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Gaseous-Fuel Safety Assessment

Status Report

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for presentation at the

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ABSTRACT

The Los Alamos National Laboratory, in support of studies sponsored by the Office of Vehicle and Engine Research and Development in the US Department of Energy, has undertaken a safety assessment of selected gaseous fuels for use in light automotive transportation. The purpose is to put into perspective the hazards of these fuels relative to present day fuels and delineate criteria for their safe handling. Fuels include compressed and liquefied natural gas (CNG and LNG), liquefied petroleum gas (LPG), and for reference, gasoline and diesel. This paper is a program status report. To date, physicochemical property data and general petroleum and transportation information were compiled; basic hazards defined; alternative fuels were safety-ranked based on technical properties alone; safety data and vehicle accident statistics reviewed; and accident scenarios selected for further analysis. Methodology for such analysis is presently under consideration.

THE USE OF ALTERNATIVE AUTOMOTIVE FUELS other than those derived primarily from petroleum were considered for many years and in fact were used in relatively minor quantities. More recently a rekindling of interest in the utilization of these fuels has emerged. The impetus for this is derived from a variety of reasons including:

- a mandate to reduce exhaust pollution
- escalating fuel costs
- concern over potential petroleum supply reduction
- a desire for self-sufficiency (import reduction)
- potential technical advantages.

The alternative fuels under consideration are by no means new energy sources. However, because their use in the automotive transportation sector was limited, an extensive commercial infrastrucutre such as exists for petroleum and its refined products has not been developed.

The expected increased usage of these fuels for routine automotive transportation has also elicited an increase in concern over their relative safety. A degree of risk is always associated with the use of energy sources. Acceptance of large scale usage of new energy sources and technologies by both government and the public-at-large can be expedited if it can be demonstrated through adequate assessment, safety testing, and operational experience that the intrinsic risk is either equivalent to or less than that associated with the energy source presently used. Liquid petroleum products such as gasoline and naphtha are flammable, in selected situations explosive, yet are safe and acceptable when handled properly.

Under mandate as described in the Methane Transportation Research, Development, and Demonstration Act of 1980, P.L. 96-512, the United States Department of Energy (DOE) has developed an Alternative Fuels Utilization Program. The program is managed by the Office of Vehicle and Engine Research and Development (VERD). In support of VERD, the Los Alamos National Laboratory is undertaking a safety assessment of selected gaseous fuels for use in light automotive transportation.

The purpose of the assessment is to put into perspective the relative hazards of these fuels compared to gasoline and diesel fuels and to delineate criteria for their safe handling in the transportation sector.

This paper is a status report. Completed efforts are described herein but significant analysis remains to be accomplished.

TRANSPORTATION SECTOR

In 1980, the transportation sector consumed approximately 50% of the total US petroleum supply. Of this quantity, approximately 80% was used for highway motor fuels (1).* Motor fuel consumption amounted to about 1.2×10^{11} gallons (gal) (gasoline, diesel, and LPG). Gasoline alone accounted for about 1.0×10^{11} gal (2). LPG sold for internal combustion engine use amounted to about 5.0×10^{8} gal although not all was used for mobile transportation purposes (3). On-highway transportation use of distillate fuel oil (diesel) amounted to about 1.4×10^{10} gal (3). The quantity of natural gas used as a motor fuel was very minor relative to these quantities.**

Of the 1.2×10^{11} gal of motor fuel consumed, about 8.0×10^{10} gal were used by personal passenger vehicles and motorcycles, about 4.0×10^{10} gal were used by trucks [all gross vehicle weight (gvw) classes] and approximately 0.1×10^{10} gal by buses (4). A discussion of resource availability and the impact upon fuel production is given by Fleming (5).

A total of about 1.6×10^{8} vehicles were registered in 1980 (6). This number can be subdivided as follows:

o	passenger vehicles	1.2×10^{8}
o	trucks	3.5×10^{7}
o	buses	5.5×10^{5}
o	motorcycles	5.8×10^{6}

Light trucks (< 10,000 lb gvw) represent about 85% of the truck fleet.

The use of diesel fuel in passenger vehicles has increased recently and in 1980, diesel-powered passenger vehicles represented about 4.4% of new vehicle registrations.

