HOW TO SURVIVE A HYPERSONIC HIT
A Case Study: Innovative Naval Compartment Fire Boundary Penetrations For The Final Fight

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Abstract
The case study canvasses potential issues and proposes options in the final fight against modern naval warfare. Addressing if damage control equipment has advanced at the same rate as weapon technology.

The research suggests that naval firefighting and damage control doctrine has seen minimal technological enhancement compared to weapons and the lack of modernisation to the standalone damage control equipment. The case study proposes to review current naval and maritime fire safety technologies that could address the late stages of a compartment blast event.

The paper concludes that the point of penetration in the area of fire recoverability needs to be enhanced with procedural and technological developments to narrow gaps in prevalent compartment fire and seagoing survivability operations. By simplifying the procedure of indirect attack and the act of boundary penetration, this paper offers potential solutions and recommendations to modernise naval firefighting and lifesaving equipment.

Presenting sovereign innovative technologies to protect warfighters from ordinance induces compartment fires and documenting a unique experimental setting. The findings offer a proof-of-concept experiment to combat extreme compartment fires that validate new concepts and aim to contribute to further research efforts supporting safer methods in the final fight.

PREFACE: *To appropriately reference the work herein, please be aware the literature review and technology case study were preliminary presented on behalf of the UTS Student Capstone Project at the International Maritime Conferences (IMC 2023) and the Indo-Pacific International Maritime Exposition (Indo-Pac 2023) prior to the full paper completion.*

The UTS Capstone research proposal was reviewed by the International Maritime Committee, resulting in an abstract and undergraduate review process with Engineers Australia and the Royal Institute of Naval Architects. Leading to an invitation to present the research at IMC 2023 and requiring a Sep 2023 submission before the official UTS student Capstone project completion. Subsequently, the innovation was shortlisted for the Indo-Pac 2023 Innovation Excellence Awards, resulting in the decision to pursue IMC 2023 academic effects over submitting the complete project in the 2025 proceedings.

I hereby reference myself in the UTS Capstone Project submission, as components of the work were presented at IMC and Indo-Pac on 7 Nov 2023 and have now been updated to include the formerly absent experimental setting.

Key Words: Fire suppression; firefighting innovation; naval fire; fire at sea; Damage Control; indirect attack; human error; firefighting; novel technology; fire incidents.

1) INTRODUCTION

The assertion of a warship and crew surviving the blast effects of an adversary missile hit is heavily reliant on platform design, procedures, human response and equipment. The Australian and allied navies' superior damage control capabilities and successful outcomes in warlike and peacetime incidences can be attributed to the actions of the ship's company, training and lifesaving equipment. These achievements are underpinned by Australian and allied Defence Scientists' commitment to assessing platform integrated survivability and guaranteeing ongoing improvements across vessel design, doctrine and equipment.

Defence Science and Technology Group (DTSG) maritime experts prime a warship's integrated survivability by measuring platform capability factors in combat and non-combat incidents. Quantifying platform integrated survivability combines three naval warfare discipline fields: susceptibility, vulnerability and recoverability [1].

- *Susceptibility* – Capability measurement to defeat or avoid an enemy attack.
- *Vulnerability* – Capability measurement to tolerate initial damage, continue warfare, and protect the crew from injury or death.
- *Recoverability* – Capability measurement to take emergency action to control damage, prevent loss of ship and crew, and restore primary mission capabilities.

If ships-fitted fire suppression systems have succumbed to blast effects, firefighting kits and equipment unaided by ships' power ensure a capability redundancy and naval basic training enables an uninterrupted firefighting attack. However, there is a disparity in the technological growth of portable firefighting equipment to address modern enemy weapon effects of today. Here lies the gap between the exponential growth in weapon technology and the lifesaving damage control equipment and practices we currently possess. To reduce the growth of weapon-induced compartment fires, this case study will review transferable firefighting penetration technologies to improve maritime firefighting efforts for today's wartime threats.

Background

Surface ship integrated survivability is increasingly exposed to technological advances in weapon threats. Capable intelligence, surveillance and reconnaissance satellites, submarines, and listening technologies have reduced warship stealth management in open-ocean waters. Whereas evolving challenges of uncrewed aerial, surface and subsurface autonomous systems have affected maritime security and present weaponised risks.

Precision-guided weapons, such as anti-ship cruise missiles and anti-ship ballistic missiles, pose increasing risks to naval fleets and their responses [2]. The evolution of hypersonic missiles further compounds such threats to a surface ship's susceptibility and vulnerability and the potential for a hit to be catastrophic. Nicknamed "carrier killers" in military circles, a hypersonic missile can travel at five times the speed of sound (speed of sound in air: 740 mph; 1192 km/h), is maneuverable and has an unpredictable path—making it harder to protect by evasive actions and anti-ship missile defence systems. Assuming an active hostile engagement occurs in a future war, an adversary could deliver a successful hypersonic effect to an Australian or allied surface ship.

This future operational situation will require a renewed focus on damage control measures and the responsibilities of all crew. The state of readiness to respond and recover from an enemy missile hit can only be achieved through a combination of superior warship design, crew training and reliable damage control equipment. Understanding the critical opening minutes of responding to weapon threats and combat damage can determine the recoverability of the warship and crew. New, intelligent hypersonic weapons provide lethal reasoning to focus on modernising the damage control technology and processes to ensure today's warships and sailors can remain in the fight.

Damage Control Incidents

Superior naval platform combat survivability, damage control measures and actions have earned respect and admiration from Australian and allied crews. Notable examples include the *USS Stark* (FFG-31) in May 1987, which survived inboard missile detonations with complex propellant fires, and the *USS Samuel B. Roberts* (FFG-58) in April 1988, which effectively managed a mine explosion that severely damaged the ship's keel. The crew's resourcefulness, including innovative ways to stop flooding, exemplified their training and ability to adapt.

The crew's actions and initiative onboard *USS Samuel B. Roberts*, documented in *"No Higher Honor"* [3], continue to inspire naval personnel. Today's sailors still incorporate these learnings into their training, and many of these practices remain in maritime damage control doctrine. However, it is worth noting that the firefighting response equipment has seen little advancement since the late 1980s, creating a technology gap to counter the increased intensity and likelihood of modern missile-induced compartment fires.

2) LITERATURE REVIEW

While fire protection and fire engineering technologies are advancing, compartment fire safety management is becoming increasingly problematic in the defence and maritime industries. Traditional land-based Compartment Fire Behaviour Training (CFBT) procedures are complicated aboard seagoing vessels where the practice can involve large liquid volumes. Inaccurate monitoring can lead to unstable liquid conditions, threatening vessel stability and increasing the risk of sinking [3]. Historical incidents necessitated unique maritime firefighting procedures to overcome these challenges and are at the core of all basic maritime training.

Unstable free-surface liquid conditions and flooding events divert attention, resources and personnel towards dewatering activities and disrupt the ongoing firefighting efforts. Parallel firefighting, dewatering, and stability procedures introduce complex response actions and cognitive strain on crews throughout the firefighting response [4]. As evidenced by the Commanding Officer (CO) of the *USS Bonhomme Richard* (LHD-6) fire on 12 July 2020 within the *JAGMAN Investigation* supervised by the Vice Chief of Naval Operations [VCNO] in 2021— The necessary dewatering circumstances affected the Command and Control (C&C) capability to manage the fire or prevent further fire spreading incidences [5].

Multiple-threat firefighting and flooding events increase crew fatigue and human error and are increasingly more complex in hostile military operational environments. Effective response training is essential and involves event tree analysis and platform-assessed incident models [6]. Basic training equips crews with a core CFBT and proficiency to adapt the response to the topography of naval platforms. The crew's understanding of basic procedures and equipment is the most important asset to improve on platform-specific training to recover from combat damage, restore primary mission capabilities, and continue the fight.

Mariners are educated that if a compartment fire/explosion is not controlled quickly, it can lead to extreme compartment fire behaviours, such as flashover, backdraft, and gas fire ignition. These fire/explosion events were extensively documented in the *U.S. Navy's (USN) Major Fire Review* (MFR) [7] actioned by the Commander, U.S Fleet Forces Command (COMUSFF) and Commander, U.S. Pacific Fleet (COMPACFLT), in 2021, as well as the JAGMAN Investigation [5] and the recent April 2023 *Navy Ship Fires*, Report to Congressional Requesters by the U.S. Government Accountability Office [8]. The lessons re-learnt from the naval industrial shipboard fires revealed that compartment spaces are most vulnerable to vertical fire spread [7], [5], and [9], echoing legacy naval fire containment training and policies. Therefore, efforts to contain and cool the topside fire boundary are paramount. The literature's recurring procedural failures to prevent vertical fire spread provide insight into the operational training and equipment deficiencies to control the fire boundary.

These challenges are increasingly more prominent as global leaders in maritime operations are strained by a technology gap in compartment fire detection and firefighting protections [10], [11], [12], [13], [14], [5] and [7]. U.S. Navy COMUSFF & COMPACFLT concluded in the MFR to enforce compliance of the U.S. Navy COs to prioritise fire safety posture and actions to reduce major fire incidents. Highlighting a need for corrective measures, changes to doctrine and *"championing damage control modernization and new technology proposals."* [7, p. 31]. This call for change requires assessing how we have operated in the past and determining if we have completed the undertaking as best we could [15].

3) THEORETICAL FRAMEWORK

The literature reviewed canvasses potential issues in the options for a final firefighting and lifesaving fight against modern naval warfare. It indicates that the actions and training in penetrating compartment boundaries in the late stage of a fully developed compartment fire or explosive impact are imperative to reduce the likelihood of fires or blast effects spreading to adjacent compartments.

Fixed-fitted firefighting systems have and will succumb again to explosive effects, as was experienced by the crew during the *USS Samuel B. Roberts* damage control incident. The gas turbine installed flame-suppressing halon systems were proven ineffective in the emergency response. In similar circumstances, the compartment-fitted firemain systems used for direct tactics may no longer be intact and succumb to the kinetic effects. Potentially resulting in an untenable compartment. Modern missiles and propellant fuel loads may further intensify fires and pose complex recovery responses. Despite failing to explode, the initial missile strike on the USS Stark persisted in expelling propellant along its trajectory and igniting severe fires.

Compartment recoverability actions at this late stage of the fire lifecycle can be achieved through indirect attack extinguishment. Land-based firefighters denote the method of battling comparable, under-ventilated fires in enclosed spaces as *cutting–extinguishment*. Employed if no lives are at risk and a compartment entry is not required, it is allotted as an alternate or proceeding technique to permitting a building to self-ventilate [16]. Unlike naval firefighting, indirect attack strategies are necessary during damage control recovery states or when crew members cannot directly reach the fire. The hierarchical final phase and C&C advance of the indirect attack is represented in platform event tree analysis in the lower decks of the warship, such as the engine room and auxiliary machinery spaces [6].

Doctrine indicates that the success of an indirect attack relies on the complete containment of the fire, which involves securing all doors, hatches, scuttles, and the ship's ventilation system. Directing that all measures must be taken to establish gastight boundaries and block all potential smoke and fire travel routes. However, executing an indirect attack and ensuring effective containment is complex, as machinery and combustible materials may still be present within the compartment. In addition, residual sources can continue to supply oxygen and fuel to the fire through ventilation ducts, cableways and piping penetrations.

Reclaiming a compartment and staying operational in the face of intensifying weapon effects requires an updated review of policy and technological advancements in boundary breaching activities. Through considering civil and naval platform indirect attack firefighting procedures, this study seeks to review these recoverability options and identify areas for improvement in addressing theoretical enemy hypersonic missile strikes. Several technological enhancements in life-saving equipment for rapid containment and suppression of untenable compartment fires have been assessed. The framework considers transferable equipment and methods that can aid sailors in responding to inboard enemy detonations.

The technology review places particular emphasis on skin-penetrating tools and penetrator nozzles. These systems produce a small opening in a skin or boundary, allowing suppression agents to flow or be injected through the aperture. The purpose of the technology is to suppress or extinguish under-ventilated fires without allowing additional oxygen entry to accelerate the fire and weapon effects. The research presents a comparison of boundary penetration techniques for closed-compartment fires, including:

a. Hull Cutting
b. Unpowered Penetrator Nozzles
c. Powered Penetrator Nozzles
d. Centrifugal Fluid Driven Penetrator
e. Novel Aperture Breaching and Locking Penetrator

a. Exothermic Hull Cutting

The procedural approach to regain control of an extreme compartment fire employed in naval firefighting is to create an opening in the compartment and introduce a firehose nozzle for a targeted indirect attack [4], [6], [17], [18] and [19].

Figure 1 Revised RAN Firefighting Procedures Training Video (0:18 Seconds) [18]

Figure 2 Revised RAN Firefighting Procedures Training Video (0:22 Seconds) [18]

This solution was notably employed on the third day of the *USS Bonhomme Richard* fire, requiring personnel to be deployed by helicopter to make necessary hull cuts [5, p. 66].

The complex operation places a firefighter directly above the intense heat, involving an exothermal chemical cut and forcible entry into the volatile flammable gas layer. Resources include two competent mariners in full fire protective suits and an interchangeable supply of breathing apparatus. The crewing capability to continually relieve and replace these skilled personnel and assets are essential for executing the technique and maintaining the effects of the indirect attack.

