LA-UR--83-3028

DE84 001735

CONF-831205--2

Los Alamos National Laboratory is operated by the University of California for the United States Department of Energy under contract W-7405-ENG-36

TITLE: ALTERNATIVE GASEOUS-FUELS SAFETY ASSESSMENT

AUTHOR(S): M. C. Krupka, A. T. Peaslee, Jr., and H. L. Laquer

SUBMITTED TO: Sixth Miami International Conference on Alternative Energy Sources, December 12-14, 1983.

Los Alamos Los Alamos National Laboratory
Los Alamos, New Mexico 87545

ALTERNATIVE GASEOUS-FUELS SAFETY ASSESSMENT

M. C. Krupka, A. T. Peaslee, Jr., and H. L. Laquer
University of California
Los Alamos National Laboratory
Energy Technologies Group
Los Alamos, New Mexico 87545, U.S.A.

ABSTRACT

In support of work sponsored by the Office of Vehicle and Engine R&D of the Department of Energy, a relative safety assessment of alternative gaseous and reference liquid fuels utilized for light automotive transportation in the public sector was completed. The specific fuels considered were compressed natural gas (CNG), liquefied natural gas (LNG), liquefied petroleum gas (LPG), and the liquid fuels, gasoline and diesel. The assessment methodology describes and develops the relative hazards of these fuels from an integrated generic physicochemical property and accident scenario point of view. A technique involving a method of eliciting expert judgment combined with a comparative scoring methodology was applied in establishing fuel relative safety rankings. Limitations of this type of assessment are discussed.

Selected accident scenarios included fuel leakage in both residential and public garages; fueling line rupture at a refueling station in the presence of user vehicles or delivery vehicles; and vehicle collisions under rural, urban, and vehicular tunnel conditions.

Overall, the results obtained demonstrate dependency upon the specific application or scenario. Gaseous fuels have increased relative risks in certain situations and are relatively safe in others. The results suggest that alternative gaseous fuels are not disqualified for public usage. The assessment also provides rationale for the development of selected safe handling criteria and recommendations.

1. INTRODUCTION

Public acceptance of alternative transportation fuels in the United States (US) is contingent not only upon the requisite technical, environmental, and economic factors but also upon demonstration through adequate assessment, testing, and operational experience that the intrinsic risk is either equivalent to or less than that associated with energy carriers, e.g., gasoline, diesel fuel, presently in common use. Public safety concerns inevitably arise when new systems and the necessary supporting infrastructures are to be established, particularly where wide geographical distribution and handling by significant numbers of people will be required.

Alternative fuels for automotive transportation were considered for many years and in fact were used in the US, albeit in minor quantities. Events, both national and international over the past decade, have rekindled interest in large scale utilization of these fuels. Over time, reasons such as those listed provided the necessary impetus to proceed with further development.

- reduction of harmful exhaust emissions
- escalation of conventional fuel costs
- reduction of petroleum imports
- reduction of crude petroleum supply due to embargo or acts of war
- various technical advantages

In support of work sponsored by the Office of Vehicle and Engine R&D of the US Department of Energy, a relative (comparative) safety assessment of selected gaseous fuels for use in light-duty automotive transportation vehicles was undertaken by the Los Alamos National Laboratory. The specific fuels considered were CNG, LNG, LPG, and as reference, gasoline and diesel fuel.

2. PURPOSE

The purpose of the assessment is to put into perspective the potential hazards of the gaseous fuels relative to the reference fuels, gasoline, and diesel fuel that are used virtually exclusively in today's automotive market. The assessment addresses an R&D activity identified by the Congress in Section 6(3) of P. L. 96-512, The Methane Transportation Research, Development, and Demonstration Act of 1980.

It is well known that most hazardous materials can be handled, transported, and used given appropriate design engineering and attention paid to the necessary safety rules and regulations. Thus, fuels that may be ranked more hazardous than others for specific applications need not be eliminated from general use. Instead, establishment of criteria (experimental, engineering, or regulatory) for safe handling and operation can ensure integration of the specific fuel into the transportation sector. An additional purpose of this assessment therefore is the establishment of these safety criteria.

