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EXTENSION OF SHIP ACCIDENT ANALYSIS TO MULTIPLE-PACKAGE SHIPMENTS

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SUMMARY

Severe ship accidents and the probability of radioactive material release from spent reactor fuel casks were investigated previously (Sprung, 1995). Other forms of RAM, e.g., plutonium oxide powder, may be shipped in large numbers of packagings rather than in one to a few casks. These smaller, more numerous packagings are typically placed in ISO containers for ease of handling, and several ISO containers may be placed in one of several holds of a cargo ship. In such cases, the size of a radioactive release resulting from a severe collision with another ship is determined not by the likelihood of compromising a single, robust package but by the probability that a certain fraction of 10's or 100's of individual packagings is compromised. The previous analysis (Sprung, 1995) involved a statistical estimation of the frequency of accidents which would result in damage to a cask located in one of seven cargo holds in a collision with another ship. The results were obtained in the form of probabilities (frequencies) of accidents of increasing severity and of release fractions for each level of severity.

This paper describes an extension of the same general method in which the multiple packages are assumed to be compacted by an intruding ship's bow until there is no free space in the hold. At such a point, the remaining energy of the colliding ship is assumed to be dissipated by progressively crushing the RAM packagings and the probability of a particular fraction of package failures is estimated by adaptation of the statistical method used previously. The parameters of a common, well-characterized packaging, the 6M with 2R inner containment vessel, were employed as an illustrative example of this analysis method. However, the method is readily applicable to other packagings for which crush strengths have been measured or can be estimated with satisfactory confidence.

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DISCLAIMER

INTRODUCTION

Sea shipments of radioactive material (RAM) often involve large numbers of packagings which are in turn placed in ISO containers, for ease of handling, and several ISO containers may be placed in one of several holds of a cargo ship. Thus, the amount of RAM released in a severe collision with another ship is largely determined by the fraction of the 10's or 100's of individual packagings in the struck hold which are compromised, i.e., containment failure of the packaging. Estimates of the fraction of compromised packagings for different severities of collisions have been developed, here, on a statistical basis which makes use of collision dynamics analysis and shipment statistics originally developed for large casks (Sprung, 1995). The method is illustrated for a well-characterized packaging, the 6M with 2R inner containment vessel.

DESCRIPTION OF ORIGINAL ANALYSIS

Others (Sprung, 1995) have described an analysis of severe ship accidents and the resultant probabilities of release of RAM from shipments of spent reactor fuel in casks designed for the purpose. Their work involved statistical evaluation of the frequency of accidents which would result in damage to a cask located in one of the seven cargo holds of a typical break-bulk freighter in the event that it is struck by another ship. The striking ship was modeled as having a range of displacements, speeds, and angles of incidence on the struck ship. This analysis involved determination of the depth of penetration of the bow of the striking ship into the hold of the struck ship, as a function of the parameters just mentioned, and the characteristics of the cargo sharing the struck hold with the cask. The results were obtained in the form of probabilities (frequencies) of accidents of increasing severity and release fractions for each severity category. It was assumed that the cask would be breached under two different conditions: (1) the cask, constrained by distorted ship structure or other means, is struck by the intruding bow of the striking ship; (2) the cargo sharing the hold is compressed until the hold "goes solid" around the cask and further intrusion of the striking ship compresses the cask to failure.

EXTENSION TO MULTIPLE PACKAGES

A particular type of packaging employed in RAM shipments (6M-2R) has been sufficiently characterized by testing to permit extension of the general method developed (Sprung, 1995). The packaging analyzed here consists of an outer container (the 6M; a 55-gal drum) and an inner container (the 2R; a 6-inch or 12-inch diameter schedule 40 pipe with sealed end-caps) held in place by Celotex®. Static crush testing of the outer container (Huerta, 1983) and estimates of the Celotex® crush strength obtained from handbook values for similar materials indicated that the overall crush strength is 0.2 MPa, much less than the value of 6.9 MPa for "light cargo", and are treated as unoccupied hold-space (Sprung, 1995). The other parameter used to characterize the cargo types (Sprung, 1995) is the packing fraction (fraction of total hold area that is unoccupied before cargo begins to be compressed) which is approximated here by the square of the ratio of the diameters of the 2R and 6M containers:

