of over 100 percent, but those reduced to two lanes in each direction had increases of only 5 percent. The case studies showed that the one-lane projects experience a great number of rear-end accidents. Four-lane divided Interstate projects reduced to two-lane, two-way had percentage increases more than double those in which the roadway was simply reduced to one lane in each direction. Five-lane undivided highways with two-way left-turn lanes reduced to two lanes during construction experienced the largest accident rate increase of all road types. And finally, two-lane roads reduced to one-way alternating operations experienced worse construction accident rates than those placed on new alignment during construction.

The time-trend analysis indicated a much higher monthly increase in accidents in urban areas. However, since urban areas normally have higher accident numbers, this does not necessarily mean their construction accident experience is any worse. The linear regression analysis indicated a moderately high correlation between area type and total accident rate. The accident number and accident rate analyses both showed that construction accidents went up by a similar percentage in urban and rural areas.

The time-trend analysis showed that the first month after construction begins is not significantly different than the other months of construction and that construction zones do not necessarily have better accident experiences over time. The linear regression analysis showed a negative correlation between the length and duration of projects and the accident rate; thus, the longer the duration of a project (both in time and space), the lower the accident rate.

The accident rate analysis indicated that bridge work, followed by reconstruction of existing roadway (on the same alignment), experienced the largest percentage accident rate increases. Case studies of projects with large rate increases before to during construction showed a definite predominant accident type for each of the studies.

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REFERENCES

1. J. L. Graham, R. J. Paulsen, and J. C. Glennon. Accident and Speed Studies in Construction Zones. Federal Highway Administration, Rept. FHWA-RD-77-80, June 1977.
2. J. A. Fee and others. Interstate System Accident Research Study—1. U.S. Department of Transportation, Oct. 1970.

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Computer Model for Liquefied Natural Gas and Liquefied Propane Gas Risk Simulation

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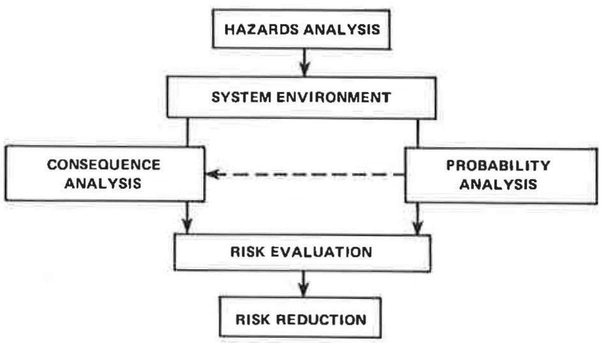
Early in 1971, the National Transportation Safety Board recommended a general framework for risk analysis of hazardous materials. The HAZ-EX computer program was developed to provide analysis of the risk to the public associated with the transportation of hazardous materials. The purpose of the program is to give project designers safety information on routes and sites during the planning stages of a project. The HAZ-EX program is a modular design whereby each module is an element of the risk analysis. The elements range from the simulation of spill dynamics to human injury criteria. The advantage of a modular approach is that updated data or alternative phenomenon descriptions can be inserted. The program capability includes material storage and ship, pipeline, truck, and rail transportation modes. Program-effects analysis capability includes prediction of injury due to toxicity, radioactivity, flammability, and explosivity. By selection of the appropriate combinations of modules, rapid comparisons can be made of site, transportation mode, transportation routes, and system alternatives. The HAZ-EX program has been applied to the storage and bulk transportation of liquefied natural gas and liquefied propane gas. The use of realistic injury and damage criteria as well as accurate physical phenomena description are extremely important. The advantage of a computerized model is speed. A few pages of computer output can apprise decision makers of the safety aspects of a proposed movement of hazardous materials. If a working definition of acceptable risks were then available, the reviewer could be easily satisfied as to the acceptability of an applicant's plans as proposed or whether modifications would be necessary. The efficacy of modifications can be evaluated by rerunning the model.

