UCRL-JC-122574
PREPRINT
CONF-951262--4

Recommended Launch-Hold Criteria for Protecting Public Health from Hydrogen Chloride (HCl) Gas Produced by Rocket Exhaust

J.I. Daniels
R.L. Baskett

This paper was prepared for submittal to the
1995 JANNAF Safety and Environmental Protection Subcommittee Meeting
Tampa, FL
December 5-8, 1995

November 1995

Lawrence Livermore National Laboratory

RECOMMENDED LAUNCH-HOLD CRITERIA FOR PROTECTING PUBLIC HEALTH FROM HYDROGEN CHLORIDE (HCl) GAS PRODUCED BY ROCKET EXHAUST*

Jeffrey I. Daniels and Ronald L. Baskett
Lawrence Livermore National Laboratory
Livermore, CA 94550
(510-422-0910), (510-423-6731)

ABSTRACT

Solid-fuel rocket motors used by the United States Air Force (USAF) to launch missiles and spacecraft can produce ambient-air concentrations of hydrogen chloride (HCl) gas. The HCl gas is a reaction product exhausted from the rocket motor during normal launch or emitted as a result of a catastrophic abort destroying the launch vehicle. Depending on the concentration in ambient air, the HCl gas can be irritating or toxic to humans. The diagnostic and complex-terrain wind field and particle dispersion model used by the Lawrence Livermore National Laboratory's (LLNL's) Atmospheric Release Advisory Capability (ARAC) Program was applied to the launch of a Peacekeeper missile from Vandenberg Air Force Base (VAFB) in California. Results from this deterministic model revealed that under specific meteorological conditions, cloud passage from normal-launch and catastropic-abort situations can yield measureable ground-level air concentrations of HCl where the general public is located. To protect public health in the event of such cloud passage, scientifically defensible, emergency ambient-air concentration limits for HCl were developed and recommended to the USAF for use as launch-hold criteria. Such launch-hold criteria are used to postpone a launch unless the forecasted meteorological conditions favor the prediction of safe ground-level concentrations of HCl for the general public. Unlike other launch-hold criteria previously considered and proposed for HCl that are based strictly on ceiling-concentration levels, the recommended concentration limits are a 2 ppm 1-h time-weighted average (TWA) concentration constrained by a 1-min 10-ppm average concentration. This recommended criteria is supported by human dose-response information, including data for sensitive humans (e.g., asthmatics), and the dose-response exhibited experimentally by animal models with respiratory physiology or responses considered similar to humans. Additionally, the recommended concentration limits are compatible with the physiological response of the human respiratory system to HCl, and are consistent with the predictive resolution and limitations of deterministic atmospheric-dispersion models.

INTRODUCTION

Solid-fuel rocket motors are used by the United States Air Force (USAF) to launch missiles and spacecraft. These motors produce ambient-air concentrations of hydrogen chloride (HCl) gas, and depending on the concentration, HCl can be irritating and toxic to humans.[1-4] The HCl gas is a reaction product exhausted from the rocket motor during normal launch or emitted as a result of a catastrophic abort destroying the launch vehicle. The diagnostic and complex-terrain wind field and particle dispersion model[5] used by the Lawrence Livermore National Laboratory's (LLNL's) Atmospheric Release Advisory Capability (ARAC) Program was applied to the launch of a Peacekeeper missile from Vandenberg Air Force Base (VAFB) in California.[6] This deterministic modeling approach was particularly applicable because VAFB is located in the complex coastal terrain of southern California.

---

*This work was performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

Model results revealed that under certain forecasted meteorological conditions, the centerline of the HCl cloud, created by a normal launch or a catastropic-abort situation, could pass over locations where the general public is located, including base housing, or the nearby cities of Casmalia or Lompoc. For example, under the specific set of meteorological conditions forecast for the time of launch of a Peacekeeper missile test in November 1994, the model predicted that a hypothetical catastrophic abort could lead to HCl cloud passage over base housing. For this situation, Fig. 1 presents the magnitude of the model-derived 5-min, time-averaged centerline ground-level air concentrations for HCl during the cloud passage over both the location of base housing, 10-km downwind, and also closer to the source, at a location only 4-km downwind.

