D. 0.00133). The 1st, 5th, and 10th percentiles of that distribution were 0.00086, 0.00104, and 0.00115 mg/kg/day, respectively. Clewell et al. (1998) suggested that the 5th percentile of 0.00104 mg/kg/day provides a scientifically based, conservative basis that incorporates the pharmacokinetic variability across the U.S. population of child-bearing women and that no other uncertainty factor for interindividual variability would be needed. To the benchmark-estimated NOAEL of 21 ppm derived from the Seychelles 29-month data, Clewell et al. (1998) applied an uncertainty factor of 3 to account for data base limitations. (Note: The 66-month Seychelles data was not yet published at the time; hence the reliance on the 29-month Seychelles data for the benchmark analysis.) Consequently, Clewell et al. (1998) concluded that using a NOAEL of 7 ppm (21 ppm / 3 (UF) provides additional protection against the possibility that effects could occur at lower concentrations in some populations. Based upon this reasoning, they recommended a health guidance value (i.e., an RfD) of 0.0004 mg/kg/day. If a modifying factor of 1.5 is used to further address the domain-specific findings in the Faroe study, a final MRL of 0.3 μg/kg/day results.

The above benchmark analysis of 29-month data from the Seychelles Child Development Study strongly supports the MRL of 0.0003 mg/kg/day calculated by ATSDR in this profile. Similarly, addressing the Seychellois 66-month data from the perspective of using the mean value (15.3 ppm) of the highest exposure group in the study, a method prescribed in ATSDR's published guidance for MRL development (Chou et al. 1998), also results in an identical MRL. ATSDR therefore has high confidence that this level is protective of the health of all potentially exposed human populations.

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APPENDIX B

USER'S GUIDE

Chapter 1

Public Health Statement

This chapter of the profile is a health effects summary written in non-technical language. Its intended audience is the general public especially people living in the vicinity of a hazardous waste site or chemical release. If the Public Health Statement were removed from the rest of the document, it would still communicate to the lay public essential information about the chemical.

The major headings in the Public Health Statement are useful to find specific topics of concern. The topics are written in a question and answer format. The answer to each question includes a sentence that will direct the reader to chapters in the profile that will provide more information on the given topic.

Chapter 2

Tables and Figures for Levels of Significant Exposure (LSE)

Tables (2-1, 2-2, and 2-3) and figures (2-1 and 2-2) are used to summarize health effects and illustrate graphically levels of exposure associated with those effects. These levels cover health effects observed at increasing dose concentrations and durations, differences in response by species, minimal risk levels (MRLs) to humans for noncancer end points, and EPA's estimated range associated with an upper- bound individual lifetime cancer risk of 1 in 10,000 to 1 in 10,000,000. Use the LSE tables and figures for a quick review of the health effects and to locate data for a specific exposure scenario. The LSE tables and figures should always be used in conjunction with the text. All entries in these tables and figures represent studies that provide reliable, quantitative estimates of No-Observed-Adverse- Effect Levels (NOAELs), Lowest-Observed-Adverse-Effect Levels (LOAELs), or Cancer Effect Levels (CELs).

The legends presented below demonstrate the application of these tables and figures. Representative examples of LSE Table 2-1 and Figure 2-1 are shown. The numbers in the left column of the legends correspond to the numbers in the example table and figure.

LEGEND

See LSE Table 2-1

(1) Route of Exposure One of the first considerations when reviewing the toxicity of a substance using these tables and figures should be the relevant and appropriate route of exposure. When sufficient data exists, three LSE tables and two LSE figures are presented in the document. The three LSE tables present data on the three principal routes of exposure, i.e., inhalation, oral, and dermal (LSE Table 2-1, 2-2, and 2-3, respectively). LSE figures are limited to the inhalation (LSE Figure 2-1) and oral (LSE Figure 2-2) routes. Not all substances will have data on each route of exposure and will not therefore have all five of the tables and figures.

(2) Exposure Period Three exposure periods - acute (less than 15 days), intermediate (15–364 days), and chronic (365 days or more) are presented within each relevant route of exposure. In this example, an inhalation study of intermediate exposure duration is reported. For quick reference to health effects occurring from a known length of exposure, locate the applicable exposure period within the LSE table and figure.