Liquefied gases will be an important source of energy in the coming decade. Liquefied natural gas (LNG) and liquefied propane gas (LPG) both offer environmentally sound response flexibility, especially since the technology has been developed to ship these products in bulk as cryogenic, or pseudo-cryogenic in the case of LPG, products rather than as liquids under pressure. However, such proposals have not been without controversy. A recent press report succinctly states the issues that must be addressed, "Critics...of the proposal...want to be certain it is as safe as possible." Hence, an important aspect of import and transshipment proposals for LNG and LPG is an understanding by project planners and systems designers of the attendant hazards and public risk of these products as they move through the transportation (including storage) network. While the products may be in varying states, the physical and chemical properties of the products of concern relate primarily to, hypothetically, spilled product. How such material properties could pose a threat and how such a threat can be eliminated or minimized is the object of hazards and risk analyses.

We developed an approach and an analytic computer program, called HAZ-EX, to systematically evaluate the transportation and storage of hazardous materials. The computer program design is consistent with the general framework recommended by the National Transportation Safety Board in that emphasis is placed on the initial and intermediate steps of the analysis (1).

The HAZ-EX program is a modular design, whereby each module is an element of the risk analysis. The elements range from the simulation of spill dynamics to human injury criteria. The program capability includes material storage and ship, pipeline, truck, and rail transportation modes. Program effects analysis capability includes prediction of injury due to toxicity, radioactivity, flammability, and explosivity. By selection of the appropriate combinations of modules, rapid comparisons can be made of site, transportation modes, transportation routes, and system alternatives.

Figure 1. Analytic approach.



The HAZ-EX program has been applied to the storage and bulk transportation of LNG and LPG as cryogenics. Exposure to injury and damage from thermal radiation, vapor cloud travel, and detonation were of interest. The use of realistic injury and damage criteria as well as accurate physical phenomena description are also extremely important. The first step of a hazards analysis (see Figure 1) is a hypercritical examination of the proposed transportation and storage system, the properties of the hazardous material, a definition of failure or accidental events, and a detailed description of the environment in which the project would be implemented, i.e., the system environment. The methodology of fault-tree and failure mode analysis is applicable in this approach (2). The output of the analysis is the definition of credible accidents or failure events.

The system environment refers to the aggregate of all external factors that could possibly affect the system or be affected by the system and its credible failure events. The system environment may include factors such as traffic patterns, demography, land use planning, precipitation, wind speed distribution, failure or accident statistics of similar existing systems, severe storm and flood occurrences, and seismicity. The environment in which the proposed system is to operate may, to a large extent, determine the probability of accidents or failure events and their consequences. The importance of such data cannot be overstated with respect

Figure 2. Hazards consequence analysis.