Atmospheric-dispersion models provide ensemble mean concentrations (i.e., expected values) representative of the averaging times for which the dispersion coefficients were derived,
typically 15 to 30 min. To determine concentrations with shorter time averages (e.g., 5-min), a

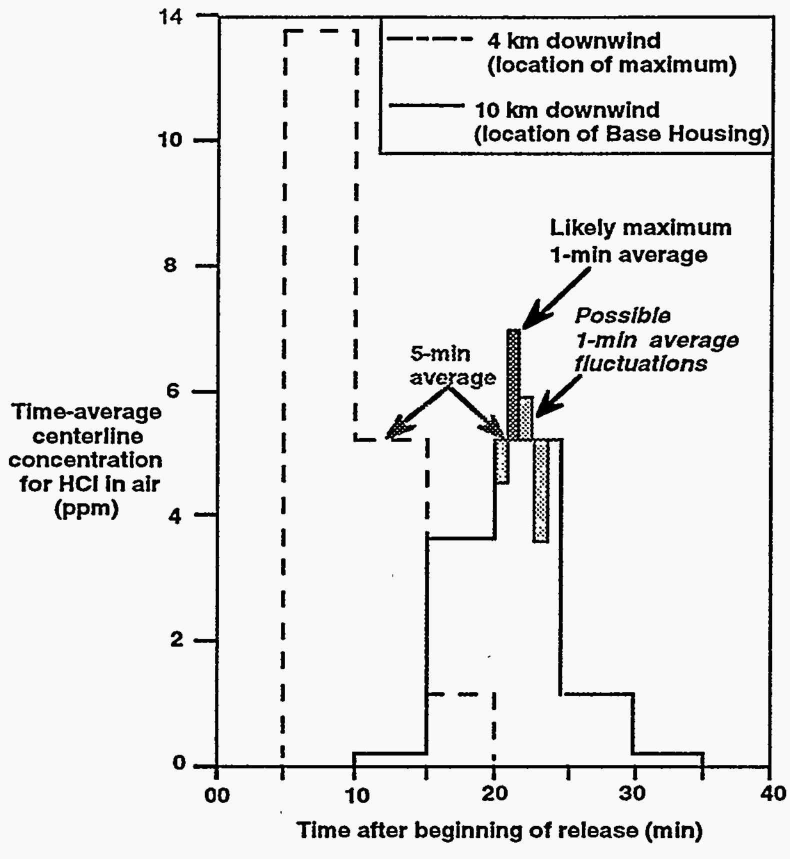

Figure 1. The 5-min average centerline HCl concentrations predicted at two locations for a hypothetical catastrophic abort of a Peacekeeper missile using meteorological forecast conditions for 18 November 1994 at VAFB (northwest flow directed towards base housing). Likely maximum 1-min average concentration applicable to base housing was derived from 5-min average using "peak-to-mean" power law (see text).

widely-used averaging-time power law,[7,8] commonly called a "peak-to-mean" power law, was applied:

$$C_p = C_a \left(\frac{T_p}{T_a} \right)^{-k}, \qquad (1)$$

where C_p is the peak (p) concentration (ppm or mg/m^3) for the shorter averaging time, T_p; C_a is the average concentration or mean predicted over the longer averaging time, T_a; and k is a constant, typically equal to a value of about 0.2.[7-9] Accordingly, the likely 1-min-maximum average HCl concentration that is shown in Fig. 1 to occur at base housing during the maximum 5-min average concentration (about 7 ppm), was calculated analytically by again applying the "peak-to-mean" power law.

To protect public health in the event of predicted HCl cloud passage directly over populated areas, scientifically defensible, emergency ambient-air concentration limits for HCl were developed and recommended to the USAF for use as launch-hold criteria. Specifically, launch-hold criteria are used to postpone a launch unless the forecasted meteorological conditions favor the prediction of safe ground-level HCl concentrations at housing facilities on VAFB, where family members may reside, or over the nearby communities of Casmalia or Lompoc. These recommended concentration limits for HCl were formulated to be compatible with the physiological response of the human respiratory system to HCl, and to be consistent with the predictive resolution and limitations of the dispersion models used to estimate potential atmospheric concentrations of HCl from a Peacekeeper missile launched from VAFB.