3. GENERAL ASSUMPTIONS

In the US, fleet-operated passenger car, light truck, and van vehicles are presently the prime users of gaseous (alternative fuels).

To evaluate the impact of major public usage of the gaseous fuels, it is necessary to consider the future whereby a significant increase in gaseous fuel usage becomes the norm. Therefore, certain general assumptions were made in the analysis that serve as background and are applicable to the accident scenarios chosen. These include:

- several million vehicles operating on various gaseous (alternative) fuels will be on the nation's highways.

- such vehicles will be operated by the public and are individually controlled.

- vehicles will be designed for mono-fuel operation.

- mechanical operation of the vehicle will be reasonably similar to present day operation so as to minimize perturbations to society's acceptance of these vehicles.

- o habits of the public with respect to such practices as parking, driving, and refueling will be reasonably similar to present day practices.

4. GENERAL ASSESSMENT METHODOLOGY

Safety assessments represent a blending of technical data, expert judgment, prescribed assumptions or conditions, selected analytical methodologies, and where possible, some historical statistical information on similar type systems. The concept of "blending" and the information obtained generally requires the integration of various expert group activities. Such an approach was utilized in this study. The assessment however does not include components of the more rigorous risk management approach, e.g., a discussion of the potential for hazard mitigation or preventability. This is beyond the scope of this study.

The overall methodology is basically conventional to the point of the actual judgmental and analytic portions of the assessment. The methodology describes and develops the relative hazards of the specific fuels from a combined generic technical property-scenario point of view. A computerized reference literature survey was made to provide initial background information for the study and to maintain reference to any new developments during the course of the study. The survey was augmented by organizational contacts through telephone, mail, personal discussion, and attendance at certain fuel technology meetings.* Pertinent vehicle accident data and existing safety test data for gaseous-fueled vehicles were reviewed. Selected physicochemical property data were compiled. These property data provided the underlying technical base for the analysis and were used individually, in combination with one another, or in combination with certain engineering parameters. Specific and plausible accident scenarios were selected.

The interactive group method was used to elicit expert judgment in developing the relative safety rankings for the fuels. The interactive group method involved a multidisciplinary group of persons (panel of experts) who met face-to-face and who were allowed to respond spontaneously to questions. The questions concerned the likelihood of an event such as a fuel explosion occurring given a particular fuel's physical properties and a vehicle accident scenario. The group members' judgments, their estimates of likelihood, were used as data input to the analysis model to illustrate the relative risks posed by each of the five fuels under selected conditions. Credentials of the judgment panel have been listed and further details of the group method described [1].

Fuel relative safety rankings were determined using a comparison technique, basically a scoring methodology, the description, mathematical basis, and limitations of which have been presented elsewhere [1]. This methodology was used in contrast to a more rigorous risk analysis whereby, for example, probabilities would be determined for (a) a gaseous-fueled vehicle accident occurring (this is basically the same as for a petroleum-fueled vehicle), (b) release of gaseous fuel in an accident, and (c) increase/decrease of fatalit-

---

*Nonpetroleum Vehicular Fuels III Symposium, Institute of Gas Technology, Arlington, VA (October 12-14, 1982) and Twentieth Automotive Technology Development Contractor Coordination Mtg., US DOE, Dearborn, MI (October 25-28, 1982).

ies, injury, or damage. Data to support the more rigorous risk analysis is minimal or does not exist and is difficult and time-consuming to obtain with subsequent increase in cost.

5. ASSESSMENT LIMITATIONS

Certain general limitations apply to this assessment.

- The assessment is restricted to consumer or end user situations only as opposed to a total safety assessment.

- The assessment expresses the safety of the gaseous and liquid fuels based upon the relative expectation of creating the primary hazards, fire, explosion, and physiological damage. The assessment does not address the potential end results (severity) of these hazards, specifically fire and explosion material damage, injuries or fatalities, and numbers of physiologically induced injuries or fatalities.

- The assessment represents a generic approach to determining the relative safety of the gaseous fuels through the examination of the physicochemical properties of the fuels and a select few engineering parameters under the constraints imposed by selected accident scenarios. A limitation, therefore, is that additional hazards or the mitigation of hazards introduced by specific and detailed design engineering technology are <u>not</u> completely addressed.

