SAND2015-8891J

# Navy Enhanced Sierra Mechanics (NESM): Toolbox For The Prediction Of Navy Shock/Damage Due To Weapon Engagement

**To Appear In:** IEEE Computing In Science & Engineering

**Authors:** Dr. E. Thomas Moyer, Senior Technologist, NSWC Carderock Division

Dr. Garth M. Reese, Sierra Structural Dynamics Product Team Lead, Sandia National Laboratory

Dr. Alan J. Luton, Senior Engineer, NSWC Indian Head EODTD

Dr. Najib Abboud, Principal & CTO, Weidlinger Associates Inc.

## Table of Contents

## Abstract

The U.S. Navy is developing a new suite of Computational Mechanics tools (Navy Enhanced Sierra Mechanics, NESM) for the prediction of the ship response, damage and shock environments transmitted to vital systems due to weapon engagement. NESM includes fully coupled Euler-Lagrange solvers tailored for ship shock/damage predictions. NESM development leverages the Office of Naval Research investments in both the Implosion FNC MURI and the DYSMAS program, as well as the Department of Energy Advanced Scientific Computing program investment in the Sierra Mechanics toolset. NESM is optimized to support High Performance Computing architectures providing physics based ship response/damage predictions needed to support the design and assessment of highly survivable ships. NESM is being employed to support current ship design/acquisition programs while being further developed for future fleet needs.

## Introduction

The HPCMPO CREATE™ program [1] was initiated to develop Physics Based software designed to optimally exploit current and future High Performance Computing (HPC) platforms in support of Department of Defense (DoD) Acquisition Programs. By employing High-Fidelity Modeling & Simulation (M&S) earlier in the design process, design features can be matured and fully evaluated earlier than with current practices reducing the technical, cost and schedule risks evidenced in our current practice. Additionally, the need for expensive and time consuming physical testing can be reduced and focused optimizing the required balance between M&S and physical testing. Each of the U.S. military services (Army, Navy, and Air Force) identified technology areas where the development of High-Fidelity, Physics Based M&S could provide the most benefit for future acquisition programs.

One area the U.S. Navy identified for CREATE development was the prediction of Ship Shock/Damage when subjected to threat weapon engagement. The U.S. Navy has proudly developed highly survivable ships with demonstrated capability for centuries. Our ships are designed to withstand UNDEX Shock, they include specific protection technologies to defend against other specific threat engagements and are subject to survivability evaluation assessments in accordance with Live Fire Test & Evaluation (LFT&E) requirements [2]. Our current practices, while robust and effective, rely heavily on physical testing to support the design and validation of ship capability and hardness. This physical testing, out of necessity, is performed fairly late in the design process. Design limitations and deficiencies are determined at a time when remediation can add considerable cost and schedule slip to the acquisition process. Additionally, the design of new survivability technologies, which involve development and iteration of prototype systems, significantly adds to the cost and schedule of the program limiting our ability for innovation.

Modeling & Simulation has been an important and useful adjunct supporting Ship Shock/Damage design & assessment for many years. Advances in Computational Mechanics (CM) and the rapid development of HPC, however, provide the opportunity to significantly enhance the ship design/assessment process by exploiting M&S earlier in the design process and in a more prominent role, identifying more controlled and focused physical experiments to provide the M&S process with those elements which "fill in the gaps" of current inherent limitations in M&S capabilities. The need for large scale (or full scale) physical proto-type testing as well as full ship validation testing (which inherently must be performed late in the acquisition process and at significant cost) can be greatly reduced.

NSWC/Carderock Division (NSWCCD) is the U.S. Navy Warfare Center charged with leading the design, assessment and R&D engineering required for Ship Vulnerability. In FY 2007, Carderock initiated a Requirements Definition Process and Analysis Of Alternatives (AOA) to determine the optimal approach to the development of a CREATE Ship Shock/Damage toolset. The requirements definition included coordination of input from the Technical Warrant Holders (TWHs) for Shock Ships and Vulnerability Reduction, other U.S. Navy Laboratories with specific experiences and responsibilities for their respective technology areas, and the Navy Program Executive Offices (PEOs) for Surface Ship, Aircraft Carrier and Submarine Acquisition. The requirements were validated by the TWHs and used for the basis of the AOA. From a CM perspective, the top level requirements included:

1. Threat Weapon Loading Characterization Technologies
2. Ship Dynamic Response/Damage Modeling Technologies

Due to the wide variety of threat engagement characteristics as well the varieties of ship response characteristics (e.g. hull rupture, structural buckling, vibratory shock environments), it was clear multiple CM technologies would be required to cover the requirements space.

The technical approach chosen from the AOA process was to leverage the investment and success of the Department of Energy (DOE) Advanced Scientific Computing (ASC), Sierra Mechanics Product to provide a basis enhancements needed to address Ship Dynamic Response/Damage Modeling Technologies. Sierra Mechanics provides a massively parallel suite of CM tools which include a Structural Dynamics (SD) solver providing the basis for efficient and accurate prediction of shock response as well as a Solid Mechanics (SM) solver providing the basis for the prediction of ship damage. For modeling threat loading, we chose to leverage the Office of Naval Research (ONR) investment in developing the DYSMAS [3] tool for developed for performing dynamic simulations of weapons effects loading on structures. DYSMAS includes a massively parallel Eulerian solver (DYSMAS/FD). DYSMAS also has a general Fluid/Structure Interaction (FSI) capability. The product was named Navy Enhanced Sierra Mechanics (NESM). The first production release of NESM occurred in April 2011 with the release of NESM v1.0.

During the past several years, NESM development has focused on enhancing the Lagrangian capabilities in Sierra Mechanics to increase the capability and fidelity of the structural response and damage to ship structures (due to threat weapon engagement). Enhancements included improved structural element capability, advanced material deformation and damage modeling, multi-scale modeling, acoustic shock modeling for deep submergence as well as various capabilities to improve the usability. The next release of NESM v4.0 (April, 2016) provides state-of-the-art features to address the spectrum of UNDerwater EXplosion (UNDEX) scenarios as well as several requirements to assess AIRborne EXplosion (AIREX) threat engagements. Starting in 2013, we embarked on the development of the Navy Energetic Modeling Oracle (NEMO) which will provide a testbed Eulerian capability coupled in parallel to Sierra Mechanics as part of the NESM suite. NEMO addresses various challenges in CFD and FSI providing the software framework for the next chapter of NESM development. NEMO will be included in NESM v4.0.

## NESM Development Team

The NESM Development Team consists of engineers and scientists from NSWC/Carderock, Sandia National Laboratories, NSWC/IHEODTD and Wiedlinger Associates, Inc. A group of highly skilled, integrated compliment of ~10 Full Time Equivalent (FTE) developers with advanced degrees forms the nucleus of the team. Verification and Validation studies are performed by NSWC/CD Survivability Analysts representing the U.S. Navy “State Of The Art”.

## NESM Architecture

By leveraging multiple existing software development efforts, NESM has succeeded in rapidly and cost-effectively producing a robust toolkit for the U.S. Navy survivability and weapons effects community. These efforts span multiple organizations, time zones, programming languages, and disciplines; this breadth of content mandates adherence to rigorous software engineering practices.

