A Methodology for the Transfer of Probabilities between Accident Severity Categories*

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INTRODUCTION

Evaluation of the radiological risks of accidents involving vehicles transporting radioactive materials requires consideration of both accident probability and consequences. The probability that an accident will occur may be estimated from historical accident data for the given mode of transport. In addition to an overall accident rate, information regarding accident severity and the resulting package environments across the range of all credible accidents is needed to determine the potential for a release of radioactive material from the package or for an increase in direct radiation from the package caused by damage to packaging shielding. This information is usually obtained from a variety of sources such as historical data, experimental data, analyses of accident and package environments, and expert opinion. The consequences of an accident depend on a number of factors including the type, quantity, and physical form of radioactive material being transported; the response of the package to accident environments; the fraction of material released from the package; and the dispersion of any released material.

One approach for the classification and treatment of transportation accidents in risk analysis divides the complete range of critical accident environments resulting from all credible accidents into some number of accident-severity categories. The types of accident environments that a package may be subjected to in transportation are often classified into the following five groups: impact, fire, crush, puncture, and immersion. A "critical" accident environment is one of a type that could present a plausible threat to a package. Each severity category represents a portion of all credible accidents, and the total of all severity categories covers the complete range of critical accident environments. This approach is used in the risk assessment codes RADTRAN (Neuhauser and Kanipe 1992) and INTERTRAN (Ericsson and Elert 1983).

Accident-severity categories are ordinarily illustrated on a set of axes forming a grid, as shown in Figure 1 and Figure 2. The axes indicate critical accident environment types and describe the ranges of the parameters used to define the severity categories from zero (no accident) to some value which includes the most severe credible accident. Not all possible types of accident environments present a plausible threat to a package, and these environment types are usually not included in the set of axes on which the severity categories for that package are defined. For example, crush is not considered a critical type of accident environment for massive spent nuclear fuel highway transportation casks because a crush environment severe enough to present a threat to one of these casks is implausible. Although Figures 1 and 2 show two critical types of accident environments (impact and fire), any number of critical environment types may be considered in a severity category scheme. The magnitudes of the most severe credible accident environments depend on a number of

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factors including the mode of transport, route characteristics, etc., and usually requires consideration of accidents that are plausible but have never actually occurred. An infinite number of accident environments can be imagined, and a risk analysis need not include those environments that either are physically implausible or have probabilities less than some predetermined cutoff value (e.g. probability less than 10^{-6} per annum).

No constraints are placed on the number or definition of severity categories by the accident-severity category approach, although the previously mentioned codes do provide a maximum on the number of categories. As such, past studies have used different numbers and definitions of severity categories to represent the range of all credible accidents. The authors are not suggesting that restrictions should be placed on the number or definition of severity categories. Each investigator should have the freedom to use any number of categories, defined in any manner as is appropriate for the situation being analyzed. At times the division between two categories is made at an environmental condition where a change in the integrity of the package is anticipated and, thus, is dependent on a specific package.

Some of the differences that can exist between severity category schemes are indicated by the differences between Figure 1 and Figure 2. The category scheme depicted in Figure 1 is similar to schemes published in a 1977 U. S. Nuclear Regulatory Commission report (U.S. Nuclear Regulatory Commission 1977). The scheme shown in Figure 2 consisting of twenty response regions, comparable to severity categories, is similar to a scheme published in a 1987 U. S. Nuclear Regulatory Commission study performed by the Lawrence Livermore National Laboratory (Fischer et al. 1987). Not only are the number of categories different between Figures 1 and 2, but the parameters used to define the categories are also different and no correspondence exists between the definitions of any two categories in the different schemes. The differences in number and definition of severity categories used in different studies make direct comparisons between schemes, with the exception of total risk values, extremely difficult. These differences may also lead to confusion and misinterpretation. An example of such misinterpretation is discussed in Luna, et al. (Luna et al. 1986).

To address these problems, a methodology has been developed which will allow accident probabilities associated with one severity category scheme to be transferred to another severity category scheme. The methodology will permit meaningful comparisons of different studies at the category level in cases where the accident probability information used to determine the category probabilities initially is not available or is not adequate to determine category probabilities across the range of the critical accident environments. If the initial accident probability information is available and adequate, probabilities may be calculated directly for a different category scheme.