- The results obtained permit safety rankings to be ascertained for the fuels <u>within each scenario</u> and apply <u>only</u> to that specific scenario. It must be stressed that the rankings obtained are <u>relative to one another</u> within the given scenarios. Numerical values obtained should not be considered as absolute likelihoods of occurrence or risk.

- It should be stressed that the primary hazard categories were chosen to assist in the analyses. Their existence does not suggest or guarantee that they will indeed become a reality.

- The combined expert group judgment approach and scoring methodology has certain precision limitations.

6. PHYSICOCHEMICAL PROPERTY DATA AND HAZARD IDENTIFICATION

The relative safety assessment of the alternative gaseous fuels relies upon a technical base of selected fundamental physicochemical properties as well as certain design engineering parameters. Properties are listed in Table 1. In addition, a set of composite or modified properties were introduced primarily to take into account the constraints of the various accident scenarios and to minimize the explicit variables that would require consideration. These are tabulated in Table 2. Their precise definition is given in Reference 1. Not every property listed was used in any given scenario analysis.

For purposes of this paper, properties of natural gas and methane are used interchangeably. Similarly, properties of LPG and propane are used interchangeably.

TABLE 1. Selected Physicochemical Properties of Alternative Automotive Fuels†††

Property	Natural Gas* CNG	Natural Gas* LNG	LPG**	Gasoline	Diesel Fuel***
Flammability limits, vol. % in air	5.3 - 15.0	---	2.1 - 9.5	1.0 - 7.6	0.5 - 4.1
Detonability limits, vol. % in air	6.3 - 13.5	---	3.1 - 7.0	1.1 - 3.3	---
Minimum ignition energy in air, mJ	0.29	---	0.27	0.24	0.3 (est.)
Autoignition temperature, K(°F)	813 (1004)	---	730 (855)	501 - 744 (442-880)	533 (500)
Energy content, lower heating value					
1. Btu/gal	19 760 @ 2400 psi, 294 (70)	76 300 @ NBP, 1 atm	82 450	116 400 (AV)	129 400 (AV)
2. Btu/lb	21 300	21 300	19 770	18 900 (AV) (60° API)	18 310 (AV)
Diffusion coefficient in NTP air†, cm/s	0.16	---	0.10	0.05	---
Density of gas relative to air = 1.00	0.555	---	1.56	3.4	>4.0 (est.)
Vapor pressure or equivalent ††, atm	1	1	1	0.6 - 0.8 @ 311 (100)	0.0005 @ 311 (100)(calc.)
Threshold Limiting Value (TLV), ppm	asphyxiant	asphyxiant plus cryogenic burn	1000	500	500
Storage Conditions	Compressed Gas @ 2400 - 3000 psig	Liquid @ 25-60 psig	Liquid @ 105-140 psig	Liquid @ ambient T&P	Liquid @ ambient T&P

*Properties are primarily those of methane. It is recognized however, that natural gas sources vary in composition. Property values therefore deviate to a small extent from pure methane.

**Properties are primarily those of propane. For automotive application, only the special grade HD-5 is suitable.

***Properties refer to Grade No. 2 diesel fuel.

†NTP equals 293.15 K (68°F) and one atmosphere; NBP equals normal boiling point.

††For gaseous fuels, refers to "equivalent vapor pressure" when released from high pressure storage container, or maximum possible pressure in ambient environment.

†††Detailed references for these numerical values are given in Reference 1.

Table 2. Selected Modified Properties

Contact Temperature	Fluidity
Delivery Pressure	Persistence
Dispersion	Specific Energy Release
Equivalent Vapor Pressure	Storage Pressure
Fuel Dispersion	Heat Capacity (system)

Three categories of hazard were identified and defined as primary hazards. They included fire, explosion, and physiological damage.

The generic term physiological damage encompasses a number of effects including (a) general toxicity due to oral ingestion, inhalation of fuel or combustion products (smoke and gases) and skin contact; (b) asphyxiation; (c) high temperature burn; (d) cryogenic (low temperature) burn; and (e) physical injury due to explosion, over-pressure, and flailing hoses.