Exothermic hull cutting operations are legacy basic training for the indirect attack of the naval procedural firefighting response [19]. During the investigation into the scientific practicalities, it was observed that the available sources only provide anecdotal evidence, leaving much to be desired for accessible research into the techniques' effectiveness. Conversely, it is essential to note that employing a lead-acid battery to initiate the chemical process of the exothermic torch carries certain risks. As highlighted by the US Coast Guard’s Commandant Instruction Nov 2022 [17], locating the cutter batteries near heat sources can cause them to emit combustible and explosive hydrogen gas. Increasing heat will escalate the issue. Directing water over a battery fire can lead to an explosion, whereas directing saltwater to a lead-acid battery results in a chemical reaction, producing toxic chlorine gas. Some consider this practice as presenting an unacceptable risk to naval personnel.

b. Unpowered Penetrator Nozzles

Another practice included in the case study for indirect attack solutions involves aviation-accepted firefighting fuselage breaching activities. The method is aided by the traditional land-based firefighting tool techniques, where axes or hooligan tools are employed to forcibly puncture boundaries.

A commercial example in Figure 3 is the *Water Mist Lance* and *Penetration Hammer* [20], designed to extinguish fires inside enclosed spaces. The technology application is available to the maritime commercial shipping industry and complies with SOLAS regulations II 2/10.7.3.

Figure 3 Water Mist Lance and Special Hammer Solution for Manual Penetration on Shipping Containers Within Reach [20, p. 2]

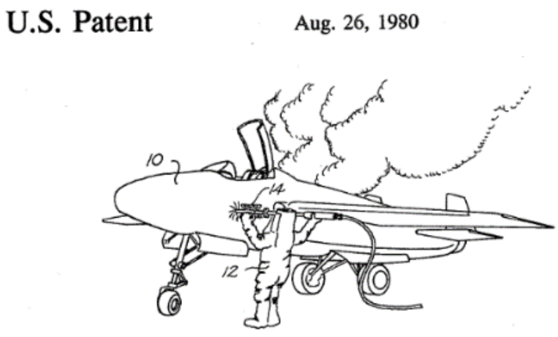


Figure 4 Fire Extinguishing Apparatus Having a Slidable Mass for A Penetrator Nozzle. Administrator: NASA [21, p. 2]

The unpowered piecing nozzles represent an innovation on traditional methods to inform manual impact-driven suppression or extinguishment applicators. These Penetrator Nozzles find applications in aviation, structural firefighting and containerised goods fires [22]. Nozzle penetration through the skin, wall or boundary aided by specialised hammers battering ram, pierce hardens nozzle and hammer striking plate accessories, all aim to drive a hardened steel point into the compartment [23]. The hose connection allows fluid communication through the piercing lance to the nozzle to deliver a firefighting agent and various successful spray patterns. Most commonly used in aircraft fires, the unpowered penetrator technology has limited viability to breach warship bulkheads and decks. The strike may produce a spark that can lead to explosive incidences in the combustible smoke gas layer above a fire. The case study observes that a wide implementation of the technology onboard warships could present an unacceptable degree of risk to the damage control efforts.

c. Powered Penetrator Nozzles

One option to manage a compartment fire is assisted penetration through the deck or bulkhead (vessel walls and floors) by applying powered impact or aperture-cutting technology to deliver suppression agents.

In Figure 6, Cuthbertson [24] was the first to devise a portable hand-held pneumatic impact tool. The design was further adapted to perform pneumatic rotary drilling operations to enter the outer compartment boundary and fight hard-to-access aviation fires [22]. As viewed below, Figure 5 design offers a further improvement on the previous unpowered penetrator.

Figure 5 U.S. Aircraft Skin Penetrator Agent Applicator Tool (SPAAT) Pneumatic Rotary Drill *[25, p. 1]*

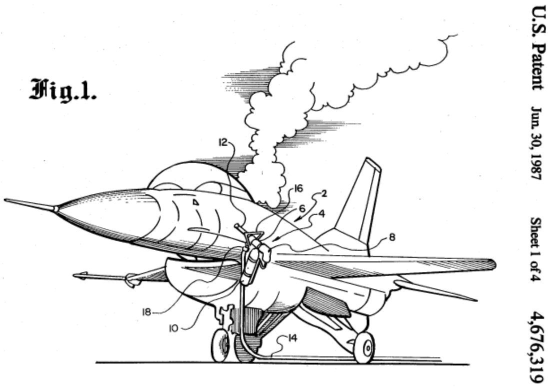


Figure 6 Fire Fighting Tool and Method Administrator: Oceaneering [24, p. 2]

Forty-one marine firefighters tested the kit and noted that during drilling, constant pressure was required to penetrate a boundary. Drilling times were long, leading to excessive wear and resulting in the tip becoming torn from the drill bit [26]. Test reports were documented by Naval Air Systems Command (NAVAIR) in 1988 for the USN Fleet Evaluation of the Aircraft Skin Penetrator, informing weaknesses of the tool to pierce boundaries of thick material, requiring twice the air supply to fully penetrate the boundary [26, p. 27]. One marine firefighter described the tool as bulky and *"Heavy in weight to smaller personnel, which made it difficult to handle and control"* [26, p. 77] (Q4, E.). Since the final report, the technology has seen minimal adoption for ships' internal structural firefighting.

Other shortfalls in the drilling method exist in creating an unsealed opening between decks, introducing fresh oxygen during the water spraying that can intensify a compartment fire. These weaknesses, alongside the spark-producing hot work at the point of penetration, enhance the potential for backdraft and flashover of the explosive environment. Resulting in the research papers' observation that the system is underprepared to address a hypersonic hit and seagoing naval firefighting.

d. Centrifugal Fluid Driven Penetrator

In 2014, Delcourt and peer Garis stressed that fire/explosion detection and fire control operations for ISO shipping containers and dangerous goods cargo were largely a manual tasking unaided by suitable technology [27]. Their research into the matter resembled common issues faced by naval firefighters. By 2017, two innovative individuals working from their garage proposed a novel solution, designing a water turbine-operated drill equipped with an internal penetrator to redirect the water flow.

The system Secured the 2019 '*Safety and Sea Award'* for the best safety product in firefighting. Moreover, it is expected to strengthen the posture of cargo fire safety for merchant fleets with *AQ.P. Moller-Maersk,* one of the world's leading shipping companies, implementing a full-scale adoption of the commercially developed *HydroPen Fire* kit in the Maersk fleet [28].

Figure 7 HydroPen™ Fire [28]

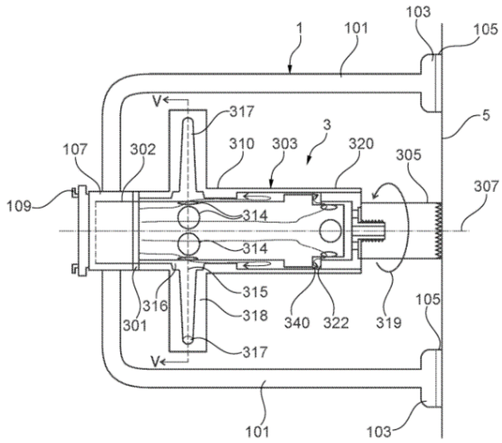


Fig. 1

Figure 8 Fire Fighting Device Administrator: Viking Life Saving Equipment AS [29, p. 3]

The invention offers a new methodology in boundary penetration techniques and an advancement in the capability gap of merchant seafaring crews to fight shipping container fires. Other announcements imply that the innovation is engaged with VIKING Fire, one of the world's largest providers of maritime fire safety equipment.

However, the centrifugal dispersal of ships fitted fireman water internal the structure presents a potential compounding free surface water issue that could threaten platform stability. The researched background in naval firefighting and stability issues had notable near-miss structural and sinking events, like that of *USS Samuel B. Roberts* and *USS Bonhomme Richard.* This raises concern in the mass of water needed to produce the *HydroPen* boundary breaching effect. Applying this system for a naval inboard missile hit incident could require additional preventive dewatering activities and an increased cognitive load on the crew.

An assessment for deployment within inner naval vessel compartments requires additional structural analysis and review of resources. In the case study's context, to increase the human response and reduce the escalation of the C&C stability management load of the naval damage control activity, the technology is not of priority interest for further research in naval warfighting. It remains well suited to open stored cargo.

e. Novel Aperture Breaching and Locking Penetrator

A simplified solution addressing the previous equipment issues was presented at the International Maritime Conference in May 2022 [30]. In Dec 2021, the technology was independently reviewed by the Royal Australian Navy (RAN) and recognised with the Chief of the Navy's Innovation Excellence Award. It is a novel Breach and Attack Tool (BAT) that offers a straightforward, self-locking and gas-tight boundary penetration designed to overcome most of the issues of the previously assessed techniques.

The BAT system could protect against extreme fire behaviour by introducing a gastight steaming effect to cool the compartment and suffocate the fire. Once fitted, it can be securely locked and operated unmanned, removing crew from the vicinity of danger and plugging gaps in current fire safety procedures.

Figure 9 Breach and Attack Tool (BAT) Wormald Australia New Product Testing – 200 L/min [31]

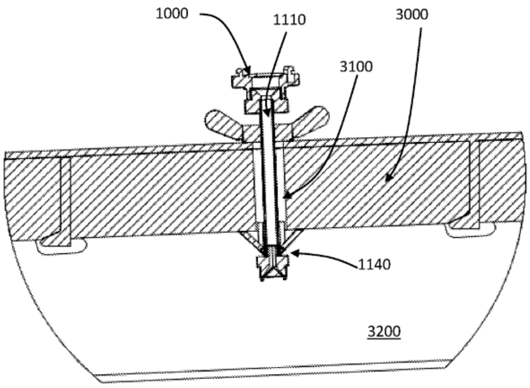


Figure 10 Firefighting Accessory and Method Therefor Administrator: Manderson Engineering Innovations Pty Ltd (ME-Innovations) [32, p. 10]

Figure 10 depicts the BAT with a water mist nozzle. Combined with temperature-monitored short on/off cycles, this practice could achieve the desired effects and eliminate the issues of free surface water. Compared to facing the fire with an exothermic cutter in areas of extreme heat or by hatch entry for direct tactics – the prospect of the set-and-forget tool could be lifesaving.

It could be said that the formerly assessed equipment techniques are complicated, whereas the BAT's intuitive operation can quickly, safely, and effectively apply a cooling effect to a naval compartment fire. The design aligns with the USN identified constraints of the 1988 SPAAT operational requirements: 1,3,10: featuring a suitable retaining arrangement to prevent the penetrator from becoming dislodged or falling if unattended and 1,3,11: "*Human Engineered*" for operational use in a naval fire environment [26, p. 42].

Arranged in Figure 9, the portable BAT system kit includes an emergency circular hole saw and drill for the incursion. Raising similar operational hot work issues of the SPAAT, the BAT can overcome the high-risk drilling activity by preparing platform-engineered preset conduits to facilitate entering and sealing the boundary [33].

4) FINDINGS

Expanding on the effects of rapidly enhancing weapon technology. The literature review revised naval recoverability options, the inherent unmatched equipment and an evaluation of available systems for mitigating extreme munitions induced compartment fires. Summarising the research, case study and technology, the findings represent four key facts and challenges.

- *Firefighting Challenges and Risks in The Face of Evolving Combat Threats*

Naval platforms are a complex and challenging environment to fight compartment fires, and the lack of recoverability and firefighting posture of inboard ordnance-induced fires has never been more prevalent. With a focus towards solutions that reduce cognitive strain and human error during complex damage control states, a simple, robust and effective approach is required to respond to these challenges successfully.

- *The Importance of An Indirect Attack Capability.*

Experience shows that past approaches have been marginally successful but are now outdated to address the challenges of today. Evidence suggests that the frequency and intensity of fires in the maritime and naval industrial environments are rising. Current procedures have proven ineffective in managing fire mishaps, free surface flooding and fire growth at the late stages of containment. Major fire investigations share common threads of ineffective skillsets and technology to combat extreme compartment fire behaviour and a need for new compartment breaching and agent delivery capabilities.

- *A Comparison of The Available Indirect Attack Technologies.*

While several technologies are available for indirect attack, their practical applications towards real-world naval incidents have been limited. These existing approaches are well-suited to their original industry applications, such as container fires and aircraft. However, none but one has offered a comprehensive solution to the current naval threats. Although these technologies provide a starting point, all available systems remain underutilised in efforts to enhance current naval indirect attack and damage control procedures.

- *The Ongoing Need for Modernisation in Firefighting and Damage Control Equipment*

The core challenge is represented by an ongoing need for modernisation in firefighting and damage control equipment—allied naval officials advising at the highest levels for actions, research and collaborative efforts to advance firefighting capabilities. The facts from marine investigations each demonstrate the challenges to recoverability and a growing weakness of response actions to minor mishaps through to major fires ashore during peacetime. The worst-case scenarios, as perceived by some navy personnel, could manifest in the outcome of a major war.

The findings present a pressing concern about the lack of progress with capability, particularly broader effects on modern navy personnel training, skills and individual readiness. This effect may reduce training opportunities and the preservation of crew damage control initiatives and innovative actions. Hindering a platform's greatest asset, its crew and their individual and collective ability to avert mishaps, overcome incidences and prevent catastrophic events. Without a renewed and equivalent focus on increasing the capability measurement for damage control and firefighting equipment, Naval sailors and officers of tomorrow will inherit a weakness in recoverability capabilities.

5) RECOMMENDATIONS

Most nozzles can discharge firefighting agents through an aperture created by drilling or exothermic cutting. However, there is a need, in a research capacity, to pave the way for the development of an approach that delivers appropriate naval and marine situational indirect fire attack options. This can be achieved by new thinking, methods and technology to penetrate a boundary safely.

