An Assessment of Simplified Methods To Determine Damage From Ship-to-Ship Collisions*

M.B. Parks, D.J. Ammerman
Sandia National Laboratories

INTRODUCTION

Sandia National Laboratories (SNL) is studying the safety of shipping radioactive materials (RAM) by sea, the SeaRAM project (McConnell et al. 1995), which is sponsored by the U.S. Department of Energy (DOE). The project is concerned with the potential effects of ship collisions and fires on onboard RAM packages. Existing methodologies are being assessed to determine their adequacy to predict the effect of ship collisions and fires on RAM packages and to estimate whether or not a given accident might lead to a release of radioactivity. The eventual goal is to develop a set of validated methods, which have been checked by comparison with test data and/or detailed finite element analyses, for predicting the consequences of ship collisions and fires. These methods could then be used to provide input for overall risk assessments of RAM sea transport. The emphasis of this paper is on methods for predicting effects of ship collisions.

A concern regarding the safety of RAM transport by sea is the possibility of another ship striking the RAM-carrying ship leading to leakage of a RAM package(s). One basis for this concern is the large amount of kinetic energy of the striking ship. Kinetic energies in excess of those for the regulatory impact test exist. This is due to the relatively large mass of some cargo ships and oil tankers, even though ship velocities are relatively small (usually less than 13.4 m/s). *However, it is not appropriate to assess possible damage to RAM packages based only on kinetic energy.*

A better metric is the acceleration imposed on the RAM packages during impact. Type B packages are designed to be leak-tight after being dropped from a height of 9 meters onto an essentially unyielding surface. Typical rigid body uniform accelerations experienced during impact are in the range of 50 to 200 G or higher. However, the highest levels of acceleration during a ship collision are less than 10 G e.g.(Lenselink 1992), much less than expected for the 9-meter drop. The lower accelerations are due to the 'flexibility' of the

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impact surface, which is the deformable RAM-carrying ship and the bow of the striking ship. *Thus, only quasi-static, "crush" types of loading are of concern.*

Only cases in which the RAM-carrying ship is struck by another ship are considered as possible threats to RAM package integrity. Other collision scenarios in which the RAM ship strikes another ship or a rigid pier, or runs aground are not believed to pose a threat to the packages since the packages are stowed well away from the impact location.

There are two types of analyses that are necessary to determine if a given ship collision might lead to leakage from a RAM package. The first is a global analysis, devoted to the deformation of the ships during a collision, with the main output being relative velocity of the striking ship as a function of depth of penetration into the struck (RAM-carrying) ship. The second analysis would be concerned with the "local" behavior of a RAM package. The loading condition would be the bow of the striking ship on one side of the package backed by the internal structure of the struck ship or cargo on the other. The potential for damage to the package depends on the remaining velocity of the striking ship upon reaching the required depth of penetration (i.e., the package location) and the relative stiffness and strength of the striking ship bow, the RAM package, and the supporting structures in the struck ship.

SUMMARY OF GLOBAL SHIP COLLISION MECHANICS AND RELATED LITERATURE

Because of the complexity of the deformation processes during ship collisions, most prediction methods have been based on simplified methods for estimating the amount of damage to the respective ships. The methods are normally composed of two main steps. First, the amount of energy to be absorbed during impact must be computed. This step is sometimes referred to as the "external mechanics" part of the problem. The second step is to determine how the struck and striking ships deform in order to absorb the kinetic energy.

To simplify the ship collision mechanics, only collisions at near right angles are considered in this program. This seems to be a reasonable assumption for assessing the safety of RAM transport by sea, since transverse penetration into the RAM-carrying ship is the primary concern in a collision and such penetration will be greatest in a right angle collision.

External Mechanics

Calculation of energy to be absorbed is relatively straightforward, based on conservation of momentum and energy principles for an inelastic collision of two bodies (Minorsky 1959). First, assume that the center of gravity of the striking ship passes through that of the struck ship, such that there is no rotation of the ships during the collision. Also, assume that the angle between the striking and struck ship, α, is near 90°. The mass of the struck ship and striking ship is M_A and M_B, respectively, with initial velocities of V_A and V_B before the collision, as shown in Figure 1.