PAST CONSIDERATIONS

Previously considered launch-hold criteria for protecting public health from excessive exposure to HCl were developed as ceiling-concentration levels, either not to be exceeded regardless of exposure duration, or not to be exceeded during a specified exposure period. Such criteria were consistent with the emergency planning guidance recommended by government agencies[10] and the American Industrial Hygiene Association (AIHA)[11] for developing such emergency concentration limits. Even the State of California Environmental Protection Agency[12] and the National Research Council (NRC) of the National Academy of Sciences (NAS)[4] have proposed and recommended concentration levels for HCl for protecting public health that should not be exceeded during a 1-h exposure period. For example, the State of California recently proposed an ambient-air concentration of 0.04 ppm (0.06 mg/m^3) as the ceiling limit for the acute 1-h reference exposure level (REL) for HCl.[12] Similarly, the most recent NRC/NAS recommended short-term public emergency guidance level (SPEGL) for HCl is 1.0 ppm (1.49 mg/m^3) for an exposure period lasting up to 1-h.[4]

However, on the basis of our assessment of the inhalation toxicology data for HCl that is applicable to humans and available in the literature, none of the previously mentioned ceiling-concentration limits appear realistic or suitable for use as launch-hold criteria for this compound. Our assessment of the inhalation toxicology data for HCl applicable to humans appears next, followed by our recommendations for launch-hold criteria for this compound.

ASSESSMENT OF APPLICABLE INHALATION TOXICOLOGY DATA

Hydrogen chloride is an irritant gas that is extremely water soluble and so will be absorbed, neutralized, or otherwise processed by the first moist tissue it contacts. Accordingly, elements of the upper respiratory tract of humans, particularly the nose and pharynx, are most likely to intercept and be affected by elevated concentrations of HCl.[13] In fact, nasal-dosimetry modeling for humans reveals that 80% of highly soluble pollutants inhaled through the nose can be absorbed in the nasal cavity under quiet breathing flow rates.[14] Although this powerful scrubbing capacity of the nasal passages for water soluble compounds also has been demonstrated in rodents, humans typically breathe oronasally and so a direct extrapolation between these species is not necessarily applicable.[15] Indeed, Kaplan et al.[16] determined that the mouse, rat, and guinea pig were more sensitive than the baboon to the lethal effects of HCl and suggest that anatomical differences in the respiratory tracts of rodents and primates might account for these differences in sensitivity and the location of respiratory tract injury that was observed. Furthermore, the United States Environmental Protection Agency (USEPA)[17] reports that the upper airways of a human child are more closely approximated by the baboon than by other mammalian species (e.g., rodents), and the complexity of the respiratory tract in humans increases with age. On the basis of these considerations, the baboon seems to be the closest animal model for assessing the human dose-response from inhalation of concentrations of HCl gas in the atmosphere.

Although the guinea pig does not appear to be the perfect choice for a model for human dose-response to HCl, this organism does exhibit certain sublethal respiratory responses to HCl, such as a tendency for bronchoconstriction, that are comparable to those of humans, and under conditions of moderate exercise, the guinea pig does develop an increased susceptibility to the effects of HCl.[18] Therefore, specific dose-response data for exercising guinea pigs were also considered to be suitable for extrapolation to humans.

The two critical animals studies that are directly applicable to human populations were performed by Kaplan et al.[19] and Malek and Alarie[20]. Kaplan et al.[19] showed that the baboon suffered no irritation or adverse effects following inhalation exposure for 5 min to HCl at a concentration of 190 ppm (285 mg/m^3). Malek and Alarie[20] determined that exercising guinea pigs suffered only mild irritation following exposure to an HCl concentration of 107 ppm (161 mg/m^3) administered continuously for 30 min.