$$1 - (6\text{ inches}/24\text{ inches})^2 = 1 - 1/16 = 0.9375.$$

This factor represents the fraction of the cargo-hold area (assuming the 6M-2R containers completely fill the hold in a 1-D calculation) that must be collapsed by the striking ship before "solid" conditions are obtained, the point at which remaining collision energy begins to compress the inner, 2R, containers. The crush strength (to the point of breaching) of the 2R container and contents simulating plutonium oxide powder was estimated at 30 MPa from dynamic impact testing (Bonzon, 1977). This value is comparable to that of "medium cargo", i.e., 34.5 MPa (Sprung, 1995). Note that use of a dynamic crush strength is an approximation since ship collision velocities are much lower than those employed by Bonzon. The initial steps of collapsing ship's structures, ISO containers, 6M drums and Celotex® onto the 2R containers are depicted schematically in Figure 1 in the Appendix.

Table 1 lists the frequencies of collisions with different penetration distances for the various cargo types analyzed in histogram form by Reardon (private communication). At the accuracy that is consistent with Reardon's analysis, the cumulative frequency of collisions resulting in penetration to <23.4 m (0.9375×25 m ≈ 23.44 m) is between 0.84 and 0.87 (summing frequencies in Table 1). The frequency of all collisions resulting in compromise of one or more 2R containers is then between 0.13 and 0.16. In order to estimate frequencies of collisions resulting in specific fractions of the 2R containers being compromised (between 0 and 100%), frequencies of collisions for cargo with compression strengths of the order of the 2R containers (30 MPa) must be estimated. The frequency versus penetration distance (D), for "medium cargo" (34.5 MPa) and distances of <7.5 through <15 m in Table 1, was normalized and fitted by an exponential function:

$$\mathrm{Freq}(D_1 \text{ to } <D_2) = C[\mathrm{EXP}(-0.71D_1) - \mathrm{EXP}(-0.71D_2)],$$

for D shifted to a range of 0.0 through 7.5 m and beyond, and C equals the cumulative frequency for crushing of the 2R's ($0.13 < 0.15 < 0.16$). This function was used to interpolate frequencies corresponding to penetration values between 23.4 m and ≥ 25 m and the corresponding fractions of 2R containers breached determined on the basis of a 1-D volume calculation. For the simple "none or all" case, this yields frequencies of 0.10 (0 to <100% compromised) and 0.05 (100% compromised).

A more detailed set of fractions of compromised containers can be determined by breaking the same penetration interval into more segments; Table 2 presents an example of such a subdivision. Results of this type are useful for uncertainty and sensitivity analysis of accident risk.

Table 1 - Frequencies of Collisions Having Various Penetration Distances

	Cargo Types			
Penetration (meters)	None (Cumulative)	Light *pf=0.6 (15m) (Cumulative)	Medium *pf=0.2 (5m) (Cumulative)	Heavy *pf=0.5 (12.5m) (Cumulative)
0.0	0.495 (0.495)	0.495 (0.495)	0.495 (0.495)	0.495 (0.495)
<2.5	0.018 (0.513)	0.018 (0.513)	0.018 (0.513)	0.018 (0.513)
<5.0	0.034 (0.547)	0.034 (0.547)	0.034 (0.547)	0.034 (0.547)
<7.5	0.049 (0.596)	0.049 (0.596)	0.376 (0.923)	0.049 (0.596)
<10.0	0.059 (0.655)	0.059 (0.655)	0.062 (0.985)	0.059 (0.655)
<12.5	0.050 (0.705)	0.050 (0.705)	0.012 (0.997)	0.050 (0.705)
<15.0	0.054 (0.759)	0.054 (0.759)	0.002 (1.000)	0.294 (1.000)
<17.5	0.036 (0.795)	0.167 (0.926)	0.000 (1.000)	0.000 (1.000)
<20.0	0.047 (0.842)	0.054 (0.980)	0.000 (1.000)	0.000 (1.000)
<22.5	0.028 (0.870)	0.016 (0.996)	0.000 (1.000)	0.000 (1.000)
<25.0	0.035 (0.905)	0.003 (1.000)	0.000 (1.000)	0.000 (1.000)
□25.0	0.094 (1.000)	0.000 (1.000)	0.000 (1.000)	0.000 (1.000)