METHODOLOGY

A methodology for transferring probabilities between accident-severity category schemes was previously considered in a study performed at Sandia National Laboratories (Spanks 1990). This earlier study developed a matrix to transfer accident probabilities from an eight-category scheme similar to the one shown in Figure 1 to a twenty-category scheme similar to the one shown in Figure 2. Spanks proposed mapping the two severity category schemes onto a common set of axes to form two overlying grids. In this case, correlations between the mechanical parameters of impact speed and cask structural response and the thermal parameters of fire duration and cask thermal response were needed to map the two schemes onto a common set of axes. The probabilities associated with the eight-category scheme were then transferred to the twenty-category scheme using an "equal area weighting" technique which assumes that the accident probability is constant for all accident environments within each severity category.

The assumption that accident probability is constant across the range of accidents represented by each severity category is not representative of actual accident experience. The methodology described in this paper maps the severity category schemes onto a common set of axes to form overlying grids, as was done by Spanks, but transfers probabilities between accident-severity category schemes based on the probability of occurrence of each parameter used to define the severity categories (the parameters along the axes of the overlying grids).

The first step in applying the methodology to transfer probabilities between accident-severity category schemes is to map the schemes onto an appropriate common set of axes. This step, depending on the parameters used with the original axes of the schemes and available accident probability data, may require information or assumptions about package characteristics, accident scenarios and environments, possible impact targets, or other factors in order to relate the original category-defining parameters to the parameters along the common set of axes. In order to be appropriate for the transfer methodology, the parameters for the common set of axes must be chosen such that relationships between probability of occurrence and each of these category-defining parameters can be obtained. The parameters used for the common set of axes may or may not be among the parameters used for any of the original axes. The most commonly reported relationships of probability of occurrence to accident environments use simple accident parameters such as some form of impact velocity, fire duration, etc. Care should be taken not to misinterpret these or any other accident parameters. For example pre-accident speed, velocity change in an impact, and equivalent speed onto an unyielding target are different parameters but might all be loosely referred to as "impact velocity." The methodology described here cannot be used with a scheme in which the parameters defining the severity categories are not explicitly defined.

After the severity category schemes are mapped onto an appropriate common set of axes, the two schemes that are to have probabilities transferred between them are overlaid. To illustrate this, consider the three-category scheme shown in Figure 3 and the four-category scheme shown in Figure 4. Both of these schemes are depicted on a common set of axes. For the purpose of illustration, consider that these simple accident-severity category schemes are for studies of spent nuclear fuel truck transport, have impact and fire as the critical types of accident environments, consider pre-accident speeds of zero to 160 km/hr to be credible, are only for accidents that involve fires, and consider fire durations for an 800 °C, hypothetical, fully engulfing fire of up to two hours. Figure 5 shows the overlay of these two category schemes. The severity categories are not required to be graphically depicted and overlaid to apply the transfer methodology. The boundaries of every category in both schemes need only be accounted for mathematically; however, graphical depiction can provide a good physical awareness of the problem.

Since pre-accident speed and fire duration are the parameters used to define the severity categories depicted in Figure 5, relationships between probability of occurrence and both pre-accident speed and fire duration are needed to apply the methodology to the transfer of probabilities between these category schemes. Information on the severities of transportation accidents provided in a study published by Sandia National Laboratories (Clarke et al. 1976) is used in this study to obtain the needed relationships. The cumulative probability distribution of pre-accident speed shown in Figure 6 and the cumulative probability distribution of fire duration shown in Figure 7 are both adapted from Clarke et al. The cumulative probability distribution shown in Figure 7 was generated, because of a lack of historical accident data, by a Monte Carlo prediction scheme for a model of the expected duration of truck fires for trucks carrying only nonflammable cargo. The relationship shown in Figure 7 is assumed, for the purpose of illustrating the transfer methodology, to be equivalent to the 800 °C, hypothetical, fully engulfing fire used to define the severity categories in Figure 5.

Transportation accidents are random events and as such are not well suited for recording, in exact engineering terms, the environments created during an accident. This lack of historical data describing accident environments in exact terms and the measures necessary to convert data or model results to the parameters used to define severity categories may result in a loss of resolution with the transfer methodology.

