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COMPARATIVE ANALYSIS OF HYDROGEN
FIRE AND EXPLOSION INCIDENTS

Progress Report No. 3
for Period March 1, 1978 - June 30, 1978

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ABSTRACT

Approximately 140 additional hydrogen incident reports have been compiled during this reporting period to increase the total number of reports to about 420. A preliminary analysis of the data shows that 60 percent of the reported incidents have been hydrogen explosions and that 82 percent of the casualties have been due to explosions. Inadequate hydrogen detection of leaks, incomplete purging, etc., was a primary cause factor in 36 percent of the incidents. Recommendations are presented for research in explosion protection, hydrogen leak and flame detection, and ignition sources associated with high speed emergency releases of hydrogen.

A multivariate regression analysis has been conducted to compare the severity of hydrogen and natural gas losses at Factory Mutual insured plants. The results indicate that, after accounting for the effects of deductibles, occupancy type and inflation, there is no statistically significant difference between the severity of hydrogen and natural gas losses.

A simple calculation of the frequency of hydrogen and natural gas incidents at ferrous metal processing plants indicates that there have been significantly more hydrogen incidents per unit volume or per unit energy of gas consumed. A similar calculation is presented for petroleum refinery incidents, but with less conclusive results.

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FOREWORD

This report describes work performed under Department of Energy, Contract No. EE-77-C-02-4442 during the four-month period, March 1, 1978 to June 30, 1978. The overall objectives of the study are: 1) to conduct a comparative evaluation of the safety records of hydrogen and natural gas; 2) to identify hydrogen safety aspects requiring further research or standard/code modification; and 3) to quantitatively assess the relative hazards of alternative modes of hydrogen storage, transport, utilization, and disposal.

In the first quarterly report, available sources of hydrogen and natural gas accident data were described, as well as statistics on hydrogen and natural gas production and use.

In the second quarterly report, a tabulation of hydrogen incidents was presented and discussed in terms of generic types of accidents. A brief preliminary comparison of property damage from hydrogen and natural gas incidents was also presented.

In this progress report, computer tabulations are presented for the causes and factors involved in the hydrogen incidents in our data bank. A thorough statistical comparison of property damage from hydrogen and natural gas incidents at FM insured plants is described. The more sophisticated comparison in this report clarifies the results of the preliminary comparison in the second progress report.

The following organizations and personnel have provided valuable assistance to the authors during this report period: Mr. David Jeffries (Factory Mutual Engineering Corporation), Factory Mutual Loss Analysis Department, Mr. Paul Ordin, Industrial Risk Insurers, Kemper Insurance Co. HPR Dept., the American Petroleum Institute, the Occupational Safety and Health Administration, and the Association for the Promotion of German Fire Protection (VFDB).

I

STATUS OF HYDROGEN INCIDENT REPORT COMPILATION

During this reporting period, approximately 140 additional hydrogen incident reports have been collected from the sources listed in Table I. These reports are currently being processed, together with the 280 incident reports already in the computer data bank.

Several of the sources listed in Table I complement the previous sources (Table I of Quarterly Report No. 2⁽¹⁾) in that they expand our coverage of current hydrogen use. For example, many of the NASA incidents involve liquid hydrogen operations associated with rocket propulsion. The reports from Industrial Risk Insurers and the American Petroleum Institute provide increased representation from refineries and petrochemical plants, which are the two largest hydrogen users. Most of the VFDB reports describe explosions involving hydrogen filled, lighter-than-air balloons. Although hydrogen-filled balloon explosions are not directly relevant to the industrial use of hydrogen, they have illustrated a lesson about the differential permeability of rubber to oxygen and hydrogen diffusion.

During the next reporting period a detailed statistical tabulation and analysis will be conducted using the approximately 420 incidents in the completed data bank. A preliminary tabulation and discussion of the 280 incidents previously entered in the data bank is presented in Section II of this report.