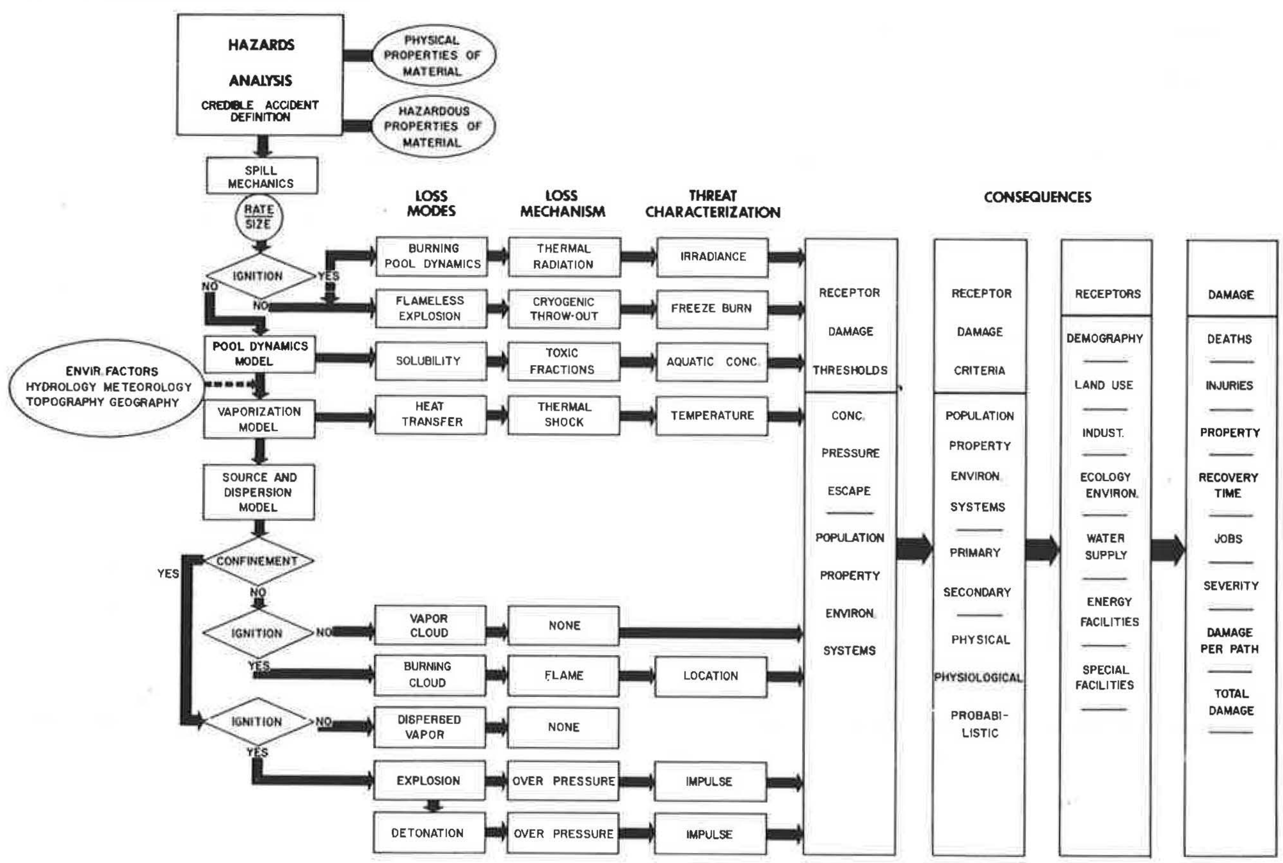


Table 1. Elements of risk analysis.

Hazard	Consequence	Probability	Risk	Evaluation and Mitigation
Material properties	Physical spill models	Spill producing accidents	Exposure to damage	Identify peaks
Project definition	Loss modes	Spill size, rate	Damage	Everyday activities
Accident statistics	Loss mechanisms	Environmental conditions	Exposure range	Other materials
Transportation corridor	Threat characterization	Design conditions	Probable range of damage	Other activities
Fault tree	Damage thresholds	Loss modes		Sensitivity
Accident scenarios	Damage criteria	Damage severity		Operational guidelines
Mitigating factors	Physiological models			
Regulatory requirements	Definition of receptors			
Credible accident scenarios	Damage			
	Damage occurrence			
	Temporal relations			
	Possible range of effects			

to routing, siting, and operating an LNG-LPG system.

The analysis of the consequences of credible accidents is perhaps the most controversial aspect of a risk analysis. In this step of the analysis the dynamics of a spill or product release are described (i.e., modeled) and the implications to population and property are determined. The various pathways and elements of the consequence analysis for LNG and LPG can be viewed in the form of a logic diagram (Figure 2). For each credible accident, the appropriate spill, spread, vaporization, and dispersion models are available in the HAZ-EX program to describe spills in water, releases from pressured pipelines, and releases from ruptured tank trucks. When and whether or not ignition or confinement occurs in the development of the accident scenario are important factors in determining which and perhaps how many loss mechanisms could be realized. The various branch points in the sequence are of course probabilistic in nature and to a great extent depend on the event that causes the release and the environment in which it occurs. For example, in a collision scenario in which a cargo tank of a cryogenic LNG or LPG tanker was penetrated, immediate ignition would likely occur. Based on oil tanker experiences, the probability of ignition is between 0.9 and 1.0 (the certain event). The probability of immediate ignition is not as high for accidents involving pressurized tank trucks, rail cars, and liquid pipelines, since failure of the containment vessel attributed to nonpenetrating damage is an additional consideration, as are rocket effects of the containment vessel in some cases.

