# Physics-Based Modeling to Reduce Extensive Full-Scale Testing

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## ABSTRACT

*Historically, submerged-launched weapons systems required extensive offboard surfaced and/or submerged launch tests at a test facility and many years of platform-based testing before they could be operationally deployed. Computer-based launch simulations were limited by computational capabilities, and they needed empirical tuning factors to be able to correlate with launch tests. Increased computational performance has allowed the Johns Hopkins University Applied Physics Laboratory (APL) to develop detailed physics-based eject and underwater launch models that do not depend on empirical factors for improved predictive performance. Focused subscale testing and limited-scope full-scale tests are used to benchmark the new physics-based codes. The ultimate goal is to decrease the fiscal and scheduling constraints to fielding new systems. This article provides an overview of underwater launch phenomenologies, the historical approaches to evaluating launch system concerns, a high-level perspective of ongoing physics-based model developments, and our way ahead.*

## BACKGROUND

The Johns Hopkins University Applied Physics Laboratory (APL) has actively participated in developing, testing, and evaluating submerged-launched missiles for the Navy for many decades. Launcher systems have grown in complexity and sophistication, requiring detailed understanding of the interactions among the launcher, missile, and platform for successful launch operation. In recent years, staff members in the Strategic Deterrence Mission Area in APL's Force Projection Sector have been tasked by the Navy to develop physics-based eject system and underwater launch (UWL) models to augment those that have been used historically by both APL and the prime contractors who build the launcher and missile systems. The objective of this effort is to implement new modeling techniques to complement the historical knowledge base while decreasing the time required to develop and deploy new UWL systems.

### UWL Phases and Concerns

Underwater missile launch is a complex process usually involving gas, steam, and water in multiphase compressible flow with fluid–structure interactions. Understanding UWL phenomena and their impact on the phases of launch from a submerged platform is key to successful and safe deployment of any missile. The phases of UWL can be categorized as depicted in Fig. 1: in-tube, base-exit/near-tube, underwater travel, surface broach, and in-air free fall.

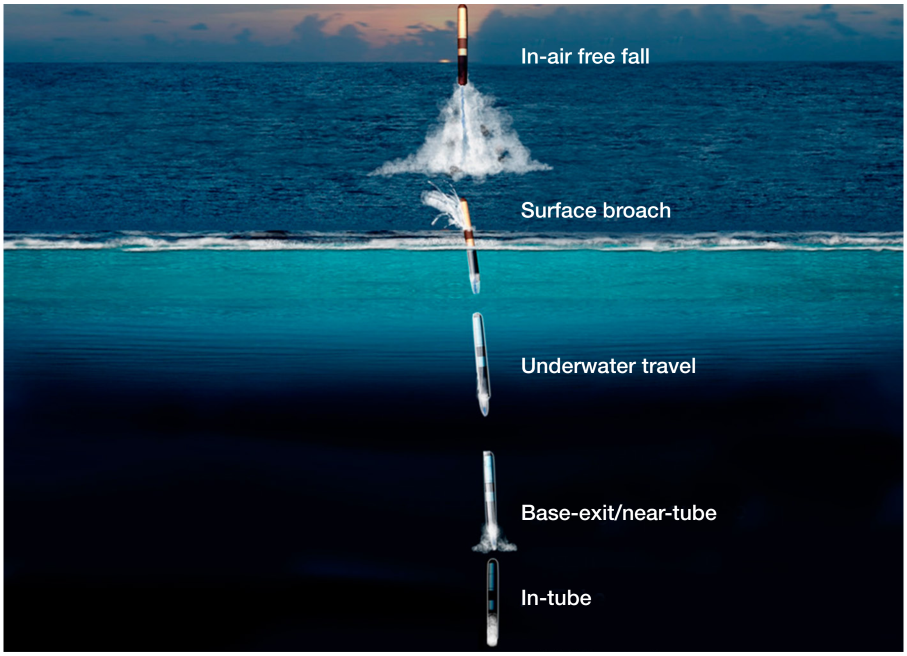


**Figure 1.** UWL phases. The five phases of UWL impart different stresses and loads on the missile, the missile tube, and the platform itself.

