ESTIMATING THE DANGERS PRESENTED TO PORTS AND WATERWAYS FROM THE MARINE TRANSPORTATION OF HAZARDOUS CARGOES: AN ANALYTICAL MODEL

by

Robert R. Wells
Lieutenant Commander, U. S. Coast Guard

Herbert G. Blecker
Chemical Engineer, U. S. Coast Guard

Bruce L. McDonald
Lieutenant Junior Grade, U. S. Coast Guard

Prepared in conjunction with the Study to Develop a Coast Guard Role in Ports and Waterways

12 December 1969

31

Potential Hazard of an Incident, (PHI = ∅)

In the context of marine transportation of hazardous materials, the potential hazard of extravehicular damage resulting from an accident is important as a management planning tool. Intuitive estimation of potential hazard has guided field operations and should rightly continue to do so. However, a formalization of these hazards may provide the basis for a measure of effectiveness of both preventative and remedial programs. Conceptually it is possible to compare the anticipated benefits of programs aimed at hazard reduction with the cost of accomplishing such reductions.

As a first step toward formalization let us consider how the potential hazard might be usefully expressed. Following the results of The Report of the Panel on Cargo Size Limitations of National Academy of Sciences' Committee on Hazardous Materials a general expression for the threat is:

$$\text{HAZARD} = \frac{(\text{Probability of Occurrence})\ (\text{Extent of Expected Damage})}{(\text{Effect of Damage Reduction Activity})}$$

This equation shows certain important fundamental relationships. The hazard varies:

a. directly with the likelihood of an accident,

b. directly with the extent of probable damage, and

c. inversely with the amount of effective remedial action taken.

Further examination of the subject shows that the expectation of extravehicular damage resulting from a hazardous material container failure is also a function of at least the following additional general items.

a. type of damage, "i"

1. lives lost
2. injuries
3. property damage
4. Ecological damage *

b. type of accident, "j"

1. collision
2. grounding
3. fire/explosion
4. other

c. commodity group involved, "k", Commodities can be categorized in a vast variety of ways. Suppose they are categorized as follows:

1. Burnable

   (a) Yes
   (b) No

2. Corrosive

   (a) Yes
   (b) No

3. Radioactive

   (a) Yes
   (b) No

4. Poisonous

   (a) Class X
   (b) Class Y
   (c) Class Z
   (d) No

5. Pollutant

   (a) Air
   (b) Water
   (c) Both
   (d) None

---

*Ecological damage is defined as observable perturbations in the balance of nature that are considered to be unpleasant, unhealthy, dangerous, or costly.

6. Explosive

(a) Class U
(b) Class W
(c) No

d. geographic location, "l"

1. New York Lower Harbor
2. New York East River
. .
. .
. .
. .
100. Cross-Florida Barge Canal
. .
. .
. .
. .
1000. Puget Sound
. .
. .
. .
. .
1,000,000. Cook Inlet

It would appear useful to concern ourselves with not only the commodities that fit into only one category, but also those that have multiple characteristics. All the possible combinations, considering one and only one subdivision of each category, total 2 x 2 x 2 x 4 x 4 x 3 = 384. Although the number is large, it is much smaller than the number of individual substances regulated. The categorization presented is not necessarily the best and certainly not the only such practical partition. However, the concept of multiple characteristics seems useful and is recommended for use in analysis and regulation.

One basic problem with the formulation above is the difficulty in representing remedial action in a precise manner. Among other inadequacies there is no provision for the case when post-incident action worsens the situation. In an attempt to overcome the perceived deficiencies and to aid in analysis of the mission area, the model was reformulated in the following more comprehensive manner.

$$\phi_{jkl} = \sum^{i} H_{ijkl} \quad \text{for any set of values for "j", "k" and "l".}$$

$$H_{ijkl} = P_{jkl} \left\langle D_{il} \left\{ R_{ijkl} \, (1-G_{ijkl}) + B_{ijkl} - R_{ijkl} \, (1-G_{ijkl}) B_{ijkl} \right\} \right\rangle$$

where $0 \leq P_{jkl}$, R_{ijkl}, G_{ijkl}, $B_{ijkl} \leq 1$ for all sets of values of "i", "j", "k" and "l".