An overarching design approach at the forefront of all development efforts funded under the NESM project is high performance computing and massive parallelism. To this end, each product under the NESM umbrella was designed to optimally exploit HPC architectures. The expertise of the Sierra teams (at Sandia National Laboratories) is invaluable in helping us achieve this goal.

## NESM Toolkit Design

The target user base must model a wide variety of phenomena, including incident loads (due to threat weapons), structural dynamics, structural mechanics, and coupled fluid-structure interaction events. To meet these varied requirements, NESM has assembled a multitude of software tools into a single comprehensive toolkit. A high-level description of the toolkit is shown in Figure 1. While the program has funded incremental developments in pre- and post-processing tools, the vast majority of our efforts are focused on the computational "engines," which are items within the figure's dashed-lines.

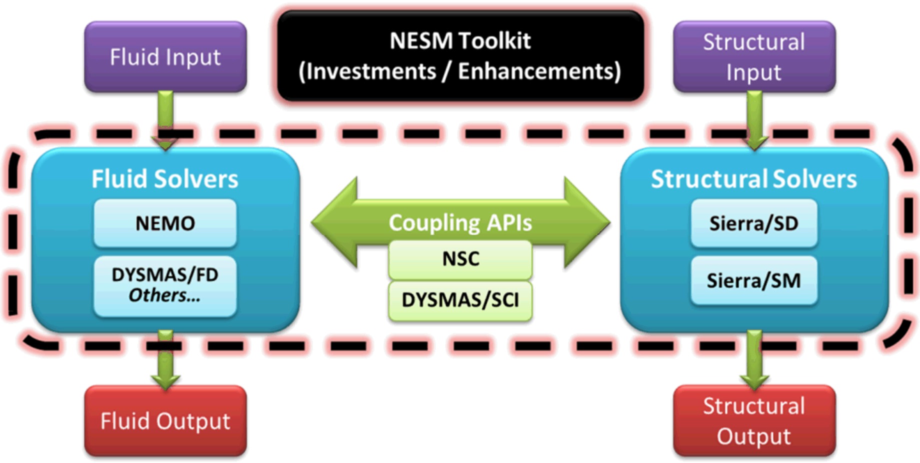


**Figure 1: Notional design of the NESM software toolkit**

When NESM analysts begin a project, there are many stand-alone capabilities they require. These capabilities include (but are not limited to) Finite Element Model (FEM) checkout/verification, basic structural analysis (modal, static, implicit/explicit transient), and threat characterization. By leveraging many of the Sierra tools (detailed below) NESM provides structural analysis capabilities to meet many of these needs. One focus of the NESM project has been to tailor/enhance the core capabilities in Sierra's Lagrangian solver packages to better meet the needs of our community. The community's fluid dynamics requirements are fulfilled by leveraging the Eulerian hydrocode capabilities contained in both DYSMAS/FD (detailed below) and NEMO (detailed below). All of these tools can be run individually. Each of these tools exhibits favorable scalability, allowing for massively parallel solutions.

Espousing a modular approach, the NESM toolkit contains multiple coupling communication Application Programming Interfaces (APIs). As detailed in the DYSMAS/SCI section of this paper, DYSMAS/FD is coupled to Sierra/SD and Sierra/SM using the Standard Coupler Interface (SCI) serial protocol.

The latest coupling communication API added to NESM is called the Navy Standard Coupler, or NSC. This API was developed under an effort to test and examine new FSI approaches, which are discussed below in the NEMO section of this document. The NSC API is designed for massively parallel scalability, leveraging the architectures of the latest high-performance computing platforms. The FSI code-to-code communications are realized via a new MPI-based code-coupling interface which uses level sets to locate the fluid-structure interface and a bounding box approach to enhance cross-processor communication efficiency. The NSC API is a flexible framework which allows for parallel-fluid to parallel-structure communication of data-intensive messages between codes. The API is well documented and contains driver utilities to allow ease-of-implementation and testing.

## Software Engineering

Each tool's development team has made software engineering decisions to fit the tool's specific intended uses and the team's skillset. Despite varied approaches to writing and maintaining the tools, each tool follows modern software engineering practices.

The tools are written in a variety of languages; Sierra is primarily C and C++, DYSMAS/FD is Fortran90, and NEMO is primarily Fortran90. Accessory tools are written in Fortran and Python. All the NESM tools employ modern code architecture, including dynamic memory allocation, pointers, derived data types, modules, and classes/objects (where applicable). They are written to be highly modular and allow for incorporation and testing of new algorithms. The code communication APIs are all written to be language agnostic, and the language that a developer chooses for a specific task is often a combination of both preference and convention.

Organizing these codebases is accomplished via industry-standard configuration management software. The version control applications used by the team are Git and Apache™ Subversion. The DYSMAS/FD team uses Jenkins as their continuous integration tool. Best practices encourage frequent commits with clear messages. All tools utilize DoxyGen for automatic code documentation and flow diagrams.

The team follows an Agile software management style with three-week sprints, synchronized across the products and teams. This management approach creates transparency and visibility throughout the development process; stakeholders and developers are able to frequently discuss progress and collaborate to produce a better piece of software. The end-of-sprint slides are published online to the CREATE Portal and review meetings are open to the entire community.

Because these tools are used by the DoD analyst community to support acquisition programs, strict software verification is a critical aspect of our development process. Each site has its own infrastructure to address this subject. Many of these practices have evolved by leveraging the excellent habits of the Sierra teams, which have grown out of the ASC initiative. As an example, both the DYSMAS/FD and NEMO teams use customized test harnesses (DYSMAS Test Harness [DTH] and NEMO Regression Tester [NERT], respectively) to ensure quality control. Customized unit test frameworks also exist (e.g. NEMO's NUnit) to facilitate more rigorous software verification. Thorough, comprehensive verification and validation bolsters software quality control efforts.

NESM supports a subset of the system platforms that are supported by the Sierra Mechanics project. Current target architectures include the following libraries: MPI (OpenMPI 1.6, IntelMPI 4.1, Cray MPICH), Compiler (Intel 14.0, GCC 4.7), 64-bit OS (RHEL, SUSE, CLE). The list of supported architectures evolves as the DoD rolls out new Distributed Supercomputing Resource Centers (DSRCs).

### Related Products

The toolkit contains a number of auxiliary tools to enhance usability and productivity. An example preprocessing tool is the Sandia Analysis Workbench Model Builder, which is a meshing and geometry engine (Cubit) together with an input deck generator (Sierra Editor). Additionally, NSWC Carderock is developing a fluid grid generator which creates input decks for either DYSMAS/FD or NEMO, based on rules developed out of a mesh convergence study conducted in 2015. On the postprocessing side, any tool compatible with the ExodusII binary database format may be used, allowing users to select the tool with which they are most familiar. Supported visualization tools include ParaView and VisIt; both of these are implemented in client-server fashion on the DSRCs. For time-history extraction, the team developed the Exodus Data Miner (ExoDM), a Python-based code which includes features like interpolation and filtering.