The relationships between probability of occurrence and each parameter used to define the severity categories should be as representative as possible of the information used to originally determine the accident probability associated with each category in the scheme that one is transferring from. The purpose of these relationships is to indicate how an accident probability associated with any severity category is distributed within that category so that it may be appropriately transferred to categories in another scheme. The relationships are not used to calculate probabilities directly, but since they are used to determine how accident probabilities are distributed to categories in a different category scheme, they should be consistent with actual accident experience.

To illustrate the transfer of probabilities between severity category schemes, consider that the three-category scheme shown in Figure 3 has a probability associated with each category and these probabilities are desired to be transferred to the four-category scheme shown in Figure 4. The overlay of these two schemes depicted in Figure 5 shows that the range of accident environments represented by category A of the three-category scheme encompasses all accident environments represented by category 1 and part of the environments represented by categories 2, 3, and 4 of the four-category scheme. The probability associated with category A, therefore, should be distributed to categories 1, 2, 3, and 4 of the four-category scheme.

The fraction of accident probability associated with category A to be distributed to each of the four categories in the four-category scheme is determined by use of the cumulative distributions shown in Figures 6 and 7. The joint probability of occurrence for category 1 and for the portions of categories 2, 3, and 4 encompassed by category A is calculated from these cumulative distributions. The value calculated by dividing each of these joint probabilities by the sum of the four joint probabilities gives the fraction of accident probability associated with category A to be distributed to each of the four categories (1, 2, 3, and 4) in the four-category scheme. The parameters of pre-accident speed and fire duration are modeled as independent of each other, which appears reasonable based on accident data (Clarke et al. 1976). For a severity category scheme in which dependence between the parameters defining the scheme is modeled, additional steps or other methods must be used to determine the distribution of the category probabilities within the categories and subsequently transfer the probabilities to another category scheme.

To illustrate the procedure described above, note from Figure 6 that 86% of the truck accidents occur at pre-accident speeds less than 70 km/hr and 72% occur at pre-accident speeds less than 50 km/hr. Figure 7 shows, for truck accidents involving fires, that 97% have fire durations less than 0.5 hours and 79% have fire durations less than 0.25 hours. The joint probability of occurrence for category 1, which includes pre-accident speeds up to 50 km/hr and fire durations up to 0.25 hours, is calculated as

(0.72) X (0.79) = 0.57.

Likewise, the joint probability for the portions of categories 2, 3, and 4 encompassed within category A is calculated;

for the portion of category 2 as (0.72) X (0.97 - 0.79) = 0.13,

for the portion of category 3 as (0.86 - 0.72) X (0.79) = 0.11,

and for the portion of category 4 as (0.86 - 0.72) X (0.97 - 0.79) = 0.03.

The sum of these four probabilities equals 0.84.

The fraction of the accident probability associated with category A to be distributed to category 1 can now be calculated as

0.57 / 0.84 = 0.68.

Similarly, the fraction of the accident probability associated with category A to be distributed to categories 2, 3, and 4 is calculated;

for category 2 as 0.13 / 0.84 = 0.16,

for category 3 as 0.11 / 0.84 = 0.13,

and for category 4 as 0.025 / 0.84 = 0.03.

A convenient check on this step is that the fractions should add to one for each category that probabilities are being transferred from. The fractions calculated above for category A do add to one,

$$0.68 + 0.16 + 0.13 + 0.03 = 1.00.$$

Following a similar procedure shows that the range of accident environments represented by category B of the three-category scheme encompasses a portion of the accident environments represented by categories 2 and 4 of the four-category scheme. The accident probability associated with category B is distributed to categories 2 and 4 in the following fractions: 0.84 to category 2, and 0.16 to category 4.

Likewise, the range of accident environments represented by category C of the three-category scheme encompasses a portion of the accident environments represented by categories 3 and 4 of the four-category scheme. The fraction of the accident probability associated with category C to be distributed to category 3 was calculated to be 0.79 and the fraction to be distributed to category 4 was calculated to be 0.21.