* **pf is the cargo packing fraction, the fraction of the hold that is not occupied by cargo.**

Table 2 - Example of Frequencies of Occurrence for a Typical Set of Compromised Container Fractions (55 gal 6M & 6 inch 2R)

Percent of Containers Compromised	Corresponding Penetration Distance	Frequency of Occurrence (Cumulative)
0	0.0 to <23.4 m	0.850 (0.850)
>0 to <10	23.40 to <23.56 m	0.015 (0.865)
10 to <20	23.56 to <23.72 m	0.014 (0.879)
20 to <50	23.72 to <24.20 m	0.033 (0.912)
50 to <100	24.72 to <25.00 m	0.036 (0.948)
100	≥25 m	0.052 (1.000)

As a further example of the method developed here, another 6M-2R configuration is useful: a 55-gal 6M containing a 12-inch diameter 2R. In this case the packing fraction becomes:

$$1-(12 \text{ inches}/24 \text{ inches})^2 = 1- 1/4 = 0.75 .$$

Again, from Table 1 (no cargo, penetration = 0.75 x 25 m = 18.75 m ≈ 19 m) it can be determined that the cumulative frequency of collisions resulting in no compromised 2R containers is approximately 0.80 and the frequency for some or all of the compromised containers is 0.20. The results of a subdivision of the numbers of containers compromised like that used in the example above (but with C=0.20) is presented in Table 3.

Table 3 - Example of Frequencies of Occurrence for a Typical Set of Compromised Container Fractions (55 gal 6M & 12 inch 2R)

Percent of Containers Compromised	Corresponding Penetration Distance	Frequency of Occurrence (Cumulative)
0	0.0 to <19.0 m	0.800 (0.800)
>0 to <10	19.0 to <19.6 m	0.069 (0.869)
10 to <20	19.6 to <20.2 m	0.045 (0.914)
20 to <50	20.2 to <22.0 m	0.062 (0.976)
50 to <100	22.0 to <25.0 m	0.021 (0.997)
100	≥25 m	0.003 (1.000)

CONCLUSIONS

A method for estimating the consequences of maritime collision accidents that might compromise shipments of large numbers of small packagings has been formulated on the basis of previous analysis of consequences for shipments of large, single packagings (spent fuel casks). Conservative estimates of frequencies of ship collisions as a function of accident severity for casks have been extended to multiple packagings with an accuracy and a conservatism consistent with the cask analysis. Substantial conservatism consists in assuming that the ship structures (decks, bulkheads, etc.) are rigid; in reality they will also deform as cargo compression approaches "solid" conditions, dissipating much of the energy assumed, here, to be applied to crushing 2R containers. In addition, the entire area of a hold will not be completely filled with 6M-2R packagings; as a result, greater bow-penetration can occur without compression of the 6M's and Celotex®. Finally, the compression geometry of the 2R containers in a "solid" hold will more nearly approximate isostatic compression than the conditions (~ uniaxial compression) experienced in dynamic testing; the actual pressure required to compromise a 2R container may be expected to exceed the 30 MPa assumed in this analysis.

The present results substantiate the expectation that, for the same quantity of material, the consequences of collisions involving large numbers of packagings are substantially reduced compared to the case of a single packaging, i.e., potential releases are much less than the total inventory of the shipment. The method is readily applicable to other packagings for which crush strengths are available or can be estimated with satisfactory accuracy, and yields results suitable for defining distribution functions which may be employed in sensitivity or uncertainty analysis of accident risk.