## Sierra Mechanics (Structural Dynamics & Solid Mechanics)

The Department of Energy (DOE) has heavily invested in high performance, high-fidelity finite element software for the analysis of weapon systems and components. The Sierra software suite has capability in thermal mechanics, fluid dynamics, structural dynamics and solid mechanics along with relevant coupling between these diverse physics. Because of DOE's need for predictive modeling, a key element of this capability has been scalability, which has been demonstrated repeatedly. Verification, a critical component of this success, depends on robust software quality engineering and on domain specific tools for assessing model accuracy. For example, the feature coverage tool provides information about the physics models exercised in the tests, and ties analysts' models to existing verification tests [4].

A solid computational framework forms a critical part of this development. This includes tools for linear algebra, linear solvers, contact search and enforcement, code coupling and parallel services. The software is based on distributed computing through MPI, but is being transitioned to next-generation platforms, which will require multiple levels of parallelism, including threads. Development continues on next-generation hardware such as the Xeon/Phi, IBM/OpenPOWER [5] and GPUs.

The Sierra Structural Dynamics module provides high performance analysis of full ship components. Analysis of eigen problems, frequency domain problems, and fluid structure coupled transient dynamics are required. Models up to many millions of degrees of freedom require effective parallel strategies with excellent scalability [6]. Superelement models permit efficient assembly of detailed components.

NESM Team enhancements to the general structural dynamics capabilities include additional element formulations for specialized beams, shells, and specialized user defined mounts, as well as more general capabilities such as Dynamic Design Analysis Method (DDAM) and hydrostatic balance. Modal based solutions (including superelement reduction) are built on a filtered selection of eigenvectors, to improve performance and accuracy. Selective Component Mode Synthesis (SCMS) [7] was an important development which can significantly reduce transient structural computing requirements.

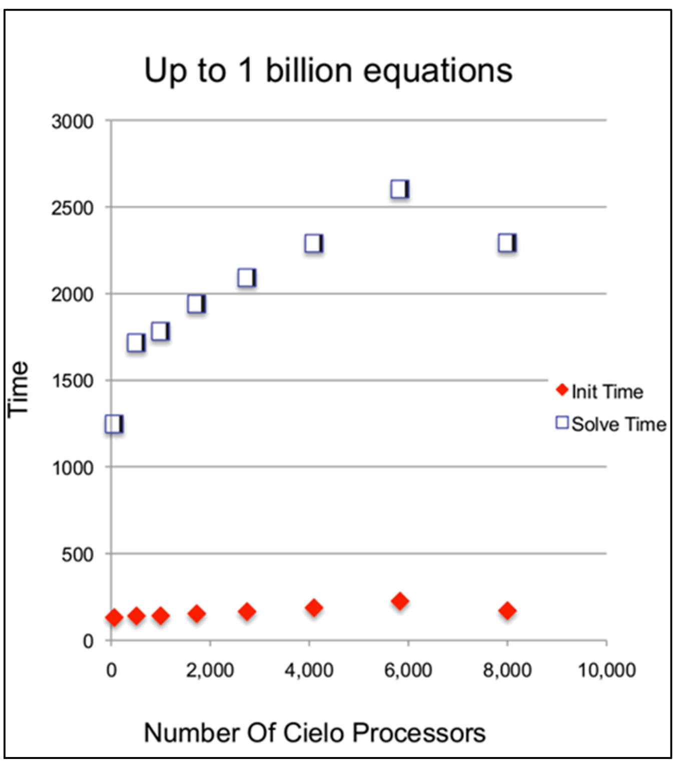

**Figure 2: Sierra/SD scalability**

Parallel solvers have been enhanced to better respond to needs for very high accuracy required by some ship models [8]. Ongoing development of linear solvers is essential to maintain compatibility with emerging and future hardware platforms, and to manage ever increasing model size. Solvers, and the application in general, accommodate specialized handling for filtering rigid body modes.

Structural dynamics provides a wealth of options for model damping. In addition to system proportional methods, damping may be applied through viscoelastic materials, proportionally by block, or as modal contribution to a direct transient response [9].

Additional capabilities include a fully coupled suite of acoustics analysis including nonlinear acoustics, and infinite elements, as well as inverse methods for identification of loads and materials composition. NESM Team enhancements allow for deeply submerged ship UNDEX response predictions using acoustic approximations for the fluid.

The Sierra Solid Mechanics module provides robust solution to problems of high nonlinearity in contact, damage and fragmentation. Implicit and explicit time integration and quasi-statics are fully scalable in parallel. Capabilities exist for coupling to thermal, fluids, and hydro codes.

NESM Team enhancements include coupled Navy applications with the addition of nonlinear beams, lofted composite shells, and Navy mounts. This module offers a variety of material failure modeling capabilities, such as material failure via element deletion, cohesive zone and localization elements, and automatic remeshing with Sandia developed Nodal Based Tetrahedral elements. Additionally, ONR developed material models w/ failure have been added and validated for NESM applications.

Multi-scale solutions are necessary to analyze detailed portions of a ship that may have undergone severe damage. The finely meshed portions of the model in the damaged region can be effectively coupled to coarser outer regions through multi-point constraints and edge-to-face contacts. Such multi-scale solutions enable attaching coarse exterior shell models to refined models of either shells or solid meshes. This feature has been a core focus of the NESM Team collaboration and supports the NESM Automated Mesh Refinement future capability (see below).

The material model library offers over 50 models including EOS and user defined models. An arbitrary contact capability is available that is massively parallel capable and satisfies momentum balance and frictional surface interface conditions. General all-to-all contact capabilities are applied when significant damage or crush occurs.  Time scaling techniques permit explicit time steps that are much larger than the traditional stable step sizes.

Flexibility in the software is important on both the structural and fluids domains. Navy specific (and general user defined) mounts and user defined materials provide extensibility to the software that broadens general capabilities to meet needs specific to ship structures.

## DYSMAS/FD Euler Solver

The central code of the DYSMAS Fluid Dynamics (FD) package is DYSMAS/FD, which is a massively parallel multi-material Euler equation solver originally designed to simulate UNDEX effects.  DYSMAS/FD was developed as part of the ONR DYSMAS program [10].  The DYSMAS/FD theory is documented in [3].  DYSMAS/FD is capable of modeling the entire range of UNDEX phenomena including explosive detonation, shock physics, bubble dynamics, cavitation, and fluid/structure interaction (FSI).  DYSMAS/FD employs an explicit finite-volume higher-order Godunov scheme to accurately capture shocks, and has also been enhanced to accurately capture low pressure phenomena associated with cavitation and UNDEX bubble behavior.  Solutions can be obtained in one, two, or three-dimensions and a robust rezone capability exists for mapping flow fields between different meshes.  Highly-efficient simulations can thus be obtained by initially modeling the flow field as two-dimensional and then rezoning when three-dimensional effects become important (for instance, just before a shock wave impinges on a structure).

DYSMAS/FD includes a robust Equation Of State (EOS) package capable of representing many material types including ideal and non-ideal explosives.  Methods used to model detonation include instantaneous burn, prescribed burn, and reactive burn.  In addition, a mixed burn algorithm that varies burning according to the amount of locally available air can be employed.