Each path in the consequence tree leads to a characterization of the threat element (Figure 2). In the HAZ-EX program, the threat characterization expresses the relation between the loss mechanism and spatial-temporal distance. Accurate threat characterization is a necessary ingredient of a safe, yet realistic, system design.

Once the threat is known, the consequences of hypothetical accidents can be examined. The outcome is the damage. For some threats precise data on specification of thresholds or criteria may be lacking, and it may be somewhat tempting to be conservative and accept low-threshold criteria in order to be on the safe side when dealing with long-term exposure to materials whose threats may be unknown, cumulative, and unavoidable. There is no similarity to LNG-LPG where the threats are well enough known to allow definition of effective mitigation actions and the assignment of mitigation priorities in order to achieve a safe project. Nevertheless, such guidelines must be predicated on realistic damage criteria or else the planners and designers will be misled.

Some of the guidelines, for example, suggest the use of a thermal radiation criteria of 5-s exposure to 17 MW/m^2 (1500 $Btu/ft^2 \cdot s$) in order to determine a safe distance. Experimental data indicate that exposure to such a level for five times the duration on bare skin leads to blistering, somewhat akin to common sunburn (3). The above concept is not only conservative but also technically flawed. A dosage approach is technically more correct and more realistic in that the human response to the threat (i.e., to flee or seek shelter in a shadow) and subsequently the determination of the need and form of countermeasures can be evaluated. The vulnerability model and the effective dosage approach of determining resulting physiological effects is employed in the HAZ-EX program (4). However, the dosage concept is used carefully in the HAZ-EX program since there is a threshold irradiance level below which no significant injury will occur. For LNG-LPG fires involving even massive, unconfined spills of 25 000 m^3 (32 700 yd^3), the time duration of a fire would only be about 6 to 8 min. Hence, in the HAZ-EX program the threshold level is taken as 14 MW/m^2 (1230 $Btu/ft^2 \cdot s$). Time-integrated exposures above this level are used to determine human fatalities for those who take no protective action and to determine the availability of time and the need to flee or seek shelter.

PROBABILITY ANALYSIS

In the development of an accident and the determination of its safety impacts, probabilistic concepts enter in a number of ways. When and where a spill could occur, what environmental conditions could exist, and the response of receptors are questions for which the answers are probabilistic in nature. In terms of the ultimate risk values, probability values enter both as multiplicative and additive factors. An uncertainty in a specific probability factor may relate to uncertainty in the result in a complicated way; indeed, a significant uncertainty in a specific probability value may be of no significance in the result. One of the advantages of a computerized approach such as HAZ-EX, is the ability to perform sensitivity analyses rapidly.

Determination of some of the needed probability values is relatively straightforward, e.g., reliable wind velocity probabilities can be obtained from sources such as the STAR program (5). Others, especially where and when, and also how large, a spill could occur are not so straightforward. The salient probability aspects in the overall context of the risk methodology presented here is of a general nature; however, the items are slated specifically toward LNG-LPG analyses (see Table 1). The probability item indicated as design conditions is particularly relevant with respect to flammable vapor clouds composed of methane or propane gas (and perhaps certain other gaseous products). Specifically, the possible range of effects for vapor clouds relates to parameters such as soil moisture state, if a spill were on ground, wind velocity, and atmospheric stability.