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TABLE I
ADDITIONAL HYDROGEN ACCIDENT REPORTS
COLLECTED IN THIRD REPORT PERIOD

Source	Type of Occupancy	Number of Reports
NASA ¹	NASA and Contractor Facilities	~100
American Petroleum Institute ² - 1977	Oil Refineries	14
Industrial Risk Insurers	Refineries and Chemical Plants	13
Kemper Insurance Cos.	Paper Mill, Semiconductor Plant	2
OSHA	Industrial Gas Plant, Electronics Plant	2
VFDB - Assoc. for the Promotion of German Fire Protection ³	Hydrogen Balloons used at Fairs	9
	Total	~140 ⁴

Notes:

¹ The NASA reports were furnished by Mr. Paul Ordin, formerly of NASA Lewis Research Center

² These 1977 reports are in addition to the 31 API reports previously collected for the period 1973-76

³ Only three of the nine VFDB incidents have been translated into English

⁴ These 140 reports are in addition to the 280 reports previously collected

II

PRELIMINARY ANALYSIS OF HYDROGEN LOSSES

2.1 ACCIDENT DATA BANK TABULATION

Table II shows the distribution by industry of the 280 hydrogen incidents discussed in this section. All of the major hydrogen use industries are represented, but not necessarily in proportion to their relative hydrogen consumption (Table I of Quarterly Report No. 1⁽²⁾).

The largest number of incidents listed in Table II is from the chemical industry. Of the 83 incidents from the chemical industry, 26 occurred at ammonia plants and 24 at chlor-alkali plants. One explanation for the large number of ammonia plant incidents is the high gas pressures needed for ammonia synthesis. The large number of chlor-alkali plant incidents is due, in part, to many hydrogen-chlorine runaway reaction explosions. Representative hydrogen explosion case histories from an ammonia plant and a chlor-alkali plant have been described in Quarterly Report No. 2, p 8⁽¹⁾.

The property damage distribution for the 280 hydrogen incidents is shown in Figure 1. Although it is not obvious from Figure 1, the damage distribution approximates a log-normal distribution function, which is a commonly encountered statistical distribution function in studies of insurance losses. The log-normal distribution has been employed in the statistical comparison of hydrogen and natural gas losses as described in Section III.

The numbers of fires, explosions, and other types of hydrogen incidents are listed in Table III. There have been about twice as many reported explosions (165) as fires (74) in the data set. Furthermore, explosions have been responsible for 63 of the 77 reported casualties (injuries and fatalities). The casualty figures are also listed on a normalized basis in Table III as the number of casualties for each type of incident. Explosions have resulted in an average of 0.38 casualties per incident, while fires have caused 0.11 casualties per incident. Thus, hydrogen explosions have been at least twice as troublesome as hydrogen fires, both in terms of the number of incidents and the number of casualties per incident.

Before a hydrogen fire or explosion can occur, a combustible hydrogen-oxidant mixture must exist. Figure 2 is a histogram of the reported primary

TABLE II
REPORTED HYDROGEN INCIDENTS BY INDUSTRY

Industry	No. of Incidents
Chemical	83
Oil Refining	33*
Power Plants	~30
Metalworking	26
Electronics	19
Food Processing	9
Other or Unidentified	80

* 16 additional refinery incidents during 1977 are currently being compiled to make a total of 49 refinery incidents.

FIGURE 1
HYDROGEN INCIDENT STATISTICS - 1961 - 1977
DAMAGE DISTRIBUTION FOR ALL INCIDENTS (1977 DOLLARS)

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TABLE III
CASUALTY DISTRIBUTION AND TYPE OF HYDROGEN INCIDENT

Type of Incident	No. of Incidents	No. of Casualties	Casualties Per Incident
Fire	74	8	0.1081
Explosion	165	63	0.3818
Pressure Rupture	12	1	0.0833
Unignited Release	20	1	0.0500
Fire and Explosion	3	0	0.0
Other	<u>6</u>	<u>4</u>	<u>0.6667</u>
Total	280	77	0.2750

causes of the combustible mixtures involved in the hydrogen incidents. The first four categories shown in Figure 2, i.e., external and internal leaks and inadequate purging and ventilation, have in common the undetected presence of the combustible hydrogen-oxidant mixture where it did not belong. These four categories together account for 36 percent of all of the reported incidents. It is clear from this tabulation that more effective hydrogen detection techniques would result in a significant reduction of hydrogen accidents.

The other two high-frequency cause categories in Figure 2 are vessel/pipe ruptures (15.0 percent) and venting incidents (12.5 percent). Vessel/pipe ruptures have resulted mainly from materials or welding deficiencies, while venting incidents are usually associated with excessively low or high hydrogen vent rates. Typical accident case histories have been provided in Quarterly Report No. 2⁽¹⁾.