As noted by the NRC/NAS[4], most human health-effects data for inhalation exposure to HCl consists of qualitative observations and uncertainties with respect to analytical methods. Nevertheless, these data collectively suggest that prolonged exposure by healthy individuals to concentrations of HCl up to 10 ppm (15 mg/m^3) may be tolerated without any adverse effects, and HCl concentrations of 50 to 100 ppm (75 to 150 mg/m^3) may be tolerated for up to an hour, although irritation to the throat was reported after short exposure to an HCl concentration of 35 ppm (52.5 mg/m^3).[4,21] Also, the threshold limit value (TLV) ceiling-limit for HCl that has been adopted by the American Conference of Governmental Industrial Hygienists (ACGIH)[22], appears to be based on the unsubstantiated statement by Elkins[23] that a 5 ppm (7.5 mg/m^3) concentration of HCl will be immediately irritating when inhaled. Most importantly, a recent study performed by Stevens et al.[24] revealed no clinically significant health effects occurred in adult asthmatics exposed to HCl concentrations of 0.8 ppm (1.2 mg/m^3) and 1.8 ppm (2.7 mg/m^3) for a 45 min duration that was divided into alternating equal periods of exercise, rest, and exercise. Interestingly, Spengler et al.[25] report that on the basis of exposure to sulfuric acid (H_2SO_4) aerosol, asthmatics may be 2 to 10 times more sensitive than normal individuals in the population. Finally, based on data compiled by

Amoore and Hautala[26], and assuming these data are lognormally distributed, the 90% confidence interval for detection of HCl odor by members of the general public appears to range from as low as 0.032 ppm (0.048 mg/m^3) for the more sensitive, to as high as 18.5 ppm (27.6 mg/m^3) for the less sensitive. An odor detection threshold that is just below a concentration level that can lead to adverse health effects can serve as a powerful warning signal to seek shelter or protection from a potentially hazardous situation.

In all of the relevant animal and human studies of inhalation exposure to HCl that were just mentioned, the irritating effects from the HCl never appeared to occur instantaneously, but took some time to develop. This suggests that, to a certain degree, the complexity of the upper respiratory tract of humans can protect individuals against immediate insult or limit symptoms from elevated exposures of short duration to reversible, mild effects that are not clinically significant. However, we recognize that deleterious effects could occur immediately after exposure to an extremely high instantaneous concentration of HCl [e.g. probably much greater than 200 ppm (300 mg/m^3), even for sensitive individuals], but this threshold has not been sufficiently established. For example, Kaplan et al.[27] report that there was little evidence of deep lung penetration of HCl in adult male baboons exposed for 15 min to concentrations of 500 ppm (750 mg/m^3) because of the effective removal or scrubbing of HCl in the passages of the upper respiratory tract. Yet, these animals and baboons exposed for 15 min to concentrations of 5000 ppm (7500 mg/m^3) did experience visible signs of irritation of the eyes and oral and nasal mucosa (possibly during the first 5 min of exposure), but the symptoms were not reported to be incapacitating or life threatening, and post-exposure studies revealed no exposure-related morphological changes or permanent impairment of respiratory function.

To account for uncertainties in extrapolating directly from a healthy primate to a healthy human, we apply a 10-fold safety factor to the 190 ppm (285 mg/m^3) HCl concentration delivered for 5 min to the baboon with no observed effects. This calculation suggests that no adverse health effects should be experienced by healthy humans exposed to an HCl concentration of approximately 20 ppm (30 mg/m^3) that is sustained for 5 min.

For members of the population with respiratory systems affected by airway disease (e.g., asthma), exposure to a 20 ppm (30 mg/m^3) concentration that is sustained for 5 min may produce effects. Therefore, we assume that the guinea pig model is representative of such sensitive members of the population. To again account for uncertainties in extrapolating directly from the guinea pig to a sensitive human, we apply a 10-fold safety factor to the 107 ppm (161 mg/m^3) concentration of HCl administered continuously to the guinea pigs during 30 min of exercise. On the basis of this calculation, sensitive individuals in the population exposed to HCl concentrations of 10 ppm (15 mg/m^3) for up to 30 min could suffer mild effects, but these are not expected to be clinically significant and should be quite reversible. It is also possible that a shorter duration of exposure to this same concentration would produce no effects in such sensitive individuals. Alternatively, it is important to remember that Stevens et al.[24] demonstrated that humans with asthma that were exposed to a lower concentration of HCl (i.e., 1.8 ppm vs 10 ppm), even during periods of exercise, and for a longer duration (i.e., 45 min vs 30 min), experienced no significant clinical effects.