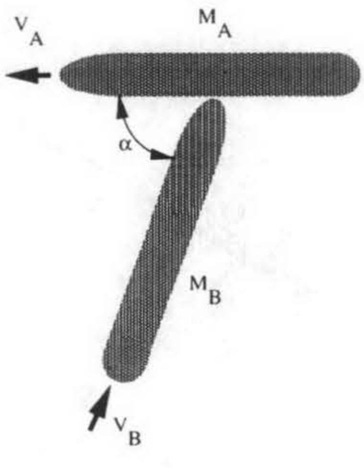

Figure 1. Ship Collision Parameters

Based on conservation of momentum and kinetic energy perpendicular to the struck ship before and after the collision, the following expression can be derived for the amount of energy absorbed by deformation of the ship structures, ΔE_k:

$$\Delta E_k = \frac{1}{2}\frac{M_B(M_A + \Delta M)}{M_A + M_B + \Delta M}(V_B \sin\alpha)^2 \quad (1)$$

As shown, ΔE_k is a function of the masses of the respective ships, the initial velocity of the striking ship, the angle between the ships just before impact, and the effective mass of water surrounding the ships that effects the collision mechanics, ΔM. The proper value of effective water mass is somewhat uncertain. Based on experiments of a ship hull vibrating in deep water, Minorsky estimated the effective mass to be 40% of the mass of the struck ship, M_A.

Internal Mechanics

It is the second step of the solution process, solving the "internal mechanics" problem, that is the most difficult. This step requires estimation of how the two ships deform in order to absorb the required amount of energy, ΔE_k. One of the earliest methods is an empirical approach developed by Minorsky in which a linear relationship was established between the amount of energy to be absorbed and the volume of material within the ships that is deformed during the collision:

$$\Delta E_k = (414.5R_T + 121{,}900) \text{ ton-knots}^2 \quad (2)$$

R_T is known as a resistance factor, and is basically equal to the total volume of damaged structural materials in the striking and struck ships, except for the outer hull of the struck ship, which is accounted for in the constant term. The units of R_T are ft^2-in. The method for computing R_T is given in Minorsky's original paper. Minorsky studied 26 actual ship collisions, all of which involved nearly right-angle collisions. From these collisions, nine were finally used to fit a straight line between the points of ΔE_k and R_T. This line is represented by Equation 2 and is shown in Figure 2. The remaining collisions were not used since they involved relatively lower amounts of energy absorption and exhibited considerable scatter. This so-called "Minorsky Method" has been widely used and appreciated because of the simplicity that it brings to this complex problem. However, it does not account for the detailed mechanics of the collision process and, because of its empirical nature, it may not be applicable for ship designs and impact velocities that are outside the range of the parameters for which the method was developed.