Figure 3 is a histogram showing the frequency of ignition sources involved in hydrogen fires and explosions. The three most commonly known ignition sources are electrical sparks (14.6 percent), electrostatic discharges (9.6 percent), and high temperature spontaneous ignition (16.8 percent). Electrostatic discharges are not well understood, but they are often associated with high-velocity hydrogen releases such as might occur during emergency venting. High temperature spontaneous ignitions are generally attributed to accidental releases of hot, pressurized hydrogen in oil refineries or chemical plants. It would be interesting to analyze some of the reported spontaneous ignitions to determine whether the released hydrogen was above the autoignition temperature after it mixed with enough air to be in the flammable concentration range.

Equipment involved in the reported hydrogen incidents are listed in Table IV. The two most frequent equipment categories are Boiling Water Reactor (BWR) off-gas treatment systems (28 incidents) and furnaces (26 incidents). BWR off-gas incidents were described in Quarterly Report No. 2. Furnace incidents involve metal heat-treating furnaces and some naphtha or natural gas reformer furnaces. Hydrogen atmosphere furnaces are particularly hazardous because they have to be carefully purged to avoid confined, high temperature hydrogen-air mixtures susceptible to explosions.

FIGURE 2

HYDROGEN INCIDENT STATISTICS - 1961 - 1977
DISTRIBUTION BY PRIMARY CAUSE

FIGURE 3
HYDROGEN INCIDENT STATISTICS - 1961 - 1977
DISTRIBUTION BY IGNITION SOURCE

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TABLE IV
HYDROGEN INCIDENT STATISTICS - 1961 - 1977

Equipment Involved	No. of Incidents	%
Compressor	19	6.79
Furnace	26	9.29
Heat Exchanger	12	4.29
Turbine Generator	6	2.14
Epitaxial Reactor	5	1.79
Electrolysis Cell	7	2.50
Battery	2	0.71
BWR Off-Gas System	28	10.00
Tank Trailer	16	5.71
Hydrogen Reformer	12	4.29
Other/Unknown	<u>147</u>	52.50
Total	280	

2.2 RECOMMENDED SAFETY RESEARCH

The foregoing discussion of accident report tabulations has demonstrated the need for three areas of hydrogen safety research. These areas are 1) hydrogen leak and flame detection, 2) hydrogen explosion protection measures, and 3) electrostatic ignition and high temperature spontaneous ignitions of released hydrogen.

In the area of leak and flame detection, it would be advantageous to develop odorants and flame illuminants so as to avoid having to rely on expensive and elaborate detection instruments.⁽³⁾ It will probably be easier to develop flame illuminants than odorants because almost any impurity can render a hydrogen-air flame visible. One interesting new hydrogen flame illumination technique has been the use of intumescent paints, which char, swell, and emit pungent gases when heated to about 200°C (ref 4, p 166). By swelling these paints can provide a thermal protective shield for walls exposed to fire. Testing is needed to quantify the effectiveness of intumescent coatings, both as an illuminant and as fire protection for hydrogen storage vessels.

New hydrogen leak detection techniques may possibly evolve as a spin-off from current research on natural gas leak detection. The gas industry has been conducting studies of new gas odorant additives that would not be subject to pipeline fading or to absorption by soil after leaking from a buried pipe.⁽⁵⁾ Another promising leak detection technique being developed for inaccessible pipes is the use of acoustic instrumentation calibrated to recognize gas jet noise radiated from a leak site.⁽⁵⁾ It would be advantageous to extend the scope of these studies to include hydrogen leaks as well as natural gas leaks.

In the area of hydrogen explosion protection, research is needed to develop building and equipment design guidelines for avoiding damaging overpressures. In particular, testing is needed to determine explosion venting requirements for hydrogen-air deflagrations within furnaces, compressors, process rooms, buildings, etc. The tests should provide correlations of peak explosion pressure as a function of vent area, and enclosure size and shape for worst case gas mixtures. Similarly, there is a need to determine overpressures for outdoor vapor cloud explosions adjacent to buildings and other structures. The vapor cloud explosion data would determine the adequacy of existing guidelines for safe separation distances for hydrogen storage and process facilities⁽⁴⁾.