The ability of the DYSMAS/FD Eulerian solver to accurately simulate UNDEX loading was endorsed by a JASON study entitled “Navy Ship Underwater Shock Prediction and Testing Capabilities” [11].  Specifically, the 2007 JASON report concluded that the “comparisons demonstrate that the DYSMAS code DOEs an excellent job reproducing the liquid response to the explosion.”

DYSMAS/FD parallelization is based on the Message Passing Interface (MPI) standard and the domain decomposition technique.  In this method, each DYSMAS/FD process on every core solves the governing equations for its own portion of the fluid mesh.  At every time step, the processes exchange information across the mesh subdomain boundaries.  The DYSMAS/FD code has been structured to be a “coarse-grained” application, that is, the information exchange between processes is minimized per time step. In addition, the amount of information exchanged is minimized. These strategies lead to a highly efficient and scalable code for parallel computations. In July of 2014, excellent scalability was demonstrated with a series of simulations, the largest being 4.1 billion cells with 32,768 cores.

### DYSMAS/SCI (Standard Coupler Interface)

The simulation of UNDEX effects on nearby structures is achieved by coupling the DYSMAS/FD fluid solver with the structural solver. The coupling is accomplished by using the DYSMAS/SCI. The SCI is a communications protocol for the two-way exchange of information between a fluid code and a structure code. The SCI couples the two codes using the embedded mesh approach, that is, the meshes for the two codes are independent. Thus, the fluid mesh can be constructed easily without regard to the structure mesh. Geometry routines compute the intersection between the meshes and the transformation of quantities from one mesh to the other.

There are two choices for the time integration of an SCI-coupled simulation. The original DYSMAS method is known as concurrent time stepping or CTS. With CTS, both the fluid and structural codes execute simultaneously to advance their respective solutions to an agreed upon time. They then exchange information and the process repeats. As a result of new applications for DYSMAS where the CTS coupling stability was severely stressed, a new procedure known as sequential time stepping, or STS, was implemented. In this scheme, one code waits while the other solves its equations of motion. This permits updated boundary conditions to be used for the code that advances second. This staggered strategy leads to improved stability for certain classes of problems.

The DYSMAS/SCI coupling scheme was originally designed for naval applications and thus is capable of modeling the UNDEX holing of thin-walled structures, which can be problematic for many hydrocodes. Currently, the SCI operates in a serial manner, communicating between the fluid solver (DYSMAS/FD) and the structural solver via master nodes.

## NEMO

The NESM toolkit includes a new Eulerian Hydrocode capability that will serve as a testbed for advanced simulation capabilities emerging from academia in key areas such as fluid-structure interaction (FSI) and multi-phase computational fluid dynamics. The Navy Energetic Modeling Oracle (NEMO) is a new software development effort that will provide an extensible framework for testing new fluid solver approaches [12]. The guiding philosophy behind NEMO is to introduce technologies that are tailored for the needs of the ship design and acquisition community. Technologies that reduce analyst time, computation turnaround time, and increase accuracy are given priority as they will result in reduced costs to the Navy. NEMO will be first released as part of NESM v4.0 in April, 2016.

As a proof-of-concept, the first approach NEMO implements is based on the FInite Volume Exact Riemann (FIVER) approach developed by the Farhat Research Group at Stanford University [13]. The FIVER framework treats discontinuities in the flow field as one-dimensional Riemann problems, including discontinuities at fluid-fluid interfaces and fluid structural interfaces. Three dimensional solutions are provided using a standard operator splitting technique that builds upon one dimensional solutions in the cardinal directions. The effectiveness of this approach was demonstrated under the ONR Implodables Multidisciplinary University Research Initiative (MURI) [14]. While the FIVER approach has had demonstrated successes, NEMO aims to be approach agnostic and as the NEMO framework undergoes continual development new technologies will be explored and incorporated as needed. In this way NEMO will readily adapt to the evolving needs of the Navy acquisition community.

NEMO focuses on providing accurate and robust Fluid Structure interaction capabilities, which are critical for Navy survivability computations. The aforementioned FIVER approach, which is NEMO's starting point, has demonstrated stability in a variety of challenging multi-physics problems. Stability has proved to be critical for full ship survivability calculations. These calculations are inherently expensive due to analyst engagement time, and considerable analyst effort can be wasted applying ad-hoc stability controls in order to run calculations to completion. Large scale calculations that ultimately produce unstable solutions (in the late time response regime) result in lost analyst time and can result in great expense.

Through the FIVER approach, NEMO also improves code robustness via the elimination of mixed cell algorithms in the fluid solver. The FIVER framework treats discontinuities in the flow field as one-dimensional Riemann problems, including discontinuities at fluid-fluid interfaces. Rather than employing ad-hoc schemes to homogenize fluid properties over the cell, the FIVER approach handles the discontinuity explicitly. The homogenization process can result in unphysical fluid energy states that can cause calculations to grind to a halt by imposing extremely small CFL conditions. NEMO also includes Volume Of Fluid methods to handle fluid-fluid interfaces, enabling direct comparison of both methodologies.

Experience with full ship survivability simulation has demonstrated that scalability of the FSI algorithm is critical as computational power increases. With increases in computing capability, available resolution on the fluid and structural sides increases. This improvement in resolution also carries an overhead in communication so that it becomes important that the FSI approach also scales well with increasing numbers of computational domains. The NEMO code employs a fully parallel FSI approach that will achieve the requisite scalability. This approach is designed for massively parallel scalability, leveraging the architectures of the latest HPC platforms within the DoD.

NEMO utilizes the Navy Standard Coupler (NSC) which is a new MPI-based fully parallel coupling communication interface. This communication API is a flexible framework which allows for fully parallel (fluid and structure) communication of data-intensive messages between software analysis packages. The NSC API architecture is built to enable a flexible and extensible environment for investigation of coupling schemes of different orders of accuracy. The NSC API is a surface to volume approach which fully supports interfacing to Navy shell model structural FEMs and permits the failure of shell elements.

The initial release of the NEMO code will be included with NESM v4.0. The initial capability is based on the FIVER framework, however, the main goal of NEMO is to provide a testbed for advanced Eulerian capabilities. As such the capability provided will be readily extensible and adaptable to other emerging fluid solver technologies.

## Verification & Validation

Significant effort has been invested in the ongoing Verification and Validation (V&V) of NESM. References [7], [15], [16], [17], [18], [19], and [20] provide the details of these efforts. For this publication, several test cases were chosen to demonstrate NESM capabilities. These test cases run the gamut from shock testing, where little to no structural damage is expected, to more severe testing, where at least moderate structural damage is expected. Experimental testing produces data which can be compared to NESM results. V&V helps develop confidence in the software and its ability to predict ship response, damage and shock environments.