ϕ_{jkl} = total expected loss for a specific single incident

H_{ijkl} = expected loss or damage of type "i", from accident "j", with commodity group "k", in location "l"

P_{jkl} = probability of accident "k" occurring with commodity group "k", in location "l".

D_{il} = maximum possible loss of type "i" within the radius of concern at location "l".

R_{ijkl} = fraction of D_{il} likely to result from accident "j" with commodity group "k".

G_{ijkl} = fractional reduction in expected loss (D x R) from corrective action taken after accident "j" with commodity group "k".

B_{ijkl} = fraction of D_{il} caused by inappropriate action taken after accident "j" with commodity group "k".

The quantity contained within the braces, { }, is bounded by the values of 0 and 1. Subtraction of the term R(1 - G)B prevents double counting the loss effected by both lack of corrective action, R(1 - G), and implementation of exacerbating action, "B". The variables "P", "D", "R", "G" and "B" will now be individually discussed more fully.

P_{jkl} - The Probability of an Accident Occurring

The symbol P_{jkl} is a shorthand notation for the expression "What is the likelihood of an accident of type "j" in location "l" involving a commodity grouping of type "k"?" The subscript "i" does not appear because the probability that an accident will occur is independent of the several types of damage that would occur as a result of it. Each P_{jkl} is viewed as being composed of a number of sub-factors which describe the chain of circumstances and conditions that lead or contribute to an accident. There are at least three immediate problems:

a. What are the relative effects of the sub-factors on P_{jkl}?

b. What are the sub-factors? and

c. How can these sub-factors be quantified?

In response to the first problem, it appears that there are two broad types of sub-factors. The first type, which can be termed CRITICAL sub-factors, are of such a nature that the absence of any of them would preclude the occurrence of the accident. The other sub-factors are CONTRIBUTORY in nature. Such a component even when present in its most severe form does not ensure the occurrence of an accident nor does its absence make the occurrence impossible. Obviously it is desirable to isolate CRITICAL items and examine the possibility and practicality of eliminating one of them.

The sub-factors probably combine in a complex multiplicative manner. For example, if

C_a is the ath of m critical sub-factors of P where $a = 1, 2, \ldots, m$; and

E_b is the mean condition of the bth of n contributory sub-factors of P where $b = 1, 2, \ldots, n$; E_b is expressed as a multiple of the incident producing effect of the minimum condition of the bth sub-factor;

then

$$P_{jkl} \simeq \left\langle f(C_1 \times C_2 \times \ldots \times C_m)\right\rangle^{\left[1 - \frac{\sum_{b=1}^{n}\left(1 - \frac{1}{E_b}\right)}{n}\right]}$$

This expression says that the critical sub-factors are at least mutually multiplicative and are perhaps further functionally related. The only constraint on such a function is that its value must be limited to the interval from 0 to 1 inclusive. Further, since $\left(1 - \frac{1}{E_b}\right)$ is also limited to the interval from 0 to 1 (for all b), the exponent is in turn limited to the same interval. Consequently, the value of P_{jkl} is likewise limited to that interval as required by the laws of probability. If any C_a equals zero, then P_{jkl} will equal zero. If all E_b's equal one, then the exponent becomes one and the contributory sub-factors have no effect. Finally, as all $E_b \rightarrow \infty$ simultaneously than the exponent $\rightarrow 0$ and $P_{jkl} \rightarrow 1$, i.e., the accident is nearly certain to occur.

An initial answer to the second problem has been developed. Four broad types of accidents have been defined and sub-factors for them have been tentatively identified. Table 1 lists these terms. It will be noted that several characteristics appear under more than one accident type, but only personnel competence or familiarity is common to all types of accidents. It is felt that identification of additional universal characteristics will aid in establishing the generality of the model and hence its widespread utility.