In the area of hydrogen ignition, research is needed to determine emergency venting criteria for avoiding electrostatic and high temperature spontaneous ignition. For example, it would be helpful to determine whether a critical vent velocity exists for triggering electrostatic discharges in ungrounded or corroded vent lines. In the case of high temperature spontaneous ignition, it is important to determine how hot, pressurized hydrogen should be vented so that it will cool to below the ignition temperature before it forms a flammable mixture with ambient air.

III

STATISTICAL COMPARISON OF HYDROGEN AND NATURAL GAS LOSSES

3.1 LOSS SEVERITY COMPARISON

In Quarterly Report No 2⁽¹⁾, a preliminary comparison of hydrogen and natural gas loss severity was presented based on reported fire and explosion incidents at Factory Mutual insured occupancies. The preliminary comparison showed that the median hydrogen fire loss (\$30 thousand) was only 22 percent higher than the median natural gas fire loss (\$24.5 thousand); but the median hydrogen explosion loss (\$80 thousand) was 4.0 times the median natural gas loss (\$20 thousand). Since several different interpretations of these statistics are possible, a more rigorous statistical loss severity study was conducted during the present reporting period. The major objective of the rigorous statistical study has been to determine whether the observed difference in hydrogen and natural gas loss severity is due primarily to the respective gases, or to other factors which influence the loss data.

3.1.1 The Regression Model

The analysis described in this section is based on a sample of 410 claims for a total of \$48,662,640 at Factory Mutual insured occupancies during the period 1968-1977. It should be noted that because this study is based on insurance claims, it is restricted to losses which are greater than the corresponding deductible. The dollar value of the loss* is taken as the measurement of loss severity. In the following model, the loss is assumed to follow a log-normal distribution. The validity of this assumption is verified in Appendix A.

The statistical technique used to correlate the loss data is known as multiple (i.e., multivariate) regression analysis. In this technique the correlation takes the form:

*The computational procedure used for calculating the dollar value of the loss is:

$$L = (\text{pdam} + \text{pduam} + \text{pdded}) / \text{pctfm}$$

where

pdam - is the adjusted amount paid on the claim;

pduam - is the unadjusted amount remaining on the claim;

pdded - is the deductible;

pctfm - is the percentage of at-risk dollars insured by FM placing companies.

$$Y = b_0 + \sum_{i=1}^{20} b_i X_i \quad (1)$$

where:

$Y = \log (\text{loss})$

$X = \{x_1, x_2 \dots x_{20}\}$ is the vector of independent variables defined in Table V

$b = \{b_0, b_1 \dots b_{20}\}$ is a vector of coefficients to be estimated as explained below.

Regression analysis is designed to choose the vector of coefficients, b , which minimizes the sum of squares of deviations between observed values of Y and the model's predicted values of Y . In addition, a coefficient is estimated only if it contributes significantly to the predictive capability of the model; otherwise, it is assumed to be equal to zero. In order to accomplish this a stepwise regression algorithm is used.

The stepwise algorithm initially enters all elements of X into a candidate (for entry into the model) tableau. At each iteration the variable in the tableau which provides for the greatest reduction in the unexplained variation of Y is entered into the model and removed from the tableau. The procedure terminates when none of the variables in the tableau can significantly reduce the unexplained variation in Y . For the remaining X_i in the tableau, b_i is assumed to be equal to zero. Thus, the final correlation contains only a subset of the variables X_i , namely those variables which significantly influence the value of Y .

The 20 independent variables, X_i , listed in Table V fall into the following five groups: 1) deductible value, 2) FM Index (an inflation index listed in Appendix A.2), 3) type of peril (fire or explosion), 4) type of gas (hydrogen or natural gas), and 5) type of risk/occupancy. The deductible and FM Index are continuous variables that, on the basis of previous loss studies at FM, are known to influence property damage claims. The discrete variables for peril and type of gas are included because of the results of the preliminary comparison conducted during the last reporting period.