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Sprung, J. L., et al., "Radiological Consequences of Ship Collisions that Might Occur in U.S. Ports During the Shipment of Foreign Research Reactor Spent Nuclear Fuel to the U.S. in Break-Bulk Freighters," Proceedings of Waste Management 95 Conference, Tucson, AZ, February, 1995.

APPENDIX

Figure 1a - Initial Configuration of Struck Ship's Hold

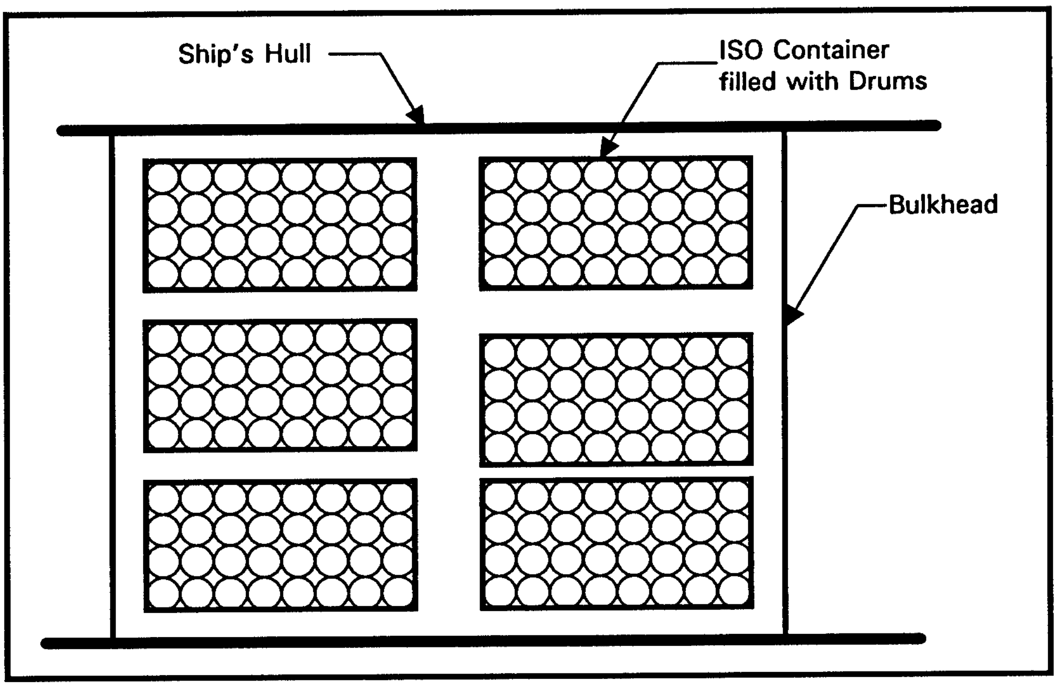


Figure 1b - Intermediate Stage of Compressing "Unfilled" Hold Area

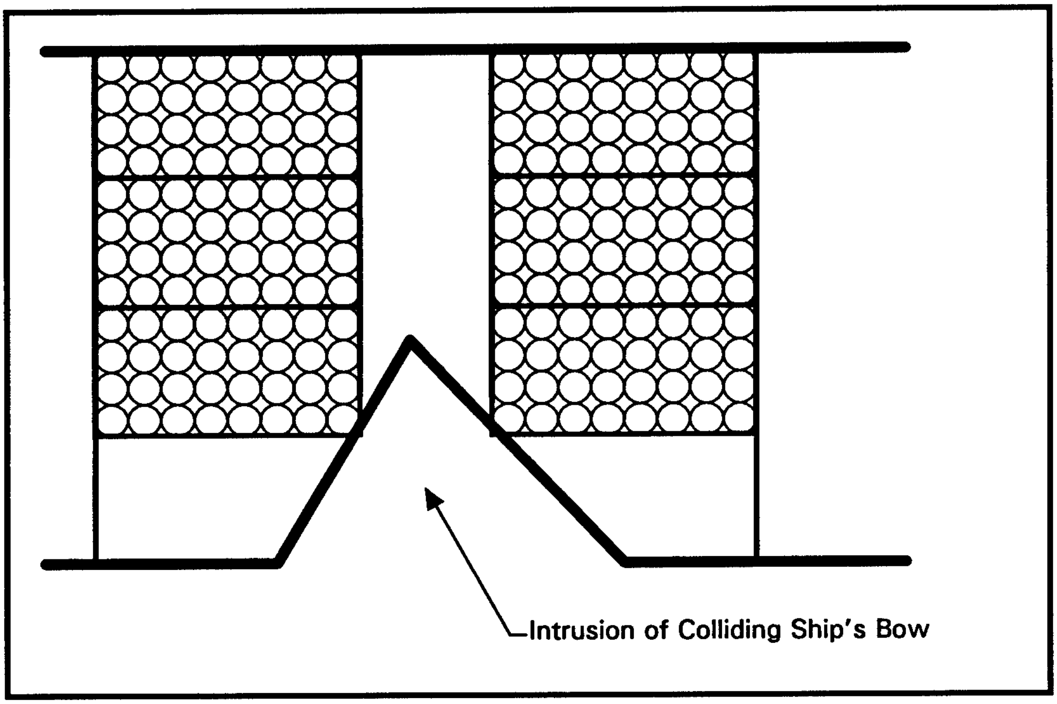
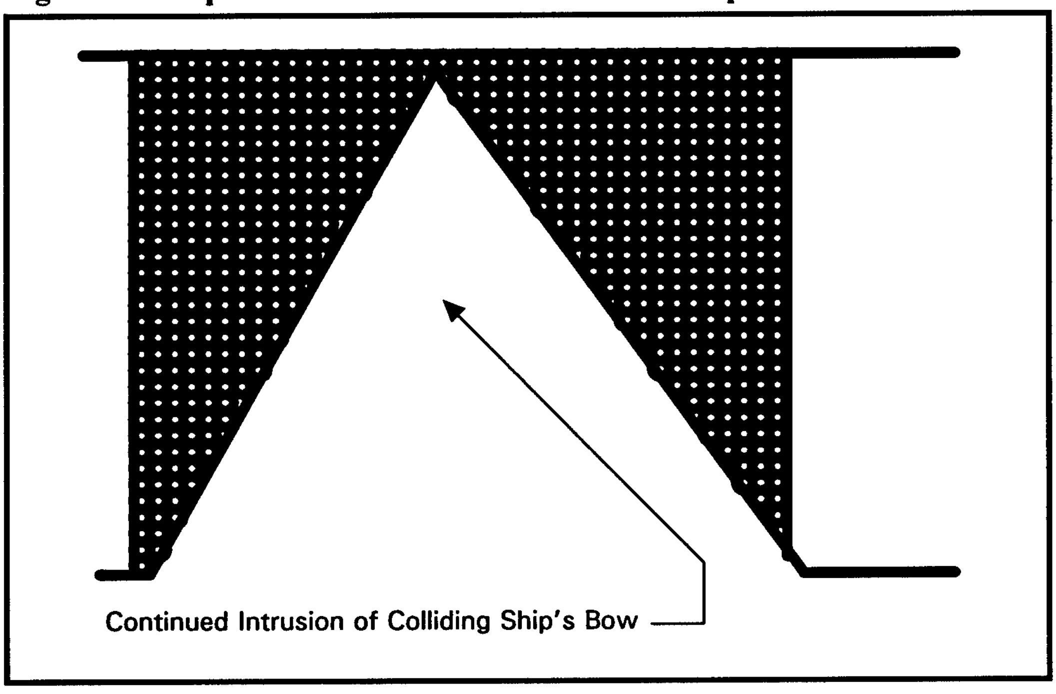


Figure 1c - Ship's Hold when All Structures are Collapsed onto 2R Containers



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