AN ENGINEERING ASSESSMENT OF THE PROBABILITY FOR DAMAGE TO RADIOACTIVE MATERIAL TRANSPORT CASKS DUE TO BARGE COLLISIONS

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Abstract

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The conditional probability for damage to radioactive material (RAM) transportation casks due to barge collisions was examined using level III methods from risk and reliability theory. For each of 12 500 collision cases examined, a time domain simulator for marine collisions was used to generate data concerning penetration, residual energy and relative velocity at each time step. The simulator developed for this purpose represents an extension of Minorsky's one dimensional collision model to three dimensions (six degrees of freedom). The model also includes the contributions of Jones and Van Mater which account for hull membrane structural resistance up to the point of hull rupture. Twenty-five hundred realistic randomly generated barge collision cases were simulated for each five classifications of US navigable waters (total of 12 500 simulated accidents). Monte Carlo methods were used to develop, from the set of predicted collision state variables, the joint demand processes for the struck barge cargoes. These demand processes were then compared with RAM cask capabilities in order to estimate the conditional probabilities of RAM cask damage given a collision in a specified classification of navigable waters.

1.0.0 INTRODUCTION

Several recent studies have determined that 80 percent of the operational reactor sites in the United States of America could utilize barge transportation for some portion of the spent fuel shipment. This paper presents, in synoptic form, a portion of a larger study [1] prepared for Sandia National Laboratories concerning the risk factors associated with barge transportation of radioactive material (RAM) as a consequence of barge collisions, rammings and groundings. The portion of that larger study here presented concerns only barge collision accidents. This topic, barge collisions, has also been presented at somewhat greater length than the present paper before the Society of Naval Architects and Marine Engineers [2].

The objective of this study was to estimate the conditional probabilities for specified levels of RAM transport cask damage, given that a barge collision has occurred on a specified classification of U.S. domestic navigable waters. No attempt was made in these studies to correlate the specified levels of RAM cask damage with probabilities for release of cask contents. The estimation of these conditional probabilities for RAM cask damage was developed using well known concepts from risk and reliability theory wherein the probability that system demand exceeds system capacity is evaluated. The usual representation of this relationship is:

$$F(D>C) = \int_{-\infty}^{\infty} f_D(x) * F_C(x)\,dx = \int_{-\infty}^{\infty} [1 - F_D(x)] * f_C(x)\,dx$$

where: $F(D>C)$ is the probability that demand exceeds capacity
$f(\,)$ is a probability density function
$F(\,)$ is a cumulative probability function

and the subscript 'D' and 'C' denote process demand and capacity (also known as capability) respectively.

The demand and capability distributions are seen to be of central importance to the determination of the probability for RAM cask damage. The remainder of this paper will describe the developement of these demand and capability distributions, and the details of the logic used to compose the final estimates of the conditional probabilities for cask damage.

2.0.0 DEMAND DISTRIBUTIONS

Demand distributions were developed which correspond to RAM cask capability with respect to identifiable cask damage processes. The selected measure of the demand process was the joint distribution of residual collision energy and relative velocity when the bow of the striking vessel crosses the cargo loading inset plane. Demand processes across two cargo loading inset planes were studied, one inset one-fifth of the barge beam which corresponds to the ANSI standard for barge transportation of high level waste [3] , and the other inset 3.8 meters or one-fifth of the barge beam, whichever is greater. This latter loading restriction is designated the 'alternate loading restriction' within this study.

U.S. domestic navigable waters were grouped into five classifications for the purposes of this study, those being:

1) The so-called "Western" rivers
2) The Mississippi River system
3) The Gulf Intracoastal Waterway
4) Other inland rivers and waterways
5) Coastwise voyages offshore

Joint distributions of penetration distance, residual collision energy and relative velocity were determined using Monte Carlo techniques operating on collision case data generated using a time domain simulator. This time domain simulator was developed as a generalization and extension of Minorsky's [4] original one-dimensional ship collision model. The features of the simulator used for this study are:

1) The simulator used for this study was extended to three-dimensions and a total of six degrees-of-freedom (three horizontal plane DOF per vessel).
2) The tensor properties of hydrodynamic added mass were included. (See references [1, 2] for further details).
3) The hull shell membrane resistance of Jones and Van Mater [5] was incorporated to replace the empirical constant of Minorsky's original analysis.
4) Friction was included.
5) As a time domain simulator the joint demand process can easily be determined at any intermediate instant of the collision process evolution.