Such a suitable maritime penetration should restrict fire by-product egress and prevent oxygen from entering the opening. — offering a focus to innovate on an approach to providing penetration that does not suffer from these issues. For this reason, the case study recommends further attention to simplifying the action of entering the boundary.

Solution to Research Gap – Facilitate an Inert Gastight Breach

The following recommendations present an investigation of repurposing naval in-use and industry technology. Combining solutions that are theoretically capable of avoiding escalating fire or flood within a vessel's internal structure and providing suppression capability practical to vessel stability—merging a basic strategy and intuitive design supportive of integrating human factors to restore individual fire attack preparedness.

Figures 11 and 12 illustrate sacrificial diaphragms for pressure relief systems. A concept transferred from pressure vessel safety solutions to inform explosion relief panels for shipping containers [27]. The model could be ideated further to facilitate controlled penetrator access.

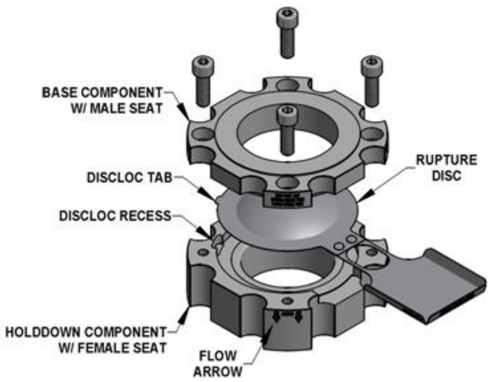


Figure 11 Fike Reverse Acting Bursting Disc Assembly [34, p. 2]

Figure 12 Explosion-Relief Panels, Delcourt & Garis, (2014) P.10 [27, p. 16]

A potential solution could be transferring similar rapid boundary opening concepts to support an emergency penetrator nozzle breach and entry. Leveraging international boiler and pressure vessel code, designed to withstand high heat and pressure environments. Coupling the investigative research of academic material studies and the maritime industry, offers insight to prepare a better naval compartment breaching and indirect attack solution.

Assessing inert breaching diaphragms capable to provide a small emergency access operation linked with a self-securing, gastight, and remotely supplied agent penetrator – The BAT [30]. The industry solutions present an available nozzle penetrating concept technology that could assist in overcoming extreme compartment fire behaviours and increase baseline naval firefighting training, readiness and procedural safety.

Recommendation –Access Facilitation Conduit & Engineered Boundary of Weakness
Figure 13 presents the patent drawing of a USN codified platform system, also known as a NAVSEA-approved asset; it illustrates a Deckbox [35]. A commonly used system onboard USN and RAN warships. The deck penetrating system houses Remote Operator Gear (ROG) to actuate the mechanical isolations to remotely isolate compartments and fuel sources during action states. The adjacent illustration is of a r rupture disc manufacturing method that supports various International Standards with the final product common within naval stores.

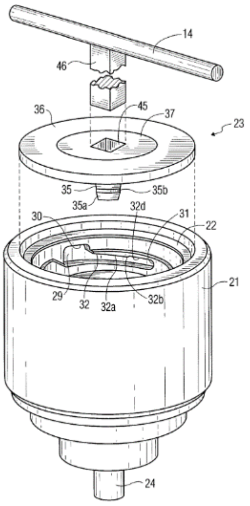


Figure 13 Deck Box for Marine Vessel Administrator: BFG Marine, Inc [36, p. 1]

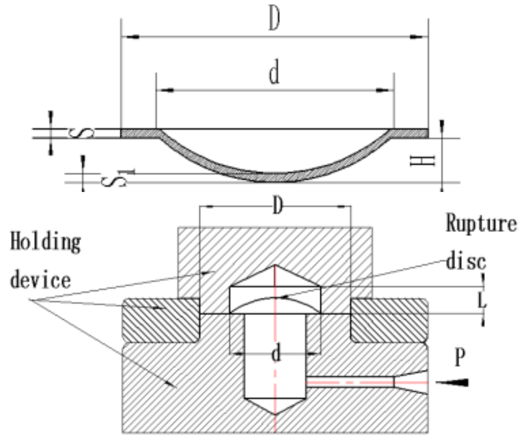


Figure 14 Holding Device of The Rupture Disc for Hydroforming [37]

The two systems represent existing technology onboard RAN and allied warships that could provide Naval-accepted architecture for integrating a potential firefighting Access Facilitation Conduit and greater indirect attack capabilities. A barrier seal or sacrificial diaphragm could be constructed like a burst disc, alternatively known as a rupture disc. A system that supports a breach diaphragm of varying thicknesses, inert materials and diameters will provide the capability for a sacrificial boundary of weakness to withstand naval compartment pressure and deck continuity requirements. While providing an emergency point of entry.

6) PROPOSED INTEGRATION

Implementation A – Access Facilitation Conduit
The evolution and design of the industry and USN codified components are detailed in the Figures below. Figures 15 and 16 present a primary rupturable membrane secured in a clamping arrangement. Including a secondary rupturable membrane, in addition to a primary, for detecting a high-pressure event such as a fire/explosion in the compartment. Located on the compartment side, the secondary rupturable membrane can include a bimetallic strip that, when ruptured, the electrical connection is lost, and a signal will raise the alarm indicating a potential compartment fire or explosion. Offering a rapid alert, combined with an indication of a specific location, allows C&C to initiate faster, more direct crew response and recoverability actions.

Focusing on transferable technology employing an inert sacrificial rupture disc supports rapid gastight penetration into a compartment fire/explosion. Where the rupturable membrane or burst disc is retainable by a replaceable clamping arrangement. Coupled with the BAT, it presents an option that overcomes the former indirect attack technology issues.

PREFACE: *The following technology presented is cited prior art of* WO2023215944, *11 May 2022. No inventive steps or concepts have been developed herein. The recommendations and options are of a committed service person, understanding that a sailor cannot present a problem without having a solution to recommend.*

Figure 15 is a section view with the rupture disc and burst alert sensors intact. Figure 16 shows sensors and/or transmitter and/or circuitry for a ship-integrated platform alert system.

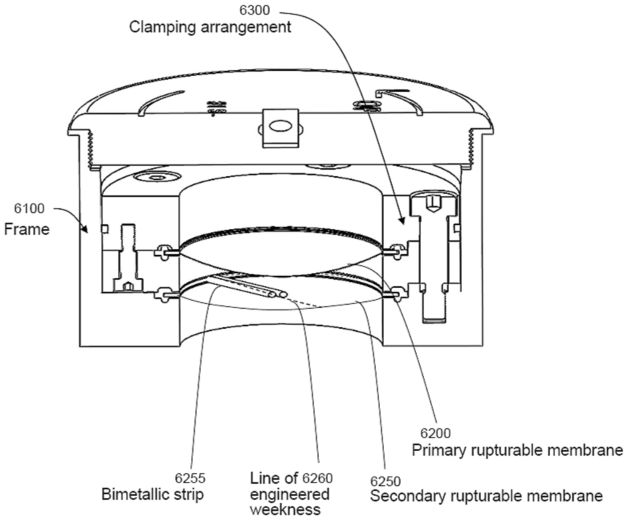


Figure 15 Access Facilitation Conduit Administrator: ME-Innovations [33, p. 77]

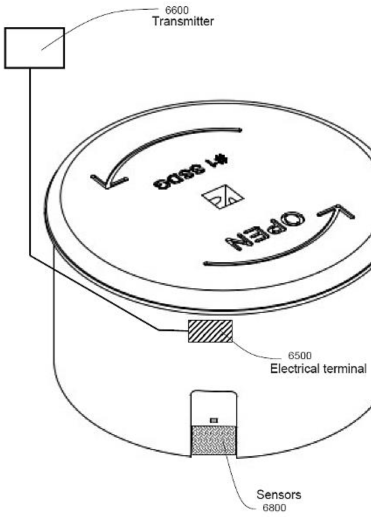


Figure 16 Access Facilitation Conduit Administrator: ME-Innovations [33, p. 78].

Figure 17 offers a section view of an example application welded flush mounted to the deck. Figure 18 is a rendered computer-aided drawing of the BAT and deckbox in the deployed configuration.

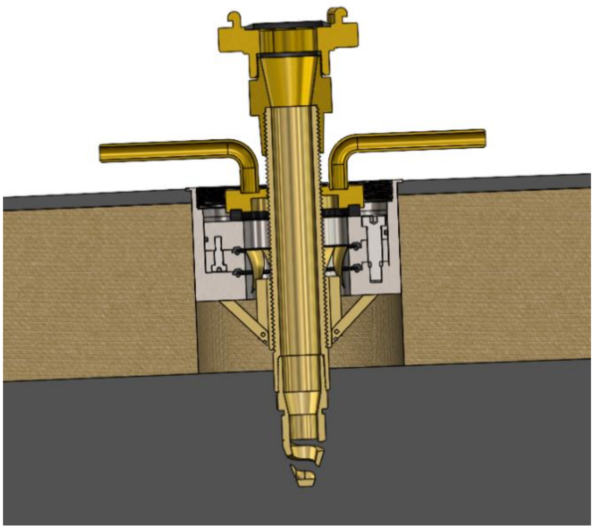


Figure 17 BAT and Access Facilitation Conduit [31]

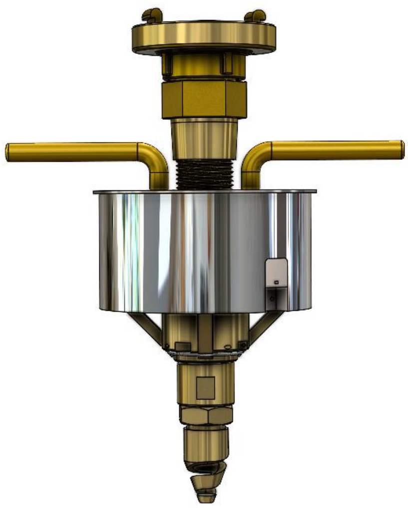


Figure 18 BAT and Access Facilitation Conduit [31].

Implementation B - Industrial Maintenance Environment Temporary Fitted System

The contemporary design below is configured with the same deckbox frame. However, it is fitted with a removable and complementary flange. The frame is mounted within the aperture fitted into the barrier, hatch, bulkhead or deck. This construction and assembly design allow the access facilitation conduit (deckbox) to be adapted in maintenance environments to include an agent connector pipe and supports a temporary alternate fire extinguishing system.

With the flange arrangement matching the inner annular retaining formation. It supports interchangeable securing of the penetrable burst disc or the agent connector within the same deckbox frame—providing a passage to allow firefighting connection a ready nozzle within the compartment during the maintenance period when ships fitted systems are shut down.

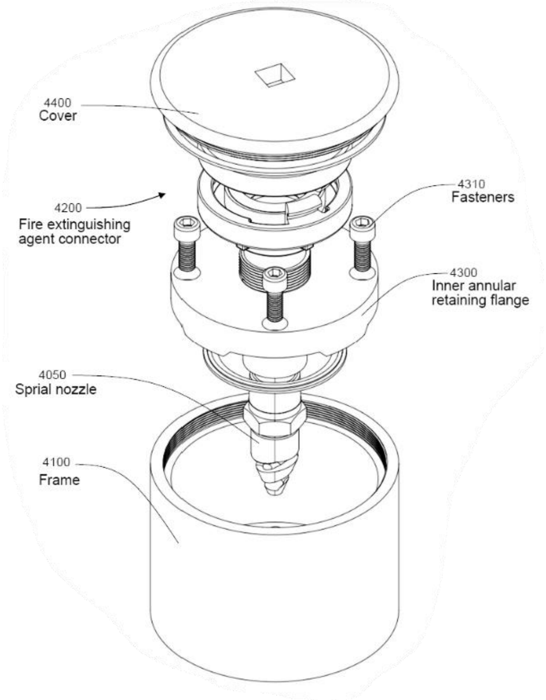


Figure 19 Access Facilitation Conduit Administrator: ME-Innovations [33, p. 67]

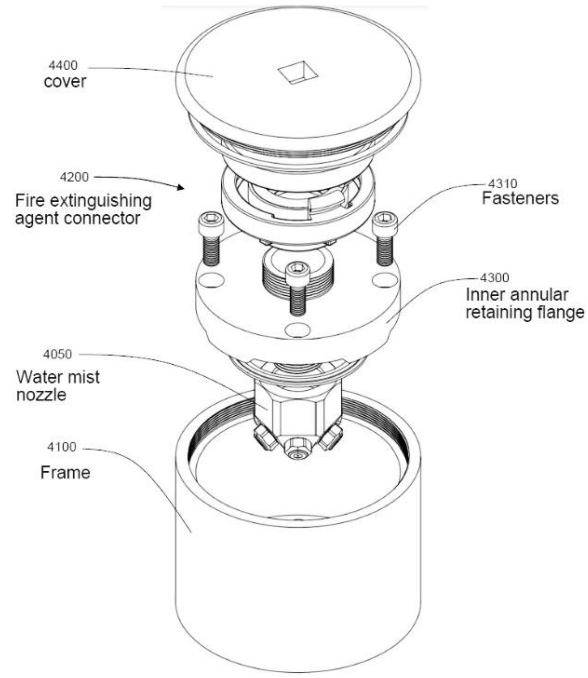


Figure 20 Access Facilitation Conduit Administrator: ME-Innovations [33, p. 60]

Figures 19 -22 are exploded views with a Male and a Female lower fitting, one adaptable to a Spiral Nozzle and the other a Water Mist Nozzle. Please note that the rupturable membrane assembly is removed from the frame; the internals are replaced with a connector and firefighting passage.