The in-tube phase involves launch ejector loads on the missile and the resultant egress of the missile from the launch tube. Generally, missile launch begins with the initiation of an ejector that pressurizes the space under the base of the missile. This high-pressure gas ejects the missile in a piston-like fashion. In addition to the vertical motion of the missile, currents and sea forces can induce missile lateral motions. These motions cause interactions between the missile and the launch tube lateral supports, affecting the survivability of the missile structure. The missile six-degree-of-freedom (6DOF) kinematics is critical to successful launch, and accurate simulation is of vital importance for predicting launch performance.

The base-exit/near-tube phase is the beginning of the underwater travel phase. During this phase, the missile is "uncorked" from the launch tube and a "base bubble" (a large, nonspherical gas cavity in the region directly behind the missile) forms and remains attached to the missile base throughout underwater travel. During the uncorking event, the base bubble interacts with the base of the missile, the missile tube muzzle hatch, and other platform structures, resulting in loads that are important to consider during the missile and platform design process.

The underwater travel phase of the launch encompasses hydrodynamic loading on the missile, which drives the pitch and pitch rate of the missile as it ascends through the water column. Venting from internal missile cavities is controlled so that the drop in hydrostatic pressure will not cause damaging differential pressure across missile structures. The missile trajectory is also affected by this venting. The pressure differential at the extreme lower tip of the base bubble can lead to phenomena that occur in numerous other events, including high-speed water entry and underwater explosions.[1]

The surface broach phase is a continuation of the underwater travel phase. During this phase, the missile trajectory is affected by interaction with surface waves and the resultant loads from those interactions. In addition, when the base bubble and missile vent gas communicate with the free atmosphere during missile broach, "kicking" moments may result, possibly affecting loads on the missile and the missile pitch rate.

During the in-air free fall phase, there are changes in the missile's pitch angle, pitch rate, vertical velocity, and height above the ocean surface, affecting the missile's transition to successful flight recovery. Prior to reaching the end of the in-air free fall phase, the missile transitions to powered flight by igniting the first-stage rocket motor. Accurate modeling and simulation (M&S) of the conditions at first-stage ignition is important in predicting the launch's success under various launch conditions and sea states.

## Historical Methods to Evaluate UWL Concerns

Early development of UWL systems relied heavily on extensive full-scale testing so that the development team could investigate phenomena, mitigate risks, and develop the necessary knowledge base to support system design. This situation was due in large part to the nascent nature of M&S in the 1960s through the 1980s. Test programs included development of expensive surface and submerged facilities and support equipment as well as representative launcher equipment and test vehicles. As missiles evolved to provide increased range and capacity, the test equipment needed to become significantly larger, more complicated, and expensive.

Tighter development budgets and improved computational capabilities have led to increased reliance on M&S, enabling new systems to be developed for less cost and on shorter schedules by reducing the need for extensive full-scale test programs. A key challenge when relying heavily on M&S is ensuring that the models

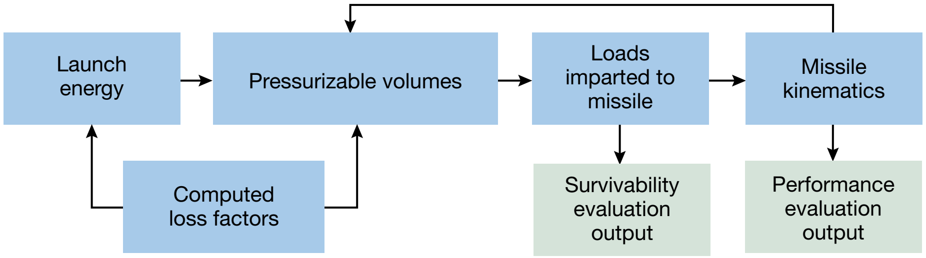


**Figure 2.** High-level ejector model framework. A high-level ejector model framework accounts for complex physical phenomena and system energy losses by using actual physics-based loss factors instead of textbook-based values.

capture all phenomena in sufficient fidelity to allow the team to fully assess operational risks. Current modeling efforts focus on more effectively predicting performance to reduce the likelihood of failure occurring in future systems and thus avoiding costly redesigns and schedule overruns.

