HYDROCODE METHODOLOGIES FOR UNDERWATER EXPLOSION STRUCTURE/MEDIUM INTERACTION

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The applicability of the general-purpose continuum mechanics codes, or “hydrocodes,” to underwater explosion structure/medium interaction (UNDEX-SMI) is assessed. It is shown that some hydrocode methodologies are applicable to UNDEX-SMI analysis of thin-walled structures, but only if the codes employ “structural elements.”

OVERVIEW OF HYDROCODES

Continuum mechanics is a superset of the largely independent fields of solid mechanics (of which structural dynamics is a subset) and fluid mechanics. Computational continuum mechanics is a superset of the largely independent fields of computational fluid dynamics (CFD) and computational solid mechanics (CSM, of which computational structural dynamics, or CSD, is a subset). The general-purpose codes (hydrocodes) described herein concern themselves with the response of solid and fluid materials under such highly dynamic conditions (e.g., detonation and impact) that shock wave propagation is a dominant feature [1,2,3,4,5]. Basically, the general-purpose methods make fewer approximations than either of the more special-purpose CFD or CSM methods. Hydrocodes numerically solve the more fundamental time-dependent equations of continuum mechanics (compared to, for example, the Navier-Stokes equations of fluid dynamics), thereby fulfilling requirements for which neither traditional CFD nor CSM codes are fully suitable. The ever-expanding scope of CFD, CSM, and hydrocode capabilities has, however, created a semantic difficulty: it is impossible to delineate strictly between hydrocodes and either CFD or CSM codes. Hydrocodes are therefore defined as simulation tools for multi-material, compressible, transient continuum (i.e., fluid and/or solid) mechanics. Some hydrocodes have even implemented the capability to practically model structural dynamics, allowing an even wider applicability. This structural analysis capability is crucial to SMI analysis of thin-walled structures.

Hydrocodes have provided more than simply "hydrodynamic" simulations of material behavior for a long time, but in keeping with the common terminology, the misnomer “hydrocodes” is here equated with “general-purpose codes.” An alternate, though less widespread, term is "wavecodes," due to the wave-capturing nature of these codes. Also, the term "hydrocodes" is reserved by some for the Eulerian versions of the general-purpose codes.

The development of hydrocode capabilities has traditionally been driven largely by military requirements, since few non-military applications involve explosives or high-velocity impact. However, this class of tools has more recently found commercial applicability (and corresponding development drive) in such diverse fields as automobile and shipping container...
crashworthiness [6,7,8,9], automobile airbag deployment [6,10], automobile and train occupant reaction to crashes [6], bird impact on aircraft [6,11], and sheet metal stamping [12,13].

The Lagrangian, Eulerian, Coupled Eulerian/Lagrangian (CEL), and Arbitrary Lagrangian/Eulerian (ALE) general-purpose methods are described in the sections that follow. A simple illustration is included for each method, depicting a structure/medium interaction whose geometry is illustrated in Figure 1. It represents a two-dimensional analog of the type of problem that

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**Figure 1. UNDEX-SMI Analysis Example**
challenges most aspects of underwater explosion structure/medium interaction (UNDEX-SMI): an underwater explosion that causes large structural distortion and displacement and in which bubble collapse and cavitation effects are very important. The early expansion of the explosion products sends a strong shock wave into the surrounding water. The shock quickly deforms the structure, resulting in a cavitation region in the water close to the structure. The cavitation region eventually closes as the bubble continues to expand, and a water jet is shown to form as the bubble collapses. None of the examples are actual computations; they only illustrate the capabilities and limitations of the methods. All general-purpose methods are theoretically capable of modeling true SMI since no major coupling approximations are made. The methods are, therefore, judged on practicality instead of capability. The individual code developers should be consulted for up-to-date code capabilities and projected improvements.