No claim is made for the uniqueness or infallibility of the sub-factors cited. To the contrary, they are the result of thoughtful but superficial examination of the problem. Additional factors should be considered. The experience of those working closely with both the public and industry is needed to confirm, modify, or repudiate the items listed as well as identify others. It is felt such identification can be accomplished by consideration of numerous potential incidents in different locations for different commodity groupings. Central analysis of factors thus generated will hopefully yield pertinent commonalities. Sub-factors that are amenable to control by regulation and administration under new or existing legislation are especially important.

The third problem is amenable to solution through a well-conceived collection and analysis of data to yield statistically significant estimates for the sub-factors previously identified. Since such quantification is long range in nature, interim estimates must continue

TABLE 1 - ACCIDENT SUB-FACTORS

	Accident Types (j)			
	COLLISION	GROUNDING	FIRE/EXPLOSION	OTHER
CRITICAL SUB-FACTORS (a)	Traffic Density Relative Speed Size of Vessel	Water Depth/Draft Speed (over ground) Size of Vessel	Temperature/ Pressure Quantity of Cargo	
CONTRIBUTORY SUB-FACTORS (b)	Personnel Competence Visibility Wind/Current Channel Re- strictions	Personnel Competence Visibility Wind/Current Channel Re- strictions	Personnel Competence Stowage Packaging Prior Cargo Adjacent Cargo	Personnel Competence Corrosion Container Design Handling Equipment Failure Handling Procedures

to come from the experience and judgment of decision makers. Even in the long run, several sub-factors will probably not be quantifiable by reason of insufficient data and wide variability. These factors will necessarily receive the continued attention of the manager who will have more time to devote t them because of the quantification of other factors.

Although it is most difficult to quantify the individual factors which produce P_{jkl}, it may be possible to estimate P_{jkl} itself. The Casualty Analysis Division of the Office of Merchant Marine Safety can provide information on accidents that have occurred, broken down by type, commodity involved, and place of occurrence. Before probabilities can be computed; however, it is necessary to know how many times an accident could have occurred. The number of accidents that have occurred divided by the number of opportunities for occurrence is an estimate of the probability of occurrence. It has been learned that the Army Corps of Engineers gathers data on the number of shipments of each commodity that enters each port annually. From this it is believed that an estimate of the opportunities for accident can be estimated.

The Hazardous Materials Division, in issuing special permits for the shipment of certain selected commodities, has accumulated data on number of shipments and packaging failures for many of these commodities. These files present another pertinent source of data for determination of probability factors.

Such estimates of P_{jkl} would be of great value in estimating the expected potential hazard associated with different types of ope... ns. They would not be as valuable as estimates based on the measurement of separate factors, however. The method just described yields an overall probability, but it is of no help in deciding what sub-factors should be attacked in order to reduce the total probability significantly. Therefore, if one is thinking in terms of prevention, it would be beneficial to attempt a description of the function which defines P_{jkl}.

D_{il} - Total Value In The Port Area

D_{il} in the formula designates the maximum value which would be lost in the event that everything in the port was destroyed. The term has the "i" and "l" subscripts indicating that the total value in the port includes different types of valued items and varies from port to port. It does not have the "j" and "k" subscripts. The "j" is omitted because the total amount of value in a place is the same no matter what type of accident occurs. For example, a port contains the same number of people regardless of whether there is a collision, a grounding or neither. Similarly "k" is omitted because the amount of value in a given port is independent of the type of commodity being carried by a vessel which enters it. This means, of course, that the value of the port does not include the value on the vessel entering it. The reason that the value present on the vessel is excluded from the analysis is that the objective of the program for which this study is being performed is the safeguarding of ports. The Coast Guard has another program whose objective is the safety of vessels, and it was believed advisable not to confuse the benefits of its success with the benefits of port safety.

As noted above, "D" is subscripted by "i". Value takes different forms including human life, real estate and other types of property. Theoretically, it would be possible to express all different types of value in common terms, e.g., dollars. In practice this cannot be done without introducing a great deal of subjectivity. For example, it would be hard to reach agreement as to the value of human life. Consequently, the decision was made to state the expected harm, "H", in terms of harm to different types of valued quantities rather than a single overall harm. The decision maker will be forced to make an evaluation as to the absolute and relative significances of harm to different types of values, and the formula herein described will provide a framework within which he may make the decision; but it will not make the decision for him.