Approximately 1.5×10^{12} vehicle miles were traveled in the US in 1980 (6).

A brief discussion of the number of vehicles, injuries, and fatalities involved in vehicular accidents will be presented later.

PHYSICOCHEMICAL PROPERTY DATA

The comparative safety assessment of the alternative automotive fuels considered herein relies heavily upon the fundamental physicochemical properties of the fuels. Selected property data for these fuels were compiled and are shown in Table 1.***

The properties of natural gas and methane are considered to be equivalent in this report. Methane is the primary constituent of the natural gases used as fuels although they may contain small quantities of other hydrocarbons. Moisture and a small amount of sulfur are also present. Similarly, the properties of LPG and propane are considered to be equivalent. For the automotive fuel application, a special grade under tight ASTM specifications, HD-5, is used. This grade contains propane in excess of 90%.

*Numbers in parentheses designate references at end of paper.

**Total mileage accumulated by natural gas-powered vehicles is assumed to be about 2.1×10^{8} miles over the years 1970-1981. Using conversion factors of 15 miles per gallon and 100 ft^3 per gallon of gasoline equivalency, about 14×10^{8} ft^3 of gas were used over this time period.

***Additional property data will appear in the final report to be published at a later date.

Table 1. Selected Physicochemical Properties of Automotive Fuels

	Natural Gas*		LPG*	Gasoline	Diesel
	CNG	LNG			
Expansion Ratio, Liquid → Gas	600-650		270-310	~156	(Est. ~ 125)
Specific Gravity (Relative to Air = 1.00)	0.55	--	1.45-1.56	3.4-3.9	--
Energy Content, Btu/gal	19760	94150	87380	10500-11500	130000-138200
Energy Content, Btu/lb	21300	21300	19700	18200-19200	19200-19700
Flammability Limits, Vol. %	5.3-15.0	--	2.4-9.5	1.0-7.6	0.5-4.1
Detonation Limits, Vol. %	6.3-13.5	--	3.1-7.0	1.1-3.3	--
Autoignition Temp., K	813	--	765-875	501-744	~520
Ignition Energy, Min., mJ	0.29	--	~0.24	0.24	(Est. ~ 0.25)
Flash Point, K	gaseous	--	gaseous	230	310-340
Flame Temp., K	2148	--	2243-53	2470	--
Diffusion Velocity in Air (NTP)**, cm/s	≤0.51	--	--	≤0.17	--
Buoyant Velocity in Air (NTP), cm/s	0.8-6	--	nonbuoyant	nonbuoyant	nonbuoyant
Heat Release Rate, Pool, kW/M^2	--	168	--	352	560
Burn Velocity in Air (NTP), cm/s	37-45		40-47	37-43	~34
Viscosity at NBP,** Poise	--	0.0011	0.002	~0.002	(Est. ~ >0.004)
Storage Conditions	Gas, Compressed (2400 psig)	Liquid @ NBP	liquid under pressure (~6-8 atm)	liquid @ ambient T&P	Liquid @ ambient T&P

*Methane and natural gas are used interchangeably in this report. LPG and propane are similarly used interchangeably.

**NTP = 1 atm and 293.15 K; NBP - normal boiling point, LNG = 111.6 K.

HAZARD IDENTIFICATION

In any comparative safety analysis or risk assessment, it is necessary to define within reasonable limits the boundary conditions for the given system. The choice of parameters is critical. For the alternative fuels under investigation, those hazards contributing to the risk of using the specific fuel are identified herein as primary hazards. They include:

- fire
- deflagration/detonation
- cryogenic damage
- physiological damage

On a secondary or sublevel of hazard definition, one can generate a set of conditions or generalized properties that lead to the primary hazard. This sublevel has as its basis and is derived from, an interactive matrix of fundamental physicochemical properties. The latter in turn represent a third or hard technical data level required as a basis for selected techniques of safety analysis. Selected sublevel hazards are shown in Table 2.