RISK

Once the hazard, consequence, and probability analyses have been completed, the computation of the risk is anticlimactic and straightforward. The distinctions between the risk of exposure to damage and the risk of damage is perhaps most evident if the question of human injury and fatality risk is examined. The risk of exposure would be a numerical probability value on an annual per person basis of being within the possible range of effects, whereas the risk of damage for the exposed population is the annual per person probability of being injured or fatally injured. The difference between the two relates to fatality thresholds, protection, and countermeasures. The range of effects, perhaps both distance and time, associated with either risk measure is useful for analysis of transportation corridors.

A comparison of the project risk values or peaks to other activities and a sensitivity analysis comprise the risk evaluation step of the analytic approach. In the evaluation step, sensitivity analyses will pinpoint critical areas or perhaps assumptions requiring further scrutiny.

The discovery of risk peaks and an examination of their origin points the way for needed mitigation actions, including perhaps operational restrictions. A risk peak is a combination of circumstances of either or both consequence and probability origin that contributes a significant portion of the risk. The computerized HAZ-EX program is of significant value in identifying and pinpointing peaks and risk reduction considerations.

In summary then, a few pages from the computer output can apprise decision makers of the safety aspects of the proposal. If a working definition of acceptable risks were then available, the reviewer could be easily satisfied as to the acceptability of the applicant's plans as proposed or whether modifications would be necessary.

REFERENCES

1. Special Study—Risk Concepts in Dangerous Goods Transportation Regulations. National Transportation Safety Board, Jan. 1971.
2. H. Napedensky. Risk Assessment, Methodologies. LNG Risk Assessment Symposium, Institute of Gas Technology, Chicago, Feb. 10, 1977.
3. A. Stoll and C. Greene. Relationship Between Pain and Tissue Damage Due to Thermal Radiation. Journal of Applied Physiology, Vol. 14, No. 3, 1959, pp. 373-382.
4. Vulnerability Model. U.S. Coast Guard, U.S Department of Transportation, Rept. CG-D-136-75, June 1975.
5. STAR Program. National Oceanic and Atmospheric Administration, U.S. Department of Commerce, Asheville, NC.

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Crash Testing of Nuclear Fuel Shipping Containers

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In an attempt to understand the dynamics of extra severe transportation accidents and to evaluate state-of-the-art computational techniques for predicting the dynamic response of shipping casks involved in vehicular system crashes, a program was organized to investigate these areas. This program, which began in 1975, encompasses the following distinct major efforts. The first of these uses computational methods to predict the effects of the accident environment and, subsequently, to calculate the damage incurred by a container as the result of such an accident. The second phase involves the testing of one-eighth-scale models of transportation systems. Through the use of instrumentation and high-speed motion photography, the accident environments and physical damage mechanisms are studied in detail. After correlating the results of these first two phases, a full-scale event, involving representative hardware, is conducted. To date two of the three selected test scenarios have been completed. Results of the program to this point indicate that both computational techniques and scale modeling are viable engineering approaches for the study of accident environments and physical damage to shipping casks.

For the past several years the U.S. Energy Research and Development Administration (ERDA) through the Division of Environmental Control Technology has pursued a coordinated program to address the problems and perspectives of the transportation of radioactive materials. A part of that program has been the collection and analysis of data on the frequency and severity of accidents involving trains, highway vehicles, and aircraft within the United States. Significant correlations of these data, along with the basic data collection, are contained in the Transportation Environment Data Bank at Sandia Laboratories (1). This information has been used in a variety of programs.

As significant as this data collection is in the determination of the risk of exposure to accidents in the transportation segments of the nuclear fuel cycles, it does not relate the severity of the accident to the damage inflicted on the containers used to ship radioactive materials. ERDA recognized this need and initiated programs to evaluate that relationship. The first such program involved testing of full-scale casks in severe environments at Oak Ridge and Sandia. Following successful completion of these tests, full-scale testing of complete cask transport systems in highway and rail transport modes was initiated.

When these two programs are completed, it should be possible to predict the probability of causing various levels of damage to shipping containers as the result of transportation accidents. The remaining step is to correlate package damage and release fractions (i.e.,