(3) Health Effect The major categories of health effects included in LSE tables and figures are death, systemic, immunological, neurological, developmental, reproductive, and cancer. NOAELs and LOAELs can be reported in the tables and figures for all effects but cancer. Systemic effects are further defined in the "System" column of the LSE table (see key number 18).

(4) Key to Figure Each key number in the LSE table links study information to one or more data points using the same key number in the corresponding LSE figure. In this example, the study represented by key number 18 has been used to derive a NOAEL and a Less Serious LOAEL (also see the 2 "18r" data points in Figure 2-1).

(5) Species The test species, whether animal or human, are identified in this column. Section 2.5, "Relevance to Public Health," covers the relevance of animal data to human toxicity and Section 2.3, "Toxicokinetics," contains any available information on comparative toxicokinetics. Although NOAELs and LOAELs are species specific, the levels are extrapolated to equivalent human doses to derive an MRL.

(6) Exposure Frequency/Duration The duration of the study and the weekly and daily exposure regimen are provided in this column. This permits comparison of NOAELs and LOAELs from different studies. In this case (key number 18), rats were exposed to 1,1,2,2-tetrachloroethane via inhalation for 6 hours per day, 5 days per week, for 3 weeks. For a more complete review of the dosing regimen refer to the appropriate sections of the text or the original reference paper, i.e., Nitschke et al. 1981.

(7) System This column further defines the systemic effects. These systems include: respiratory, cardiovascular, gastrointestinal, hematological, musculoskeletal, hepatic, renal, and dermal/ocular. "Other" refers to any systemic effect (e.g., a decrease in body weight) not covered in these systems. In the example of key number 18, 1 systemic effect (respiratory) was investigated.

(8) NOAEL A No-Observed-Adverse-Effect Level (NOAEL) is the highest exposure level at which no harmful effects were seen in the organ system studied. Key number 18 reports a NOAEL of 3 ppm for the respiratory system which was used to derive an intermediate exposure, inhalation MRL of 0.005 ppm (see footnote "b").

(9) LOAEL A Lowest-Observed-Adverse-Effect Level (LOAEL) is the lowest dose used in the study that caused a harmful health effect. LOAELs have been classified into "Less Serious" and "Serious" effects. These distinctions help readers identify the levels of exposure at which adverse health effects first appear and the gradation of effects with increasing dose. A brief description of the specific endpoint used to quantify the adverse effect accompanies the LOAEL. The respiratory effect reported in key number 18 (hyperplasia) is a Less serious LOAEL of 10 ppm. MRLs are not derived from Serious LOAELs.

(10) Reference The complete reference citation is given in chapter 8 of the profile.

(11) CEL A Cancer Effect Level (CEL) is the lowest exposure level associated with the onset of carcinogenesis in experimental or epidemiologic studies. CELs are always considered serious effects. The LSE tables and figures do not contain NOAELs for cancer, but the text may report doses not causing measurable cancer increases.

(12) Footnotes Explanations of abbreviations or reference notes for data in the LSE tables are found in the footnotes. Footnote "b" indicates the NOAEL of 3 ppm in key number 18 was used to derive an MRL of 0.005 ppm.

LEGEND

See Figure 2-1

LSE figures graphically illustrate the data presented in the corresponding LSE tables. Figures help the reader quickly compare health effects according to exposure concentrations for particular exposure periods.

(13) Exposure Period The same exposure periods appear as in the LSE table. In this example, health effects observed within the intermediate and chronic exposure periods are illustrated.

(14) Health Effect These are the categories of health effects for which reliable quantitative data exists. The same health effects appear in the LSE table.

(15) Levels of Exposure concentrations or doses for each health effect in the LSE tables are graphically displayed in the LSE figures. Exposure concentration or dose is measured on the log scale "y" axis. Inhalation exposure is reported in mg/m^3 or ppm and oral exposure is reported in mg/kg/day.

(16) NOAEL In this example, 18r NOAEL is the critical endpoint for which an intermediate inhalation exposure MRL is based. As you can see from the LSE figure key, the open-circle symbol indicates to a NOAEL for the test species-rat. The key number 18 corresponds to the entry in the LSE table. The dashed descending arrow indicates the extrapolation from the exposure level of 3 ppm (see entry 18 in the Table) to the MRL of 0.005 ppm (see footnote "b" in the LSE table).