Collectively, the relevant dose-response data for HCl suggest that it is unlikely that even sensitive individuals in the general population would suffer significant adverse health effects from inhalation exposures to HCl concentrations that range from about 2 to 10 ppm (3 to 15 mg/m^3) and last for up to 30 min. Furthermore, evidence from medical case studies[28,29] suggest that it is unlikely such concentrations of HCl are acute or high enough to be directly responsible for the development of reactive airway dysfunction syndrome (RADS) in individuals with no preexisting respiratory disease. However, we should mention that there may be some small fraction of individuals in the population who possess an extremely high idiosyncratic sensitivity to HCl, and they might be affected by such exposures. Nevertheless, we believe the exposures to be low enough so that if symptoms do develop in these particularly sensitive individuals, they are short lived, minor, and reversible. Furthermore, protecting all members of an exposed population from *any* observed effects is probably unrealistic, given the uncertainties and limitations of both the toxicological data and the deterministic atmospheric-dispersion model.

RECOMMENDED LAUNCH-HOLD CRITERIA

On the basis of the dose-response data just reported and the fact that deterministic air-dispersion modeling can readily produce 30-min to 1-h average concentrations for HCl, which can be converted to 1- to 5-min average concentrations, we recommend using as a launch-hold criteria a time average concentration, constrained by some short-term concentration limit (not necessarily an instantaneous ceiling limit). Accordingly, we believe the most reasonable HCl exposure limit for protecting public health is the combination of a 2-ppm 1-h average constrained by a 10-ppm 1-min average. Even though some sensitive individuals might experience mild symptoms from such exposure, these effects should be transient, reversible, and experienced by only a very small fraction of the population. Furthermore, the magnitude and duration of brief excursions above the 10-ppm average, during the 1-min averaging time, are not expected to be sufficient to overwhelm the ability of the human upper respiratory tract to effectively scrub or neutralize the exposure or otherwise limit the effects from the exposure to minor and reversible symptoms of short duration. The NRC/NAS[1] even published time-weighted average concentrations for short-term exposures to HCL , which included a 2-ppm time-weighted average for a 1-h exposure duration, for consideration as short-term public limits (STPLs) for HCl that would prevent irritation that could lead to significant discomfort, and also objectionable odors.

The USAF recently assembled the Rocket Emission Work Group (REWG) to reach some concensus regarding public exposure concentration limits for HCl. The launch-hold criteria for HCl proposed by this organization for protecting public health is also a 2-ppm 1-h time-weighted average, but constrained by a ceiling limit not to exceed 10 ppm for any length of time. This recommendation may be too conservative because instantaneous ceiling limits appear not to account for evidence that the complex human respiratory tract can effectively scrub, neutralize, or otherwise limit exposures associated with brief concentration fluctuations greatly exceeding 10 ppm. Moreover, application of such a ceiling limit would require using probabilistic modeling and consideration of concentration fluctuation distributions to determine instantaneous HCl air concentrations, and scientists have only recently begun to measure and understand the magnitudes of such concentration fluctuations in the atmosphere.

ACKNOWLEDGMENT

Technical discussions and correspondence with members of the Rocket Emission Work Group (REWG), especially Dr. Joseph Prince and Mr. John Hinz (the chairperson and host at Armstrong Laboratory on Brooks Air Force Base, TX) were extremely valuable and most appreciated. Additionally, we extend our gratitude to Lt. Col. Albert Sisk and his colleagues, as well as Lt. Col. Gene Killan, at Peterson Air Force Base, CO, and to Dr. William Robison, Mr. Terry Lindman, Mr. Jack Robbins, and Dr. Jim Ellis at the Lawrence Livermore National Laboratory for their interest, comments, and support.

REFERENCES

1. National Academy of Sciences (NAS), National Research Council Committee on Toxicology, *Guides for Short-Term Exposures of the Public to Air Pollutants. II. Guide for Hydrogen Chloride,* National Academy of Sciences, Washington, DC (1971), Report N°. APTD–0764,
available from National Technical Information Service (NTIS), Springfield, VA, Accession N°. PB-203-464.