The primary hazards form the basis for the generation of a set of uncertainty nodes in event sequences that are subsequently analyzed to determine relative safety.

The specific relationships between the primary hazards and the properties of the fuels have been discussed in significant detail previously [2,3,4].

7. PRELIMINARY RELATIVE SAFETY RANKINGS

Preliminary relative safety rankings were generated based upon comparisons of selected individual property data. Only qualitative results are obtainable and are of a variable and general nature. It is emphasized that these rankings are based solely upon isolated technical data without the appropriate weighting of such factors as the practical importance of one property over another and the effects of various external constraints, for example, confinement or engineering technology. Although an understanding of property-hazard relationships is obtained, the rankings <u>cannot</u> be extended to predict the safety of gaseous-fueled vehicles in actual operation. The rankings confirm the results of previous qualitative studies [3,4].

8. ASSESSMENT OF ACCIDENT DATA FROM VEHICLES USING ALTERNATIVE FUELS

Current US accident statistics for alternative gaseous fuel-powered vehicles both private and fleet-operated suggest that the overall safety record is good. Similarly, but admittedly without the benefit of detailed data, the overall safety record in various foreign countries is impressive.

There are some problems encountered however, when making direct comparisons to liquid fuel-powered vehicles. The number of gaseous-fueled vehicles and their corresponding operational mileage is still very small relative to the huge numbers of vehicles using liquid fuels. On a rigid statistical basis, the observation that very few fire and explosion accidents were encountered to date may be statistically minor or insignificant.

In the US, an additional bias exists because CNG-powered vehicles are operated almost exclusively in the fleet mode. For most fleets a high degree of maintenance, centralized vehicle control, training of operators, and good record keeping are part of the fleet's advantage in operation. Thus, statistics derived from fleet operation do not necessarily transfer over or are equivalent to those generated by the driving public.

The general lack of significant amounts of gaseous fuel-powered vehicle accident data creates difficulty in assessing the relative safety of these vehicles. In a real sense, there are problems in utilizing rigorous quantitative analysis methods that require such data. Indeed, such data paucity was a contributing factor in the decision to use the expert group judgment approach.

9. ASSESSMENT OF VEHICLE SAFETY TESTING

Large-scale safety testing and risk analysis of both US and foreign gaseous-fueled vehicles have been minimal. Although US fleet and Italian public operation suggest a low level of concern, questions still exist as to safety, especially for large-scale public operation in the US. Although some vehicle and component testing are done by manufacturers, the test information is generally proprietary and hence unavailable. With respect to those tests conducted in the United States, the available test data are probably obsolete due to the introduction of "unit-body" vehicular construction over the past decade. Recent full-scale impact testing has been done in The Netherlands and Canada [5,6].

The lack of significant amounts of data pertaining to accidents has a parallel with respect to vehicle safety and fire testing. Minimal data exists and in some areas is obsolete. As noted previously, such data paucity was again an additional contributing factor in the decision to use the expert group judgment approach.

10. ACCIDENT SCENARIO SELECTION

To assess the potential hazards due to gaseous-fueled vehicle operation and determine the relative safety rankings for the fuels, it is necessary to introduce additional factors that will assist in the discrimination between fuels. The selection and analysis of events within accident scenarios is one method of accomplishing the above.

Scenarios were chosen to represent situations similar to those in existence at present and of interest to the user or vehicle owner. Should the large number of vehicles envisioned utilizing alternative fuels materialize, actual operational habits may indeed be different.

These scenarios are considered to be credible in <u>major</u> detail. There are however, a number of detailed and specific assumptions associated with the individual scenarios. In certain cases, these assumptions may conceivably create worst case situations.

The scenarios chosen include:

- Parking and storage/enclosed garage/fuel leakage
  Case A - residential
  Case B - public

- Fuel line rupture/fuel release
  Case A - user vehicle/station
  Case B - delivery vehicle/station

- Vehicle collision/rural/fuel release

- Vehicle collision/urban/fuel release

- o Vehicle collision/tunnel/fuel release

The major hazards considered were fire, explosion, and physiological damage. Both immediate and delayed ignition factors were considered in the analysis of the event sequences that produced those hazards. Comparisons were made on the basis of equal energy loss of fuel for all fuels considered in each scenario studied.