The basic structural interaction mechanism of Minorsky wherein the energy absorbed is proportional to the volume of in-plane structure deformed (a constant pressure process) was retained.

For each navigable domain 2500 accident cases were simulated. The engineering parameter vectors required as input to the time domain collision simulator were developed in two stages. First, a striking vessel type and length are chosen according to their joint frequency distributions in the U.S. Coast Guard Commercial Vessel Casualty database over the period from 1963 to 1980. The physical dimensions, displacement and design speed of the striking vessel are determined by random generation from conditional distributions with constraints to ensure realistic design. Then the physical dimensions, relevant structural parameters, loading conditions and speed are randomly determined for the struck barge using joint distribution data for the general cargo barge populations operating in the various navigable domains. The relative heading and the velocities of the two vessels at the instant of collision are also determined from random distributions conditioned on the operating domain and vessel types.

The final state of each simulated collision was classified as one of the following five conditions:

1) A glancing blow (minimal damage is presumed)
2) Collisions where the struck barge shell is dented but not ruptured
3) Collisions where the total penetration distance is less than the one-fifth beam ANSI inset
4) Collisions where the total penetration was greater than the ANSI inset and less than the alternate inset
5) Collisions where the total penetration was greater than both the ANSI inset and the alternate inset.

The distributions of collision penetration distances obtained for two important classifications of navigable waterway are shown in Table I. Residual collision energy and relative collision velocity when crossing the ANSI and alternate cargo inset planes respectively are shown in Table II. Similar data for the other waterways studied are given in reference [1].

The distributions of the various components of the demand processes were fit to analytical forms using least squares methods. The coefficients for the important relative velocity processes when crossing the cargo

TABLE I. DISTRIBUTION OF COLLISION PENETRATIONS (BASED ON 2500 SIMULATED COLLISIONS PER WATERWAY)

	Mississippi	Offshore
Glancing Blows	2.96%	26.68%
Non Hull Ruptures	8.64%	9.72%
Penetrations Less than 0.2*Beam	62.76%	47.12%
Between ANSI and Alternate Insets	23.84%	2.16%
Greater than Alternate Inset	1.80%	14.32%
	100.00%	100.00%

TABLE II. RESIDUAL ENERGY (GJ) AND RELATIVE VELOCITY (m/sec)

	Mississippi			Offshore		
Percentile:	50%	75%	95%	50%	75%	95%
Energy at ANSI Plane	6.1	9.5	22.8	11.6	26.6	84.3
Velocity at ANSI Plane	2.0	2.9	3.9	3.1	4.6	7.0
Energy at Alt. Plane	3.8	9.2	24.9	11.9	29.7	91.6
Velocity at Alt. Plane	1.7	2.1	4.9	3.1	4.6	6.9

TABLE III. LEAST SQUARES FIT DISTRIBUTIONS FOR RELATIVE VELOCITY

$\log_{10}[1/(1-F(x))] = A x + B x^2$, where x is velocity (m/sec)

	MIN. VELOCITY	A	B
Western Rivers	0.55	-7.62×10^{-2}	1.58×10^{-1}
Mississippi	0.79	-7.81×10^{-2}	9.95×10^{-2}
Gulf Intracoastal	0.25	-3.14×10^{-2}	1.26×10^{-1}
Inland	0.00	1.56×10^{-2}	8.47×10^{-2}
Offshore	1.05	-3.80×10^{-2}	3.61×10^{-2}

loading inset planes are given in Table III. Similar data for other processes are given in reference [1].