### NESM V&V Example (Sierra/SD - DYSMAS/FD): Floating Shock Platform

The Floating Shock Platform (FSP) is a barge structure heavily utilized for shock qualification and provides an excellent platform for initial code validation. In 2012, six UNDEX shots were conducted against the FSP as part of the UNDEX induced crew injury test series [15]. The FSP was outfitted with the variable frequency deck simulator fixture (DSF) and was equipped with three Hybrid III Anthropomorphic Test Devices (ATDs), two standing and one seated, in various orientations and locations. Representative shipboard structure, consisting of a bulkhead, a desk with seat, and a bench, were welded to the DSF to serve as ATD impact surfaces. The FSP test setup is shown in Figure 3.

**Figure 3: Floating Shock Platform test setup**

A linear elastic finite element model (Figure 4) provided the basis for the V&V efforts of this study. The model consisted of approximately 42,000 elements and 37,000 nodes constructed of plate, beam, spring and mass elements. The structure of the FSP, DSF and equipment primarily consisted of plate and beam elements while the mass elements primarily represent ballast and mass smearing.

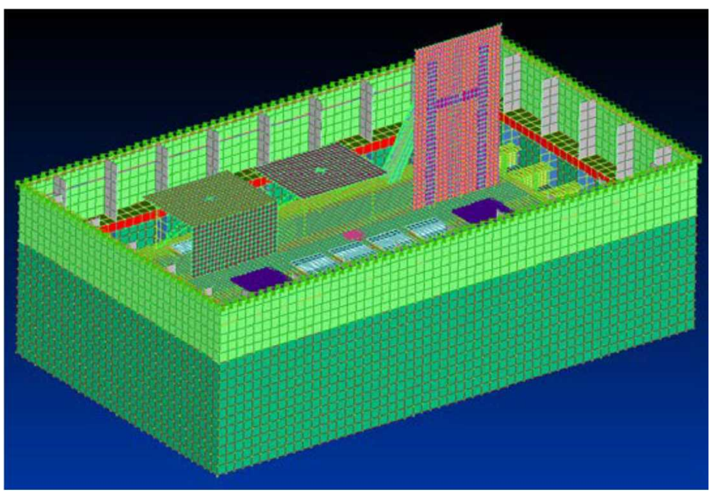

**Figure 4: Floating Shock Platform finite element model**

A 2D axisymmetric fluid grid was used to propagate the shock wave out until a termination criterion was reached, typically just before the shock wave impinges on the structure. Then a 3D fluid grid was used to continue the simulation, requiring the state of the 2D simulation to be mapped onto the 3D grid by revolving about the vertical axis. Both grids have a refined mesh zone of which the extent and resolution is dependent upon the physics intended to be captured during that particular phase of the UNDEX. The 3D fluid model consisted of approximately 103 million elements.

Overall, NESM predicted the response of the FSP to UNDEX loading; based on correlations between simulation and test demonstrates NESM was able to capture the physical response characteristics due to both the shock and bubble pulse loadings. One example is the response of the FSP along the inner bottom, captured at gage V5006V (Figure 5). The plot shows three test records which are compared to simulation at the corresponding FEM node. The response of the model is observed to be consistent with test records, although kickoff velocity is slightly under predicted.

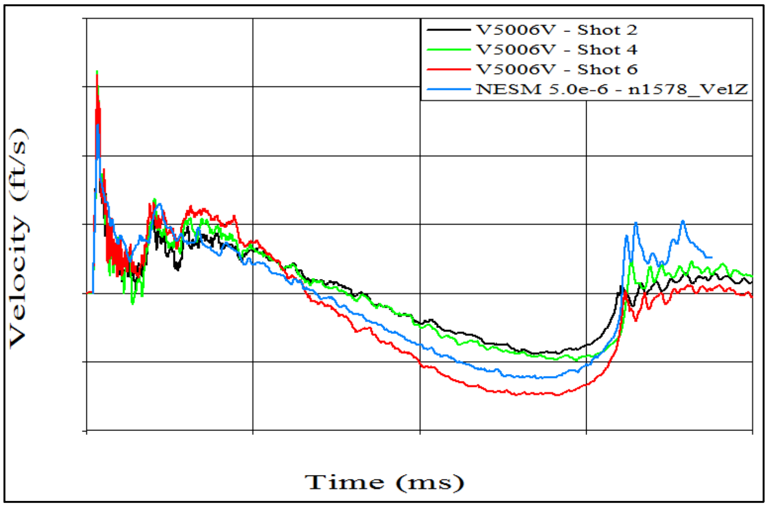


**Figure 5: Floating Shock Platform inner bottom response**

## NESM V&V Example (NEMO): Free-field UNDEX

Underwater explosions exhibit a number of unique phenomena, and accurate modeling of these is critical to ensure the accuracy and reliability of analyst predictions. As a charge is detonated, a high-pressure shockwave emanates from the rapidly expanding explosive gas products. This shockwave propagates through the water and results in an incident pressure, much like in an above-water event. Once the shockwave reaches the air-water free surface, a tensile wave develops and propagates back into the fluid as a pressure release. When this release interacts with the shockwave, a "surface cutoff" effect can be seen in the fluid. Additionally, the tensile wave causes the water to cavitate. A region of bulk cavitation occurs near the water surface and closes after the fluid pressure and momentum allow for equilibration in this region. In later time, the explosive gas bubble will collapse back on itself, resulting in secondary loading. The gas bubble may pulse a number of times before its energy is dissipated or it migrates to the free surface and vents into the atmosphere.

The free surface cutoff phenomenon can be seen in Figure 6 below. This result is shown for both NEMO and DYSMAS/FD, and both codes compare well with experimental data. The two curves are nearly indistinguishable at this scale. Additionally, an analytic method of images can be derived to show both the peak pressure and surface cutoff arrival time. The analytic methods compare favorably with the hydrocodes, permitted the time histories are sufficiently far-field from the charge location.

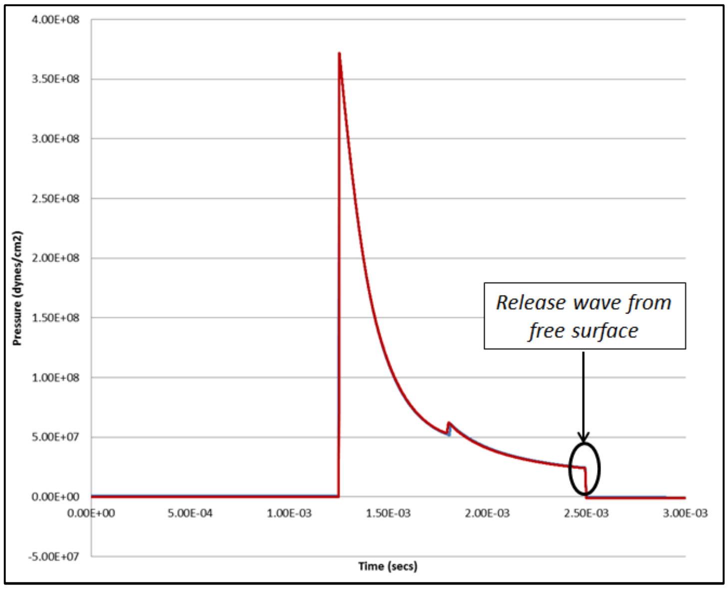


**Figure 6: Free-field UNDEX event showing surface cutoff**

## NESM V&V Example (Sierra/SM - NEMO): Hydrobulge

The Hydrobulge is a canonical validation problem used to characterize the accuracy of hydrocodes. In this experiment, an air-backed aluminum cylinder is filled with water and a charge is detonated in the center of the aluminum tube [21]. The structure is plastically deformed and the resulting structural response can be used to characterize the behavior of the explosive charge.