LAGRANGIAN HYDROCODES

The computational mesh of a Lagrangian model remains fixed on the material, as illustrated in Figure 2. Since the mass within each element remains fixed, no mass flux at interelement boundaries must be computed; thus the computation is relatively straightforward and fast. Material distortions correspond to Lagrangian mesh distortions, leading to reductions in time steps and/or breakdown in problem advancement. Mesh rezoning tends to extend the application of Lagrangian codes to large distortion problems, but introduces complexities and corresponding solution inaccuracies. The calculation is also no longer strictly Lagrangian if the mesh is rezoned. The distorted (elongated) elements defining the water at the edge of the bubble in Figure 2 are apparent. These distorted elements (exceedingly thin and wide) would likely cause the time step to drop to unacceptably small values, in effect stopping the calculation. The unfavorable mesh evolution is due, in part, to the quadrilateral elements (six-sided "hexahedral" elements in 3D) that define the discretization; were such a mesh composed of triangular elements (four sided "tetrahedral" elements in 3D), more distortion would be allowed since triangular/tetrahedral elements tend to be more robust. This point is illustrated by the fact that shaped charge liner collapse is commonly and effectively modeled using codes that employ triangular/tetrahedral elements. Even if more robust elements were employed, the Lagrangian method would still ultimately break down as the bubble collapses upon itself, since the mesh that defines the explosion products cannot simply "get out of the way." The general limitation of most Lagrangian hydrocodes to relatively low-distortion computations limits their applicability to local and global shock/structure interaction analysis.

Predecessors of modern Lagrangian hydrocodes were HEMP [14], TOODY [15], 2DL [16] and HONDO [17]. EPIC [18], various versions of DYNA [19,20,21,22,23], and PRONTO [24,25,26,27] are the most prominent Lagrangian hydrocodes, but the Lagrangian modules of the Coupled Eulerian/Lagrangian (CEL) codes (described in a subsequent section) are also available. Any Arbitrary Lagrangian/Eulerian (ALE) code (also described below) can also be run in purely Lagrangian mode. Traditional (implicit) Lagrangian solid/structural mechanics codes like NASTRAN [28], NIKE [29,30], and ABAQUS [31] are not suitable, or not efficient, for highly dynamic analyses in which shock waves are dominant. The EPIC code is based primarily on triangular elements in 2D and tetrahedral elements in 3D, and is therefore more robust for large
distortion problems. Several attempts have been made at coupling the hydrodynamic and structural capabilities of DYNA3D for UNDEX-SMI analysis [32,33].

Lagrangian hydrocodes have been successfully coupled and linked to Eulerian hydrocodes such that large distortion fluid dynamics calculations can be made within an Eulerian framework. These types of codes are described in a following section. The Arbitrary Lagrangian-Eulerian (ALE) method, described in a following section, can be considered a variant of the Lagrangian method; in effect, the Lagrangian method is a subset of the ALE method.

Figure 2. Lagrangian Hydrocode UNDEX-SMI Example
Other Lagrangian methods that have potential application to UNDEX-SMI analysis but are not as mature as the standard method include the Free Lagrange Method (FLM) [34,35] and Smoothed Particle Hydrodynamics (SPH) [36,37,38]. A Free Lagrange mesh distorts as the material distorts, but the connectivity of the elements changes as the mesh distorts. This concept is illustrated in Figure 3, which could illustrate the mesh distortions accompanying shear banding. The elements that define the domain are redefining their connectivity as the mesh distorts; this is not possible in a standard Lagrangian code. Research codes that are examples of FLM include CAVEAT-GT [39] and TRIX [40]. In SPH, Lagrangian "particles" dynamically interact with no fixed, permanent connectivity (as in FLM), as shown in Figure 4. Lagrangian hydrocodes that have implemented SPH concepts as analysis options include EPIC [41,42] and PRONTO [43]. Both FLM and SPH are particularly attractive for large shear distortion problems, overcoming the main limitation of traditional Lagrangian hydrocodes. An UNDEX-SMI event would probably be modeled using Lagrangian particles, or Free-Lagrange elements, to trace fluid motions and continuously interact with fully Lagrangian structural elements (Figure 4), thus creating a coupled SPH/Lagrangian or FLM/Lagrangian method. Since the "mesh" of SPH and FLM codes is not rigidly interconnected, the methods do not break down as an underwater explosion bubble collapses upon itself. UNDEX-SMI problems have been attempted with the PRONTO SPH/Lagrangian approach [43].