2. National Academy of Sciences (NAS), National Research Council Committee on Medical and Biologic Effects of Environmental Pollutants, *Chlorine and Hydrogen Chloride,* National Academy of Sciences, Washington, DC (1976), pp. 125–144, 172–174, 213–217, 249–272.

3. National Academy of Sciences (NAS), National Research Council Committee on Toxicology (1987), *Emergency and Continuous Exposure Guidance Levels for Selected Airborne Contaminants. Volume 7. Ammonia, Hydrogen Chloride, Lithium Bromide, and Toluene,* National Academy Press, Washington, DC (1987), pp. 17–30.

4. National Academy of Sciences (NAS), National Research Council Subcommittee on Permissible Exposure Levels, Committee on Toxicology, *Permissible Exposure Levels and Emergency Exposure Guidance Levels for Selected Airborne Contaminants,* National Academy Press, Washington, DC (1991), pp. 37-52.

5. Sullivan, T.J., J.S. Ellis, C.S. Foster, K.T. Foster, R.L. Baskett, J.S. Nasstrom, and W.W. Schalk III, "Atmospheric Release Advisory Capability: Real-Time Modeling of Airborne Hazardous Materials," *Bull. Am. Meteorol. Soc.* 74, 2343–2361 (1993).

6. Baskett, R.L., and J.C. Pace, *ARAC Dispersion Modeling Support for Jan-Mar 1995 Vandenberg AFB Launches: Prepared for Lt. Col. Albert Sisk, Chief, Operations Tests and Evaluation*
Branch, HQ AFSCP/DOTO, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-ID-121547 (1995).

7. Turner, D.B., *Workbook of Atmospheric Dispersion Estimates,* Office of Air Programs, U.S. Environmental Protection Agency, Research Triangle Park, NC, Office of Air Programs Publication N°. AP–26, [Revised 1970; Reprinted by Federal Emergency Management Agency (FEMA), Washington, DC, January 1982, Publication N°. TD–18].

8. Bowen, B.M., "Long-Term Tracer Study at Los Alamos, New Mexico. Part II: Evaluation and Comparison of Several Methods to Determine Dispersion Coefficients," *J. Applied Meteorol.* 33, 1236–1254 (1994).

9. Hino, M. "Maximum Ground-Level Concentration and Sampling Time," *Atmosph. Environ.* 2, 149-165 (1968).

10. U.S. Environmental Protection Agency (USEPA), Federal Emergency Management Agency (FEMA), and U.S. Department of Transportation (DOT), *Technical Guidance for Hazards Analysis,* National Response Team (NRT), U.S. Government Printing Office, Washington, DC (December 1987).

11. American Industrial Hygiene Association (AIHA) Emergency Response Planning Guideline Committee, *Emergency Response Planning Guideline—Hydrogen Chloride,* AIHA

Emergency Response Planning Guideline Committee, Akron, OH (published 28 March 1989; and included in *AIHA Emergency Response Planning Guidelines,* AIHA, Fairfax, VA, 1992).

12. Das, R., T.R. Parker, J.R. Fowles, M.J. Lipsett, R.J. Jackson, G.V. Alexeeff, R. Paige, P. Lopipero, L. Moore, and S. Campleman, *Technical Support Document for The Determination of Acute Toxicity Exposure Levels for Airborne Toxicant—Draft for Public Comment,* Office of Environmental Health and Hazard Assessment, California Environmental Protection Agency, Berkeley, CA (January 1995), Appendix C—Hydrochloric Acid.

13. Henderson, Y., and H.W. Haggard, *Noxious Gases and the Principles of Respiration Influencing Their Action, Second Revised Edition,* American Chemical Society Monograph Series (Reinhold Publishing Corp., New York City, NY, 1943).

14. Scherer, P.W., K. Keyhani, and M.M. Mozell, "Nasal Dosimetry Modeling for Humans," in *Nasal Toxicity and Dosimetry of Inhaled Xenobiotics: Implications for Human Health* (Taylor and Francis, Washington, DC, 1995), pp. 85–97.