HAZARD/PROPERTY INTERRELATIONSHIPS

The relationships between the hazards of several fuels [natural gas (methane), gasoline, diesel] and the fundamental physicochemical properties of those fuels have been discussed in significant detail by Hord, Bowen, and others (7,8). Our comparisons also include LPG. The fundamentals of combustion, flames, and detonation are thoroughly discussed in many texts, e.g., Lewis and Elbe (9). It suffices here to briefly mention a couple of examples of potential pitfalls when determining relative safety based upon hazard/property considerations alone.

Analogous to the case of liquid hydrogen, spillage of other cryogenic fuels, LNG and LPG, can cool a volume of air immediately surrounding the cryogen (7). If the vapor density of the cryogen/air mixture approaches or becomes greater than that of air, the cryogen/air mixture becomes nonbuoyant and can spread to distances beyond the immediate spill zone. In time, the cryogen/air mixture will warm and rise creating a hazard over greater distances as well as lengthening the time period for the existence of the hazard.

Table 2. Selected Secondary Hazards

	Fundamental Property
Leakage	Absolute Viscosity, Molecular Weight
Mixing/Dispersion	Diffusivity, Buoyancy
Volatility (Spill)	Thermal Diffusivity, Density, Vapor Pressure (Heat of Vaporization)
Ignition	Ignition Energy, Flash Point, Autoignition Temperature
Flammability	Flash Point, Vaporization Rate (Thermal Conductivity, Heat Capacity), Composition
Radiation	Burning Velocity, Emissivity, Heat Release Rate
Mechanical Containment	Chemical, Metallurgical, and Engineering Properties (various)

The greater buoyancy of natural gas (versus gasoline, diesel, and LPG) becomes advantageous in unconfined areas by permitting rapid dispersion and dilution. Confinement, on the other hand, can reverse the assessment since a fire and possible detonation hazard is produced quickly. Hence the importance of defining boundary conditions for a given application or scenario.

SAFETY RANKING OF FUELS

A preliminary comparative safety ranking was accomplished based upon consideration of the absolute technical properties of each fuel. Each property is considered and the fuel ranked accordingly. Effects of property interactions and other boundary conditions are not considered here. Rankings are essentially qualitative. It is recognized that the methodology is relatively simple and that realistically the final assessment must ultimately take other factors into account. It does demonstrate however, that

- o certain properties contribute more to hazard generation than others
- o certain properties are neutral, i.e., fuel rankings are equivalent
- o certain properties reverse the rankings generated by others
- o safety ranking becomes a more complex problem

Comparative safety rankings are shown for a selected number of properties in Table 3.

MULTIPLE PROPERTY CRITERIA - Fuels may also be ranked according to secondary or sublevel hazard designations noted in Table 2. This was done in part by Bowen for nine fuels including methane, gasoline, and diesel (8). Rankings were made on the basis of 1-9, the largest number indicating maximum hazard. Our analysis has produced similar results with LPG included. Selected results of our analysis on the basis of 1-4, the larger number indicating maximum hazard, are presented in Table 4.

Once again, it is apparent that safety ranking of this type will yield various results although there is a trend to classify LNG and LPG as more hazardous materials. These rankings also suggest diesel fuel to be the safest. Toxicity or emission data (not shown) may however change the above. It should be emphasized again that rankings are based solely upon technical data. Stringent boundary conditions, applications, scenarios, and risk abatement strategies are not involved.

Table 3. Safety Ranking of Fuels-Selected Properties

	Ranking Order* >(more hazardous than)
Flammability Range	NG > LPG > G > D
Ignition Energy	~Equivalent
Autoignition Temperature	$\genfrac{}{}{0pt}{}{G}{D} > \genfrac{}{}{0pt}{}{NG}{LPG}; \genfrac{}{}{0pt}{}{G}{D} > LPG > NG$
Diffusion Coefficient	NG > G or G > NG**
Energy Content-Volume	D > G > NG > LPG
Energy Content-Mass	~ Equivalent
Heat Release Rate (Radiation)	D > G > NG > LPG

*NG, natural gas (methane); LPG, liquefied petroleum gas (propane); G, gasoline; D, diesel.
**Dependent upon confinement.