## ENHANCED M&S CURRENTLY UNDER DEVELOPMENT AT APL

Advancements in 21st-century high-performance computing allow for more robust and detailed numerical calculations, and APL's knowledge base, along with that of industry contractors, continues to grow. These factors enable delivery of enhanced performance predictions and lead to a better understanding of complex phenomenology in UWL. High-fidelity, accurate modeling methods allow for conceptual design evaluation and comparison before work begins to build hardware, thus decreasing the costs and time required for development of new systems. In addition, the use of multiple models independently developed by APL and industry contractors is helping to increase confidence in simulation products.

APL is working on two new and complementary modeling efforts. One focuses on ejector performance and in-tube missile kinematics, and the other focuses on phenomena affecting missile underwater travel, broach, and conditions at first-stage ignition.

### Ejector Performance and In-Tube Missile Kinematics

Simulations that predict the eject phase of launch have been used by the UWL community for many years. These legacy simulations combined 6DOF body kinematic equations, thermodynamic and classic gas dynamic relationships, and distributed loads induced by support structures to predict missile launch survivability and tube exit dynamics. These legacy models required empirical tuning to deliver high-accuracy predictions across an array of launch conditions because the models failed to capture many detailed system interactions and losses. APL is investigating methods to increase the physics-based prediction capabilities of ejector M&S tools, particularly related to predicting the impact of changes to existing systems or performance of new systems for which full-scale empirical data will not be available.

The effort to model the ejector system centers on the use of a bulk dynamics model to predict overall eject performance, coupled with more detailed models to provide high accuracy in a short time frame. The bulk model runs relatively quickly (in seconds), allowing for quick turnaround of results and iterative analyses. The bulk model is augmented with and informed by focused simulations of the particularly complex aspects of the ejector system using more detailed models. These high-fidelity models concentrate on complex physical phenomena and system energy losses that are not as well captured in the bulk model alone, and they can predict system interactions with higher accuracy. The high-fidelity simulation results are used to reduce the bulk model's prediction uncertainty by refining energy losses in the bulk model through the use of physics-based loss factors corresponding to the actual system configuration, as opposed to generic textbook-based values. Figure 2 shows a high-level ejector model framework.

Several phenomena that impact ejector performance are investigated using the more detailed models to understand multiphase flow and thermodynamic interactions. Results from these detailed models and related laboratory testing will be used to refine the bulk model formulation.

### Underwater Travel, Broach, and Conditions at First-Stage Ignition

APL is developing a new UWL simulation capability. Several commercial and open-source software applications were considered for this effort. The team agreed that having full access to solver algorithms, and developing new code, would increase knowledge of the physical and mathematical assumptions used in the code and thus result in better overall understanding of the UWL phenomena. Independent research and development funding was initially used to determine whether the complex multiphase phenomena of an UWL could be captured with the code and to develop a preliminary UWL model. This new simulation capability is a government-owned tool that will be used to address risks and conduct concept studies associated with both new platforms currently in development and future systems.

The UWL simulation uses a customized solver to capture viscous, compressible, and multiphase physics associated with motion of a solid body through a fluid. This approach is needed to model the two-phase (air/water) fluid environment that is present from the time the missile base uncorks from the launch tube through the time it broaches the surface and undergoes first-stage ignition. In addition to the flow solver, solid-body motion in the simulation requires coupling to a 6DOF physics model, so that fluid forces alter the trajectory of the missile. The team investigated several methods to allow for missile movement relative to the launch tube/platform.

## M&S VALIDATION THROUGH FOCUSED, LIMITED TESTING

Although useful in many respects, available historic full-scale test data were deemed inadequate to fully validate the new ejector and UWL models under development. Gaps between the available test data types and those needed for validation were identified, and new data-gathering efforts were and are being planned. These new data-gathering efforts take advantage of test opportunities previously planned for the future by adding new sensor systems. In addition, subscale tests to investigate specific phenomena important to UWL have been conducted or are planned. These new validation data-gathering efforts are much less expensive than the series of full-scale tests that would otherwise be needed in the absence of accurate physics-based models.

### M&S Validation Examples

To better grasp the full UWL missile–fluid coupling, the team used the APL-developed UWL solver to simulate the dynamics of a simpler problem of a solid sphere entering water. A large amount of data for this problem is available in the literature (e.g., the series of experiments described by Yan et al.[2]).