The natural applicability of Lagrangian hydrocodes with structural analysis capability to highly dynamic problems spawned the automobile crashworthiness simulation industry. Many explicit codes are currently applied to, and/or developed explicitly for, automotive crashworthiness; LS-DYNA3D [21], ABAQUS/Explicit [44], and PAM-CRASH [45] are examples. Two features of crash simulation codes are advanced contact algorithms (for structural members folding upon themselves) and Adaptive Mesh Refinement (AMR) algorithms, since many plastic hinges form.

**EULERIAN HYDROCODES**

Eulerian hydrocodes advance solutions in time on a mesh fixed in space, as illustrated in Figure 5, instead of a mesh fixed on the material, as is done in a Lagrangian solution. By advancing the solution on a computational mesh fixed in space and time, Eulerian codes avoid the Lagrangian problem of mesh distortions. Correspondingly, and unlike Lagrangian simulations, time steps can remain roughly constant during simulations, and bubble jetting simulations become feasible. The difference between Eulerian computational fluid dynamics (CFD) codes and
Eulerian hydrocodes is primarily the inclusion of material strength (flow of solids) and multimaterial capability in the hydrocodes. Furthermore, Eulerian hydrocodes are strictly transient dynamics solvers; they are not designed to solve steady-state fluid flow problems.

The usual sequence of logic within Eulerian hydrocodes, unlike traditional CFD codes, consists of a Lagrangian computation at every time step, followed by a remap (advection) phase which restores the slightly distorted mesh to its original state.

Figure 4. SPH/Lagrangian Hydrocode UNDEX-SMI Example
Cells (or elements) containing more than one material are common in Eulerian hydrocode computations; the presence of multiple fluid and/or solid materials within a cell is the main reason that these codes are computationally expensive, and sets them apart from more traditional CFD.
codes. This situation calls for numerical algorithms that prevent artificial material diffusion (the mixing of materials across a material interface) within these mixed cells. The convergence to a common state parameter (e.g. pressure) within a multimaterial cell can also result in considerable expense, particularly if the higher order accuracy of the Lagrangian phase is to be retained. The additional computational effort expended in the remap phase is largely responsible for the discrepancy in comparative Eulerian versus Lagrangian computational expense.

Since solid materials are defined within Eulerian cells whose properties must be uniform, several modeling limitations present themselves. Several cells must define the thickness of any plate structure to capture its bending stresses; this necessitates prohibitively fine zoning. Furthermore, structural properties of a solid will be “smeared” with the fluid properties of any adjacent water within a mixed cell. Combined, these facts result in Eulerian UNDEX-SMI (local and global shock- and bubble/structure interaction) computations being highly impractical.

The most prominent Eulerian hydrocodes are CTH [46,47,48,49,50,51,52,53,54,55,56, 57,58,59] and MESA [60], although the Eulerian modules of the Coupled Eulerian/Lagrangian (CEL) codes, described below, are also commonly used. Other Eulerian hydrocodes include PAGOSA, PCTH and RAGE (SAGE) [61]. Also, the more general type of Arbitrary Lagrangian/Eulerian (ALE) (see below) can be run in purely Eulerian mode. Since computational structural dynamics analysis is highly impractical in an Eulerian frame, no examples of Eulerian UNDEX-SMI analysis exist.

Eulerian hydrocodes are related to the more traditional computational fluid dynamics (CFD) codes, some of which have even demonstrated their ability to model underwater explosion bubbles [62,63]. Eulerian hydrocodes have been successfully coupled to Lagrangian hydrocodes such that detailed structural calculations can be made within a Lagrangian framework. The Arbitrary Lagrangian-Eulerian (ALE) method, described in a following section, can be considered a variant of the Eulerian method; in effect, the Eulerian method is a subset of the ALE method.

COUPLED EULERIAN/LAGRANGIAN (CEL) HYDROCODES

Coupled Eulerian/Lagrangian (CEL) hydrocodes employ both Eulerian and Lagrangian methods in their most advantageous modes in separate (or overlapping) regions of the domain. As illustrated in Figure 6, the Lagrangian shell elements continuously interact with the Eulerian fluid domain; the communication between the two coordinate systems is accomplished through "interface elements." A recommended practice concerning the application of the CEL method is to discretize solids (materials in which the material strength plays a dominant role) in a Lagrangian frame, and materials exhibiting primarily fluid behavior (little or no strength) in an Eulerian frame. The Eulerian and Lagrangian regions continuously interact with each other, allowing true coupling of a fluid and a structure. A typical CEL code is actually comprised of a family of three codes: Eulerian, Lagrangian and Coupling modules. The coupling module handles the information that is passed continuously between the Eulerian and Lagrangian modules (in both directions), in one of two ways.
In the first coupling method, "interface elements" are employed that coincide with the exterior surfaces of the Lagrangian model, forming a surface in a three dimensional model (a line in a two-dimensional model). The interface elements determine the volume of Eulerian cells that