In NEMO, this problem was used as a coupled, system-level validation test to verify multiple software routines. The loads generated via detonation (and resulting shock propagation) tested the JWL and Tillotson EOS implementations, as well as the shock capturing scheme. Coupling communication was also tested; the pressures passed to the wetted surface drove the cylinder's inner-wall response, which in turn drove the values of pressures at that interface.

The structural model and accompanying fluid flowfield are relatively small, in part due to the use of 1/8$^{th}$ symmetry in the analysis. Two structural models were used in these analyses, using either solid or shell elements to represent the aluminum cylinder. Both representations yield similar responses, with the solid model results shown in Figure 7. Analyses capture all relevant loading phenomena (incident shock, local cavitation, shock/bubble rarefaction, cavitation closure) and correlate with experimental results.

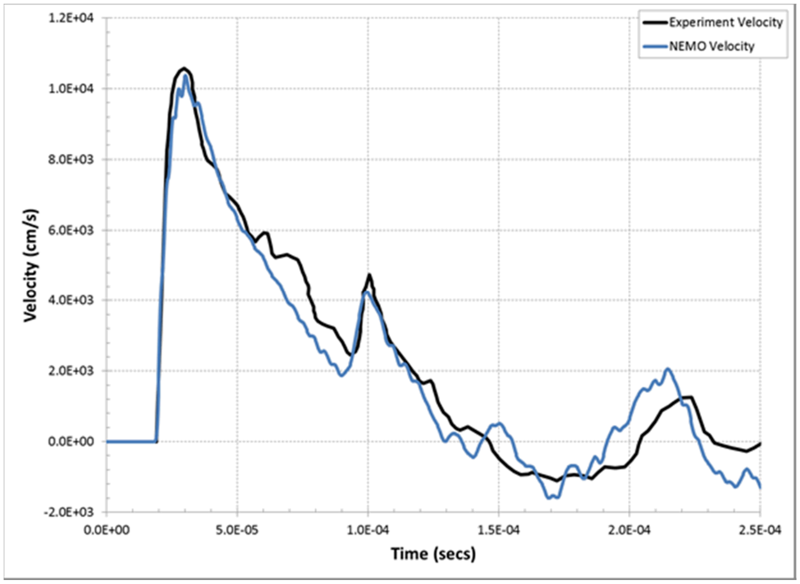


**Figure 7: Hydrobulge structural response (radial velocity)**

Accurate modeling of this problem requires few computational resources; this case has become a regression test problem and is run frequently to ensure NEMO accuracy and consistency.

## NESM V&V Example (Sierra/SM): M/V M-Star

On 27 July 2010 the M/V M-Star, a Japanese VLCC (very large crude carrier), suffered damage to the hull as a result of a boat bomb attack while transiting the Persian Gulf. Major dishing of the hull plating was observed, in addition to windows being blown out and doors blown off their hinges on the superstructure, as well as topsides damage. One crew member was injured. NSWC-Carderock was given the task of approximating the size and stand-off of the charge. NESM was one of the software packages used in support of this effort.

The finite element model required to predict structural damage was constructed. The model contained almost 300,000 elements (all shells) and a Johnson-Cook material model for steel was used to model the hull, decks, bulkheads and stiffeners. Blast loading was applied as predicted by the CONWEP Program. The loading process was independently verified using the CTH hydrocode.

To capture the extent of the shock damage, the problem took about 20 minutes, using eight processors on a Linux workstation. Figure 8 shows a picture of the ship's hull (left) along with a Sierra/SM CONWEP analysis (right).

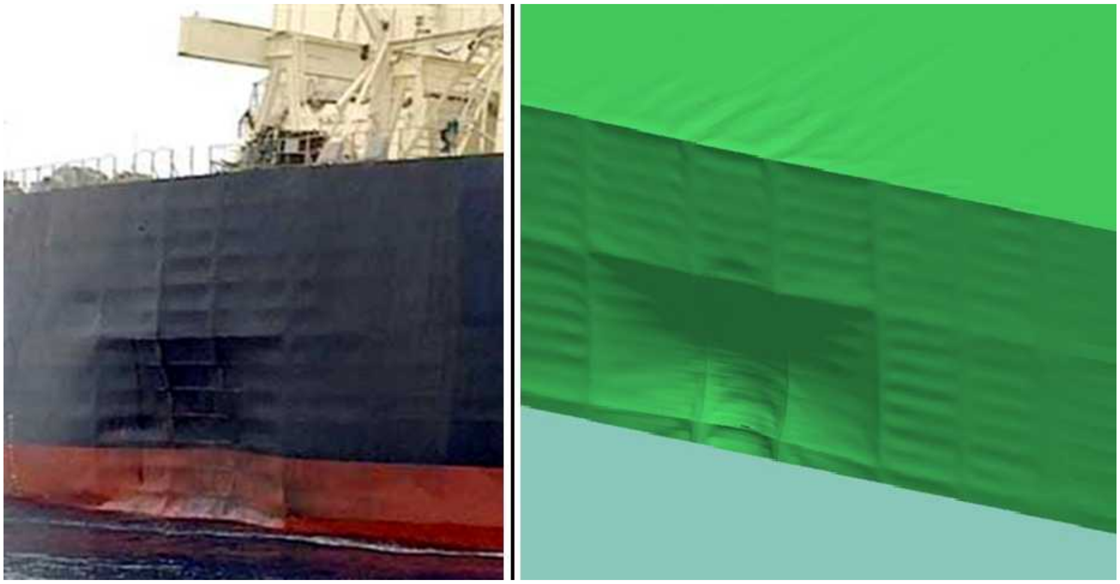

**Figure 8: M/V M-Star damage comparison**

The analysis shows the same dishing pattern and approximately the same plate deflection inward on the hull. The blue area in the finite element results represents the waterline. Some loading below the waterline was seen on the ship, which was not captured in the Sierra-SM scoping run, but was seen after running a fully coupled hydrocode analysis.

## NESM V&V Example (Sierra/SD - Acoustic): ONR Cylinder

In August of 1974, the DNA/ONR 33.6 (a steel ring stiffened right circular cylinder with flat aluminum end caps) was submerged in the Chesapeake Bay and subjected to several tests involving side-on loading from differently weighted tapered charges. The NESM/Sierra-SD acoustic shock capability was partially validated [17] using data taken from an underwater shock experiment performed on the DNA/ONR 33.6 model as well as data from comparative analyses using USA / LS – DYNA.

The DNA/ONR 33.6, surrounded by an acoustic medium (sea water), was modeled as a free-free structure using two mesh generation software programs (FEMAP & CAPSTONE). The far-field boundary condition is modeled using transient infinite elements of variable order. The combined cylinder and acoustic medium model contained 292,346 nodes and 1,343,154 elements. A cut-away view of the cylinder model surrounded by the acoustic medium is show in Figure 9.