(17) CEL Key number 38r is 1 of 3 studies for which Cancer Effect Levels were derived. The diamond symbol refers to a Cancer Effect Level for the test species-mouse. The number 38 corresponds to the entry in the LSE table.

(18) Estimated Upper-Bound Human Cancer Risk Levels This is the range associated with the upper-bound for lifetime cancer risk of 1 in 10,000 to 1 in 10,000,000. These risk levels are derived from the EPA's Human Health Assessment Group's upper-bound estimates of the slope of the cancer dose response curve at low dose levels (q_1*).

(19) Key to LSE Figure The Key explains the abbreviations and symbols used in the figure.

SAMPLE

1 6

TABLE 2-1. Levels of Significant Exposure to [Chemical x] – Inhalation

Key to figure[a]	Species	Exposure frequency/ duration	System	NOAEL (ppm)	LOAEL (effect)		Reference
					Less serious (ppm)	Serious (ppm)	
2 6 INTERMEDIATE EXPOSURE							
	5	6	7	8	9		10
3 6 Systemic	9	9	9	9	9		9
4 6 18	Rat	13 wk 5d/wk 6hr/d	Resp	3[b]	10 (hyperplasia)		Nitschke et al. 1981
CHRONIC EXPOSURE							
					11		
Cancer					9		
38	Rat	18 mo 5d/wk 7hr/d			20	(CEL, multiple organs)	Wong et al. 1982
39	Rat	89–104 wk 5d/wk 6hr/d			10	(CEL, lung tumors, nasal tumors)	NTP 1982
40	Mouse	79–103 wk 5d/wk 6hr/d			10	(CEL, lung tumors, hemangiosarcomas)	NTP 1982

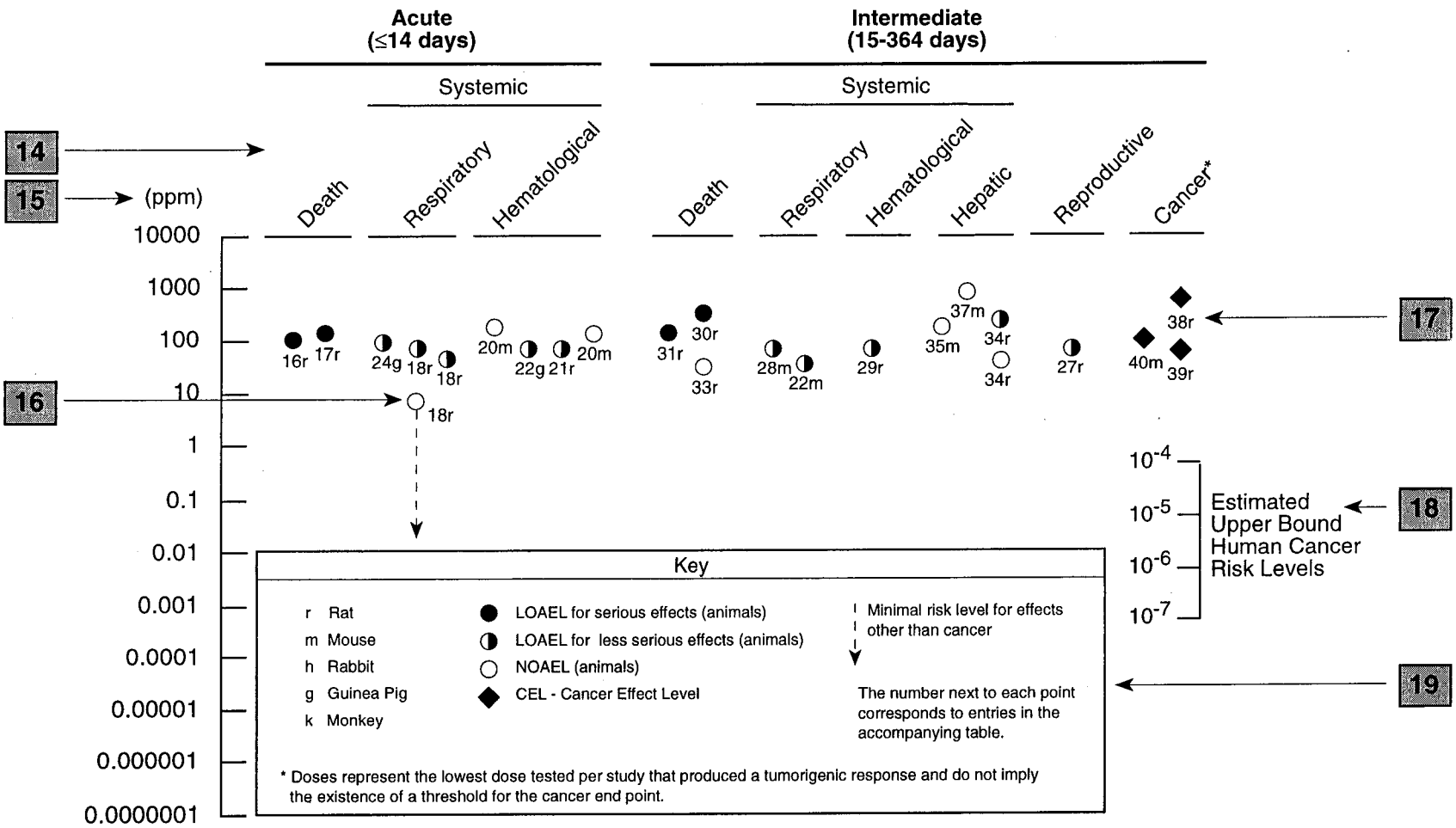
[a] The number corresponds to entries in Figure 2-1.