![Figure 6. Coupled Eulerian/Lagrangian Hydrocode UNDEX-SMI Example](image)

Lagrangian Plate Elements, and Coincident Interface "Elements"

Eulerian Grid

Partially Water-Filled Eulerian Cells

Cavitation Region

Void Eulerian Cells

Figure 6. Coupled Eulerian/Lagrangian Hydrocode UNDEX-SMI Example
are partially covered by the Lagrangian mesh. Since the surface of the Lagrangian mesh is generally not flat, this determination can be very difficult. The presence of an arbitrarily shaped Lagrangian model usually creates some small volumes in partially covered Eulerian cells; such cells are “blended” with neighboring cells to avoid the severe time step restrictions on small cells. This coupling method is used in DYSMAS/ELC [64], PISCES [65,66] and DYTRAN [67,68].

The second coupling method avoids the difficulty of calculating partially filled cells by including the Lagrangian material within the Eulerian calculation. Since the dynamics of thin materials cannot be calculated practically within an Eulerian mesh, this coupling method is not applicable to UNDEX-SMI analysis. This method is applicable to high-velocity impact analyses; it is employed in HULL [69] and the coupling of CTH with EPIC through ZAPOTEC [70].

All CEL codes can compute in a strictly Lagrangian or Eulerian mode. A feature of some CEL codes is the capability to rezone a Lagrangian mesh into an Eulerian mesh. An example of this is to begin the computation of a shaped-charge liner in a Lagrangian frame, and to convert the liner into an Eulerian computation after material distortions have made the continuation of Lagrangian computations impractical.

An UNDEX-SMI event that a CEL code would find difficult or impossible to model properly would be where thin structural members extend out into the fluid, as illustrated in Figure 7. A CEL code must define the interface between the Lagrangian region (structure) and Eulerian region (fluid), but a Lagrangian structural element (no spatial thickness) can easily "see" a single Eulerian fluid cell on both sides. Thus two separated fluid regions would be described within a single Eulerian cell - an unphysical situation. The employment of Lagrangian continuum elements for the structure would tend to overcome this problem, but then the disadvantages of using continuum elements where structural elements are more appropriate come into play.

The original Coupled Eulerian-Lagrangian code was CEL [71]. MSC/DYTRAN (formerly PISCES-3DELK) [67,68], MSC/PISCES (formerly PISCES-2DELK) [65,66], HULL [69], DYSMAS/ELC [64], AUTODYN-2D [72] and the coupling of CTH with EPIC through ZAPOTEC [70] are the primary CEL hydrocodes in use. All except the HULL and CTH/EPIC codes have some practical thin-plate structural analysis capability in 2D or 3D. Only

Figure 7. A Difficult Coupling Problem for CEL Codes
MSC/DYTRAN and DYSMAS/ELC have 3D coupled capability using “interface elements”, with substantial structural analysis capability. They are therefore the only CEL codes currently capable of practical, comprehensive UNDEX-SMI analysis (local and global shock/structure and bubble/structure interaction analysis) in 3D. The capability for modeling the interaction between an underwater explosion (primarily shock) and naval structures has been demonstrated with the CEL method using DYSMAS/ELC [73,74,75,76] and MSC/DYTRAN [77,78]. The capability to model combined shock/structure and bubble/structure interaction in 2D has been demonstrated by PISCES-2DELK [79] and DYSMAS/ELC [80,81].

**ARBITRARY LAGRANGIAN/EULERIAN (ALE) HYDROCODES**

Arbitrary Lagrangian/Eulerian (ALE) hydrocodes share aspects with both Lagrangian and Eulerian hydrocodes; Lagrangian motion is computed every time step, followed by a remap phase in which the spatial mesh is either not rezoned (Lagrangian), rezoned to its original shape (Eulerian) or rezoned to some more "advantageous" shape (between Lagrangian and Eulerian). In this way the spatial description of the mesh is neither restricted to following material motions (Lagrangian) nor remaining fixed in space (Eulerian). ALE mesh motions are based primarily on the preservation of a uniform mesh, not the capture of physical phenomena.