Table 4. Safety Ranking of Fuels-Selected Multiple Criteria

	Leakage	Flammability	Radiation	Volatility (Spill)	Dispersion (Unconfined)
CNG	4	3	1	--	1
LNG	4	3	1	4	3
LPG	3	3	2	3-4	2
Gasoline	2	2	3	2	4
Diesel	1	1	4	1	4

The ranking methodology so far detailed yields some idea of the relative hazards of these fuels, but only in a most general sense. In basic agreement with the general conclusions of Hord, a relative safety analysis of alternative fuels will now require the generation of specific accident or application scenarios.

SAFETY DATA, TESTING, AND OPERATIONAL REVIEW

General motor vehicle accident data as well as those applicable to LPG-, CNG-, and LNG-powered vehicles have been compiled and reviewed.

GENERAL MOTOR VEHICLE ACCIDENT DATA - Some pertinent motor vehicle data are presented. These data were obtained from several sources (2,6,10). It can be assumed that the great majority of vehicles involved were gasoline-powered plus a small percentage under diesel power.

In 1980, motor vehicle accidents resulted in 51,077 fatalities and approximately 2.0 x 10^6 nonfatal injuries of all types. The fatality rate per 1 x 10^8 vehicle miles was 3.38, per 10^3 registered vehicles 0.3, and per 10^4 licensed drivers, 3.5. Vehicles involved in fatal accidents numbered 63,477 of which fire was reported in 1,720 or 2.7%.* We do not to date have details on fuel type or whether explosions occurred. Fire involvement data in all types of accidents can only be estimated. Some old data suggest that fires occur in approximately 0.1% of all accidents (11). This translates to approximately 12,000 vehicles. Passenger vehicles and light trucks were the major vehicle types involved in accidents, 80%. Approximately 12 x 10^6 vehicles of all types were involved in accidents.

Head-on and various angular collision accidents represented the two most prominent multivehicle fatal accident scenarios, each causing approximately 40% of the accidents. (Rear end collisions accounted for approximately 30%.) Over 60% of fatal accidents involved a single vehicle. The majority of fatal accidents occurred on rural roads, approximately 55%.

Finally, the risk of death occurring in a passenger motor vehicle accident was estimated at 21-28 per 10^5 persons per year (averaged over 25 years).

LPG MOTOR VEHICLE ACCIDENT DATA - Statistics applicable to LPG-powered vehicles are more difficult to acquire and subsequently assess. Although some risk assessments are available for large volume usage of LPG (marine shipping and terminals, storage, rail and tanker truck shipments) such assessments may

*Communication with National Highway Traffic Safety Administration (August 1982).

not be applicable to individual motor vehicles although selected effects and characteristics of large scale accidents may be pertinent. These large scale accident data and those data concerned with consumer products (stoves, campers, etc.) are not given here.

Ford Motor Company personnel estimate that there are approximately 300,000 LPG-powered vehicles on the US highways (11). Some older studies on the use of LPG as an engine fuel covering a 30-year period listed 18 accidents, 26 injured, and two fatalities. Another 13-year period study listed 174 accidents, most relatively minor (12). The Netherlands have approximately 220,000 LPG-powered vehicles in operation. Safety record is reported very good. A number of vehicle fires were reported but no explosions (13). Full scale safety crash tests on LPG-powered vehicles were accomplished with compact European cars and some city buses. Vehicle storage tanks withstood these tests well with leakage primarily occurring from other components of the fuel system.

LNG MOTOR VEHICLE ACCIDENT DATA - Data on LNG-powered vehicles are minimal primarily due to the very few vehicles that were or are in operation. The Atlanta Gas and Light Company operates about 100 vehicles. The company reported four collisions in 1976-78 (two rear end, two side angular) no fire/explosion, no injuries, no fatalities. The company also reports three cryogenic burn incidents during transfer oprerations. LNG-fueled vehicles have traveled approximately 2.5×10^6 miles since 1975. Full scale safety crash tests on LNG vehicle storage tanks were conducted in 1971 by the US Department of Transportation (DOT) (14).