The fractions calculated above that indicate how the accident probabilities associated with each of the three categories (A, B, and C) in the three-category scheme are distributed to each of the four categories (1, 2, 3, and 4) in the four-category scheme are displayed in matrix form in Table 1. The total accident probability associated with each of categories 1, 2, 3, and 4 is calculated by summing the probabilities distributed to each of these categories from categories A, B, and C. As Table 1 shows, the accident probability of category 1 is calculated by multiplying 0.68 by the accident probability of category A. Likewise, the accident probability of category 2 is the sum of the products of 0.16 multiplied by the accident probability of category A and 0.84 times the accident probability of category B. The accident probabilities of categories 3 and 4 are calculated in a similar manner.

SUMMARY AND CONCLUSIONS

A methodology has been developed which allows the accident probabilities associated with one accident-severity category scheme to be transferred to another severity category scheme. The methodology requires that the schemes use a common set of parameters to define the categories. The transfer of accident probabilities is based on the relationships between probability of occurrence and each of the parameters used to define the categories. Because of the lack of historical data describing accident environments in engineering terms, these relationships may be difficult to obtain directly for some parameters. Numerical models or experienced judgement are often needed to obtain the relationships. These relationships, even if they are not exact, allow the accident probability associated with any severity category to be distributed within that category in a manner consistent with accident experience, which in turn will allow the accident probability to be appropriately transferred to a different category scheme.

The ability to transfer accident probabilities between severity category schemes will allow some comparisons at the category level of studies which used different category schemes. This may be useful when comparing, for a similar transport situation, older studies with more recent studies or studies done at different institutions or by different countries. The methodology will allow category probabilities from past studies to be used in current severity category schemes for comparison purposes. By promoting a better understanding of how severity categories in different category schemes relate to one another, the methodology presented in this paper will reduce some of the confusion and misinterpretation associated with comparing different studies.

The ability to transfer accident probabilities between severity category schemes will not directly allow all quantities commonly associated with severity categories to be transferred between the schemes. Risk, for example, is a function of both accident probability and consequence. If this methodology were to be used for the transfer of risk between category schemes, one could transfer the accident probabilities as outlined above and then perform a consequence analysis on the new category scheme to obtain risk values in the new scheme. The basic methodology described in this paper can, however, be used for any quantity, not just accident probability, if the relationships between that quantity and the parameters used to define the categories are obtainable. Risk, therefore, could be transferred directly between category schemes by following the steps of the methodology and substituting the relationships between risk and each of the category-defining parameters for the relationships between probability of occurrence and each of the category-defining parameters. These risk relationships, however, could be difficult to obtain because of the many factors upon which risk depends and would apply only to the particular case for which it was developed.

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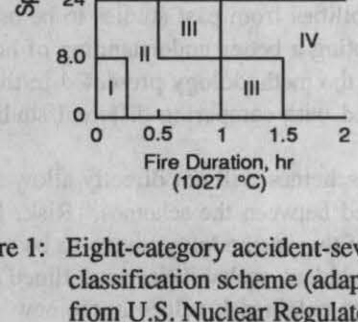

Figure 1: Eight-category accident-severity classification scheme (adapted from U.S. Nuclear Regulatory Commission 1977).

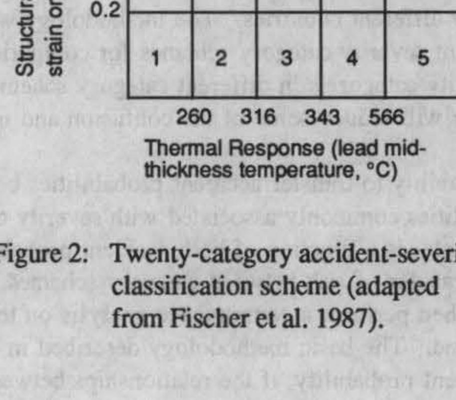

Figure 2: Twenty-category accident-severity classification scheme (adapted from Fischer et al. 1987).

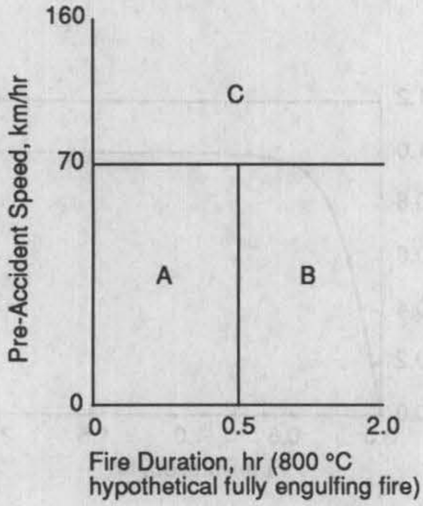

Figure 3: Three-category accident-severity classification scheme.