11. ANALYSIS MODEL FOR SCENARIOS

Modern risk analysis techniques can assign relative numerical values to perceived risks in a rational, reproducible, and traceable manner even for those accident scenarios where insufficient experience exists to permit conventional statistical analysis [7]. These techniques generally rely on the judgment of knowledgable experts.

In this study, selected accident scenarios were analyzed for three proposed automotive fuels (CNG, LNG, and LPG) for which there is no large body of accumulated accident experience and two conventional fuels (gasoline and diesel fuel) for which there is a sizeable body of accident experience. By analyzing these five fuels in parallel, the relative risks of the three new fuels to the risks of the two conventional fuels were obtained.

The basic approach in this assessment was to construct a mathematical model that would describe the accident scenario to the degree of necessary detail. The scenario is initially described by an event sequence consisting of a series of yes/no uncertainty nodes. The mathematical details of the model and the technique of weighting are described elsewhere [1].

The specific fuel properties that influence the likelihood of a "yes" or "no" outcome for an uncertainty node in the event sequence were then identified and given appropriate weights between zero and one according as to how important the experts felt each property was in determining the outcome of the uncertainty node. In addition, the chosen fuel properties were themselves intercompared and weighted as to their relative importance in contributing to the outcome (yes/no) of the uncertainty node [8]. The likelihood of a specific event occurring was calculated. Estimated precision of the technique was considered to be plus or minus 0.1.

12. EXAMPLE OF AN ACCIDENT SCENARIO ANALYSIS

As noted previously, specific and different detailed assumptions were assigned to each scenario. The following brief description of a scenario, a typical event sequence, and a set of results are given below. Other scenarios were treated in a similar manner.

12.1. Scenario--Vehicle Collision/Rural

A two vehicle angular collision occurs on a two-way traffic rural road, with one vehicle traveling at 60 mph. The vehicle with the specified fuel overturns and the integrity of the fuel system is damaged, so that 90 to 100% of the fuel is released during a 30 second time interval. Due to the nature of the accident, ignition sources are present at all critical times. Since the accident occurs in an uncongested rural area, there is ample air circulation.

Figure 1 shows the event sequence which includes immediate ignition, delayed ignition, explosion, and physiological damage.

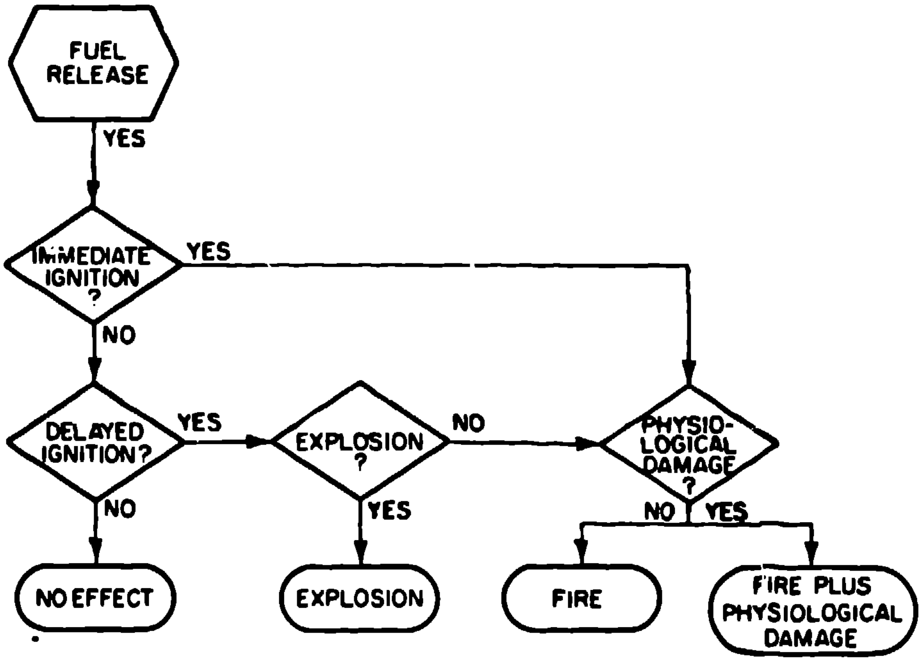

Fig. 1. Vehicle collision/rural/fuel release. Event sequence.