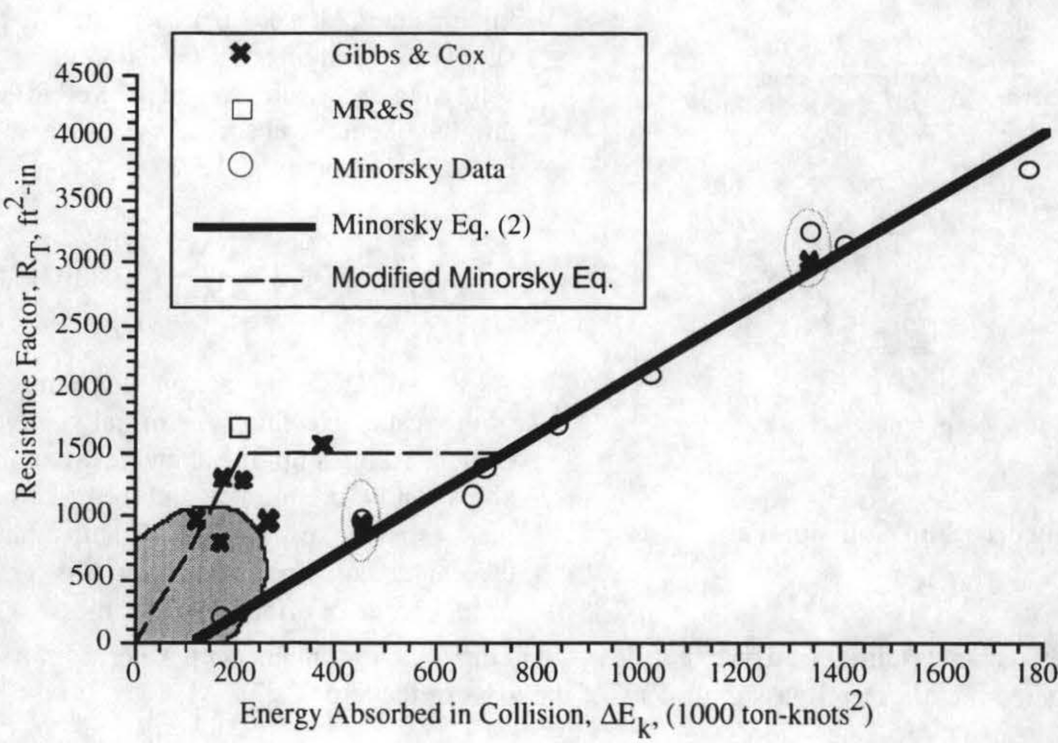

Figure 2. Comparison of Actual Ship Collision Data to Predictions from Minorsky's Equation.

There have been some attempts to check the accuracy of the Minorsky Method. These are documented in papers by (Akita 1972a) and others. Computations of ΔE_k and R_T based on additional ship collisions that, apparently, were not used by Minorsky have been performed (Gibbs and Cox 1961). The data from the Gibbs and Cox report and for the collision analyzed by MR&S (M. Rosenblatt & Son 1972) are shown in Figure 2, along with Minorsky's Equation 2 and the data that Minorsky used to obtain Equation 2. Note that two sets of points are enclosed within an ellipse. These points represent the same respective collisions. The only difference being the calculation of R_T by Gibbs and Cox and Minorsky.

As shown, there is considerable variance between some of this additional data and Minorsky's Equation for relatively low energy collisions. The shaded area of Figure 2 represents additional low energy ship collision data points available to Minorsky, but not used in developing Equation 2. Minorsky stated that the considerable scatter in the low energy range "undoubtedly stems from the fact that the masters of the striking vessels tend to underestimate their speed at impact." Better agreement with available ship collision data in Figure 2 can be obtained by modifying Minorsky's equation in the low energy range, as shown by the dashed lines. The proposed modified Minorsky equations are shown below:

For $0 \leq \Delta E_k \leq 218$ ton-knots^2:

$$\Delta E_k = 145 R_T \quad (\text{ton-knots}^2) \tag{3a}$$

For $218 < \Delta E_k \leq 744$ ton-knots^2:

$$R_T = 1500 \quad (\text{ft}^2\text{-in}) \tag{3b}$$

For $\Delta E_k > 744$ ton-knots^2:

$$\Delta E_k = 414.5R_T + 121{,}900 \text{ (ton-knots}^2\text{) (original Minorsky Equation)} \tag{3c}$$

Equation (3a) is taken from (Jones 1983) in which he and his colleagues developed a modified Minorsky Method for minor collisions. As shown in Figure 2, Equations 3a and 3b better represent the collision data for the lower energy points. Equation 3a is attractive because it begins at the origin (representing the obvious—that there is no deformed material, R_T, if no energy, ΔE_k, is absorbed) and because it traverses most of the low energy points. The physical meaning of Equation 3b is less appealing, since it indicates a constant amount of damage for increasing values of ΔE_k. However, Equation 3b does provide a more conservative estimate of damage, R_T, than Minorsky's original equation. Equation 3c is identical to Minorsky's original equation, since there seems to be good agreement with the ship collision data for these very high energy collisions. (R_T values for Equations 3a and 3b should include the hull of the struck ship using the approach described by Jones; whereas, the hull is not included in Minorsky's original equation.)

Minorsky's original work was motivated by needs to design the *Savannah*, the world's first nuclear-powered commercial ship. Protection of the nuclear reactor from collision damage was the primary concern and Minorsky's approach was employed to design the reactor protection system. During this same time period (late 1950's and 1960's), ship collision research programs were also conducted in Germany, Japan, and Italy in support of the design of nuclear powered ships. In the 1970's there was some work devoted to liquified natural gas (LNG) tanker safety in collisions; however, most of the recent and ongoing ship collision research is devoted to the safety of oil tankers involved in collisions and grounding. These programs are focused on the study of improved tanker designs to minimize the probability of oil leakage in the event of an accident.