3.0.0 CAPABILITY DISTRIBUTIONS

The structural capability of eight type B spent fuel casks of current design were modeled for impact loading processes imposed by a rigid ships bow. The casks were structurally modeled as concentric circular cylindrical shells which in most designs consisted of an outer structural shell, a gamma shield and an inner shell or liner. This structural system

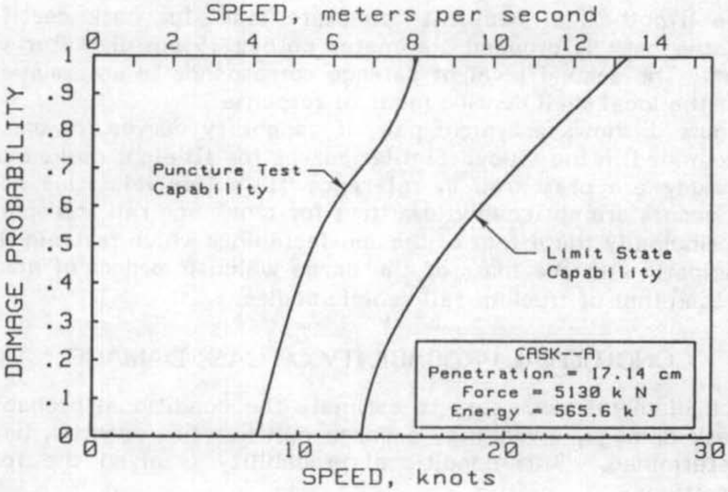

FIG. 1. Capability curves for Cask 'A'.

was conservatively modeled by considering that each shell element acted in parallel with the others without any shear stresses acting at the interfaces between adjacent shells.

The impact loading process was considered to be that of a rigid ships bow striking the cask side. The striking bow was modeled as a vertical bar stem with a 3.8 cm face width and infinite vertical extent. The basic structural response was modeled as plastic denting of the shell taking place along a mechanism consisting of five plastic hinge lines. For each shell the reactive force required to continue the indentation process at any level of indentation was determined using published shell denting curves [6, 7]. Under the presumption that the shells act in parallel the total resistance to denting was then the sum of the resistances from each shell.

The dynamics of the impact process were modeled in the time domain to determine the impact velocity required to produce specified levels of damage for an impact centered at any particular location along the cask. The time domain model assigned properties associated with infinite mass to both the transport barge and the striking vessel. Thus the base to which the RAM cask sea-fastenings attached was treated as stationary and the velocity of the striking bow was unaltered by the resistance offered by the cask. The cask was assumed to be held to the barge with elasto-plastic sea-fastenings at each end of the cask. The sea-fastenings were modeled with structural area sufficient to resist a one 'g' lateral load at 90 percent yield. During the time domain simulations the individual sea-fastenings failed when a 10 percent strain was achieved.

Capability curves for each cask design were determined from the response surfaces developed in time domain analysis of cask dynamics. Attention was focused on two levels of cask damage. The first damage level corresponded to the indentation and energy absorption associated with the hypothetical accident "puncture test" for cask certification wherein the cask is dropped one-meter onto a 15 cm diameter vertical steel bar. The second level of damage corresponds to an assumed limit state for the local shell denting mode of response.

Figure 1 shows a typical pair of capability curves for one of the casks examined in the study. Similar curves for all eight casks examined in the study are presented in reference [1]. The velocities at which damage occurs are noticeably less than for truck and rail transportation. This is principally the effect of the sea-fastenings which restrain the cask to participate with the mass of the barge which is orders of magnitude greater than that of truck or rail vehicle bodies.

4.0.0 CONDITIONAL PROBABILITY OF CASK DAMAGE

The elements necessary to estimate the conditional probability of RAM cask damage, given that a barge collision has occured, have now been determined. This conditional probability is given the following decomposition:

Damage Level	Across ANSI Boundary	Across Alternate Boundary
Cert. Test	$P_7 = P_1 \times P_2 \times P_3 \times P_5$	$P_7' = P_1' \times P_2' \times P_3' \times P_5'$
Limit State	$P_8 = P_1 \times P_2 \times P_4 \times P_6$	$P_8' = P_1' \times P_2' \times P_4' \times P_6'$

where: P_7 and P_7' are the conditional probabilities for the lower level of cask damage corresponding to the certification "puncture test", given a barge collision.