12 6 [b] Used to derive an intermediate inhalation Minimal Risk Level (MRL) of $5x10^{-3}$ ppm; dose adjusted for intermittent exposure and divided by an uncertainty factor of 100 (10 for extrapolation from animal to humans, 10 for human variability).

CEL = cancer effect level; d = days(s); hr = hour(s); LOAEL = lowest-observed-adverse-effect level; mo = month(s); NOAEL = no-observed-adverse-effect level; Resp = respiratory; wk = week(s)

SAMPLE

13 → **Figure 2-1. Levels of Significant Exposure to [Chemical X] – Inhalation**



Chapter 2 (Section 2.5)

Relevance to Public Health

The Relevance to Public Health section provides a health effects summary based on evaluations of existing toxicologic, epidemiologic, and toxicokinetic information. This summary is designed to present interpretive, weight-of-evidence discussions for human health end points by addressing the following questions.

1. What effects are known to occur in humans?

2. What effects observed in animals are likely to be of concern to humans?

3. What exposure conditions are likely to be of concern to humans, especially around hazardous waste sites?

The section covers end points in the same order they appear within the Discussion of Health Effects by Route of Exposure section, by route (inhalation, oral, dermal) and within route by effect. Human data are presented first, then animal data. Both are organized by duration (acute, intermediate, chronic). *In vitro* data and data from parenteral routes (intramuscular, intravenous, subcutaneous, etc.) are also considered in this section. If data are located in the scientific literature, a table of genotoxicity information is included.

The carcinogenic potential of the profiled substance is qualitatively evaluated, when appropriate, using existing toxicokinetic, genotoxic, and carcinogenic data. ATSDR does not currently assess cancer potency or perform cancer risk assessments. Minimal risk levels (MRLs) for noncancer end points (if derived) and the end points from which they were derived are indicated and discussed.

Limitations to existing scientific literature that prevent a satisfactory evaluation of the relevance to public health are identified in the Data Needs section.

Interpretation of Minimal Risk Levels

Where sufficient toxicologic information is available, we have derived minimal risk levels (MRLs) for inhalation and oral routes of entry at each duration of exposure (acute, intermediate, and chronic). These MRLs are not meant to support regulatory action; but to acquaint health professionals with exposure levels at which adverse health effects are not expected to occur in humans. They should help physicians and public health officials determine the safety of a community living near a chemical emission, given the concentration of a contaminant in air or the estimated daily dose in water. MRLs are based largely on toxicological studies in animals and on reports of human occupational exposure.

MRL users should be familiar with the toxicologic information on which the number is based. Chapter 2.5, "Relevance to Public Health," contains basic information known about the substance. Other sections such as 2.8, "Interactions with Other Substances," and 2.9, "Populations that are Unusually Susceptible" provide important supplemental information.