Since D_{il} is defined as the total value in a port area, it is necessary for the person using the formula to define the port area. There are several ways in which this could be done. One obvious method would be to include everything within a given distance of the harbor area. Probably any formula you choose would contain some measure of subjectivity or arbitrariness, but it is believed that this would not lead to error in the resulting calculations. The reason for this belief will become evident on reading the description of R_{ijkl} which follows the present section.

In order to apply the formula, one would have to quantify D_{il} for the ports he wanted to consider. He would also have to develop a list of values, the "i's", that he wanted to use in his evaluation. Suppose that these were human lives and real estate. Units of measure would have to be established, though it is not necessary that they be the same for each "i". The obvious measure for human lives is the unit of "life", though others are certainly possible. In the case of real estate; there are many choices. One might use dollar measures such as the value assessed for tax purposes or the market value. On the other hand, measures of capacity might be preferred. Here the value could be expressed in terms of numbers of dwelling units or square feet of office space.

The analyst will have to describe or set limits for the region which he is selecting as port area "1". In doing this, and in choosing among the alternative measures of value for the "i's", it is wise to be cognizant of the likely sources of data. There are many sources, varying in potential with the type of value being described. Consider the two examples mentioned in the above paragraph. If one were counting lives, dwelling units or office space, the Census Bureau would likely prove to be an adequate source of data. If this source were used, it would be important to define the port area "1" in terms of regions compatible with those used by the Census Bureau when collecting data. Should the decision be made to measure real estate value in dollar terms, tax records would serve as a good source of information. These will yield assessed values. The market value can be found by multiplying the assessed value by a constant. Each taxing authority can provide the average ratio between assessed and market value, from which the appropriate constant can be derived.

It is believed that data of the type described could be collected for many port areas, although it would involve a great deal of effort. There is one caveat in regard to data collection that should be noted. Although D_{il} is simply a total, the computation of R_{ijkl} requires that more detailed information be known about the distribution of valued quantities, the "i's", within the port area. Thus in the selection of data sources, one should give preference to sources which offer detailed information.

R_{ijkl} - Expected Fraction of Maximum Loss

The term R_{ijkl} appears in the formula for determining "H", the net damage expected. As discussed in the previous section, "D" is the maximum value which may be lost. R_{ijkl} is the fraction of that maximum which you would expect to be lost, should an accident occur. This is the amount that you would expect to be lost assuming that nothing is done to minimize the effect of the accident after it has occurred. "R" may assume any value from 0 to 1. If R = 0, then $D \cdot R = D \cdot 0 = 0$, or there is an expectation that the accident will cause no damage. If R=1, then $D \cdot R = D \cdot 1 = D$; or in other words, everything will be destroyed. Referring back to our discussion of value, suppose that in defining "D" the analyst has included some things which are most unlikely to be damaged by an accident. This is equivalent to saying that it is most unlikely that R_{ijkl} will assume the value of 1.

"R" is qualified by the four subscripts "IJKL" because it is believed that the fraction that will be lost depends on all of the four variables they represent. To begin with, "R" varies with the type of damage that is being considered. For example, in some hypothetical accident, one might expect that 0.1 of the total lives might be lost and at the same time might expect that 0.2 of the total property in the area would be destroyed.

In addition it is believed that the damage to be expected varies with the type of accident experienced. That is, a collision might lead to a different degree of damage than a grounding.

The degree of expected damage is also believed to vary with the harbor area in question. For instance consider two port areas, 1 and 2, each containing the same total number of lives. Thus $D_1 = D_2$, or the maximum lives that could be lost is the same in either place. Assume, however, that in port 1 most of the people live right on the waterfront. In port 2, by contrast, the people are equally distributed from the waterfront out to the radial distance which has been selected as marking the end of the port area. It is likely under such circumstances that an explosion in port 1 would kill a larger proportion of the people than would the same explosion in port 2. Thus R_1 would be greater than R_2.

Finally, the portion of the total which may be expected to be lost varies with the type of commodity that is being carried. For example, it is felt that the damage done by a collision involving a dynamite carrying vessel would be different from that of a collision involving a vessel whose cargo was baled cotten.