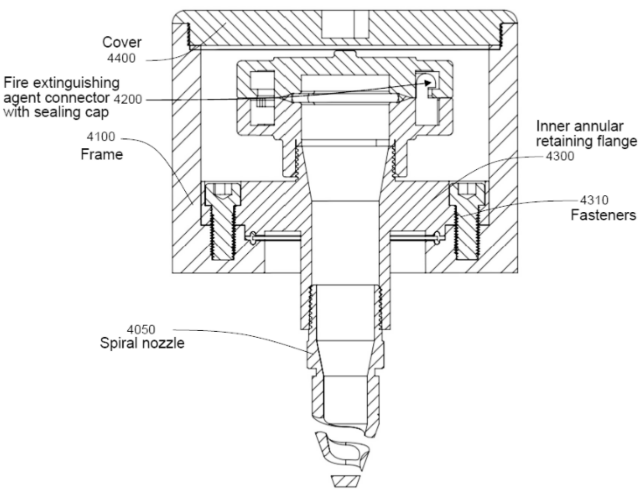


Figure 21 Access Facilitation Conduit
Administrator: ME-Innovations [33, p. 73]

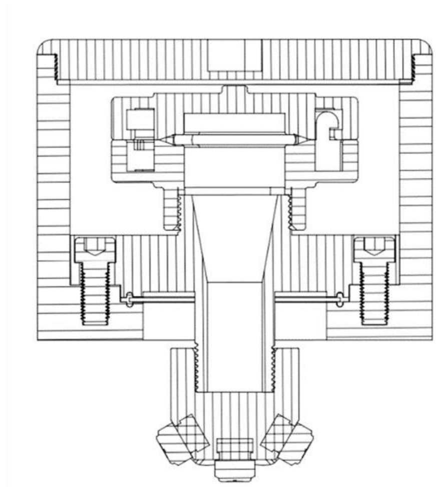


Figure 22 Access Facilitation Conduit
Administrator: ME-Innovations [33, p. 78].

7) EXPERIMENTAL METHOD

The experimental setting was motivated by validating the recommended tooling and capability to breach a boundary of engineered weakness. A notable absence of literature on punch-testing burst discs for forcible entry, resulted in a uniquely designed approach that makes the most of Commercial-off-the-Shelf (COTS) and approved industry resources. The proof-of-concept experiment approach aims to observe the force needed for a human or assistive device to enter through a sacrificial boundary. The setup involves applying a downward force to a circular punch to rupture a clamped workpiece, mimicking industry sheet metal blanking procedures, to validate the emergency punch-type breaching activity.

Drawing insights from standard sheet metal forming techniques, the experimental setting was informed by industry practices and insights from academic research in quasi-static compression operations. Leveraging the UTS Tech Labs' Shimadzu AGX 50kN Universal Testing Machine, this experiment aims to approximate the base operational requirements for a naval indirect attack breaching activity, sharing an original contribution to the material testing field.

Experimental setting literature review

Blanking operations are widely applied in mass sheet metal production industries. During this process, a sheet metal workpiece is positioned between a blanking die and a blankholder, then forcibly cut by the downward action of a punch. See diagram in Figure 23.

Setting the parameters of the blanking process is directly related to the product geometry and the desired quality of the shear cut [38]. Three focus issues in the punch operation are:

1. The contact interaction between the sheet and tooling during the process.
2. Management of the extreme deformation of the shear zone leading to fracture.
3. Predicting the onset of fracture and strain-rate behaviour of the material at high punch rate velocities.

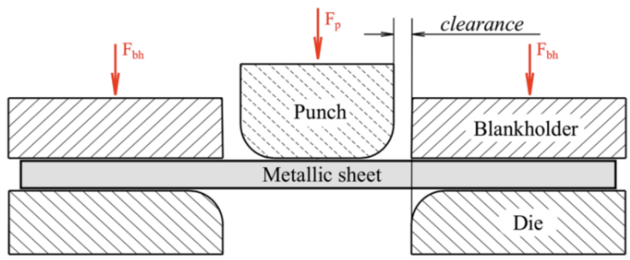


Figure 23 Blanking Process Schematic [38]

Figure 24 UniPunch - Blanking Assembly [39]

Planning a mass production workpiece and managing these issues first requires numerical models and testing of the cutting process. Most engineers make initial calculations and assessments by quasi-static simulations and Finite Element Analysis (FEA) to evaluate the design's characteristics. Reviewing the material plastic deformation, desired shear zone and the eventual planned fracture that generates the workpiece. Then, experimentation by quasi-static compression testing to compare results, to find the most reliable method and apply the optimal cut characteristics to design the mass production unit.

In the automotive industry, many experts prefer repeat experimentation under quasi-static compression [40] and [41] to evaluate the sheet metal formability and process design. This approach contributes to assessing the holistic system and supporting hardware and software tool development to provision the blanking equipment's lifecycle, reliability, and efficiency. Despite the process variations, quasi-static analysis remains the most reliable prediction capability for sheet metal forming experts [38], [40] and [41].

The American Society for Testing and Materials (ATSM) denotes punch-type tooling as the most recognised method of obtaining engineering design data and material comparisons for shear strength [42]. Punch testing is successfully conducted by expert teams in the laboratory [42], [43] and automotive factory environments [40], [41] for predicting advanced sheet metal and material formability. This approach was viewed as the closest aligned experiment process for the known and unknown technical areas of the indirect attack breaching activity.

Academic literature and industry quasi-static testing concentrate on attaining punching loads of the shear cut penetrations in relation to the stroke (displacement) for deriving the optimal sheet metal cuts, see Figure 25. While an emergency entry will require optimal efficacy, and an understanding of the load forces required, the punch-displacement, quasi-static testing literature offered a proven starting point to design an 'alike' method and test.

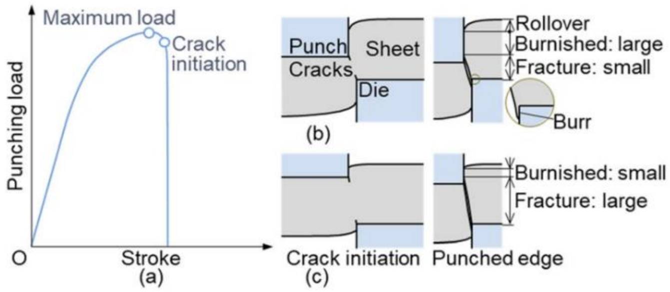


Figure 25 Load-Stroke curve and edge shear quality [43]

Understanding the nozzle/punch interaction for breaching a burst disc requires addressing the same blanking processes three key areas: contact interaction, shear zone deformation leading to fracture, and predicting the materials fracture onset. Published research serves as a guide to design an experiment capable of ascertaining the force load needed for a human or mechanical advantage to conduct the emergency punch-type breach and indirect attack.

Combining academic material testing methods with the sheet metal blanking approach, the experiment design can be simplified and rapidly assembled. Specimens of 2" diameter ferrule-type rupture discs, plus the fabrication of precision shim discs aid multiple cost-effective tests. The experimental approach is aimed at employing available COTS tooling and materials, alongside a series of quasi-static pressure experiments to provide a speedy material assessment and proof of concept, motivated by three key driving factors:

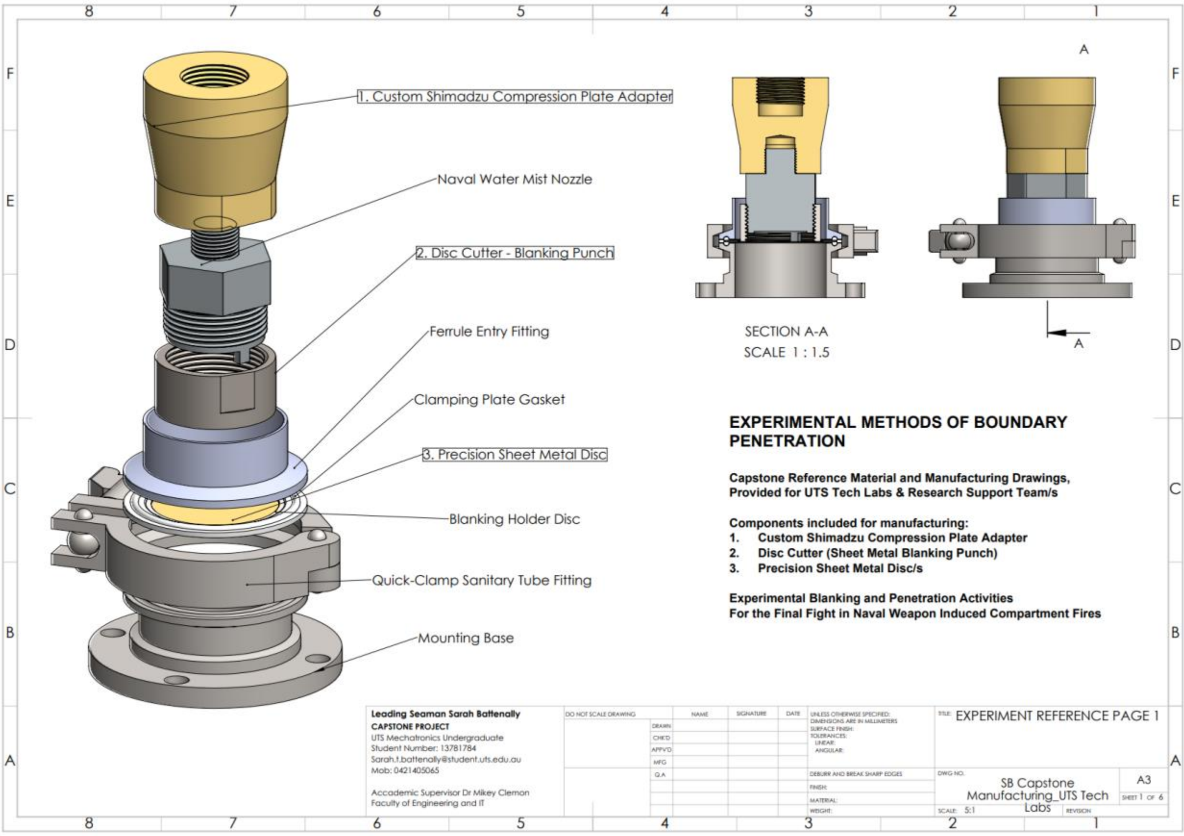
1. Lethal Reasoning: necessitating urgent damage control modernisation efforts.
2. Rapid Response: understanding that a rapid response in initial critical minutes can determine a warship's recoverability.
3. Safeguarding Warships: in developing the academic and industry testing capability necessary today, to ensure navy sailors can withstand future threats.

A punch-type entry of a rupture disc will present unique modifications to the experiments referenced in the literature. The response to an inboard missile hit is a time-sensitive emergency situation that would not support the accuracy of actual sheet metal blanking procedures. Inaccuracies have been included to ensure the translation of experimentation can be "*Human Engineered*" for the naval environment (NAVAIR) [26, p. 42].

Experiment Materials

Experimental setup

The setup, illustrated below, features a *Tri-Clover* 2" pipe ferrule, burst disc housing assembly for securing the rupture disc samples. A circular hole punch, attached to a Water Mist Nozzle, is designed to be mounted to the Shimadzu AGX load cell using a custom brass adapter. To support ongoing research efforts, all manufacturing and COTS details will be included herein.



The image (right) illustrates a modified workflow from the initial schematic proposal. The setup includes an elevated punch entry and an enclosed space beneath the disc for observing nozzle stroke and containing ruptured material. Raised 20mm above the Shimadzu test bed, it accommodates the extended stroke length and required engineering controls. All safety standards were met and informed the software test method to safeguard the Shimadzu equipment across all hole blanking operations.

List of tooling and equipment used for this experiment (not included in the illustration)

1. Shimadzu AGX 50kN Universal Testing Machine
2. Trapezium X, Shimadzu Tensile Testing Software
3. Tri-Clover Sight Glass and Mounting Flange
4. Tri-Clover Silicone Enveloped Ferrule Gaskets (x20)
5. External Micrometers, Rule and Sprit Bubble
6. Micrometer Torque Wrench (Below 10Nm)
7. ½" Socket and Combination Spanner Set
8. 3D Printed Apparatus Centering Guide
9. Mirror

Rupture Disc Housing Assembly

Figure 26 Reverse Bulking rupture disc *[44]*

Experiment Tri-Clover Sight Glass, Mounting Flange and BS&B Rupture Disc

The Tri-Clover ferrule burst discs and Tri-Clamp products were selected for enhanced commercial availability. Australia's strengths in food production ensure that sanitary pipe and clamping assemblies are readily available and often domestically produced. The intention is for the assembly to be subject to multiple force-loading and repeat clamping cycles. However, this is likely beyond the original engineering design factors. The manufacturer's installation torque settings for the disc housing assembly (7.9Nm) bring concern to the life and slope of mechanical degrade. A mitigation can be to reduce the clamping by ~15 - 25% to attain 6 – 6.8Nm. It is also recommended that duplicates of the high-pressure tri-clamps be purchased.

Further safety measures include adding extra fasteners (M8 Nuts x 8) to transfer the force load between the threaded rods and mounting flanges. Ensuring the sight glass is separated from all compressive loads and permits slight glass movement within the assembly.