15. Buckley, L.A., X.Z. Jiang, R.A. James, K.T. Morgan, and C.S. Barrow, "Respiratory Tract Lesions Induced by Sensory Irritants at the RD50 Concentration," *Toxicol. Appl. Pharmacol.* **74,** 417-429 (1984).

16. Kaplan, H.L., W.G. Switzer, R.K. Hinderer, A. Anzueto, "Studies of the Effects of Hydrogen Chloride and Polyvinylchloride (PVC) Smoke in Rodents," *J. Fire Sci.* **11**(6), 512–552 (1993).

17. U.S. Environmental Protection Agency (U.S. EPA) (1994), *U.S. EPA's Integrated Risk Information System (IRIS)—An Electronic Data Base Containing Health Risk and U.S. EPA Regulatory Information on Specific Chemicals (July 1994, Update),* Office of Research and Development, Environmental Criteria and Assessment Office, U.S. Environmental Protection Agency, Cincinnati, OH (published as CD-ROM Software in July 1994, from SilverPlatter Information, Inc., Sausalito, CA; verified as most recent update by online computer access of IRIS Database in December 1994).

18. Hartzell, G.E., A.F. Grand, and W.G. Switzer, "Modeling of Toxicological Effects of Fire Gases: VII. Studies on Evaluation of Animal Models in Combustion Toxicology," *J. Fire Sci.* **6**(6), 411-431 (1988).

19. Kaplan, H.L., A.F. Grand, W.G. Switzer, D.S. Mitchell, W.R. Rogers, and G.E. Hartzell, "Effects of Combustions Gases on Escape Performance of the Baboon and the Rat," *J. Fire Sci.* **3,** 228–244 (1985).

20. Malek, D.E., and Y. Alarie, "Ergometer within a Whole-Body Plethysmograph to Evaluate Performance of Guinea Pigs under Toxic Atmospheres," *Toxicol. Appl. Pharmacol.* **101,** 340–355 (1989).

21. Henderson, Y., and H.W. Haggard, *Noxious Gases and the Principles of Respiration Influencing Their Action, Second Revised Edition,* American Chemical Society Mongraph Series (Reinhold Publishing Corp., New York City, NY, 1943), pp. 126-127.

22. American Conference of Governmental Industrial Hygienists (ACGIH), Inc., *Documentation of the Threshold Limit Values and Biological Exposure Indices, Fifth Edition, 1986,* American Conference of Governmental Industrial Hygienists (ACGIH), Inc., Cincinnati, OH (1986).

23. Elkins, H.B., *The Chemistry of Industrial Toxicology, 2nd Edition,* (John Wiley and Sons, Inc., New York City, NY, 1959), pp. 79-80.

24. Stevens, B., J.Q. Koenig, V. Rebolledo, Q.S. Hanley, and D.S. Covert, "Respiratory Effects from the Inhalation of Hydrogen Chloride in Young Adult Asthmatics," *J. Occup. Med.* 34, 923–929 (1992).

25. Spengler, J.D., M. Brauer, P. Koutrakis, "Acid Air and Health," *Environ. Sci. Technol.* 24, 946–956 (1990).

26. Amoore, J.E., and E. Hautala, "Odor as an Aid to Chemical Safety: Odor Threshold Compared with Threshold Limit Values and Volatilities for 214 Industrial Chemicals in Air and Water Dilution," *J. Appl. Toxicol.* 3, 272–290 (1983).

27. Kaplan, H.L., W.G. Switzer, R.K. Hinderer, A. Anzueto, "A Study on the Acute and Long-Term Effects of Hydrogen Chloride on Respiratory Response and Pulmonary Function and Morphology in the Baboon," *J. Fire Sci.* 11(6), 459–484 (1993).

28. Boulet, L.-P., "Increases in Airway Responsiveness Following Acute Exposure to Respiratory Irritants," *Chest* 94, 476–481 (1988).

29. Brooks, S.M., M.A. Weiss, and I.L. Bernstein, "Reactive Airways Dysfunction Syndrome (RADS): Persistent Asthma Syndrome After High Level Irritant Exposures," *Chest* 88, 376–384 (1985).

Technical Information Department • Lawrence Livermore National Laboratory
University of California • Livermore, California 94551