Kyle A. Crum, Jerri McMichael, and Miloslav Novak

Advances in Aluminum Relative to Ship Survivability

ABSTRACT

The use of aluminum in ship structure is drawing more attention due to the development and production of new high-speed craft such as Joint High Speed Vessel (JHSV) and the Littoral Combat Ships (LCS) as well as the previous development of various Commercial Fast Ferries and Offshore Service Craft. This focus has driven increased investigation regarding aluminum survivability.

Specifically, the authors address multiple historical events often cited when discussing aluminum's survivability, including the fire that destroyed the superstructure of the *USS Belknap* (CG 26), the Falkland Island War and *USS Stark* (FFG 31). The authors then discuss the physics of aluminum combustion relative to shipboard fire and various methods applied to manage fire aboard aluminum ships. Finally, the authors discuss the current state of the art in aluminum armor offering marine designers light-weight options to increase protection as maritime operators see increasing operations and low intensity threats in the littorals.

INTRODUCTION

Aluminum's Beginnings

Because of the difficulty in extracting it from its ore, aluminum remained rare from its discovery in approx 1812 by Englishman Sir Humphrey Davy until 1888 when the advent of the Hall-Héroult process made industrial scale production feasible. In fact, the material was so precious during this time that, in 1884 when a 2.85 kg (6.28 lb) cap of aluminum was placed on top of the Washington monument, it was the largest known casting yet made. By contrast, it is estimated that world aluminum production in 1918, just 34 years later, was 180,000 metric tons and in 2010 Alcoa, a single producer manufactured 4,500,000 metric tons.

Aluminum in the Marine Industry

Aluminum came into initial use in the marine industry in the 1890's in both the French sloop-rigged yacht *Vendenesse*, 1892, and the American built *Defender*, 1895. *Defender*, FIGURE 1, was used to win the America's Cup before corrosion prohibited any further use. Though these early applications demonstrated the material's potential, alloys and fabricating techniques were not yet developed enough for wide-spread applications and the material fell into disuse.

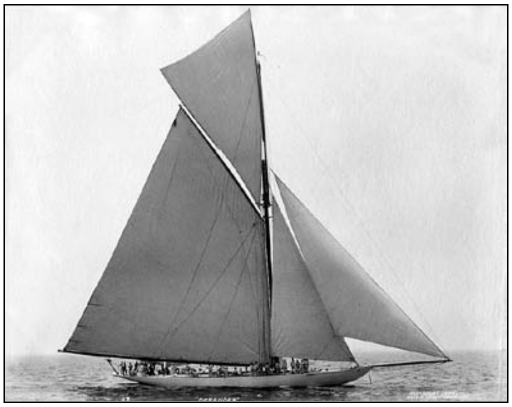

FIGURE 1 –*Defender* photographed on 30 July 1885, six weeks before the 1895 America's cup

New alloy and fabrication technology, in conjunction with the 1922 Washington Disarmament Conference limitation on overall ship displacement encouraged naval architects to reintegrate the material into designs. In 1928 this resulted in *USS Houston* (CA 30) utilizing aluminum deckhouses made from 2017 "Duralumin" with riveted construction. In 1935 aluminum was introduced as a superstructure material for the *USS Sims* (DD 409)-class and, in 1936, was introduced throughout the entire deckhouse of the *USS Gleaves* (DD 423)-class destroyers. Overall, records show over 100 US Navy ships with aluminum superstructure applications in 1940.

In parallel, the light weighting effect of the material was being utilized by commercial industry. In 1939, 14 tons of aluminum successfully replaced 40 tons of steel in the Norwegian commercial vessel *M.V. Fernplant*. This was adequately successful to motivate the conversion of three sister ships to the same configuration. In 1952 *S.S. United States* utilized ~2,000 tons of aluminum to save ~8,000 tons of weight thereby enabling the establishment of transatlantic speed records. By the 1960's it was common for both naval and commercial ships to contain aluminum in both their superstructures and hulls. Additionally, most of the common shipbuilding alloys in use today had been developed including 5052, 5083, 5086, 5454, 5456 and 6061. 6082 was registered with the Aluminum Association in 1972.