The risk/occupancy variable group was selected to reflect the different uses of hydrogen and natural gas. For example, the use of hydrogen at chemical plants entails much higher pressures and temperatures than hydrogen or natural

TABLE V
CANDIDATE VARIABLES FOR REGRESSION ANALYSIS

Continuous Variables:

- X_1 - log of Prop. Damage Deductible
 X_2 - log of the FM Inflation Index

Dummy Variables:

Variable: 1 if condition is true
0, otherwise

- X_3 - Peril = Fire
 X_4 - Gas = Natural Gas
 X_5 - (Peril = Explosion) and (Gas = Natural Gas)
 X_6 - (Peril = Fire) and (Gas = Natural Gas)
 X_7 - (Peril = Explosion) and (Gas = Hydrogen)
 X_8 - (Risk-Class = Chemical) and (Gas = Natural Gas)
 X_9 - (Risk-Class = Metal Working) and (Gas = Hydrogen)
 X_{10} - (Risk-Class = Metal Working) and (Gas = Natural Gas)
 X_{11} - (Risk-Class = Other Industrial) and (Gas = Hydrogen)
 X_{12} - (Risk-Class = Other Industrial) and (Gas = Natural Gas)
 X_{13} - (Risk-Class = Non-Industrial) and (Gas = Hydrogen)
 X_{14} - (Risk-Class = Non-Industrial) and (Gas = Natural Gas)
 X_{15} - (Risk-Class = Boiler Room and (Gas = Hydrogen)
 X_{16} - (Risk-Class = Boiler Room and (Gas = Natural Gas)
 X_{17} - Risk-Class = Metal Working
 X_{18} - Risk-Class = Other Industrial
 X_{19} - Risk-Class = Non-Industrial
 X_{20} - Risk-Class = Boiler Room

gas use at other industrial plants. In fact, the only occupancy class in which hydrogen and natural gas are often used in the same plant and in the same setting is the metalworking occupancy class. Heat-treating and annealing furnaces at metalworking plants often use natural gas for firing and a hydrogen atmosphere in the furnace work chamber. Therefore, a separate occupancy/risk category for metalworking plants was created to facilitate comparison of hydrogen and natural gas losses in a comparable setting. By the same token, the occupancy categories, boiler room and commercial-residential, were selected to isolate occupancies that may be unique to natural gas.

The distribution of hydrogen and natural gas incidents at the five occupancy categories is given in Table VI. Only the occupancy categories Metalworking and Other Industrial have proportionate representation of both hydrogen and natural gas incidents. Therefore, some of the results shown in Section 3.1.2 are based on incidents only in these occupancy categories.

The dummy variables X_5 - X_{16} in Table V represent interactions between the peril, gas, and occupancy variables described previously. By including these interaction variables as candidates for correlation, the regression model can identify any possible synergistic effects such as especially severe losses associated with hydrogen at chemical plants.

The criterion for including a candidate independent variable in the iterative correlations using eq (1), was that its coefficient, b_i , was statistically significant at the 5-percent level. That is, if a variable is not included in the final correlation, its coefficient can be assumed equal to zero with a 5-percent change of error.

3.1.2 Results of Regression Analysis

The final correlation indicated that, of the 20 independent variables listed in Table V, the only significant variables at the 5-percent level are X_1 - log of deductible, X_2 - log of Inflation Index, and X_{20} - Boiler Room occupancy class. The final version of eq (1) for this correlation is:

$$\hat{Y} = 7.951 + 0.2322 D' + 1.441 I' - (0.6080) \times C \quad (2)$$

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TABLE VI

NUMBER OF HYDROGEN-NATURAL GAS INCIDENTS

Type of Plant	Hydrogen	Natural Gas
1. Chemical	49	4
2. Metalworking	14	68
3. Other Industrial	20	159
4. Boiler Room	0	42
5. Commercial - Residential	<u>1</u>	<u>72</u>
Total	84	345

where

$Y = \text{Log loss}$

$D' = \text{Log deductible}$

$I' = \text{Log FM Index}$

$C = \begin{cases} 1 & \text{if the risk-class is a boiler room} \\ 0 & \text{elsewise.} \end{cases}$

In this correlation the coefficients of gas type, peril, and interaction terms for gas type and peril are not significant at the 5 percent level; hence, they were not included in the final equation. This means that, after removing the effects of the deductible and inflation, inclusion of the gas type and/or peril and/or interactions of gas type and peril will not significantly further decrease the unexplained variation in Y . Tests were performed on the regression model which showed that the model can be regarded as a satisfactory predictor in the sense that the range of response values predicted by the model is substantial compared with the standard error of the response. ⁽⁶⁾