Industry Rupture Discs

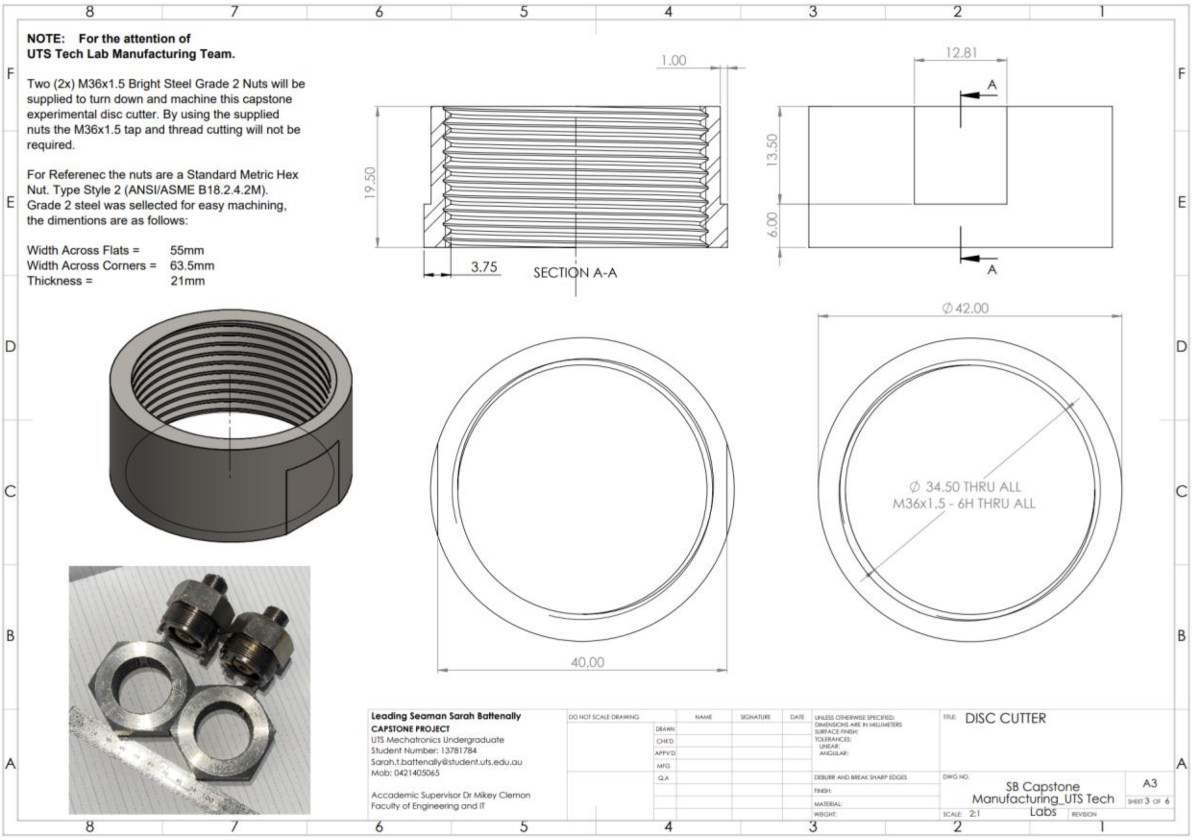
The optimal rupture disc for human penetration features a concaved design for simple human punch/nozzle placement and a circular scoring pattern to enhance the shearing effect. The BS&B System's GFR and GCR reverse buckling disks, have proven perimeter opening characteristics, and were chosen on this capability for the experiment.

Five of the GFR family rupture discs of varying pressures and temperatures were selected, with additional discs ordered from alternate suppliers for the insurance of the projects. Although international shipping delays limited the sample size to 5 industry burst discs. A direct vendor purchase was the most successful and ensured all material testing certificates were provided. Please see the BS&B rupture disc sample size below.

	MAX Operation				Material &
Rupture Disc Model	PSI	BAR	°F	°C	Thickness (mm)
1. GFR-S (Low Pressure)	27.6	1.90	270	132.22	SS316L, 0.127
2. GFR-S (Low Pressure)	27.6	1.90	270	132.22	SS316L, 0.127
GCR-SMS	46	3.17	101	125.00	SS316L, 0.127
1. GFR-S (Low Temperature)	47.3	3.26	200	93.33	SS316L, 0.127
2. GFR-S (Low Temperature)	47.3	3.26	200	93.33	SS316L, 0.127

Water Mist Nozzle

A Water Mist Nozzle is a high-precision fire suppression technology. Manufactured with finely tolerance margins that support micro water droplet sizes, forming varying patterns and desired misting capabilities. To ensure the integrity of the precision nozzle technology, effort was focused on fabricating a suitable punch/cutter protective rosette to endure the boundary breaching activity and allow the nozzle to extend into the compartment. The design approach to overcome the impact took insight from the manufacturers' protective fittings. Please see the experimental manufacturing process below.



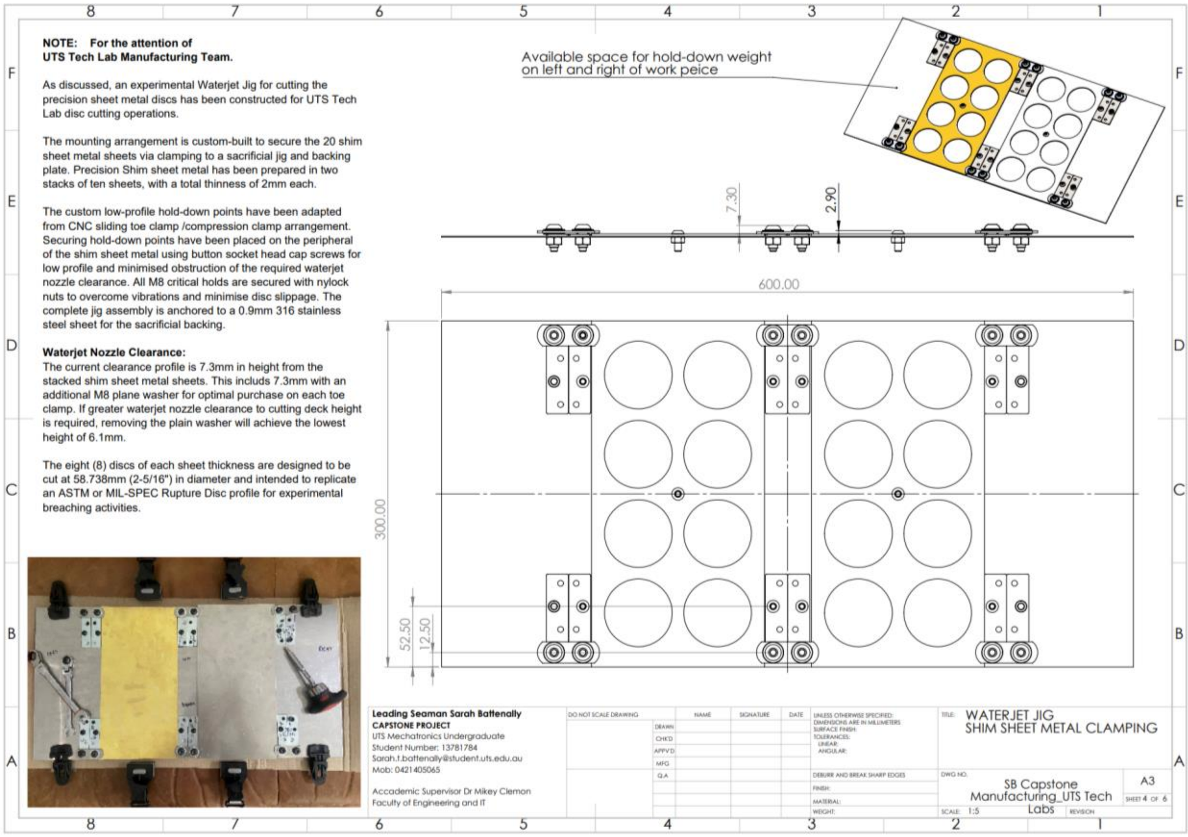
The selection water mist nozzle was aimed to model a normally fixed fitted nozzle, by a portable means, capable of producing the fine droplets at low pressure (3 to 12 Bar), with a full cone spray for emergency breaching. Once charged, the brass internals are forced outward, doubling in length and extending spray penetration clear from rosette obstruction.

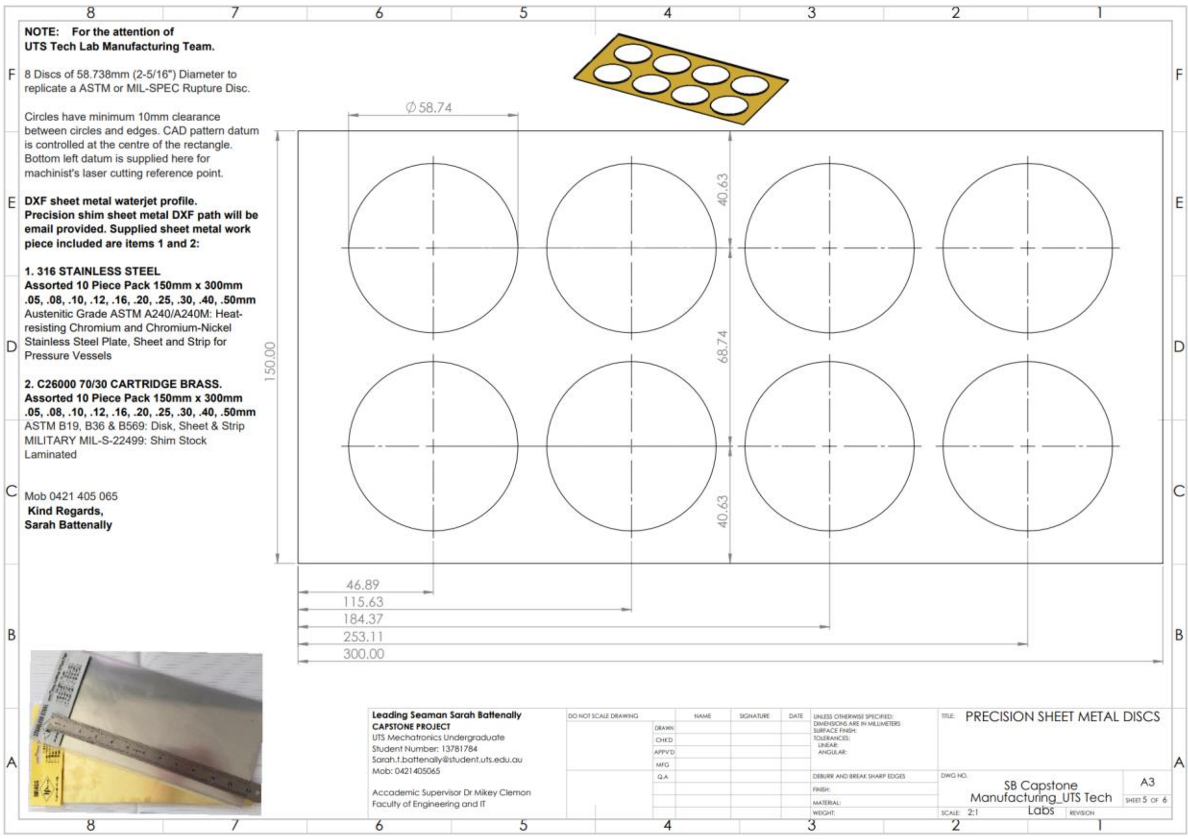
Figure 27 FlexiFOG Low-Pressure Water Mist Nozzle [45]

Experimental Nozzle with Punch- Rosette

Sheet Metal Precision Shim Burst Discs

To increase the sample size, reproduction rupture discs were fabricated for the experiment, offering a cost-effective alternative in replicating the COTS rupture disc. The process involved waterjet cutting the base material precision shim to replicate a practical substitute.