The sphere dropping into water impacts the surface, generating an air cavity that expands and then contracts and pinches off. Figure 3 shows a comparison at seven successive nondimensional times $t' = tV/D$ (where V is the initial sphere velocity and D is the sphere diameter) generated by the UWL model and the experiments described by Yan et al.[2] The strings of small black circles in the figure represent experimental data, and the blue lines represent model output. The final panel compares the cavity shape at the moment of cavity pinch-off. The depth of pinch-off is slightly more shallow in the model than in the experiment. This difference in pinch-off depths is well within the range of variability demonstrated by experiment.[2]

To investigate base bubble dynamics that occur as a missile leaves, or "uncorks," from a launch tube underwater, a subscale test was developed (Fig. 4). The test apparatus was located in a sealed chamber, and initial pressures both in the launch tube and above the water surface were reduced from atmospheric pressure to account for the smaller geometric scale. Vehicle dynamics were driven by a motion-controller rather than pressure-induced motion; they were also appropriately scaled down with the geometry. The test apparatus is in a half-plane arrangement made of Plexiglas to allow for visualization and measurement of bubble shapes. Variations on the test parameters were implemented over a series of tests to enable generation of a range of test conditions. High-speed video was used to capture the bubble contour during the uncorking event, up to and continuing past the pinch-off event. The images on the left in Fig. 4 show the beginning of the pinch as the base bubble contracts under the influence of hydrostatic pressure. The images on the right in Fig. 4 show the air cavity has separated into two distinct regions, one confined to the volume within the launch tube and a separate region traveling with and attached to the base of the vehicle. This second region forms a vortex

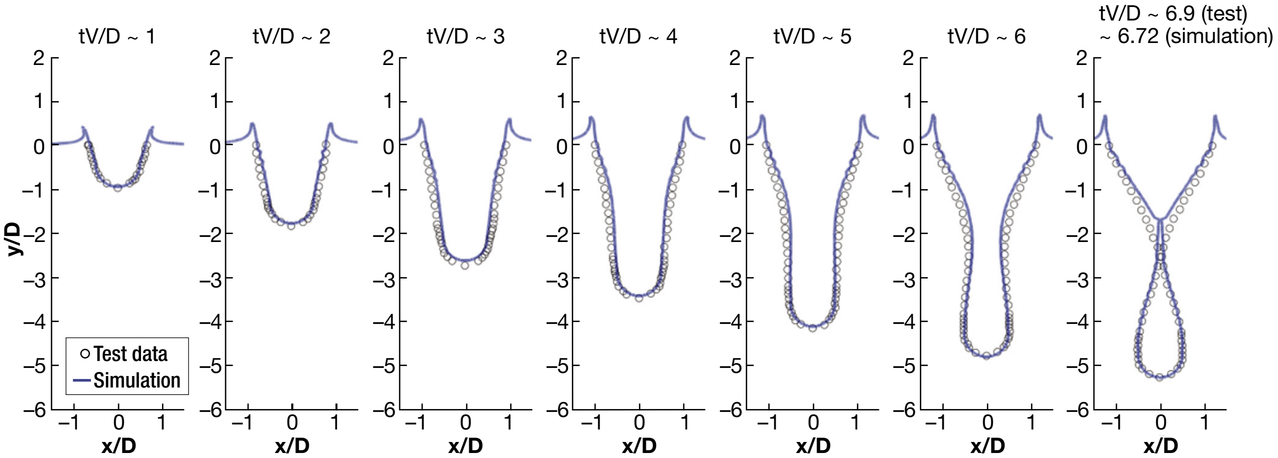
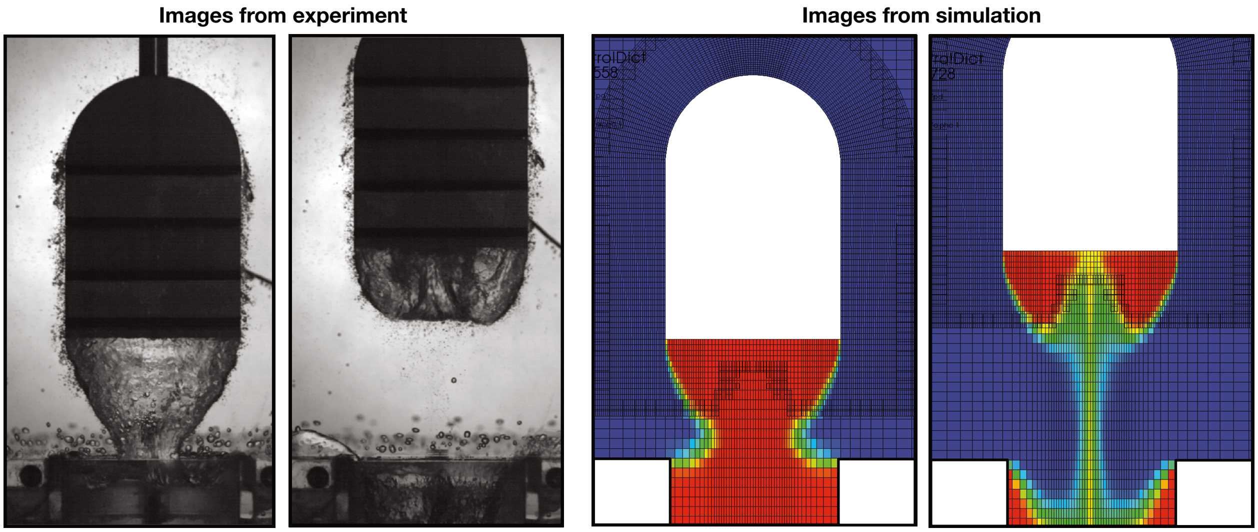