It is recognized that the proportion of the total possible damage which will in fact occur as the result of a given type of accident is not always the same. Thus when a single value of R_{ijkl} is assigned, some error will necessarily result. The value selected should represent a conservative point estimate of the expectation. In so far as individual cases deviate from the estimate, the method described here will yield an erroneous estimate of the resultant harm.

In effect the above paragraph is saying that there is no single accurate value for R_{ijkl}. Rather it can take virtually any value from 0 to 1. Of course it will take some values more frequently than others.

This raises the question as to why it was decided to use a single value for "R" rather than a probability function. There is no doubt that the latter would be more accurate; however, the benefit of making the computations in accordance with this and other distributions may not be worth the effort of doing so. Use of expected or conservative point estimates may be more cost effective.

Although the complete description of the probability function for R_{ijkl} is presently beyond practicality, it is possible to identify some of the variables and perhaps to identify in some cases their relative sensitivity. It is believed that the following list contains some of the important ones:

1. Quantity of cargo released
2. Additional quantity which might be released
3. Discharge rate
4. Dispersion rate
   a. Wind
   b. Current
   c. Temperature
5. Toxicity
6. Geographic density of "i".
7. Intrinsic resistance or protection of "i".

In addition, we may say that R_{ijkl} is a multiplicative function of the percentage of D_{il} exposed and a threat factor. This is a very broad statement, but it takes on more precise meaning when specific types of threats are examined. Consider for example an accident which releases a cloud of gas that is poisonous to human life. The expected percentage loss of life would be the fraction of the total exposed times the toxicity expressed as a kill ratio. There has been some work done in the area of measuring how gases disperse and clouds drift.** The toxicity of various chemicals has been determined and can be obtained. Also, if the population distribution is known, it is then possible to develop a function which will specify the expected loss at any point within the port area. The total expected loss of life can then be estimated by integrating the function over the entire port area. As an illustration of this procedure, a sample calculation has been developed and is presented later in this paper as part of a sample computation of the complete function for determining H_{ijkl}.

As a second example, consider the threat posed to buildings by explosions. The buildings would be damaged by the pressure wave caused by the explosion. In connection with military weapons' effects studies, there has been much investigation of the manner in which these waves develop and dissipate. With effort, it would be possible to locate and adapt formulas which would indicate the peak overpressure experienced at any point within the port area. Military experimentation has also led to the development of functions which express the likelihood that different types of structures will be destroyed at given levels of overpressure. By combining these two types of expressions with the actual distribution of buildings in a port area, it would be possible to develop a function which would yield the expected level of destruction at any point within the port area. Then by integrating the functions over the whole port area, it would be possible to approximate the expected level of destruction.

**Hewerton, A. E., "Estimating Area Affected by a Chlorine Release" Presented at the Sixty-Fourth National Meeting of A.I.Ch.E., March 16-20, 1969

There is no doubt that such computations are complex and time consuming. The difficulty is made all the worse by virtue of the extremely large number of different calculations that would be needed to evaluate R_{ijkl} thoroughly on a nation-wide basis. For instance, if one were considering three types of damage, four types of accidents, 384 groups of commodities and 50 ports, it would be necessary to make $3 \times 4 \times 384 \times 50 = 230,400$ computations. Nevertheless, if the result is valued highly enough, it can be obtained. Probably it would be found that many of the calculations can be approached in similar ways, and it is likely that automatic data processing can be used to reduce the computational burden. This last is certainly the case in respect to recalculations and sensitivity analyses of each particular R_{ijkl}.