The ALE method provides a way of coupling fluid dynamics to structural dynamics without interfacing two separate coordinate systems as is done in the Coupled Eulerian/Lagrangian method. The efficiency to be gained by straightforward coupling (the avoidance of a separate coordinate coupling module) is probably significant. In cases where structural elements can be incorporated directly within the ALE framework, the coupling is trivial. In cases where the ALE numerical method cannot incorporate structural elements, the coupling can be effected through a continuous transfer of boundary conditions without the coordinate system interactions required in the CEL method.

Two levels of ALE technology exist. One allows ALE behavior only within a material (forcing material boundaries to remain Lagrangian); an example of this "single material” or “Simple” ALE (SALE) type is illustrated in Figure 8. The material boundary between the explosion products and the water remains Lagrangian, and the mesh that defines the water remains uniform (unlike the fully Lagrangian water in Figure 2). The distinction between the mesh motions of this example and those of the purely Lagrangian example lies primarily in the elements that define the water region adjacent to the expanding bubble, as illustrated in Figure 9. In the purely Lagrangian case, those elements become exceedingly thin as the bubble expands. In the single material ALE case, those water elements are continuously rezoned such that a much more uniform mesh evolves; this has the advantage that the time step does not drastically drop as it does in the purely Lagrangian case. A disadvantage of rezoning includes the computational expense involved in rezoning from which purely Lagrangian computations are spared. This method, like the fully Lagrangian case, ultimately breaks down as the bubble collapses upon itself, since the mesh that defines the explosion products cannot simply "get out of the way."
The second level of ALE technology allows multimaterial elements to form and is therefore more generally applicable; an example of this "multimaterial ALE" is illustrated in Figure 10. In this example, most of the mesh remains fixed in space (Eulerian), but the region adjacent to the deforming structure deforms with the structure (Lagrangian). The elements that represent the region between the structure and the stationary mesh are therefore neither Lagrangian nor Eulerian; they form a bridge between the two regions. Since the mesh in the

Figure 8. Single Material ALE Hydrocode UNDEX-SMI Example
bubble region is largely Eulerian, this method does not break down as the bubble collapses upon itself.

Due to the current lack of practical structural analysis capability, some ALE hydrocodes are currently not applicable to the analysis of local and global shock/structure and bubble/structure interaction. ALE technology, however, has much potential for UNDEX-SMI analysis. Unlike the Coupled Eulerian/Lagrangian (CEL) codes, the ALE codes are each only one program, so the structure/medium coupling would be more straightforward and efficient. In fact, an ALE code with structural analysis capability would potentially be able to solve the problem shown in Figure 7, which a CEL code would find difficult or impossible to model properly. However, the coupling of fluid and structural regions through matching of element nodes creates another problem. As illustrated in Figure 11, elements that must remain Lagrangian (e.g., plates) cannot be allowed to collapse upon each other if material is entrained between them. This is the same limitation that prevents the Lagrangian and Single-Material ALE (SALE) methods from being applied to bubble jetting problems: the mesh that defines the entrained fluid cannot simply “get out of the way” of a Lagrangian interface, even if the fluid itself could.

The first attempts at creating ALE hydrocodes can be seen in the Lagrangian hydrocodes that implemented "automatic rezoning" options within material boundaries (single material ALE, or SALE). Such codes include ARTOO (based on TOODY) [82] and DYNA2D [19]. VEC/DYNA3D, LS-DYNA3D [21], and AUTODYN-3D [72] include SALE capability.

Prominent multimaterial ALE hydrocodes include CALE [83], CAVEAT [84], ALE3D [85], ALEGRA (also known as RHALE) [86] and MSC/DYTRAN [68]. ALE3D, ALEGRA and DYTRAN include Lagrangian structural elements and are therefore applicable to the computational analysis of UNDEX-SMI. Multimaterial ALE UNDEX-SMI analyses have been attempted with ALE3D [87] and DYTRAN [77].