The earlier work for nuclear-powered ships is more applicable to the present study of RAM sea transport than the more recent studies. The reason being that the nuclear-powered ship research was concerned about extremely severe collisions, since protection of the reactor, located near the middle of the ship's breadth, was its focus. Similar damage would be required to threaten onboard RAM package integrity. However, the tanker studies are primarily concerned with improving designs to resist relatively minor collisions that could rupture the oil tanks. Since it is not feasible to design tankers to resist all possible collisions, there has been little attention to the extremely severe collision scenarios.

Scale model ship collision experiments were conducted during the nuclear ship design era as described by (Akita 1972a, b). Akita developed two sets of semi-empirical expressions for the load required for a rigid bow to penetrate the breadth of a ship's structure. The first set is for what was termed the "deformation type" of failure of the deck and the second is for the "crack type" failure. He observed that the crack type failure generally occurred when the strain underneath a bow was greater than about 30%. The crack type failure mode, which is illustrated in Figure 3, is more straightforward to use and seems to result in more conservative estimates of penetration depth.

The load-deformation (P-δ) relationship based on Figure 3 may be derived from simple statics as (Akita 1972a):

$$P = 2Nq\delta\tan\theta + 2T\cos\theta \qquad (4)$$

where:

- P = collision loading from striking ship,
- δ = penetration into the struck ship,
- q = compressive reaction load per unit length on deck, $= t_d\sigma_o$,
- t_d = average deck thickness obtained by smearing deck stiffener areas over deck width,
- σ_o = effective crush stress, $n\sigma_y$,
- σ_y = deck material yield strength,
- n = reduction factor to account for deck buckling stress as a portion of the yield stress,
- N = number of deck layers,
- 2θ = stem angle of striking vessel, and
- T = membrane strength of outer hull of struck ship.

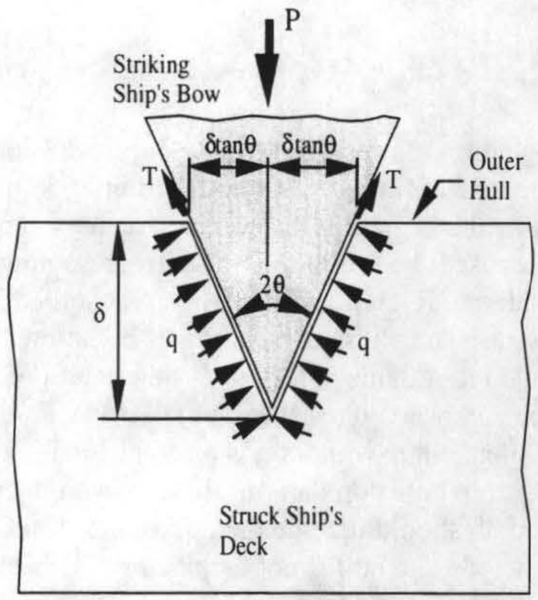

Figure 3. Deformation of Struck Ship

As indicated in Equation 4, load from the striking ship is resisted by the outer hull and decks of the struck ship. Early in the collision, load is primarily resisted by the outer hull until it fails in membrane tension as it stretches between transverse supports. After hull rupture, load is resisted almost entirely by the decks. To conservatively fit his test data, Akita assumed that the deck crushed at an average stress equal to $0.8\sigma_y$, or $n = 0.8$ according to the above definition.

As shown in Figure 4, the energy absorbed by a struck ship for a given deformation, δ_n, is equal to the area under the P-δ curve up to δ_n. The maximum deformation for a given collision, δ_{max}, can be determined by solving for δ such that the area under the P-δ curve equals the required energy to be absorbed in a collision, ΔE_k, as computed from Equation 1.

This approach is believed to be quite conservative, since it assumes all the energy is absorbed by the struck ship and none by the striking ship. This assumption would be most valid if the striking ship's bow was effectively rigid. In order to account for energy absorbed by deformation of the striking ship's bow, one could also consider the P-δ relationship of the striking ship's bow. Several studies have been conducted to estimate this relationship, such as (Akita 1972b). The maximum penetration into the struck ship can be computed by the same method as described above, given that the load on both ships, P_c, will be equal at all times and by increasing the load until the combined area under both P-δ curves equals the computed value of ΔE_k. This method is qualitatively illustrated in Figure 5. The proportion of energy absorbed by the striking and struck ships depends on their relative stiffness.