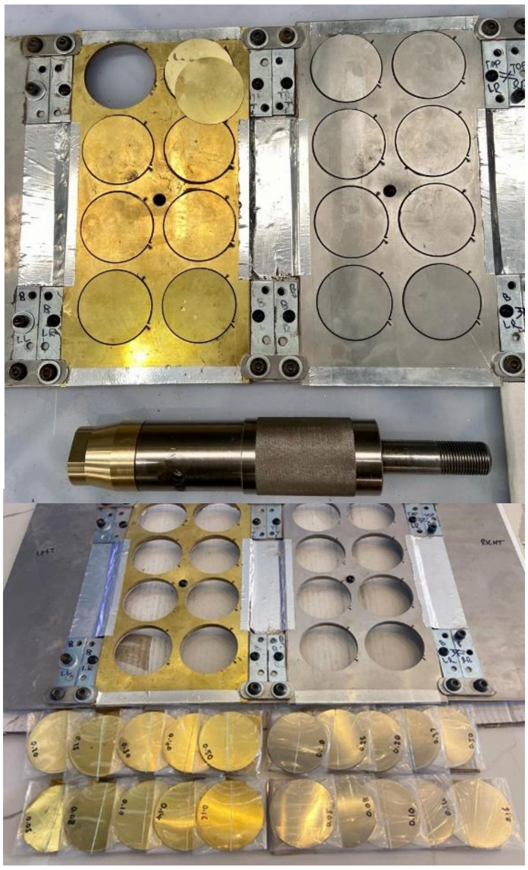




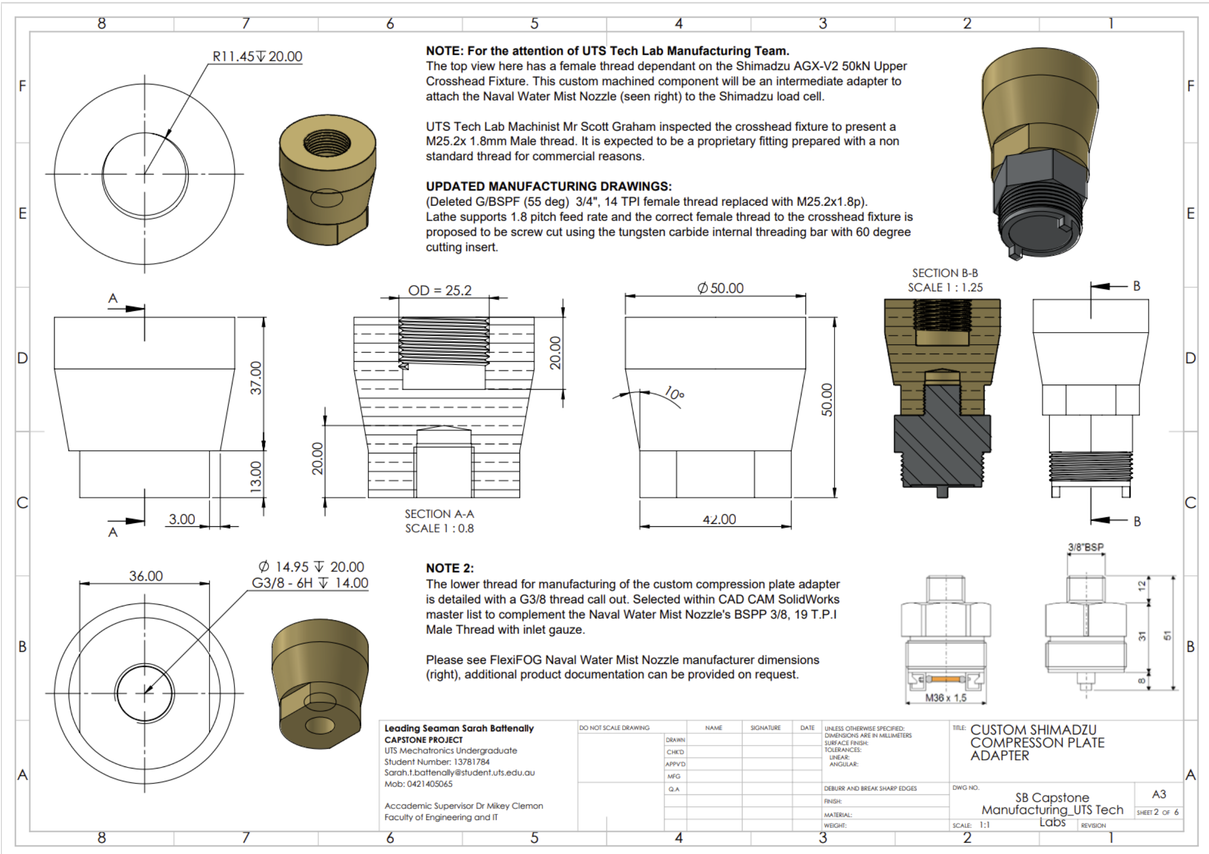
The optimal manufacturing approach involves utilising a metal laser cutter to produce the experiment's precision shim/burst discs. Leveraging the technology to generate the score pattern by defining the specific depths and widths prior to the final cut of the outer diameter. This process can be easily managed within the laser path profiling.

Due to the unavailability of the *UTS ProtoSpace* metal laser cutter, a jig was constructed for waterjet cutting. Although, without the capability to include the desired circular score pattern.

The water jet capabilities expedite manufacturing timelines by the simultaneous cutting of all 20 precision sheets. Elevating the waterjet nozzle between cuts prevents potential collisions with the jig and is equipped with programming to include material-specific tabs on the disc workpiece. Preventing them from sinking to the bottom of the catcher tank. However, abrasive material in the operations requires cleaning and re-categorising all the manufactured discs prior to testing.



<u>Shimadzu AGX-V2 and Load Center Adapter</u>



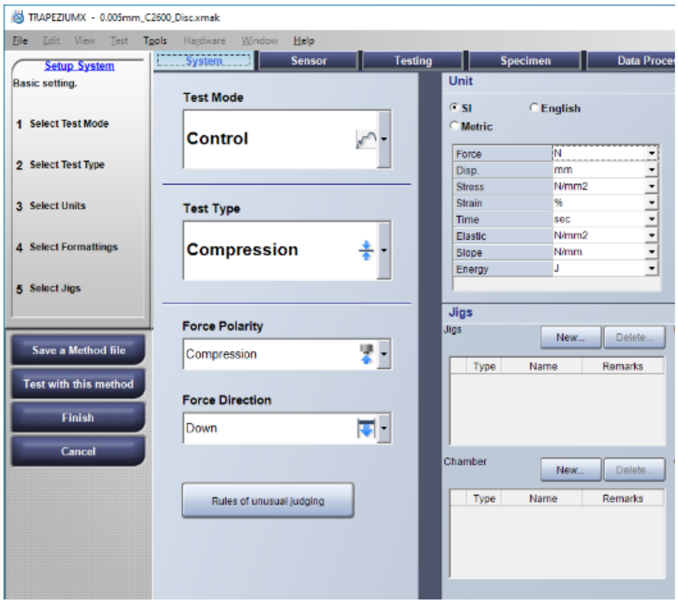
The Shimadzu AGX-V2 Series Universal Testing Machine, equipped with advanced testing capabilities and multiple precision-sensitive mountings for different load cell operations, offers valuable leverage for industry and academic research experiments. This makes it an ideal resource for the indirect attack breaching experiment, aiming to replicate academic and industry punch force quasi-static compression test methods.

The equipment and training are user-friendly, the software is designed for human ease of use and provides extensive access to research and standardised material testing by in-built documentation. However, customising fittings for commercially sensitive and proprietary technology poses significant challenges. Having difficulty obtaining manufacturing information from the supplier, the UTS Tech Lab Research Support Team quickly addressed the experiment design challenge. It was a success in producing a female internal thread by shallow screw cutting to match the proprietary Shimadzu thread formations, a solution achieved in minutes rather than days.

Experimental Methods of Boundary Penetration

Shimadzu Trapezium X Test Method

1. Test Mode: Control
2. Test Type: Compression
3. Force Polarity: Compression
4. Force Direction: Down
5. Force limit: 45kN
6. Stroke limit: 60mm



The burst disc housing assembly is raised 20mm above the Shimadzu test bed to accommodate the extended stroke length of the punch-type nozzle. A viewing glass tube (sight glass) enclosure, along with a base mirror, is positioned at the burst disc exit zone to observe the nozzle entering the simulated closed compartment.

The experimental method in Shimadzu Trapezium X software collects all results for the force applied. It provides insight into the burst disc metal shear strength behaviours when assembled in the burst disc clamping assembly.

Theoretical Force Calculations

Preliminary estimates for the water mist nozzle's punch-type peak force to penetrate, involve evaluating three key parameters: Shear Strength (τ), Material Thickness (t), and Punch Diameter (d). Evaluating the results to determine the maximum *Blanking Forces* required, resulting in a theoretical assessment of the maximum bounds of the experiment. The calculations follow: $F = \tau \times A$

$$Blanking\ Force = Shear\ Strength\ \times Contact\ Area$$

Contact Area: Perimeter & thickness	SS316L Shear Strength	Brass C26000 Shear Strength
$A = \pi \times d \times t$	$\tau = 0.8$	$\tau = \frac{Y}{\sqrt{3}}$

AUSTENITIC STAINLESS STEEL 316L

Shear Strength:
Assumed to be 80% of the Tensile Strength, following guidelines from The Handbook on Steel Bars, Wires, Tubes, Pipes, and S.S. Sheet Production. This 80% calculation is the presented value for Austenitic SS in critical applications, as further verified in The SAE Fatigue Design Handbook.

Mechanical Properties:
Referenced from the accompanying burst disc conformance certificate. The batch-tested quality inspection results of the COTS Rupture Disc base product (precision strip) were tested IAW Strip-Products ASTM A240/A240M-16. The precision trip results are included with the Objective Quality Evidence (OQE) of the purchased Rupture Disc product.

The sheet metal shims, emulating the COTS burst disc, expand the sample test size by including various thicknesses in the assessment.

CARTRIDGE BRASS C26000

Shear Strength:
Determined through the Von Mises plasticity theory, the shear strength indication is derived by comparing the magnitude of shear yield stress in pure shear. The calculated value is √3 times lower than the tensile yield stress observed in simple tension.

Mechanical Properties:
The Brass Shim Stock undergoes cold rolling with a 1/2 work-hard temper certification, registering a hardness of 110-130 Vicker's Pyramid Hardness Number (VPN). In designing an experiment to adhere to military-approved standards and offer a spark-proof breach for experimental equipment, a Cartridge Brass ASTM B19 Disc/Strip sheet metal shim was chosen, meeting the H02 half-hard standard with a specified tensile strength of 395 - 460 MPa. However, the Mechanical Engineer's Data Handbook reports the Tensile Strength for work-hardened C26000 Cartridge Brass at 180 VPN to be 600 MPa. For initial calculations of the blanking force, a conservative Tensile Strength of 500 MPa was assumed.

Theoretical Force to Punch the Burst Disc (Blanking Force)

	Material Thickness (mm)	***0.050***	***0.076***	***0.102***	***0.127***	***0.152***	***0.208***	***0.254***	***0.305***	***0.381***	***0.508***
SS316L	Theoretical Force (kN)	3.51	5.33	7.16	8.91	10.67	14.60	17.83	21.41	26.74	35.66
	Mass of Kilogram-Force (kg)	358	544	730	909	1088	1488	1818	2182	2726	3635
C26001	Theoretical Force (kN)	1.90	2.89	3.89	4.84	5.79	7.92	9.67	11.62	14.51	19.35
	Mass of Kilogram-Force (kg)	194	295	396	493	590	808	986	1184	1479	1972

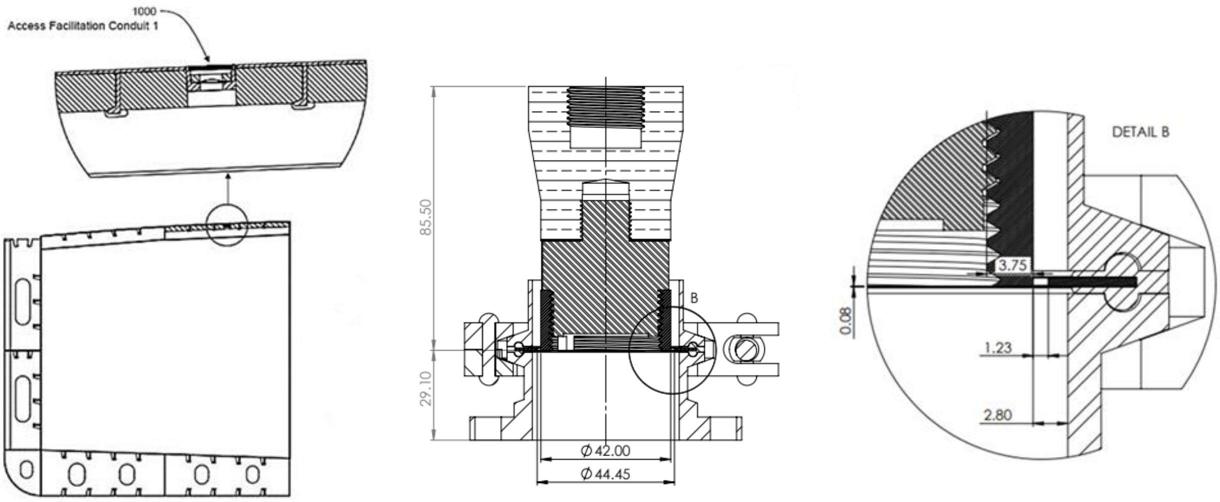
Visual Reference (t)	***0.05***	***0.08***	***0.10***	***0.13***	***0.15***	***0.20***	***0.25***	***0.30***	***0.38***	***0.50***
OD hole punch (mm)	42.00		SS316L Tensile Strength Y (MPa)					665.00		
Contact Area (mm^2)	131.95		SS 316 Shear Strength [0.8*Y] (MPa)					532.00		
Mass of Kilogram-Force (kg)	9.81		C26000 Tensile Strength Y (MPa)					500.00		
			C26000 Shear Strength [Y/√3] (MPa)					288.68		

Punch Clearance Methodology

The blanking process and punch clearance calculation involve evaluating the necessary gap or clearance between the punch, blankholder and die during the blanking operation.

$$Punch\ Clearance = Material\ Thickness\ \times Clearance\ Percentage$$

Typically, the punch clearance is significantly less than the material thickness to initiate the cutting process. Many have attempted to estimate the optimum clearance percentage in sheet forming for a given material and geometry [38]. However, it is established that the numerical issues in the area of blanking remain lacking to estimate the optimal value. Achieving the optimal clearance requires development through simulation, quasi-static experimentation and practical application. Common values are roughly between 5% and 10%.