Performance and Perception

After aluminum's implementation in naval and commercial fleets, myths surrounding several events introduced perception issues with respect to its effective use in shipbuilding.

USS BELKNAP (CG 26) FIRE

While operating in the Ionian Sea in November 1975 *USS John F. Kennedy* (CV 67) and *USS Belknap* (CG 26) collided. The Navy's official report indicates that:

> *As a result of the collision, USS KENNEDY sustained structural and fire damage which did not affect her operational capabilities. USS BELKNAP sustained major damage to the extent that the ship was taken out of commission in order to effect the repairs necessary to return the ship to an operational status. In addition to the physical damage to both ships, eight naval personnel died and forty-eight were injured as a result of this accident.*

USS Belknap's superstructure was constructed of aluminum. Many have seen post incident photos, FIGURE 2, and mistakenly assumed that the aluminum in the superstructure contributed to the fire. As described by the official Navy report this is not the case. The physical damage of was a result of a combination of effects from the collision and fire. The fire, in this case, was fueled by two charged JP-5 risers on *Kennedy* that were severed in the collision. These two risers supplied approximately 1,045 gallons per minute of JP-5 fuel directly onto the open and damaged superstructure of *Belknap*. The subsequent fire melted the superstructure.

FIGURE 2 – *USS Belknap* (CG 26) heavily damaged by fire, after a collision with *USS John F. Kennedy* (CV 67) during night operations off Sicily on 22 November 1975.

THE FALKLAND ISLANDS WAR

The United Kingdom's conflict with Argentina over the Falkland Islands in the early 1980s produced another set of myths regarding aluminum's survivability. As part of the conflict the UK deployed 44 warships, and 45 auxiliary ships to the region. The UK's lessons learned document issued after the conflict indicated that as a result of supporting an amphibious operation within range of Argentinean strike aircraft without the assistance of airborne early warning aircraft or land-based all-weather fighters, ships losses were inevitably risked.

On May 4th 1982, *HMS Sheffield* (D80) was hit amidships by an Argentinean air launched Exocet missile. The missile hit fuel tanks and serious fires that resulted necessitated the ship to be abandoned 4 hours later. Twenty crew members were lost.

Immediately after the incident some in the media mistakenly reported that the superstructure of *Sheffield* was aluminum and that this contributed to the loss. This was incorrect. Aluminum is utilized extensively in the Type 21 class frigate but, *Sheffield* was a Type 42 class destroyer. The Type 42 class design did not incorporate any substantial amount of aluminum into the design.

In total the Royal Navy lost 6 ships during the conflict, with many others damaged. Ultimately, the UK lessons learned commission concluded:

> *"… Nonetheless, there is no evidence that it [aluminum] has contributed to the loss of any vessel."*

USS STARK (FFG 31) MISSILE STRIKE

While operating in the central Persian Gulf on May 17, 1987, *USS Stark* (FFG 31) was struck by two Exocet anti-ship cruise missiles fired by an Iraqi F-1 Mirage fighter, see FIGURE 3. *Stark*, like all in her class, utilize aluminum in the superstructure design to lighten the ship and provide better performance.

FIGURE 3 – *USS Stark* (FFG 31) listing after receiving damage from two Exocet anti-ship cruise missiles fired by an Iraqi F-1 Mirage fighter on 17 May 1987.

The Navy's official report indicates that the immediate fire damage from the missile strike was caused by the rapid burning of the unexpended fuel from the two missiles. The report details that each missile injected approximately 300 pounds of unexpended propellant, calculating that 600 pounds of propellant resulted in a near instantaneous heat release of approximately 12 million BTUs. Furthermore, because the first missile's warhead failed to detonate, it turned out to be more damaging because it injected its thermal energy (burning propellant) further into the ship's structure. The second missile did detonate, allowing some of its thermal energy to escape back out through the exterior of the ship.

Subsequent to the missile event the crew, through extreme effort and expertise, was able to save the ship. It is noted that the aluminum structure performed well enough to support this effort. In fact, the official Navy report on the incident does not discuss aluminum as a factor at all.