Results are shown in Fig. 2. The likelihood for fire alone is the same for the gaseous fuels and gasoline (within data precision). Physiological damage (burn) appears slightly more likely with LPG and gasoline than with natural gas. The likelihood of an explosion is zero for diesel fuel, very low for CNG and LNG, and still quite low for the non-dispersing LPG and gasoline. For this sequence of events, CNG and LNG are safer than LPG and gasoline. Diesel fuel is the safest.

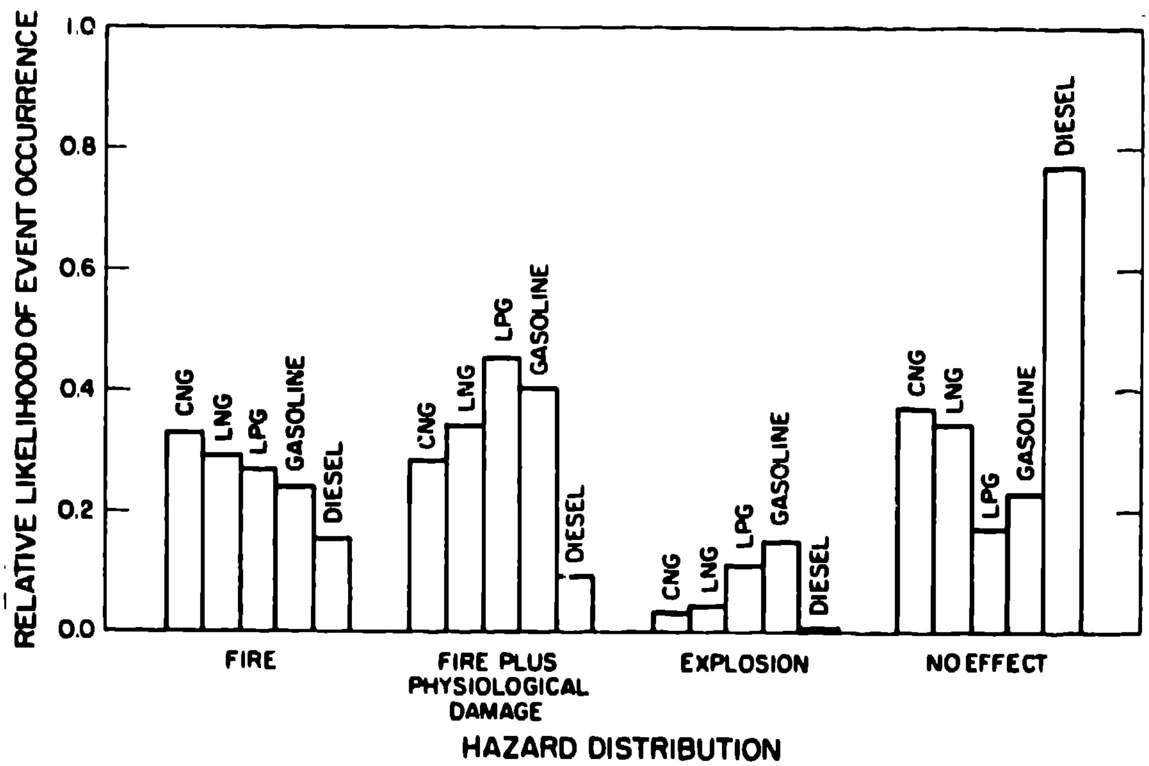

Fig. 2. Vehicle collision/rural/fuel release. Hazard distribution.

13. ASSESSMENT SUMMARY

Under the constraints of this assessment, diesel fuel stands out as being relatively and significantly safer than the other fuels.