CNG MOTOR VEHICLE ACCIDENT DATA - Estimated total mileage accumulated by natural gas fueled vehicles since 1970 is approximately 2×10^8 miles. Most of these have been accumulated by the Southern California Gas Company operating approximately 2500 vehicles on CNG. Something over 30,000 vehicles total are reported to be operating on natural gas (CNG and LNG). The total number of accidents involving CNG-powered vehicles is not available but is estimated to be approximately 1500. Very few injuries, no fatalities, a few fires, and no explosions were reported.

Safety impact testing on full scale vehicles of 1959-1968 vintage was accomplished by the US DOT (14). It should be noted that today's American vehicles are constructed quite differently. The Canadian Government has recently completed a series of impact tests (15). Several private concerns have conducted tests on fuel system components, viz., Dual Fuel Services and Beech Aircraft Companies.

Operational experience to date as reported by several organizations (in excess of 40) is said to be very good although many note some technical and psychological disadvantages and have suggested selected improvements (16).

Irrespective of the physical state in which natural gas is stored in the vehicle, vapor leakage into the vehicle is a potential problem. A study by NBS was made concerning vapor seepage into vehicle interiors and recommendations made to minimize this hazard (17).

Additional reviews of safety-related issues concerning CNG-, LNG-, and LPG-powered vehicles are planned. Partial reviews will also be made of large volume LPG and LNG spill tests. The data obtained may prove useful in our final scenario analyses.

SELECTION OF CREDIBLE ACCIDENT SCENARIOS

To pursue the relative safety ranking of alternative fuels further and to assess the hazards due to operation of gaseous-fueled vehicles, it becomes necessary to introduce additional degrees of realism, i.e., boundary conditions. The selection of credible accident scenarios with subsequent analysis is one method of accomplishing the above.

Consensus of opinion was used to select five general scenarios that warrant further analysis. These are believed to be credible in major detail. Although not precisely defined at this time, such definition will be completed shortly. It is recognized that the scenarios can assume worst case situations without definitive boundary conditions or the inclusion of specific risk abatement techniques that either already exist or can be applied. These will be taken into consideration in the final analysis.

The five scenarios include:

- Fuel Leakage - enclosed garage, parking and vehicle storage
  - Case A - Residential, attached
  - Case B - Public, ventilated
- Transfer Line Rupture, Break or Leak
  - Case A - Delivery Truck/station
  - Case B - User vehicle/station
  - Conditions of overfill, drive-off with hose attached, leakage will be examined.
- Vehicle Collision/Fuel Loss-Urban
  - Head-on/rear end/angular collisions at major interchange or business district
- Vehicle Collision/Fuel Loss - Rural
  - Highway speed and single vehicle
- Vehicle collision/Fuel Loss - Tunnel
  - High density traffic or jam, ventilation conditions

For each of the above scenarios the probabilities of the primary hazards occurring as a function of the fuel used will be examined.

RISK ANALYSIS

The operation of gaseous fueled vehicles presents some unknown degree of risk to the general public. Our efforts will be to determine whether or not such risk is equivalent to, better or worse than that already acceptable using the conventional fuels.

The program effort thus far has not yet reached the analysis stage. Our preliminary thoughts will be to consider existing levels of risk, these to be modified by constraints imposed by the chosen scenarios, and finally to estimate the risks imposed by the use of alternative fuels within those scenarios.

To assist in the risk estimations, it is tentatively planned to elicit information and judgment by convening or mail surveying a group of experts.

Four methods of elicitation of expert judgment will be examined to determine which one is the best for our purpose. The simplest is the staticized group method in which a questionnaire is filled out individually by the members of the group and the results averaged by routine statistical methods. This method is simple, but the results are generally poorer than the other three methods.

The second method is the Delphi method in which the experts reply to a mail survey. The survey results are then circulated anonymously to the group, and the group is asked to submit second round replies to the questionnaire. This process is repeated until the desired consensus is reached. The Delphi method is very time consuming.

The structured interactive group method can be likened to a face-to-face Delphi in that each expert presents his judgment to the group which remains silent to prevent spontaneous interaction. After each expert has made his presentation, the group discusses the judgments and each expert is allowed to modify his judgment in the next round of presentations. The process is repeated until the desired consensus is reached. Like the Delphi method, the structured interactive group method is time consuming.