Equation (2) provides a predictive model for $Y \equiv \log \text{ loss}$. As shown in Appendix A.3, the transformation of eq (2) to calculate the expected value, $\hat{L}$, of loss is

$$\hat{L} = A \times D^{0.2322} \times I^{1.4441} \quad (3)$$

where:

$$A = \begin{cases} 13,174 & \text{for boiler rooms} \\ 24,197 & \text{for metalworking, chemical, other industrial and} \\ & \text{non-industrial occupancies.} \end{cases}$$

The irrelevance of the type of peril and gas in the correlation for $\hat{L}$ can be illustrated by confining our attention only to metalworking and other industrial (i.e., not chemical plants or boiler rooms) occupancies. The mean and median losses in these occupancies are listed in Table VII for hydrogen and for natural gas incidents. The median losses for hydrogen and natural gas (\$26.1 and \$22.8 thousand, respectively) differ by only 12.6 percent and the mean losses differ by only 3.1 percent. Similarly, there is only a 16.6-percent difference between the median hydrogen explosion loss and median natural gas explosion loss in these occupancies. These differences, which are small compared to the overall differences between hydrogen and natural gas losses observed in the preliminary comparison, are probably due to deductible and inflation differences.

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TABLE VII
COMPARISON OF PROPERTY DAMAGE BASED ONLY ON NONCHEMICAL
INDUSTRIAL OCCUPANCIES OTHER THAN BOILER ROOMS

Gas	Type of Loss	Mean Loss (\$ Thousand)	Median Loss (\$ Thousand)
Hydrogen	Fire & Exp	96.0	26.1
Natural Gas	"	99.1	22.8
Hydrogen	Explosion	64.5	20.5
Natural Gas	"	90.0	24.6

The preceding results lead to the conclusion that hydrogen and natural gas loss severity is best explained as a function of deductible, occupancy class, and inflation rate. Once the effects of deductible, occupancy, and inflation are removed, there is no statistical evidence to support the hypothesis that hydrogen losses are more severe than natural gas losses. The apparent difference in loss severity found in the preliminary comparison is probably due to the fact that many natural gas losses occurred in boiler rooms and other low-deductible occupancies prone to relatively low-severity losses.

3.2 LOSS FREQUENCY COMPARISON

The loss frequency comparisons presented here are calculations of the number of reported hydrogen/natural gas incidents normalized by the amount of each gas consumed. The comparisons are conducted for two industries in which accident and gas consumption data are available for both gases. Comparisons conducted for the ferrous metal processing and refinery industries are described separately.

3.2.1 Ferrous Metal Processing

The steel industry uses hydrogen to reduce iron oxide ore and to prevent metal oxidation during heat treating. Hydrogen consumption for these operations in 1974 amounted to 18×10^9 scf⁽⁷⁾ (5.85×10^{12} Btu). Natural gas is used in the steel industry primarily as a fuel gas, although it also is sometimes used to generate special atmospheres for heat-treating furnaces. According to an interpolation of American Gas Association large volume sales statistics⁽⁸⁾, 578×10^{12} Btu (about 550×10^9 scf) of natural gas were consumed by the primary iron and steel industries during 1974.

The only available source of loss reports for both hydrogen and natural gas incidents at ferrous metal processing plants is the Factory Mutual data bank compiled by the FM Loss Analysis Department. During the six-year period 1971-1976 there were 14 reported hydrogen incidents and 64 reported natural gas incidents at FM insured ferrous metal plants. As shown in Table VIII, the FM incident numbers can be adjusted to estimate nationwide incident numbers by dividing by the fraction (43 percent) of large steel companies insured by the FM System.

TABLE VIII
COMPARISON OF HYDROGEN AND NATURAL GAS
INCIDENT FREQUENCIES AT FERROUS METAL PLANTS

	Hydrogen	Natural Gas
1974 Volume Consumption (10^9 scf)	18	550
1974 Energy Consumption (10^{12} Btu)	5.85	578
Incidents Reported at FM Plants (1971-76)	14	64
Adjusted Incident Number Nationwide*	32.3	148
Annual Volumetric Incident Rate (Incidents per 10^9 scf)	0.289	0.045
Annual Energetic Incident Rate (Incidents per 10^{12} Btu)	0.920	0.043

* This adjustment is equal to the number of reported FM incidents divided by the fraction of ferrous metal plants insured by FM ($13/30 = 43.3\%$).