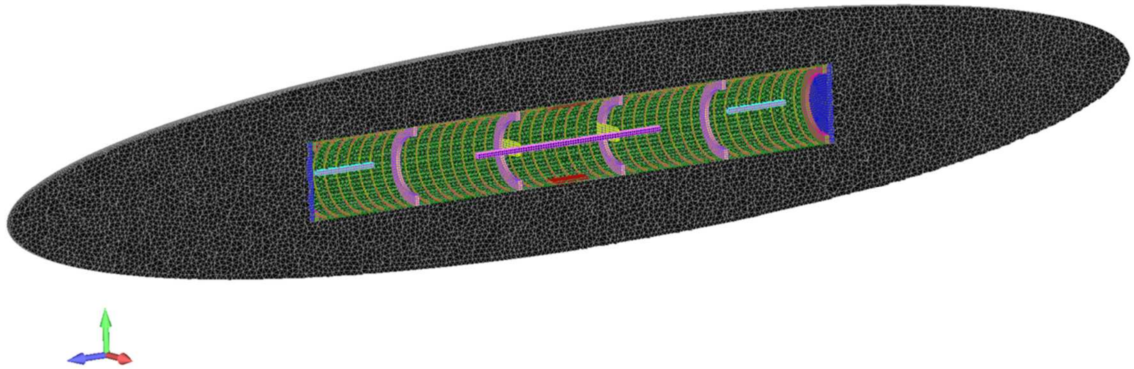

**Figure 9: ONR Cylinder finite element model**

NESM has the ability to model a spherically spreading acoustic pressure wave originating from a point source. This load type was chosen and implemented specifically to represent the UNDEX load from a tapered charge in the original experiments. The pressure amplitude function used for the validation of NESM was taken from hydrophone pressure measurements from the original test.

Overall, the correlation of velocity responses between NESM, USA / LS-DYNA, and experiment were quite good at the various locations measured around the test article. A representative plot of the results is shown in Figure 10, which shows a typical velocity response prediction from NESM results along with various USA / LS-DYNA runs as well as experimental data.

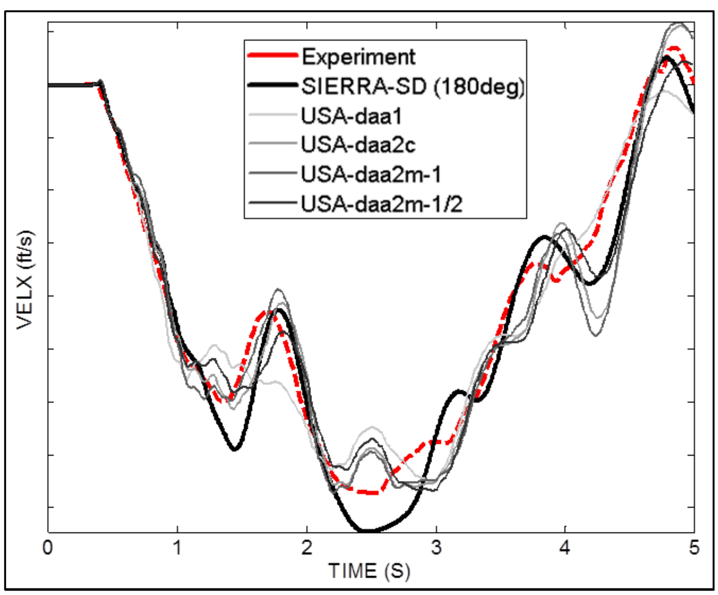


**Figure 10: ONR Cylinder velocity response**

## Future Directions

Going forward, NESM development is focused on capabilities needed to enhance M&S usage for current applications, address current limitations, and broaden the validated suite of physics. The toolkit will also continue to provide capability which minimizes user time to solution (primarily labor hours to solution). Examples of our focus areas are listed below.

### Automated Remeshing

We are actively developing the capability to take a coarse structural FEM – designed to resolve the shock environment due to standoff UNDEX engagement (but would be under-resolved for the prediction of structural damage) – and subject the coarse FEM to a structurally damaging UNDEX attack, providing an estimate of the extent of the model which is under-resolved, then automatically remesh that section of the model with sufficient detail to fully resolve structural damage. This will take maximum advantage of the Sierra/SM multi-grid capabilities developed for NESM. A detailed requirements document has been developed and vetted by the U.S. Navy vulnerability community [22] which includes a detailed description and schematic of the workflow as well as technical examples (generated manually) of the resulting, mesh-resolved (for structural damage prediction) FEM.

### Acoustic Fluid w/ Nonlinear Structure

The ability to model UNDEX phenomena approximating the fluid as an acoustic media is a critical capability used for problems at deep submergence. The existing capability is being extended to couple acoustic fluids to the nonlinear structural solver, Sierra/SM. This provides the capability to rapidly analyze nonlinear structural response to UNDEX for structures at sufficient submergence depths. This will be the first fully parallel capability for these problems available to the community.

### Mixed Explicit-Implicit Structural Response

Most ship threat engagement problems involve response over multiple time scales. The initial response to the direct shockwave loading (either UNDEX or AIREX) typically exhibits a high frequency reaction of short duration followed by a longer time vibratory response. Subsequent loading due to UNDEX bubble pulsation can introduce an intermediate frequency (w/ intermediate time duration) time scale as well. The initial response is optimally solved (from the structural perspective) using explicit time integration while the later time response should be more optimally solved using implicit time integration. NESM currently has the capability to perform the nonlinear structural time integration using explicit or implicit time integration. We plan to develop the capability to switch, back and forth as the loading dictates, for optimal NESM solution time while matching frequency content w/o creation of artificial noise inherent in "hand-off" calculations. This capability is anticipated to significantly reduce computational resource requirements for problems where later-time response impacts the Quantities Of Interest (QOIs) of the M&S.

### Ship Response Due To Complex UNDEX Bubble Loading Problems

Predicting the loading due to UNDEX bubble pulsations (particularly where bubble-structure interaction is important) is a challenging problem. Various elements of our ongoing NEMO development will focus on determination of the optimal results capable of being predicted by an Euler solver (it's been conjectured that physics beyond the Euler equations may be necessary, however, the degree and extent is unknown) by improved interface and geometry representation algorithms. Additionally, the NESM effort is enhanced by an ongoing Joint Live Fire effort funded by the Director, Operational Test & Evaluation (DOT&E) which will require needed validation data for part of the required parameter space. Continued numerical development coupled with physical testing is a priority for future LFT&E applications.

## Conclusions

The development of NESM is providing the Navy with previously unavailable capabilities greatly expanding the use of M&S in support of Shock Qualification, Vulnerability Assessment and Live Fire Test & Evaluation requirements. NESM is currently being used on several ongoing U.S. Navy Ship Acquisition Programs. Additionally, NESM continuously monitors the short term and long term needs of stakeholders, customers, and the user community, defining development requirements which respond to evolving Navy needs. NESM development (along with all the CREATE Ships products) is subject to a rigorous oversight process staffed by members of the Senior Executive Service (SES) from NAVal SEA Systems Command (NAVSEA), the Program Executive Offices, the Office Of Naval Research as well as our High Performance Computing Modernization Program Office (HPCMPO) sponsor to ensure our objectives, accomplishments, and long range plans align with the larger Navy vision.