G_{ijkl} & B_{ijkl} - Indices of Post Accident Action

Post accident response options vary from positive actions which tend to ameliorate the net hazard to negative actions which tend to magnify the net hazard. Positive post accident responses may consist of:

Actions Relative to Valued Quantity

- Medical Treatment/Antidote
- Protective Gear Issue
- Evacuation

Actions Relative to Commodity

- Containment
  - Outside
    - booms
    - put into another container
  - Inside
    - close valves
    - seal leak
- Neutralization
  - Extinguishment
  - Emulsification
- Isolation
- Redirection of flow

Negative post accident actions include the following:

Actions Relative to Valued Quantity

- Concentration
- Remove intrinsic protection
- Introduction of Remedial Substance with Deleterious Side Effects

Actions Relative to Commodity

- Misdirection of flow
- Affectation of a Wider Area
- Increase of Potency

The equation:

$$\phi_{jkl} = \sum^{i} H_{ijkl} = P_{jkl}\left\langle D_{il}\left\{R_{ijkl}\ (1-G_{ijkl}) + B_{ijkl} - R_{ijkl}\ (1-G_{ijkl})\ B_{ijkl}\right\}\right\rangle$$

which is derived from the relationship developed by NAS as previously discussed, allows a more definitive evaluation of the effect of negative as well as positive post accident responses upon the potential hazard H_{ijkl}. The use of dimensionless numbers for values of P_{jkl}, R_{ijkl}, G_{ijkl} andd B_{ijkl} and units of lives, dollars, etc., for D_{il} allow for hazard evaluation in terms of the actual estimated loss (dollars for property damage, lives for fatalities, etc.).

Positive Action

If the expressions $(1-G_{ijkl})$ and B_{ijkl} both equal zero, the net damage will be equal to zero. This is theoretically possible if and when corrective action has totally minimized the potential hazard resulting from the accident and no exacerbating action has been taken. A more realistic view of positive action is that G_{ijkl} will approach a value of 1 as the amount of positive action minimizes the damage. An example would be the case of a vessel in port carrying a portable tank leaking solvent through a faulty valve. If the leak were to go unnoticed, a fire or explosion could occur with the potential for loss of life, property damage, and ecological damage to the surrounding area. If the spilled solvent ignites engulfing the deck in flames and the fire is subsequently promptly extinguished, the value of G_{ijkl} is equal to 1 since damage has been confined to the vessel and the surrounding area is unscathed.

Negative Action

Negative post accident responses are those actions which magnify the damage expected by the accident. The values of B_{ijkl} for this action are between 0 and 1. An example of negative action can be illustrated by again considering our leaky portable solvent tank. If an inept crew were to try to extinguish the flames with hoses hooked up to gasoline tanks thereby increasing the conflagration and magnifying the expected damage to the surrounding area, the value for B_{ijkl} would be greater than 0. The value of B_{ijkl} approaches 1 as the effects of the action take on catastrophic proportions. An example is the use of an H-bomb to extinguish the blaze.

Inaction

If no post accident action is taken, then G_{ijkl} and B_{ijkl} are both equal to zero. The effect of inaction is that the net hazard will depend solely on P_{jkl}, D_{il} and R_{ijkl}.

Data Sources

There are two initial sources of information that may prove helpful in quantifying the G factor. First there are the historical records of previous incidents that may yield insight into the percentage reduction of loss attributable to particular remedial activities. The problem is how to estimate with some degree of confidence what the damage would have been without the remedial action. These same historical accounts may reveal some unintended deleterious effects (B's) of post accident action. For example, the use of detergents on an oil spill to form soluble components has the bad effect of killing fish. Other sources of information are the disaster control plans of the Office of Emergency Planning. Perusal of these plans and interviews with their authors and proponents may yield a consensus as to the fractional remedial effect of certain general actions.

An Illustrative Example

An example of the application of the model would probably be instructive. Consider the following situation. It is desired that chlorine barges be permitted to transit the Houston Ship Channel. What is the hazard of a collision involving such a barge?