The last two lines in Table VIII show the annual volumetric and energetic incident rates obtained by dividing the nationwide incident numbers by the estimated volume/energy of each gas consumed in that six-year period. The resulting comparison indicates that the hydrogen volumetric incident rate (0.289 incidents per 10^9 scf) is 6.4 times the corresponding natural gas rate. Similarly, the hydrogen energetic incident rate (0.920 incidents per 10^{12} Btu) is 21 times the corresponding natural gas rate. The fact that hydrogen has had a significantly higher fire/explosion incident rate than natural gas is consistent with the commonly accepted observation (ref 4, p 173) that hydrogen is more readily ignitable than methane, primarily because of its extremely low minimum spark ignition energy.

3.2.2 Petroleum Refining

American Petroleum Institute accident data have been used as the basis of comparison for petroleum refinery incidents. The comparison between hydrogen, natural gas, and LPG (propane) refinery incidents is shown in Table IX. The annual volumetric incident rate for hydrogen (0.0125 incidents per 10^9 scf) is about 40 percent higher than the corresponding rate for natural gas, but only about 30 percent of the LPG rate. The annual energetic incident rate for hydrogen (0.0385 incidents per 10^{12} Btu) is 4.5 times the corresponding rate for natural gas and 2.4 times the rate for LPG.

Although the results in Table V do indicate a higher incidence rate for hydrogen than for natural gas, the computed frequency rate differences are probably within the uncertainty of the API loss report data. Since the API data are based on voluntary reports by API member companies, it is impossible to estimate what fraction of the total losses are represented by the data. Thus, the incident rates in Table IX should not be compared to the ferrous metal plant incident rates given in Table VIII, which are based on a more reliable set of data. The other problem with the API data is that the gas involved in the incident is not always clearly defined, especially in the earlier loss reports. For these reasons, the petroleum refinery loss incident rates must be considered inconclusive as far as identifying statistically significant differences between the gases. This is in contrast to the comparison for ferrous metal operations, which did indicate a clearly higher loss incident frequency for hydrogen.

TABLE IX
COMPARISON OF GAS INCIDENT
FREQUENCIES AT PETROLEUM REFINERIES

	Hydrogen	Natural Gas/ Fuel Gas	LPG (Propane/Butane)
Annual Volume Consumption (10 ⁹ scf)	1,065 ¹	1,427 ²	174
Annual Energy Consumption (10 ¹² Btu)	346	1,498	456 ³
API Reported Incidents (1975-77)	40	38	22
Annual Volumetric Incident Rate (Incidents per 10 ⁹ scf)	0.0125	0.0089	0.042
Annual Energetic Incident Rate (Incidents per 10 ¹² Btu)	0.0385	0.0085	0.0161

¹Ref 7, figure for 1974

²Ref 9, figure for 1977

³Ref 10

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APPENDIX A.1

STATISTICAL DISTRIBUTION OF LOSS

DISTRIBUTION OF LOSS SEVERITY

The objective of this discussion is to determine the statistical distribution of loss severity for the sample of property damage claims attributed to hydrogen and natural gas. The log-normal distribution is favored by various studies of insurance loss and is well suited for regression analysis. This distribution is defined as follows:

For x , a r.v. (random variable), and y , generated under the transformation,

$$y = \log (x) \quad , \quad (A.1-1)$$

if

$$y \approx N (\mu, \sigma^2)^*$$

then x is said to follow a log-normal distribution.

Now for x defined as the dollar value of the loss, y , generated by the above transformation, μ , and σ^2 are estimated by the method of maximum likelihood and the adequacy of the assumption that y in $N(\mu, \sigma^2)$ is tested by the χ^2 (chi-square) goodness of fit test.

The procedure and results may be summarized:

Based on the assumption that y is normally distributed it can be shown that m.l.e. (maximum likelihood estimators) for μ, σ^2 are given by:

$$\text{Max } \hat{L} (\mu) = \hat{\mu} = [\sum y_i] / n \quad (A.1-2)$$

$$\text{Max } \hat{L} (\sigma^2) = \hat{\sigma}^2 = [\sum (y_i - \bar{y})^2] / n \quad (A.1-3)$$

where for $x_i \equiv$ the dollar value of the loss

$$y_i = \log (x_i)$$

and n is the number of observations in the sample.