## Acknowledgements

Development of the Navy Enhanced Sierra Mechanics (NESM) software suite is sponsored by the DoD High Performance Computing Modernization Program (HPCMP) as the CREATE-Ships Shock/Damage Product. This development effort is led by Naval Surface Warfare Center Carderock Division (NSWCCD) in collaboration with Sandia National Labs (SNL) and Naval Surface Warfare Center Indian Head Explosive Ordinance Disposal Technology Division

(NSWCIHEODTD). NESM employs the structural mechanics capabilities from the Sierra Mechanics suite developed by SNL under the DOE Advanced Simulation and Computing (ASC) Program, along with the Eulerian solver and Standard Coupling Interface, DYSMAS/FD and DYSMAS/SCI, from the DYSMAS suite, developed by NSWCIHEODTD jointly with the German Ministry of Defense (MoD) under a series of ONR sponsored U.S.-Germany Project Agreements. The NESM product is focused on adding the capabilities necessary to meet Navy needs for Ship Shock/Damage predictions required to address current and future ship acquisitions needs.

## Works Cited


[1] D. E. Post, C. A. Atwood, K. P. Newmeyer, R. L. Meakin, M. M. Hurwitz, S. Dey, J. N. D'Angelo, R. L. Vogelsong, N. Hariharan, S. Morton, R. Strawn, J. Livingston, A. Mackenna, J. Gorski, E. Moyer, R. P. Kendall, L. G. Votta, P. A. Gibson, D. Borovitcky, L. K. Miller, O. A. Goldfarb and S. B. Allwerdt, "The CREATE Program - A Suite of Physics-based High Performance Computing Software Applications for the Design and Analysis of Air Vehicles, Naval Vessels, Radio Frequency Antennas, and Ground Vehicles," *IEEE Computing in Science and Engineering,* Nov/Dec 2015.

[2] *10 U.S. Code § 2366.*

[3] A. B. Wardlaw, Jr., J. A. Luton, J. R. Renzi, K. C. Kiddy and R. M. McKeown, "The Gemini Euler Solver for the Simulation of Underwater Explosions," NSWC Indian Head EOD Technology Division, IHTR 2500, 2003.

[4] B. Carnes and K. D. Copps, Code Verification Using the Feature Coverage Tool, Albuquerque, NM: Sandia National Laboratories, 2014.

[5] Lawrence Livermore National Laboratories, "Next-generation supercomputer coming to Lab," 14 Nov 2014. [Online]. Available: https://www.llnl.gov/news/next-generation-supercomputer-coming-lab. [Accessed 10 Aug 2015].

[6] G. M. Reese, C. R. Dohrmann, M. K. Bhardwaj and T. Walsh, "Large Scale Implicit Calculations on Cielo," Sandia National Laboratories, Albuquerque, NM, 2011.

[7] E. Moyer, "Selective Component Mode Synthesis for Shock & Vibration Analyses," NSWC

Carderock Division, NSWCCD-66-TR-2013/014, 2013.

[8] C. R. Dohrmann, "Domain Decomposition Solver Strategies for Future Platforms," Sandia National Laboratories, Albuquerque, NM, 2015.

[9] K. F. Alvin, "Implementation of Modal Damping in a Direct Implicit Transient Algorithm," in *42nd AIAA/ASME/ASC/AHS/ASC SDM*, April 2001.

[10] G. Harris, J. A. Luton, T. McGrath, R. M. McKeown, J. St. Clair, W. Babcock and A. B. Wardlaw, Jr., "Overview of the Dynamic System Mechanics Advanced Simulation Code (DYSMAS)," NSWC Indian Head EOD Technology Division, IHSP 14-04, 2014.

[11] M. Brenner, et al, "Navy Ship Underwater Shock Prediction and Testing Capability Study," Mitre Corporation, JASON Report JSR-07-200, 2007.

[12] E. T. Moyer, N. Abboud, J. Gilbert, P. Hassig, B. Hiriyur, M. Miraglia and J. Stergiou, "Introducing the Navy Energetic Modeling Oracle (NEMO)," in *Shock And Vibration 2015*, Orlando, FL, 2015.

[13] C. Farhat, J. F. Gerbeau and A. Rallu, "FIVER: A Finite Volume Method Based on Exact Two-Phase Riemann Problems and Sparse Grids for Multi-Material Flows with Large Density Jumps," *Journal of Computational Physics,* vol. 231, pp. 6360-6379, 2012.

[14] C. Farhat, K. Wang, A. Main, S. Kyriakides, L. H. Lee, K. Ravi-Chandar and T. Belytschko, "Dynamic Implosion of Underwater Cylindrical Shells: Experiments and Computations," *International Journal of Solids and Structures,* vol. 50, pp. 2943-2961, 2013.

[15] C. Van Valkenburgh and E. T. Moyer, "Validation Study of Navy Enhanced Sierra Mechanics Using the Floating Shock Platform Model," NSWC Carderock Division, NSWCCD-66-TR-2013/025, April 2013.

[16] A. Hapij, C. Van Valkenburgh and E. T. Moyer, "Modeling and Simulation for a Full Ship Shock Trial Alternative: FY11/12 Progress," NSWC Carderock Division, NSWCCD-66-TR-2013/006, January 2013.

[17] M. Vechery, "Partial Validation of NESM Acoustic Shock Analysis Capability Using the DNA/ONR 33.6," NSWC Carderock Division, NSWCCD-66-TR-2013/014, February 2013.

[18] J. S. Craft, "NESM Structural Response Evaluation of Ex-Turku Shot 13: Close-In UNDEX With Bubble Loading," NSWC Carderock Division, NSWCCD-66-TR-2015/012, June 2015.

[19] R. J. DeFrese, "Partial Validation of Navy Enhanced Sierra Mechanics (NESM) Using the DDG-1000 Close-In Holing Test," NSWC Carderock Division, NSWCCD-66-TR-2013/015, March 2013.

[20] K. Nahshon, M. Miraglia, J. Cruce, R. DeFrese and E. T. Moyer, "Prediction of the Sandia Fracture Challenge using a shear modified porous plasticity model," *International Journal of Fracture,* vol. 186, no. 1, pp. 93-105, March 2014.

[21] "DYSMAS Sample Calculations Manual," NSWC Indian Head EOD Technology Division, June 2010.

[22] E. Moyer and Navy Enhanced Sierra Mechanics Team, "Automated Prediction of Ship Damage Due to Weapon Effects Loading," NSWC Carderock Division, Whitepaper, April 2015.

NOTES:

1. Look at anything RED.
2. Integrate/merge reference and update citation in V&V section.
3. Complete NEMO section.
4. Add NEMO examples.
5. Incorporate DYSMAS SE comments (Greg’s e-mail) in the Architecture and/or SE sections.
6. Add something about HPC needs (model sizes, load balancing, etc.) in software sections.