k = corrosive, Class Y poison and pollutant of both air and water

l = Houston Ship Channel

j = collision

$$\phi_{jkl} = H_{Deaths} + H_{prop.\ damage} + H_{injuries} + H_{ecological\ damage}$$

$$H = P\ (D \{R(1-G) + B - R(1-G)\ \ B\})$$

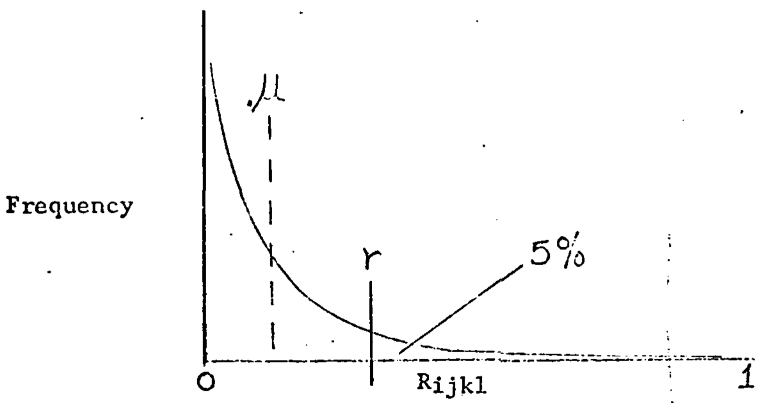
This discussion will be limited to developing H_{deaths}. P_{jkl} is the probability of any vessel having a collision in the channel. An estimate could be made by dividing the number of collisions that have occurred there by the number of transits of the channel. For our example say $P_{jkl} = .0001$.

D_{il} is the population within the area of concern. For this example the area is that within 50 miles of the channel including the termini. This includes Galveston as well as metropolitan Houston. Say D = 2 million lives.

R_{ijkl} is the fraction of the total population expected to die from the accident. This factor is a random variable contingent on the exact location of the accident, wind direction, population density, the amount of chlorine released, etc.

These parameters can be related functionally in accordance with known physical laws and their result on the population determined. Observation of a large number of sets of conditions in practice or by simulation will produce the probability distribution of "R". Consider figure 1.

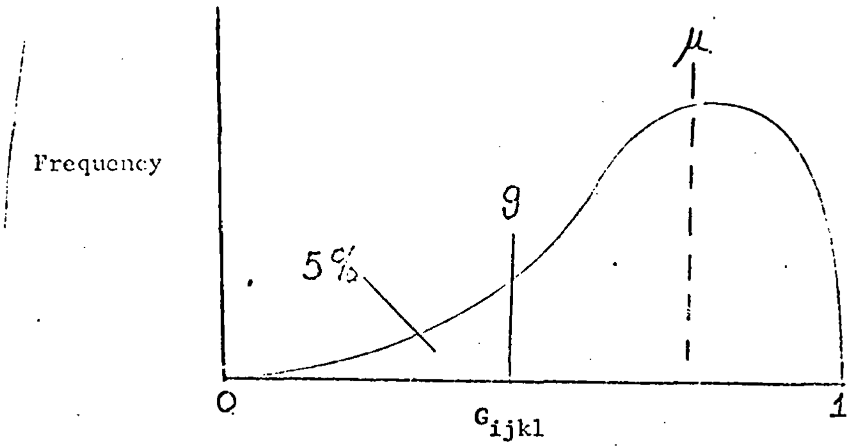
Fig. 1. - Hypothetical Frequency Function of "R"



Since this is a probability function, the area under the curve must equal one. μ is the mean or average value of "R". The area under the curve to the left of μ equals the area under the curve to the right of μ. Half the time the value of "R" will be less than μ and half the time it will be greater. "r" is the 95 percentile point of the distribution. 95% of the area under the curve is to the left of that point. Only 5% of the time will "R" actually assume a value greater than "r". This distribution can be estimated by a single value. If "r" is chosen, it will be a conservative estimate since the value of "R" (and hence the loss) will be less than "r" 95% of the time. For this example assume r = 0.3.

The "G" term describes the effect of corrective action. Similar to "R", it is a combination of factors that can be observed in nature or simulated.

Figure 2 may be a typical but hypothetic probability function for G.



In the case of the "G" parameter which represents good things such as saving lives, a conservative estimate would be the 5 percentile point (g) which is on the left side of the distribution. For this example, let g = 0.5.

The "B" term is very similar to "R" and can be obtained and estimated in like manner. A conservative estimate would be determined from an analogous distribution. It would likely be even more sharply skewed to the left. For this example, assume that "b" (the 95 percentile point) equals 0.2.