**Figure 3.** Cavity shape at nondimensional times. Modeling output (the blue lines) produces results that mirror actual experimental data (the strings of small black circles) for the air cavity that is generated when a sphere is dropped into water.



0.02 s after tube uncorking

0.04 s after tube uncorking

0.02 s after tube uncorking

0.04 s after tube uncorking

**Figure 4.** Subscale uncorking test compared with simulation. M&S results match the physical experimental results.

ring (donut shape) at 0.04 s after it exits the tube. The very close comparisons of base bubble contour between the experimental and simulation images provide confidence in the ability of the simulation code to predict behavior in a full-scale environment.

### Future M&S Validation

Other controlled laboratory tests are being planned to allow the team to gain insight into physical phenomena important to ejector system performance. Small-scale laboratory tests are being developed to increase understanding of the eject system. The test data will be used to improve ejector models. A noninvasive measurement technique is being tested that would use high-frequency acoustic transmitter/receiver pairs to measure eject flow characteristics that could also be used in a full-scale launch. This measurement will provide valuable information about the flow regime in the eject system.

In addition to the controlled laboratory tests, APL will leverage full-scale tests planned for other reasons to enable additional data collection and insight. As noted previously, historical data from past full-scale test launches were deemed insufficient to validate the new models under development. To obtain further insight into existing systems, APL is designing new sensor suites to fill data gaps during already scheduled test launches. These sensor suites will allow for validation data to be gathered and will result in enhanced understanding of phenomena in key areas of the ejector system in the underwater environment. This increased understanding of existing systems will be useful when determining and verifying which system performance drivers should be included in M&S tools for future systems.

## WAY AHEAD

APL has defined preliminary validation acceptance criteria to assess model validation. The team used historical test data to make preliminary assessments of model validity and used comparisons of output from multiple independent modeling approaches to build confidence in the absence of available data. As new sub-scale and full-scale test data are obtained, APL will continue to benchmark and improve models under development as necessary. It is anticipated that these tools will be maintained for years to come and used at the direction of the sponsor in support of both new and existing systems.

**ACKNOWLEDGMENTS:** The authors thank Dente Poland and Crystal Farmer for their program oversight and sponsor engagement. The authors thank the following APL staff members who contributed to ejector model development: Zachary Berstein, Terry Casey, Roberto Madera, Lauren Magee, Mark Mifsud, Brad Warner, Richard Welch, and John Wozniak. The authors thank the following APL staff members who contributed to UWL simulation development: Zachary Berstein, James Diorio, Jeffrey Garretson, Joseph Geiman, Joel Jorgensen, Rubbel Kumar, Ashish Nedungadi, Kevin Smith, Kareem Sorathia, and John Wozniak.

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