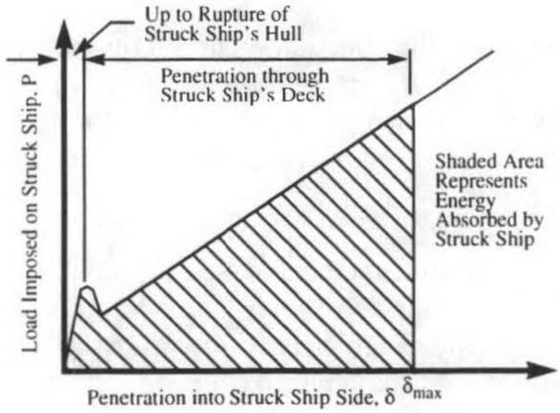

Figure 4. Typical Load-Deformation Relationship for Side of Struck Ship

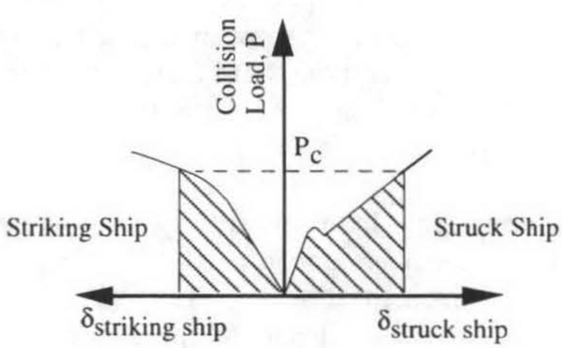

Figure 5. Qualitative View of Load Sharing Between Striking and Struck Ship

Given the P-δ relationships for both the struck and striking ships, the equations of motion can be readily solved using a spring-mass formulation. A FORTRAN program, using explicit integration to solve the equations of motion, has been successfully completed. The analysis computed the collision force, velocity reduction and energy absorption, as a function of penetration and time into the collision, and total collision time and energy absorption. Since the solution time on modern PCs is only a few seconds, multiple collision scenarios, which must be considered for comprehensive risk studies, could be considered without unreasonable computing costs or time requirements.

LOCAL BEHAVIOR OF RAM PACKAGES DURING SHIP COLLISION

During a severe collision, the bow of the striking ship could penetrate the RAM ship sufficiently to directly load a RAM package. Initial resistance to this loading would be the package tiedowns, which are likely only capable of resisting a force equivalent to, at most, 10 times the package weight. Thus, the tiedowns would be easily broken before loadings on the package would become significant. After breaking the tiedowns, the package would likely be pushed across the ship hold with little, if any, threat of leakage until a substantial ship structure is reached, such as a longitudinal bulkhead, a deck-supporting column, or the opposite side of the hull from the initial impact. Upon reaching such structure, it is possible that substantial crush loadings could be produced, depending on the stiffness and strength of the supporting structure compared to that of the RAM package. Obviously, very detailed analyses would be required to accurately assess the possibility of breaching a given RAM package under such loading conditions. Also, such an analyses would be ship specific, depending on the structural details of the RAM carrying ship. For example, if the supporting structure of the struck ship is weaker than the package, then it is possible that the package could break through the supporting structure without causing leakage from the package.

SUMMARY AND RECOMMENDATIONS FOR FUTURE DEVELOPMENT

Based on the literature studied to date, the P-δ approach illustrated in Figures 3 through 5 is believed to be the most appropriate approach for future use in risk assessments of the safety of waterborne RAM transport. Once software is written to fully implement the method, solutions for multiple ship collision scenarios can be obtained without requiring extensive computer costs or time.

Uncertainties in the global ship collision mechanics result from the assumptions required to develop a one-dimensional P-δ approach for an actual ship collision, which is a complex three-dimensional problem. However, given the conceptual agreement with Minorsky's empirical approach and the conservative comparison with Akita's ship collision experiments, it is believed that the P-δ approach will provide reasonably good estimates for safety evaluations. Further study is needed, such as comparing the method to results from detailed finite element analyses and, if possible, to actual ship collision damage, to better quantify uncertainties in the method.

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