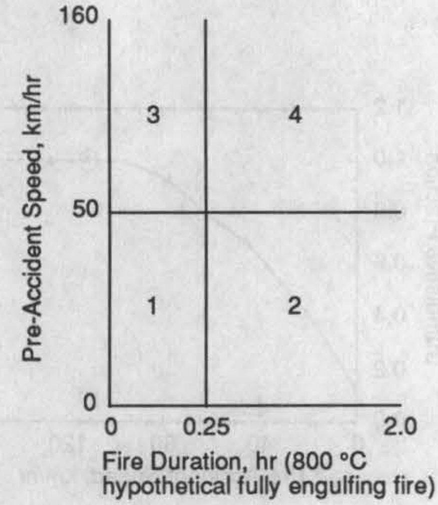

Figure 4: Four-category accident-severity classification scheme.

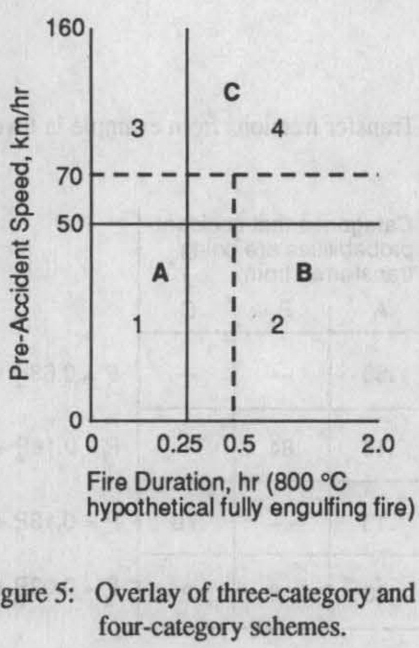

Figure 5: Overlay of three-category and four-category schemes.

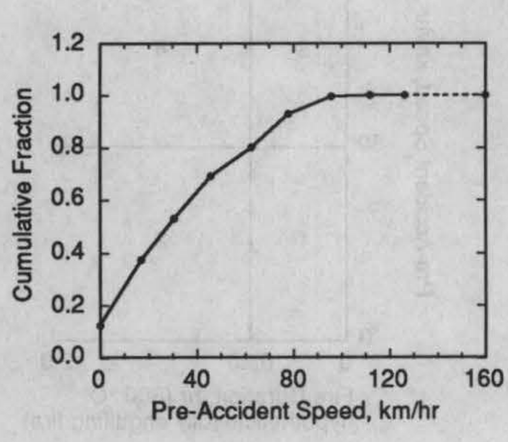

Figure 6: Cumulative probability distribution of pre-accident truck speeds (adapted from Clarke et al. 1976).

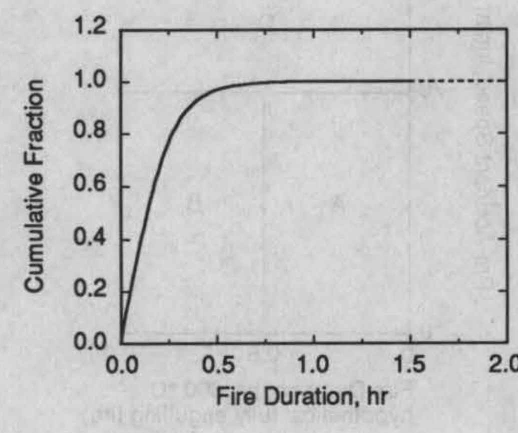

Figure 7: Cumulative probability distribution of fire duration in truck accidents involving fire (adapted from Clarke et al. 1976)

Table 1: Transfer fractions from example in text.

		Categories that accident probabilities are being transferred from.			
		A	B	C	
Categories that accident probabilities are being transferred to.	1	.68	---	---	$P_1 = 0.68P_A$
	2	.16	.84	---	$P_2 = 0.16P_A + 0.84P_B$
	3	.13	---	.79	$P_3 = 0.13P_A + 0.79P_C$
	4	.03	.16	.21	$P_4 = 0.03P_A + 0.16P_B + 0.21P_C$

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