Using as input the several values assumed above, the equation for "H" may be solved as follows:

$$H = P \ (D \{R(1-G) + B - BR(1-G)\})$$

$$H = 1\times10^{-4}\ (2\times10^{6}\ \ 3\times10^{-1}\ (1-0.5) + 2\times10^{-1} - 2\times10^{-1} \times 3\times10^{-1}\ (1-0.5))$$

$$H = 10^{-4}\ (2\times10^{6}\ \ 3\times10^{-1} \times 5\times10^{-1} + 2\times10^{-1} - 2\times10^{-1} \times 3\times10^{-1} \times 5\times10^{-1})$$

$$H = 10^{-4}\ (2\times10^{6}\ (15 \times 10^{-2} + 2\times10^{-1} - 30\times10^{-3})$$

$$H = 10^{-4}\ 2\times10^{6}\ (32 \times 10^{-2})$$

$$H = 64 \times 10^{0} = 64 \text{ deaths per shipment}$$

This result must be viewed with some caution. Each shipment is not expected to kill 64 but it is possible that once in 1000 shipments an accident would occur which would kill 64,000 persons. The values of "B" and "R" used in this example were probably much larger than the actual figures would be. The actual "R" and "B" distributions are probably so severely skewed to the left that they would be useless for explanatory purposes.

For the sake of discussion, let us assume that 64 deaths per shipment is the expected loss figure with which the manager has to work. What does this mean to him? First, if the shipment is not worth more to the port area than 64 lives, then he should prohibit it from entering. That is, the cost associated with the shipment exceeds the benefits, and to permit it would be to authorize a net loss for the area. On the other hand, if the benefits are greater than 64 lives, it would made sense to allow the shipment. Then the question would become one of determining who should bear the cost. Should the cost be borne by the people likely to be killed or should it be borne by those who make a profit from the shipment? The answer to this will probably be determined by the relative political power of the two groups. The choice is not one which is without precedent. During the early part of the present century it was discovered that a certain number of lives could be expected to be lost in the process of any major construction project. It was adjudged that the projects, e.g., bridges, dams, and sky scrapers, should be continued in spite of the certain losses. However, the law was amended so that construction companies were required to compensate by way of insurance the dependants of those workers who were lost. Perhaps the manager of the port safety program might want to consider recommending legislation which would establish a comparable scheme for hazardous cargo transport.

Evaluating Risks in Aggregate

The formulation of H_{ijkl} lends itself to the determination of various different hazards of interest to the manager. As stated previously, $\phi_{ijkl} = H_{ijkl}$ is the potential hazard for a single incident of type "j" with commodity "k" at location "l". The potential hazard over a time period "t", say a year, is

$$\phi_{kl}(t) = N_{kl}(t) \sum^{i} \sum^{j} H_{ijkl} \quad \text{where}$$

$N_{kl}(t)$ is the number of shipments of commodity group k in location l during time period t.

$\phi_{kl}(t)$ expected loss of all types for all types of accidents with commodity group k in location l during time period (t)

Similarly the potential hazard for location l is:

$$\phi_{l}(t) = \sum^{k} N_{kl}(t) \sum^{i} \sum^{j} H_{ijkl}$$

The hazard from commodity group k nationwide is:

$$\phi_{k}(t) = \sum^{l} N_{kl}(t) \sum^{i} \sum^{j} H_{ijkl}$$

Finally the hazard nationwide for all commodities is:

$$\phi(t) = \sum^{k} \sum^{l} N_{kl}(t) \sum^{i} \sum^{j} H_{ijkl}$$

Conclusions and Recommendations

The concepts and formulations presented in the foregoing pages are regarded, by those who developed them, as preliminary steps toward understanding the mechanisms and risk levels associated with the marine transport of hazardous materials in port areas. They are certainly not complete and admittedly require a great deal more development before it would be reasonable to consider using them as tools for planning or operations.

There are several different emphases which might be placed on the further development of the formula. Before any is selected, it would be beneficial to identify a group within Headquarters which is interested in using such an analysis on a continuing basis. Once this has been accomplished, the formula can be advanced with emphasis on attaining the objectives of the identified user group.