A section view of the intended shipborne application (left) and the experiment clamping arrangement (middle) is shown. Detail B provides a close-up of the punch clearance values for the COTS equipment (right). A large circular washer 0.9mm thick, SS316, ID: 44.46mm (black rectangle) was utilised as the blankholder. Provided with the COTS rupture disc to secure the clamping faces of the ferrule gasket envelope, this clamping arrangement was replicated for experimental shim discs. The blanking clearance of the experimental setting was influenced by this geometry and calculated.

$$Clearance\ Percentage = \left({}^{Punch\ Clearance}\!/_{Material\ Thickness}\right) \times 100$$

$$Punch\ Clearance\ = Blankholder - Punch\ Diameter$$

Given the experimental setting values:

$$Clearance\ Percentage = \left(\frac{2.46\ mm}{42}\right) \times 100 \qquad \approx 5.86\ \%$$

Applying the original formula, the expected punch clearance for a shear cut in the experimental material range of 0.050mm to 0.254mm is a maximum of ~0.149mm. However, for practical considerations in a naval environment, a larger clearance was adopted to prioritise a punch to safeguard the nozzle spray capabilities over efficient shear cuts. This decision allows for potential misalignment in a human operation. It is assumed a concave burst disc design with a circular score pattern will assist in mitigating these concerns.

Human Force and Shimadzu AGX Test Methods

EXPERIMENT 1

Measure the weight and peak force exerted by individuals when pushing against weight scales.

1. Place weight scales on the floor and ensure a stable flat surface.
2. Have the participants stand on the weight scales individually and record their body weight.
3. Conduct the task of pushing against the scales with both hands using a natural and forceful push.
4. Ask the individual to apply maximum effort in a controlled push manner.
5. Record the real-time weight readings from the scales during the pushing activity.
6. Identify the peak force exerted by each participant during the pushing motion.
7. Repeat the process for each participant multiple times to ensure reliability.
8. Average the recorded weight and peak force values for each participant to obtain a representative data set.

EXPERIMENTS 2 & 3

Measure punch force by quasi-static compression on C26000, SS316L shim sheet metal and COTS Rupture Discs.

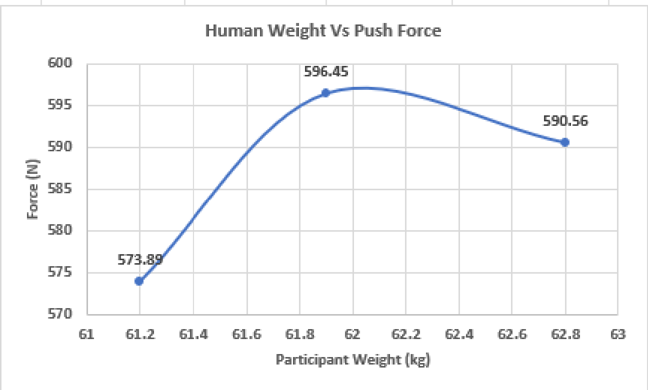
1. Fasten the Shimadzu AGX Upper Fixture for compression testing to the crosshead loadcell and the bottom circular elevation block to the bed of the testing machine.
2. Attach the custom adapter and nozzle punch assembly to the lower threaded body of the compression upper fixture.
3. With the new fixture assembly secured, perform an automatic calibration either from the unit controller or the Trapezium X program.
4. Place the specimen clamping apparatus in the center of the bed elevation block.
5. Take manual control by depressing the 'Manual' button on the controller and jogging the 'Down' button to maneuver the punch to close contact proximity to the test specimen without making direct contact.
6. Turn anticlockwise the manual fine jog knob to delicately touch and apply a 'pre-load' to the test specimen, avoiding the use of the 'Down' button.
7. Verify that the load reading is within a small range (<50N) and release (clockwise) the knob until the load is approximately zero N.
8. Install the safety guards and initiate the testing process.

Results and Discussion

EXPERIMENT 1

Human Force Results

Human Push Force		
Participant Weight (kg)	Maximum Push (kg Force)	Force (N)
61.2	58.5	573.89
61.9	60.8	596.45
62.8	60.2	590.56



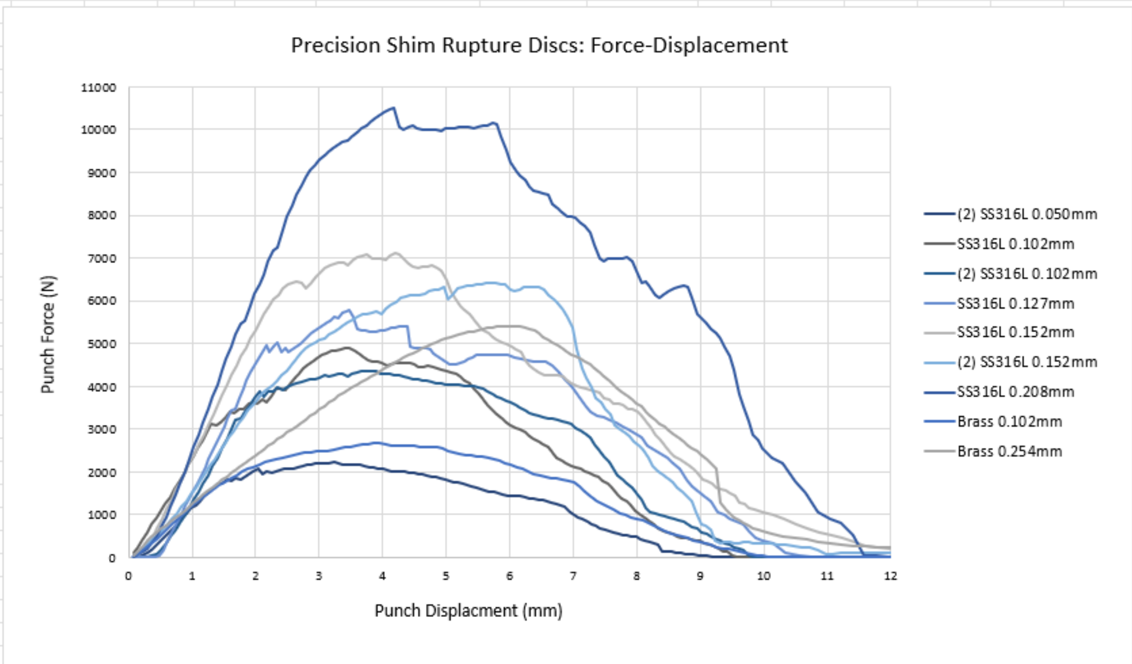
An assumption was that a human pushing on a flat ground could achieve a push ratio of 1:1. The three participants' results closely correlate to the hypothesis. However, achieving maximum force effort in a controlled motion proved challenging, necessitating an angled posture similar to the push-up position. The most effective approach resembled preparing for a seated handstand to obtain a controlled reading of applied force. Notably, a jerk motion allowed for higher force than body mass, but this method presented challenges in obtaining a reliable peak reading due to the short duration.

The three participants, women with adult physical dimensions near the 5th percentile in weight and height according to ISO 3411 Human Physical Dimensions of Operators, were selected to reflect the smaller stature of personnel serving as competent maritime firefighters in the Royal Australian Navy (RAN).

EXPERIMENT 2

Precision Shim Discs Quasi-Static Compression Testing Results

Punch Displacement at Maximum Force		
Disc Material & Thickness (mm)	Maximum Punch Force (N)	Punch Displacement (mm)
(1) SS316L, 0.050	1672.15	3.14
(2) SS316L, 0.050	2226.02	3.20
(1) SS316L, 0.102	4899.42	3.42
(2) SS316L, 0.102	4356.58	3.84
SS316L, 0.127	5795.72	3.47
(1) SS316L, 0.152	7135.65	4.22
(2) SS316L, 0.152	6415.51	5.76
SS316L, 0.208	10512.18	4.17
Brass, 0.102	2664.78	3.88
Brass, 0.254	5405.85	6.00



Discussion:
The conducted tests, along with their graphical representations, differ from the intended assessment of shear strength, with results appearing more towards evaluating the material's tensile properties.

Upon contact, the punch exhibited a pulling effect on the disc material, as seen in the images above. The disc conformed to the punch circumference. This created a deep drawing effect and delivered the perfectly cupped shim to the lower chamber. Zero of the fabricated shim discs reached the shear zone for fracture. Instead, they underwent slight stretching between the blankholder and the friction conditions of the clamping arrangement. Although minimal necking, indicative of potential fracture can be seen. The disc shim material behaved more like a membrane as the punch pushed through to the boundaries exit chamber.

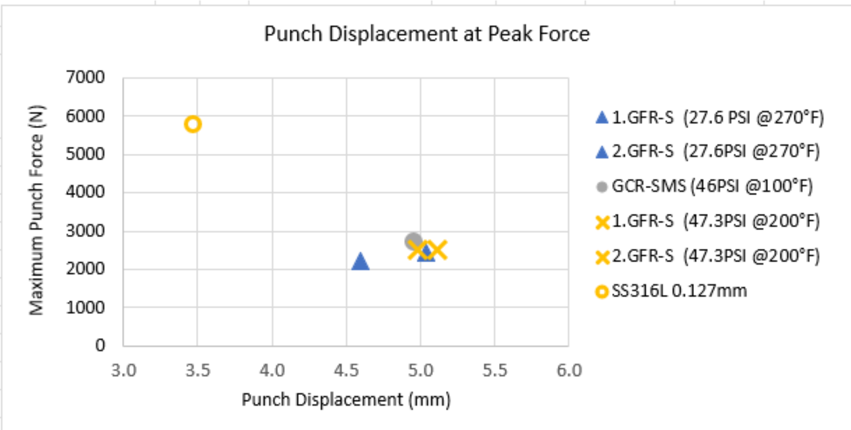
Opposing the assumed brittle behaviour of work-hardened brass shim strip and stainless-steel properties, the tests revealed that the blanking punch clearance was excessively high for the punch-type experiment. This suggests a need for further research and engineering design considerations to address better solutions for developing advanced breach testing profiles for a naval indirect attack.

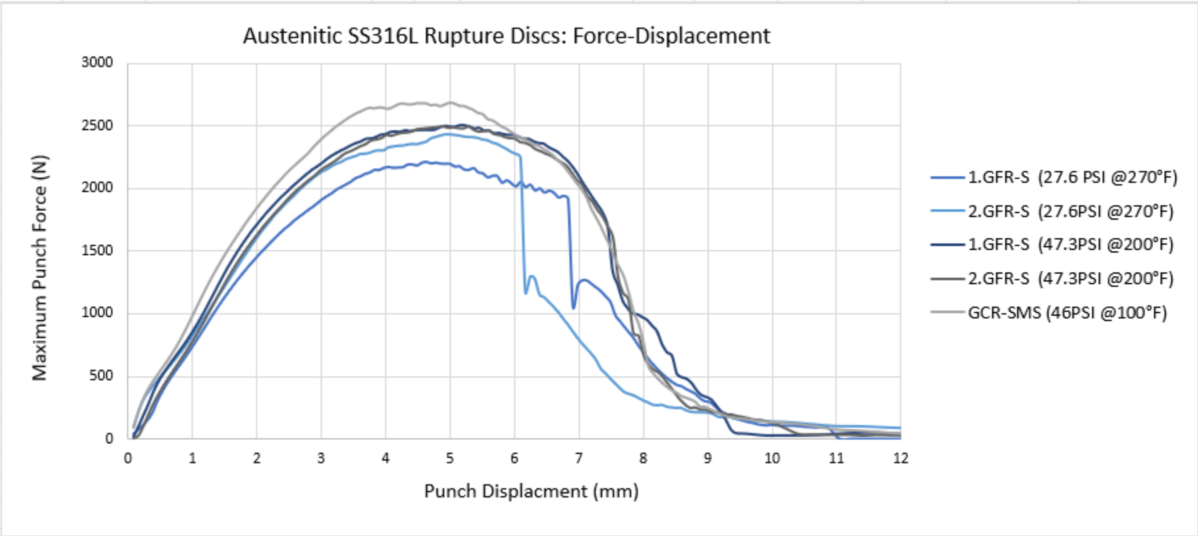
<u>*Note:*</u> several tests were removed from the sample size. This was primarily attributed to initial attempts to design the software method, including non-uniform stroke speeds for pre-load and punch operations. To establish a baseline control, a manual preload was set, and a consistent stroke speed of 3mm/min was adopted for the remaining tests. Others were deleted due to incorrect clamping hygiene, leading to an uneven opening at the blankholder.