The fourth method is the group consensus method in which the experts interact face-to-face to arrive at a consensus judgment. Although this method is the shortest in time, careful control by the discussion leader is needed to keep the group on course and careful monitoring is necessary to assure consistency and to avoid judgment degradation due to cognitive fatigue, for example.

Two analytical approaches to reduce any statistical data, group responses, and expert judgment into an overall risk analysis will be considered. If the e is sufficient data to support a fault tree analysis, this well known technique might be chosen. The disaggregation of the problem in the manner pioneered by Saaty could also be used where more weight must be placed on subjective expert judgment.

The fault tree analysis considers graphical and logical representation of possible fault and normal events for a system which can result in a predefined unwanted event (accident). The unwanted or final top event is analyzed for various ways by which it may occur. Each subevent is similarly analyzed. One arrives finally at a basic level of events or information where probabilities of occurrence or values are known with a high degree of confidence.

The Saaty pair-comparison technique considers a partitioning of the analysis into several sublevels aimed at generating a specific index value (which can be intercompared) for each fuel within a given scenario. It is basically a scoring methodology. The technical properties of the fuel provide the basis for the buildup of several levels to the final determination of the index value., viz., technical property information--secondary sublevel hazard--primary hazard--index value (18).

Our current thoughts lean strongly to the use of the group consensus method for elicitation of information and the Saaty technique as a scoring methodology.

ASSESSMENT STATUS

In review, assessment status is as follows:

- Physicochemical property data assembled
- General petroleum and vehicle usage data compiled
- Primary hazards defined
- Secondary sublevel of hazards defined
- Fuels ranked based upon both properties alone and on interactive matrix
- Safety data reviewed
- Accident scenarios selected
- Interfuel safety analysis and comparison to be initiated.

REFERENCES

1. Transportation Facts and Trends, 17th Ed. and supplements dated April 1982 and August 1982, Transportation Association of America (December 1981).

2. Highway Statistics, US Department of Transportation, Federal Highway Administration (1980).

3. Petroleum Supply Annual-1981, V. 1, DOE/EIA-3340 (81)/1 (July 1982).

4. National Transportation Statistics, US Department of Transportation, report no. DOT-TSC-RSPA-81-8 (1981).

5. R. D. Fleming and R. L. Bechtold, "Natural Gas (Methane), Synthetic Natural Gas, and Liquid Petroleum Gases as Fuels for Transportation, West Coast International Meeting, SAE paper no. 820959, San Francisco, CA (August 16-19, 1982).

6. Transportation Safety Information Report, US Department of Transportation, report no. DOT-TSC-RSPA-81-7 (June 1981).

7. J. Hord, "Is Hydrogen Safe?" NBS Technical Note 690, National Bureau of Standards (October 1976).

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

9. B. Lewis and G. von Elbe, Combustion, Flames and Explosions of Gases, 2nd Ed., Academic Press, New York (1961).

10. Fatal Accident Reporting System, 1980, US Department of Transportation, National Highway Traffic Safety Administration, report no. DOT-HS-805953 (October 1981).

11. Symposium on Nonpetroleum Vehicular Fuels II, Institute of Gas Technology, Detroit, MI (June 15-17, 1981).

12. D. Schultz, "LP-Gas Engine Fuels," Symposium at 75th ASME Meeting, ASTM Special Tech. Publ. 525, Los Angeles, CA (June 25-30, 1972).

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

14. Dual-Fuel Motor Vehicle Safety Impact Testing, US Department of Transportation report no. DOT/HS-800622, Dynamic Science, Division of Marshall Industries (November 1971).

15. Transport Canada, Motor Vehicle Traffic Safety Branch, Field Safety Impact Test Program, Winter 1981-1982. Noted in Canadian Consumer (June 1982).

16. T. J. Joyce, "Assessment of Research and Development Needs for Methane-Fueled Engine Systems," Final report for Gas Research Institute, Contract No. 5081-310-0507 (March 1982).

17. J. M. Arvidson, J. Hord, D. B. Mann, "Efflux of Gaseous Hydrogen or Methane Fuels from the Interior of an Automobile," NBS Technical Note 666 (March 1975).

18. T. L. Saaty, The Analytic Hierarchy Process, McGraw Hill, Inc., New York (1980).