Gaseous fuels have a significant explosion hazard relative to gasoline in the residential enclosed garage but are safer in terms of physiological damage. However, detailed leakage flow and mixing analysis would be required to establish a realistic situation. All fuels are relatively safe in a public garage.

For the fueling line rupture scenarios, the pressurized gaseous fuels exhibit a higher relative fire hazard level. This result arises from significant weighting given to the hazards of high pressure systems. It is also recognized, however, that present day engineering technology can reduce such hazards to acceptable levels of risk. No differentiation between gaseous fuels was made in this respect. Because of the larger volume of fuel released from delivery systems, a greater relative fire hazard exists. Analysis of very large fuel releases from delivery trucks, pipelines, or storage tanks is beyond the scope of this assessment.

With respect to collision scenarios, the rapidly dispersing natural gas fuels are relatively safer than the liquid fuel gasoline with LPG being an intermediate case due to a higher relative explosion hazard level. Within a tunnel gasoline poses a higher relative explosion hazard than the natural gas fuels.

Overall, the results obtained demonstrate dependency upon the specific scenario. Gaseous fuels have increased relative risks in some cases but are relatively safe in others. The results obtained do not disqualify gaseous fuels from public usage. It is here however, that engineering technology and safety regulations should be available to ensure relative safety in actual practice by assisting in risk reduction.

14. DEVELOPMENT OF SAFE HANDLING CRITERIA

Relative hazard levels determined from the fundamental properties can be altered in practice through the use of engineering technology and regulatory mechanisms. The scenario analyses and the safety test assessments herein suggest certain safe handling criteria that will involve these mechanisms. These criteria may be in the form of specific device development, regulations, or recommendations for necessary research or testing from which additional regulations may evolve. The criteria may simultaneously indicate gaps in the information base upon which gaseous fuel usage in the future will rest. They include:

- Development of reliable gaseous fuel detection monitors.
- Maintenance of adequate ventilation in enclosed systems.
- Development and safety testing of lightweight well-designed CNG fuel storage tanks.
- Design and reliability testing of excess flow, automatic shut off, and pressure relief devices.
- Sponsoring of long-term materials corrosion research and establishment of fuel quality standards (natural gas).

- o Development of odorant for LNG.
- o Initiation of full-scale safety vehicle impact testing.
- o Investigation of low pressure fuel storage methods.
- o Establishment and adherence to safety regulations.

ACKNOWLEDGMENTS

The authors thank Dr. R. D. Fleming of the US DOE Office of Vehicle and Engine Research and Development for his special interest and guidance in this relative safety assessment.

The consulting assistance of J. Bartlit, J. H. Altseimer, F. J. Edeskuty, and K. D. Williamson, Jr., is gratefully acknowledged.

REFERENCES

1. Krupka, M. C., Peaslee, Jr., A. T., and Laquer, H. L., "Gaseous Fuel Safety Assessment for Light-Duty Automotive Vehicles," Los Alamos National Laboratory report LA-9829-MS (1983).

2. Assessment of Methane-Related Fuels for Automotive Fleet Vehicles, US DOE Report No. DOE/CE/50179, Vol. 1-3, prepared by Aerospace Corp., El Segundo, CA (February 1982).

3. Hord, J., "Is Hydrogen Safe?", NBS Technical Note 690, Institute of Basic Standards, National Bureau of Standards, Boulder, CO (October 1976).

4. Bowen, T. L., "Hazards Associated with Hydrogen Fuel," Eleventh IECEC Meeting, Vol. 1, Lake Tahoe, CA (September 1976).

5. Van der Weide, J., "Safety Testing of LPG and Gas-Fueled Vehicles," Non-petroleum Vehicular Fuels Symposium, Institute of Gas Technology, Arlington, VA (February 11-13, 1980).

6. Gas-Powered Vehicle Evaluation Program, Report No. TES C372, prepared by TES, Ltd., for the Road and Motor Vehicle Traffic Safety Branch, Transport Canada (March 31, 1982).

7. Crouch, E. A. C. and Wilson, R., Risk/Benefit Analysis (Ballinger, Cambridge, 1982).

8. Saaty, T. L., "The Analytic Hierarchy Process (McGraw-Hill, New York, 1980).