P_8 and P_8' are the conditional probabilities for the higher level of cask damage corresponding to the assumed limit state for the local shell denting process, given a barge collision

P_1 is the probability for crossing the ANSI boundary

P_1' is the probability for crossing the alternate boundary

$P_2 = P_2' = 0.7$ is a stowage factor

P_3 and P_3' are the probabilities that the relative velocity exceeds the cask capability for the lower level of damage, given respectively that the ANSI or alternate plane has been crossed

P_4 and P_4' are the probabilities that the relative velocity exceeds the cask capability for the higher level of damage, given respectively that the ANSI or alternate plane has been crossed

P_5, P_5', P_6 and P_6' are all conditional probabilities that the residual collision energy exceeds the minimum energy absorption of the cask to the specified level of damage, given that the relative collision velocity at the cargo plane exceeds the minimum velocity required to produce the specified level of damage

TABLE IV. PROBABILITIES FOR CROSSING CARGO LOADING BOUNDARIES

	ANSI Boundary	Alternate Boundary
Western Rivers	0.1524	0.0028
Mississippi	0.2564	0.0180
Intracoastal	0.1692	0.0088
Inland Waterways	0.1836	0.0300
Offshore	0.1648	0.1432

TABLE V. CONDITIONAL PROBABILITY FOR LOWER LEVEL OF DAMAGE

	ANSI Boundary		Alternate Boundary	
	Minimum	Maximum	Minimum	Maximum
Western Rivers	7.1×10^{-5}	1.6×10^{-2}	1.3×10^{-6}	3.0×10^{-4}
Mississippi	1.6×10^{-3}	6.2×10^{-2}	1.1×10^{-4}	4.4×10^{-3}
Intracoastal	1.9×10^{-4}	2.1×10^{-2}	9.8×10^{-6}	1.1×10^{-3}
Inland	8.6×10^{-4}	3.2×10^{-2}	1.4×10^{-4}	5.3×10^{-3}
Offshore	1.6×10^{-2}	8.3×10^{-2}	1.4×10^{-2}	7.2×10^{-2}

Table IV gives the probabilities P_1 and P_1' that the cargo inset planes have been crossed.

Given that the cargo loading boundary has been crossed it is still possible that the striking bow does not encounter a RAM cask. This possibility is represented by a stowage factor, P_2 or P_2' which is given the value 0.7 as a realistic upper bound.

The probabilities P_3, P_3', P_4 and P_4' are all determined by evaluating the level III risk integral:

$$F(D>C) = \int_0^\infty f_D(x) * F_C(x)\,dx = \int_0^\infty [1 - F_D(x)] * f_C(x)\,dx$$

where the demand distributions are for relative collision velocity at the cargo inset plane and the capability distributions are for cask capability to the specified level of damage.

The conditional probabilities P_5, P_5', P_6 and P_6' were studied and approach unity with a high level of confidence. Any striking vessel which possessed adequate collision velocity at the cargo plane but did not possess sufficient kinetic energy would have to be of very small mass. The structural capability of the striking vessel under such circumstances would not lead to the expectation that penetration to the cargo plane could have occurred or that damage to the cask could result. Therefore $P_5 = P_5' = P_6 = P_6' \rightarrow 1.0$.

TABLE VI. CONDITIONAL PROBABILITY FOR HIGHER LEVEL OF DAMAGE

	ANSI Boundary		Alternate Boundary	
	Minimum	Maximum	Minimum	Maximum
Western Rivers	zero	1.4×10^{-6}	zero	2.5×10^{-8}
Mississippi	zero	1.4×10^{-4}	zero	9.5×10^{-6}
Intracoastal	zero	7.2×10^{-6}	zero	3.7×10^{-7}
Inland	zero	8.5×10^{-5}	zero	1.4×10^{-5}
Offshore	3.3×10^{-9}	6.5×10^{-3}	2.9×10^{-9}	5.6×10^{-3}

A range of final conditional probabilities, reflecting the range in cask capabilities, are developed in each navigable domain. Details of the damage probabilities by cask are to be found in reference [1]. The range of final conditional probabilities for the lower level of damage corresponding to the "puncture test" for certification are given in Table V respectively for collisions across the ANSI and alternate cargo loading planes.

The range of final conditional probabilities for the higher level of damage corresponding to the assumed limit state for the local shell denting process are given in Table VI for collisions across the ANSI and alternate cargo loading planes respectively.

The conditional probability for the higher level of RAM cask damage can be seen to be considerably greater in the case of offshore transport than that obtained in any other navigable domain. This reflects the hazard of relatively high speed collisions with large ships, a hazard that does not exist on the other classifications of navigable waters.

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