<u>EXPERIMENT 3</u>

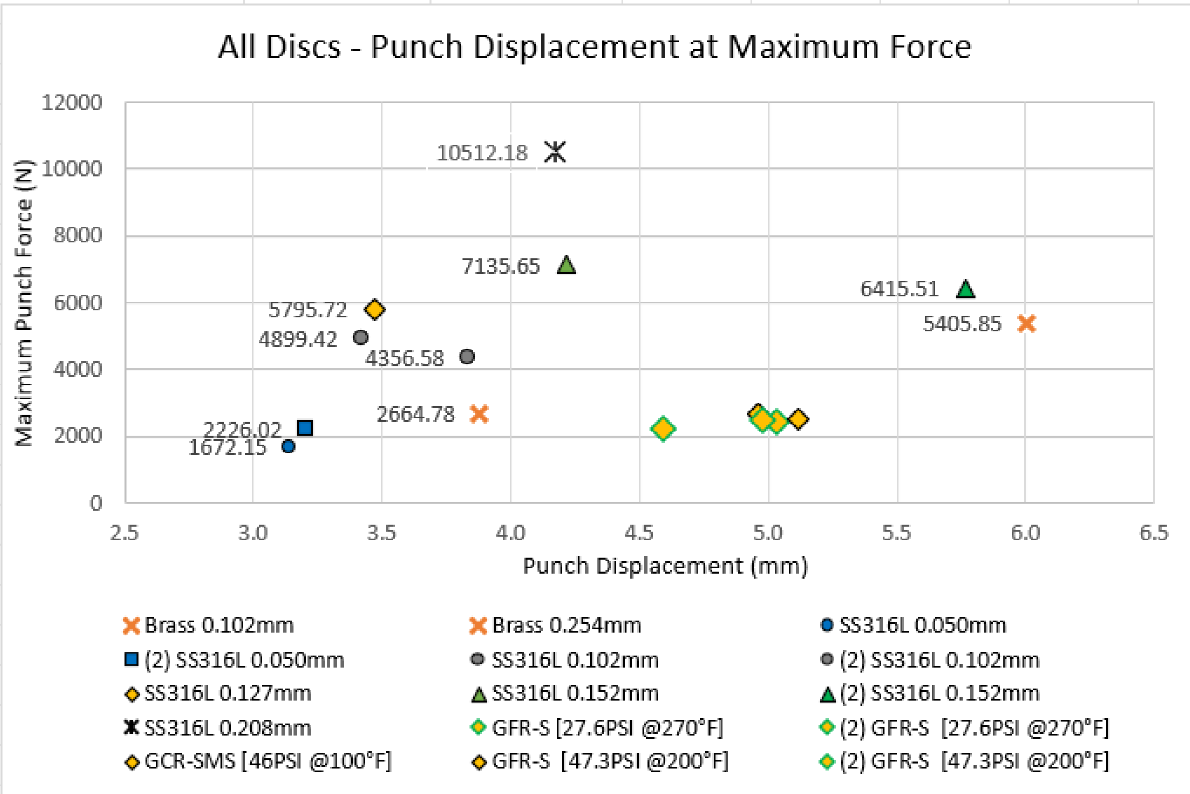
Commercial-Off-the-Shelf Rupture Discs Quasi-Static Compression Testing Results

Punch Displacement at Maximum Force		
Disc Model & Thickness (mm)	Maximum Punch Force (N)	Punch Displacement (mm)
(1) GFR-S [27.6PSI @270°F]	2213.42	4.59
(2) GFR-S [27.6PSI @270°F]	2442.48	5.03
GCR-SMS [46PSI @100°F]	2690.49	4.96
(1) GFR-S [47.3PSI @200°F]	2513.29	5.12
(2) GFR-S [47.3PSI @200°F]	2503.02	4.98





Note: A new clamp and punch/cutter were employed when testing 1. GFR-S (27.6 PSI @270°F). All COTS rupture discs are constructed from 0.127mm precision strip SS316L.



Note: Yellow diamonds with a green outline are successful opening burst discs.

Discussion:

The first and third burst discs exhibited a successful breach opening, allowing for a clean nozzle entry, as depicted in Image 1. However, the fifth disc, also opening at the score line, experienced a clamping issue and failed to allow the nozzle through the score diameter. Like the fabricated shim discs, the COTS rupture discs showed a deep drawing effect, indicating tensile properties rather than shear strength.

While the experiment did not align with the intended punch-type shear strength evaluation, it does serve as a starting point and a proof-of-concept. The results provide insight into the forces required for tearing or affecting tensile decay for a breach. The design suggests a minimum force of 2214 N or ~226 kg for tearing, making it unattainable by human force alone, showcasing the need for mechanical assistance.

Only two COTS rupture discs adhered to expectations; these were designed for high-temperature and low-pressure ruptures. The opposing lower-temperature and higher-pressure rupture discs failed to open, showing that this design selection created an increased resistance, emphasising the importance of balancing pressure thresholds with temperature expectations and human or mechanical force capabilities. The observation also highlighted the critical influence of clamping pressure on the rupture or tear state results, suggesting a need for increased clamping or ferrule sealing considerations.

The mismatch in diameters (nozzle punch circumference and score pattern) posed a challenge in the experimental setup, underscoring the need for manufacturing design considerations. While industry manufacturers of the rupture discs offer custom services, time constraints, financial limitations and lethal reasoning for pace, led to the use of readily available products. Future experiments with COTS rupture discs may benefit from starting with a range below 27.6 PSI for more efficient conduit entry designs and investigating available perimeter-scored products.

Experiment conclusion

Experiment 1, on the human force, is considered unreliable, with issues in performing a valuable test and a small sample size. However, the results closely met the assumption of a 1:1 ratio and insight into how much effort a human could apply to a deck-fitted boundary breaching design.

In experiment 2, the precision shim fabricated disc quasi-static test results were unexpected. Various factors and challenges contributed to the drawing effect, including the punch's cutting-edge design, material friction, blankholder, punch and die guide clearance, stroke speed, and the manufacturer's clamping torque. Regardless of the failure to shear, it gave a comprehensive insight into these challenges, the actual material behaviours and a greater understanding of the literature in practical experiments. The results provide an initial accord of the clearance requirements and the drawing compressive forces recommended or to be avoided for future integration of custom-fabricated shim discs.

Experiment 3's initial testing of the industry rupture discs gave exciting results, tearing and opening an access facilitation aperture as assumed, allowing full nozzle penetration. The higher temperature-rated burst discs lead to lower punch force. However, it is not a complete solution. Sample size and the number of successful tests hinder the experiment's validity. There is much more to learn with the COTS burst disc approach, which indicates a shift in the importance of a tensile tear at the region of the score pattern.

The collective findings are inherent in the challenges of experimenting with unique and innovative designs. It can be confirmed that the experiment design does not allow a human effort to conduct rapid and safe breaching activities without mechanical assistance. The results can be interpreted as relevant to the intent, although they do not accurately represent the final required experimental setting or product for the final fight. However, it offers room for improvement and a contribution to the field for others skilled in research experimentation to support further emergency breaching assessments.

8) SOLUTIONS

The current test design offers an unsuccessful form to conduct rapid breaching activities without pushing the metal disc through the bulkhead or deck with mechanical assistance.

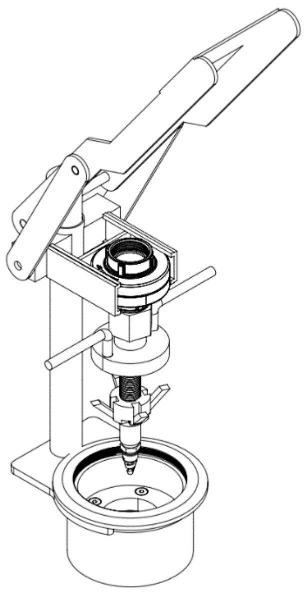
There is evidence in the forces obtained that a person in full firefighting attire responding to a hypersonic missile hit cannot conduct an unassisted penetration of the experimental boundary breaching system. The key finding of the study is that the breaching activity needs a form of mechanical advantage to work. Alternatively, custom manufacture burst discs or similar boundaries of engineered weakness with more suited materials, score or domed design patterns.

With experience deployed aboard a warship filled with artillery, many hours of sleep have been lost, assessing the reaction times required to respond effectively to a fire mishap or weapon threat. When a fire starts or the Navy experiences a loss, it is too late to read a case study, and actions need to be taken immediately. As previous lessons are re-learnt:

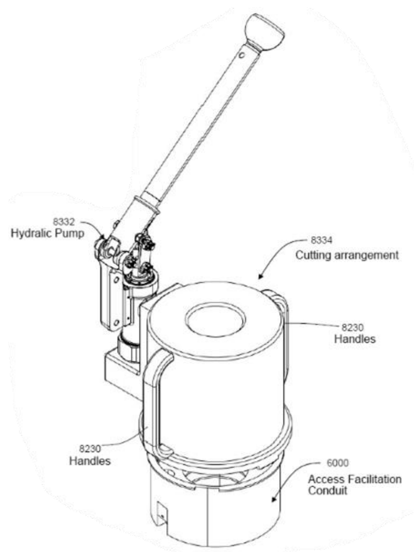
"The more you sweat in peace, the less you bleed in war" — Admiral Hyman G. Rickover, 1986.

Three solutions of force multiplier mechanisms are included to increase shear force potential or overcome the push-through issue. The first two systems are rudimentarily constructed so that, if needed, they can be built with COTS items quickly and compatible with the USN Deckbox.

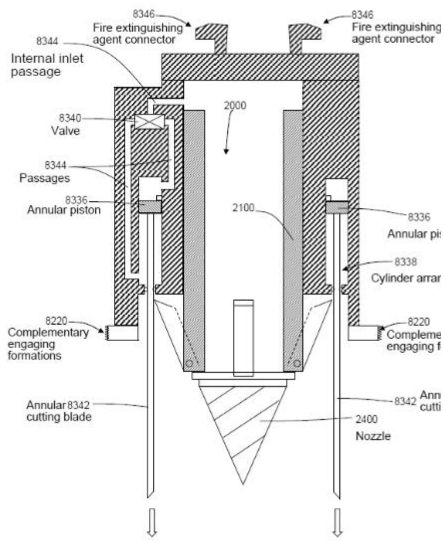
A – Mechanical Lever



B – Hydraulic



C – Hydrant Automatic



A. *Lever Force multiplying Arrangement.*	B. *Hollow Operatable Cutting Arrangement:*	C. *Hydrant Operable Cutting Arrangement:*
As expected, it offers a lever advantage. The above schematic does not fully specify the required design, particularly how the system fastens onto the Deckbox. Achievable in cyclical ways 1. Threaded into the internal of the Deckbox from where the cap is removed. 2. A tab on the lever and recess internal to the Deckbox, alike the Geka or Storz hose fittings.	The concept is to use a commercial-off-the-shelf hollow plunger with a fitting attached for mating to the safe side of the Deckbox. Utilising the central passage of the ram allows the BAT firefighting tool or a firefighting nozzle to enter through the internal passage into the fireside and the plunger to shear cut the burst disc. This system could fasten onto the Deckbox in the same complementary formations as the lever.	This image is a schematic illustration sectioned view of a hydraulic force multiplier mechanism, with threaded/ complementary engaging formations to be attached to the Deckbox. The system could utilise the hydraulic pressure of the firefighting agent to drive a cylindrical blade through the rupturable membrane and push the firefighting accessory or punch through the ruptured membrane so that the nozzle extends into the compartment.

The detailed mechanical advantage solutions A, B and C could provide firefighters with greater capability to penetrate at-risk compartment fires, mitigating the faults from the experiment and reducing safety risks. Particularly in high material strength bodies or dangerous environments such as ammunition compartments, nuclear protective boundaries, highly sensitive pressure hulls, and battery storage boundaries for addressing thermal runaway.

In a naval fleet application, the temperature and pressure behind the burst disc will also be determining factors. The final solution is to continue research for a more accurately assessed burst disc that could provide the added capability to withstand the missiles' kinetic blast, remain intact and protect the naval firefighter from the blast bi-products before breaching.

The basic experimental work aims to commit to Australia a small contribution to the allied shared area of naval recoverability. Further research is required, presenting the opportunity to develop advanced damage control breaching technologies and take a leadership position in maturing the optimal approach. Building a foundation of technological advancement in lifesaving breaching equipment may contribute to greater allied success in an eventual war. Likewise, create a great product and support our allies at a level that matches the Australian renowned academic and manufacturing talents.

9) CONCLUSION

Naval platforms are designed to be reliant in the face of enemy actions. Built to go into war, withstand severe damage, and possess the capacity and skill to recover whilst remaining active in combat. They are resilient to damage and recoverable by sailors' key training and understanding in combat survivability.

Naval platforms must be ready to respond to hostile inboard detonations and remain able to return fire with a lethal hit. However, technological and procedural gaps in at-sea fire recoverability have generated critical issues for those who serve in the military maritime operational environment. A small smouldering fire through to a fully developed compartment fire within a Warship is a highly complex and extremely challenging management task for warfighters and our navy's firefighters.

The recoverability efforts of *USS Stark* (FFG 31) and *USS Samuel B. Roberts* (FFG-58) and their remarkable actions during the Iran and Iraq war presented exceptional crew capability, platform damage tolerance and damage control procedures. However, damage control kits and equipment unaided by ships' power to respond independently to the platform condition in emergencies have seen minimal comparative development from this period, especially in contrast to the advancements in modern missile technologies.

Enemy weapon induced fires present the greatest threat to warships' vulnerability and recoverability. As assessed by DSTG experts Gamble et al. and Woolley et al., managing recoverability and human factors are increasingly more complex in operational environments, where extreme fire phenomenon, crew fatigue and cognitive loading are compounded by the exposure to ongoing weapon threats.

A Naval capability focus on susceptibility and vulnerability and measures towards their advancements has diverted attention away from our people and firefighting training. The result is a lack of innovation for modernised firefighting equipment and recoverability measures to combat advanced weapon-induced fires.

Firefighting within a vessel has seen extreme prospects of exothermic hull cutting, numerous investigations, testing into aircraft penetration technology and widespread adoption of ISO shipping container suppression methods using water-operated drilling. An increasingly challenging situation has seen the available compartment fire penetrating technologies incompatible with the naval firefighting task at hand.

Forward-deployed warships have only the onboard recourses, capabilities, and limited options or assistance to recover from major compartment fires when active in theatre. Although in facing these evolving challenges, it is imperative that further contributions are made to the last operational layer in managing the combat damage from an enemy hypersonic hit. For this reason, the research, technology assessment and experiment recommend further attention to simplifying the action of entering the boundary. With a call for change to remove barriers and support research for enduring change to the training and readiness of our crews in the face of the final fight.

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List Of Abbreviations

CFBT	Compartment Fire Behaviour Training
CO	Commanding Officer
VCNO	Vice Chief of Naval Operations
USS	United States Ship
HMAS	His Majesty's Australian Ship
U.S.	United States
COMUSFF	Commander, U.S. Fleet Forces Command
COMPACFLT	Commander, U.S. Pacific Fleet
C&C	Command and Control
RAN	Royal Australian Navy