Figure 9. Comparison of Lagrangian and Single-Material ALE
The ALE method can be considered a superset of both the Eulerian and Lagrangian methods, since both types of mesh motions are incorporated within an ALE scheme. The ALE method cannot, however, be considered a superset of the Coupled Eulerian/Lagrangian (CEL) method, since the ALE method makes no provision for allowing an Eulerian region to interact directly with a Lagrangian interface. ALE hydrocodes are more general than ALE CFD codes, in that ALE hydrocodes allow simulations of materials with strength.

Figure 10. Multimaterial ALE Hydrocode UNDEX-SMI Example
SUMMARY

Many simulations of structural response must include the dynamics of the surrounding medium. Such are the intended capabilities of the general-purpose methods, or “hydrocodes.” The hydrocodes are computational tools that make minimal assumptions about the physical phenomena exhibited by the many classes of problems they are applied to. Detonation physics, shock wave propagation, bubble dynamics, and large-strain structural plasticity and failure are some of these classes; underwater explosion structure/medium interaction is a combination.

Several general-purpose (hydrocode) methods are in general use: Lagrangian, Eulerian, Coupled Eulerian-Lagrangian (CEL) and Arbitrary Lagrangian-Eulerian (ALE) hydrocodes and their derivatives. All general-purpose methods are theoretically capable of solving problems in structure/medium Interaction (SMI). However, the lack of infinite computer resources and the availability of Lagrangian “structural elements” allow the assessment of methods to be based on practicality rather than capability. Only those codes that include structural elements (i.e., thin plates, etc.) as well as fluid dynamics modeling capability (including detonation physics) are capable of practical SMI analysis of thin-walled structures; prominent three-dimensional hydrocodes are so categorized in Table 1.

General capabilities of the various hydrocode methods are summarized in Table 2. Since hydrocodes (like most other analytical tools) provide no measure of accuracy, analysis capability is defined as the possibility to generate a model that will produce accurate results.

Lagrangian hydrocodes with structural elements, though applicable to structure/medium interaction, are not suited to model the large material distortions prevalent in longer-duration, bubble/structure interactions, and are therefore of limited utility.
Eulerian hydrocodes, though practical for modeling large distortion continuum dynamics, can be dismissed as impractical for UNDEX-SMI analyses, due to their inability to *practically* model thin-plate structures.

The Coupled Eulerian/Lagrangian (CEL) hydrocodes were *developed for* structure/medium interaction calculations, specifically fluid/structure interaction, in which both the structure and its surrounding medium are modeled within their traditional frames of reference:

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Table 1. Descriptions and Potential SMI Applicabilities of Prominent 3D Hydrocodes
Eulerian for fluid dynamics and Lagrangian for structural dynamics. CEL hydrocodes with structural elements are therefore practical for UNDEX-SMI analyses; such models have been demonstrated.

The Arbitrary Lagrangian/ Eulerian (ALE) hydrocodes, developed with many of the same goals as the CEL codes, overcome some difficulties inherent in the CEL codes associated with coupling the Eulerian and Lagrangian coordinate systems, but introduce others. Multimaterial ALE (MMALE, as distinguished from Single-material ALE (SALE)) hydrocodes with structural elements are potentially applicable to UNDEX-SMI analyses, though few models have been

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<td>Single-Material ALE (SALE)</td>
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<td>Multi-Material ALE (MMALE)</td>
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Table 2. Potential SMI Applicabilities of Hydrocode Methods
demonstrated with this relatively new method.

In summary, the simulation of underwater explosion structure/medium interaction with hydrocodes is practical. Of the four hydrocode methodologies (Lagrangian, Eulerian, Coupled Eulerian/Lagrangian, and Arbitrary Lagrangian/Eulerian), only the Eulerian method is not practical for UNDEX-SMI analysis. All other methods are applicable to various extents, and then only if the codes under consideration employ structural elements (i.e., thin plates and beams). The most versatile methods are the CEL and Multi-Material ALE.

ACKNOWLEDGMENTS

This work was sponsored by the Office of Naval Research, through the Undersea Warheads and Explosives Project (Dr. Judah Goldwasser). The author is indebted to numerous reviewers; in particular, Stephen Zilliacus of the Carderock Division of the Naval Surface Warfare Center, and Vera Revelli of Sandia National Laboratories, Livermore, California.

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