Furthermore, assuming that y is $N(\mu, \sigma^2)$ with mean and variance estimated

* N - Normally Distributed with mean μ , variance σ^2

by $\hat{\mu}$, $\hat{\sigma}^2$, the χ^2 statistic measures discrepancy between actually observed frequencies and expected frequencies for the sample. In performing the χ^2 test, the data are partitioned into the cells in such a manner that 10 percent of the observations are expected to fall into each cell if y is normally distributed.

The computed χ_c^2 statistic is given by

$$\chi_c^2 = \sum_{k=1}^{10} [(O_k - e_k)^2 / e_k] \quad (A.1-4)$$

where O_k = actual number of observations in cell k

e_k = expected number of observations in cell k .

Based on the result of the χ^2 test, the assumption that y is normally distributed is not rejected. Results are summarized in Table A-1.

TABLE A-1
RESULTS OF χ^2 TEST FOR LOG-NORMAL ASSUMPTION

Cell	Interval	$P_k =$ $\Pr[a < y \leq b]$	ϕ_k	$\epsilon_k = P_k * N$	$\frac{(\phi_k - \epsilon_k)^2}{\epsilon_k}$
1	$-\infty < y \leq 7.746$	0.10	41	41	0
2	$7.746 < y \leq 8.486$	↓	37	↓	0.390
3	$8.486 < y \leq 9.038$		40		0.024
4	$9.038 < y \leq 9.503$		47		0.878
5	$9.503 < y \leq 9.951$		39		0.098
6	$9.951 < y \leq 10.399$		53		3.512
7	$10.399 < y \leq 10.864$		35		0.8278
8	$10.864 < y \leq 11.416$		37		0.390
9	$11.416 < y \leq 12.156$		41		0
10	$12.156 < y \leq \infty$		40		0.024
Totals		1.0	410	410	6.144

Summary

$N = 410$ is the number of observations in the sample

$\hat{\mu} = 9.951$ $\hat{\sigma} = 1.723$

$v = \text{deg. freedom} = 7$; $\chi_c^2 = 6.144$

$\Pr. [\chi_v^2 > \chi_c^2] \approx 0.50$

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APPENDIX A.2

FM INFLATION INDEX

The FM Loss Analysis Department uses a set of price indexes for updating the value of the losses which have occurred in the past. For example, the loss which cost FM \$1.00 in 1967 would have cost FM \$1.71 in 1977. The indexes for various years are as follows:

<u>Year</u>	<u>FM Index</u>	<u>Year</u>	<u>FM Index</u>
1932	.229	1956	.732
1933	.232	1957	.764
1934	.261	1958	.779
1935	.273	1959	.795
1936	.277	1960	.806
1937	.300	1961	.811
1938	.290	1962	.823
1939	.290	1963	.833
1940	.297	1964	.845
1941	.323	1965	.870
1942	.355	1966	.924
1943	.378	1967	1.000
1944	.390	1968	1.040
1945	.413	1969	1.102
1946	.535	1970	1.161
1947	.686	1971	1.239
1948	.588	1972	1.322
1949	.580	1973	1.468
1950	.604	1974	1.660
1951	.661	1975	1.710
1952	.656	1976	1.790
1953	.675	1977	1.905
1954	.682		
1955	.698		

APPENDIX A.3

TABLE A-2

DERIVATION OF LOSS SEVERITY EQUATIONSDerivation of Loss Expectancy

$$E(L) = \hat{L} = \exp(\hat{y} + s^2) = \exp(\hat{y}) * \exp(s^2)$$

where

$$\hat{y} = b_0 + b_1 \text{ Log } D + b_2 \log I + b_3 C$$

$$\text{Exp}(\hat{y}) = \exp(b_0 + b_3 C) * D^{b_1} * I^{b_2}$$

where

D = the deductible

I = the FM Index

C = 1 if the dwelling is a boiler room

0 otherwise

$$s^2 = 2.14299$$

$$b_0 = 7.951, b_1 = 0.2322, b_2 = 1.441, b_3 = -0.6080$$

Case 1 Boiler Rooms

$$C = 1$$

$$\hat{L} = \exp(7.951 - 0.6080 + 2.14299) D^{0.2322} I^{1.441}$$

$$\hat{L} = 13174 * D^{0.2322} I^{1.441}$$

Case 2 All Other Risk-Classes

$$\hat{L} = \exp(7.951 + 2.14299) D^{0.2322} I^{1.441}$$

$$\hat{L} = 24,197 * D^{0.2322} I^{1.441}$$