MRL users should also understand the MRL derivation methodology. MRLs are derived using a modified version of the risk assessment methodology the Environmental Protection Agency (EPA) provides (Barnes and Dourson 1988) to determine reference doses for lifetime exposure (RfDs).

To derive an MRL, ATSDR generally selects the most sensitive endpoint which, in its best judgement, represents the most sensitive human health effect for a given exposure route and duration. ATSDR cannot make this judgement or derive an MRL unless information (quantitative or qualitative) is available for all potential systemic, neurological, and developmental effects. If this information and reliable quantitative data on the chosen endpoint are available, ATSDR derives an MRL using the most sensitive species (when information from multiple species is available) with the highest NOAEL that does not exceed any adverse effect levels. When a NOAEL is not available, a lowest-observed-adverse-effect level (LOAEL) can be used to derive an MRL, and an uncertainty factor (UF) of 10 must be employed. Additional uncertainty factors of 10 must be used both for human variability to protect sensitive subpopulations (people who are most susceptible to the health effects caused by the substance) and for interspecies variability (extrapolation from animals to humans). In deriving an MRL, these individual uncertainty factors are multiplied together. The product is then divided into the inhalation concentration or oral dosage selected from the study. Uncertainty factors used in developing a substance-specific MRL are provided in the footnotes of the LSE Tables.

APPENDIX C

ACRONYMS, ABBREVIATIONS, AND SYMBOLS

ACGIH	American Conference of Governmental Industrial Hygienists
ADI	Acceptable Daily Intake
ADME	Absorption, Distribution, Metabolism, and Excretion
AFID	alkali flame ionization detector
AFOSH	Air Force Office of Safety and Health
AML	acute myeloid leukemia
AOAC	Association of Official Analytical Chemists
atm	atmosphere
ATSDR	Agency for Toxic Substances and Disease Registry
AWQC	Ambient Water Quality Criteria
BAT	Best Available Technology
BCF	bioconcentration factor
BEI	Biological Exposure Index
BSC	Board of Scientific Counselors
C	Centigrade
CAA	Clean Air Act
CAG	Cancer Assessment Group of the U.S. Environmental Protection Agency
CAS	Chemical Abstract Services
CDC	Centers for Disease Control and Prevention
CEL	Cancer Effect Level
CELDS	Computer-Environmental Legislative Data System
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CFR	Code of Federal Regulations
Ci	curie
CL	ceiling limit value
CLP	Contract Laboratory Program
cm	centimeter
CML	chronic myeloid leukemia
CNS	central nervous system
CPSC	Consumer Products Safety Commission
CWA	Clean Water Act
d	day
Derm	dermal
DHEW	Department of Health, Education, and Welfare
DHHS	Department of Health and Human Services
DNA	deoxyribonucleic acid
DOD	Department of Defense
DOE	Department of Energy
DOL	Department of Labor
DOT	Department of Transportation
DOT/UN/ NA/IMCO	Department of Transportation/United Nations/ North America/International Maritime Dangerous Goods Code
DWEL	Drinking Water Exposure Level

ECD	electron capture detection
ECG/EKG	electrocardiogram
EEG	electroencephalogram
EEGL	Emergency Exposure Guidance Level
EPA	Environmental Protection Agency
F	Fahrenheit
F_1	first-filial generation
FAO	Food and Agricultural Organization of the United Nations
FDA	Food and Drug Administration
FEMA	Federal Emergency Management Agency
FIFRA	Federal Insecticide, Fungicide, and Rodenticide Act
FPD	flame photometric detection
fpm	feet per minute
ft	foot
FR	*Federal Register*
g	gram
GC	gas chromatography
Gd	gestational day
gen	generation
GLC	gas liquid chromatography
GPC	gel permeation chromatography
HPLC	high-performance liquid chromatography
hr	hour
HRGC	high resolution gas chromatography
HSDB	Hazardous Substance Data Bank
IDLH	Immediately Dangerous to Life and Health
IARC	International Agency for Research on Cancer
ILO	International Labor Organization
in	inch
IRIS	Integrated Risk Information System
Kd	adsorption ratio
kg	kilogram
kkg	metric ton
K_{oc}	organic carbon partition coefficient
K_{ow}	octanol-water partition coefficient
L	liter
LC	liquid chromatography
LC_{Lo}	lethal concentration, low
LC_{50}	lethal concentration, 50% kill
LD_{Lo}	lethal dose, low
LD_{50}	lethal dose, 50% kill
LT_{50}	lethal time, 50% kill
LOAEL	lowest-observed-adverse-effect level
LSE	Levels of Significant Exposure
m	meter
MA	*trans,trans*-muconic acid
MAL	Maximum Allowable Level
mCi	millicurie
MCL	Maximum Contaminant Level

MCLG	Maximum Contaminant Level Goal
mg	milligram
min	minute
mL	milliliter
mm	millimeter
mm Hg	millimeters of mercury
mmol	millimole
mo	month
mppcf	millions of particles per cubic foot
MRL	Minimal Risk Level
MS	mass spectrometry
NAAQS	National Ambient Air Quality Standard
NAS	National Academy of Science
NATICH	National Air Toxics Information Clearinghouse
NATO	North Atlantic Treaty Organization
NCE	normochromatic erythrocytes
NCI	National Cancer Institute
NIEHS	National Institute of Environmental Health Sciences
NIOSH	National Institute for Occupational Safety and Health
NIOSHTIC	NIOSH's Computerized Information Retrieval System
NFPA	National Fire Protection Association
ng	nanogram
NLM	National Library of Medicine
nm	nanometer
NHANES	National Health and Nutrition Examination Survey
nmol	nanomole
NOAEL	no-observed-adverse-effect level
NOES	National Occupational Exposure Survey
NOHS	National Occupational Hazard Survey
NPD	nitrogen phosphorus detection
NPDES	National Pollutant Discharge Elimination System
NPL	National Priorities List
NR	not reported
NRC	National Research Council
NS	not specified
NSPS	New Source Performance Standards
NTIS	National Technical Information Service
NTP	National Toxicology Program
ODW	Office of Drinking Water, EPA
OERR	Office of Emergency and Remedial Response, EPA
OHM/TADS	Oil and Hazardous Materials/Technical Assistance Data System
OPP	Office of Pesticide Programs, EPA
OPPTS	Office of Prevention, Pesticides and Toxic Substances, EPA
OPPT	Office of Pollution Prevention and Toxics, EPA
OSHA	Occupational Safety and Health Administration
OSW	Office of Solid Waste, EPA
OTS	Office of Toxic Substances
OW	Office of Water
OWRS	Office of Water Regulations and Standards, EPA

PAH	Polycyclic Aromatic Hydrocarbon
PBPD	Physiologically Based Pharmacodynamic
PBPK	Physiologically Based Pharmacokinetic
PCE	polychromatic erythrocytes
PEL	permissible exposure limit
PID	photo ionization detector
pg	picogram
pmol	picomole
PHS	Public Health Service
PMR	proportionate mortality ratio
ppb	parts per billion
ppm	parts per million
ppt	parts per trillion
PSNS	Pretreatment Standards for New Sources
REL	recommended exposure level/limit
RfC	Reference Concentration
RfD	Reference Dose
RNA	ribonucleic acid
RTECS	Registry of Toxic Effects of Chemical Substances
RQ	Reportable Quantity
SARA	Superfund Amendments and Reauthorization Act
SCE	sister chromatid exchange
sec	second
SIC	Standard Industrial Classification
SIM	selected ion monitoring
SMCL	Secondary Maximum Contaminant Level
SMR	standard mortality ratio
SNARL	Suggested No Adverse Response Level
SPEGL	Short-Term Public Emergency Guidance Level
STEL	short-term exposure limit
STORET	Storage and Retrieval
TD_{50}	toxic dose, 50% specific toxic effect
TLV	threshold limit value
TOC	Total Organic Compound
TPQ	Threshold Planning Quantity
TRI	Toxics Release Inventory
TSCA	Toxic Substances Control Act
TRI	Toxics Release Inventory
TWA	time-weighted average
U.S.	United States
UF	uncertainty factor
VOC	Volatile Organic Compound
yr	year
WHO	World Health Organization
wk	week
>	greater than
≥	greater than or equal to
=	equal to

<	less than
≤	less than or equal to
%	percent
α	alpha
β	beta
γ	gamma
δ	delta
µm	micrometer
µg	microgram
q_1^*	cancer slope factor
–	negative
+	positive
(+)	weakly positive result
(–)	weakly negative result