MYTHS PERTAINING TO ALUMINUM COMBUSTION

Compounding the misconception of aluminum's survivability in the shipboard incidents described is a misconception that aluminum can combust in atmospheric conditions.

Aluminum is found as an ore and has to be refined into the engineering material we use today. This process is not permanent; the material wants to achieve the lower energy state as it is found in nature, with an ionic bond between the metal and oxygen. The process that is undertaken to reach the desired lower energy state is chemically identical for both corrosion (rusting) and combustion; the important factors are speed and the relevant environment.

Aluminum does not burn under atmospheric conditions, nor does it support or encourage combustion or flame spread. This is seen practically throughout industry. The welding process is commonly used in fabrication of aluminum components. This process utilizes an electric beam to melt filler wire and the base materials into a continuous joint. The process utilizes an inert shielding gas to protect the quality of the joint, not to preclude combustion. If the inert covering gas fails, the weld often will contain flaws as a result of the atmosphere's interaction with the electron-beam, but this does not constitute combustion. In another practical manufacturing example, the casting practice heats material until it becomes liquid. Then the material is poured into a mold and allowed to cool, producing a desired shape. This process is often performed under no purging gas and in an open environment. Oxides resulting from materials interacting with the atmosphere are common, but combustion is not, see FIGURE 4.

The only real difference between aluminum and steel is that aluminum loses its strength at a much lower temperature, meaning that an aluminum vehicle that has burnt will generally melt giving the appearance of burning. This is evidenced by FIGURE 2. Though this is the appearance, significant research, such as the Aluminum Association's Testing at Southwest Research, has shown aluminum does not participate in the combustion process under atmospheric conditions.

FIGURE 4 – Worker skimming molten aluminum during the manufacturing process.

Ultimately, it takes a pressure of 25 psi with an environment of complete oxygen for solid aluminum to sustain combustion. These conditions are highly unlikely to exist (or persist for long) during a shipboard fire. For reference atmospheric pressure is 14.7 psi and oxygen is typically only 21% of the atmosphere.

A contrasting fact to this discussion is that aluminum powder is a common component of rocket fuel. NASA indicates that solid booster propellant consists of an ammonium perchlorate (oxidizer, 69.6 percent by weight), aluminum (fuel, 16 percent), iron oxide (a catalyst, 0.4 percent), a polymer (a binder that holds the mixture together, 12.04 percent), and an epoxy curing agent (1.96 percent). Again, aluminum requires an environment consisting of highly effective oxides, catalysts, pressure and heat before it can be made to combust. These conditions do not occur, or cannot be made to persist, in shipboard fire.

FIRE MANAGEMENT

Brief History of Fire Protection at Sea

The key body overseeing the safety of commercial shipping is the International Maritime Organization or IMO, but many other bodies issue standards. These standards include US military specifications, Royal Navy Defense Standards, British Standards, Naval Engineering Standards among others.

According to IMO, its safety rules (Safety of Life at Sea or "SOLAS") were first developed as a reaction to the sinking of *RMS Titanic* in 1912. The convention in 1914 generated the first consensus regarding requirements, but these were unable to come into force because of World War I. Consequently, these agreements were carried over to a conference in 1929, where the first rules were implemented.

Subsequent to the implementation of these initial rules, experience taught lessons in practicality. In 1934 *SS Morro Castle* caught fire while transiting from Havana, Cuba back to New York, New York causing the loss of 134 passengers and crew. Investigations of this incident played a major part in the development of the non-combustible construction regulations which today form the basis of the IMO fire safety regulations for passenger ships. These lessons, and the vast experience gained as part of World War II produced improved rules, limiting combustibles and generating new rule parts pertaining exclusively to fire safety.

The IMO rules and regulations continued to develop as additional experience was gained. Eventually, SOLAS Chapter II was split and Chapter II-2 was dedicated completely to construction pertaining to fire protection, fire detection and fire extinction. These rules continue to evolve.

IMO, standards typically describe fire divisions as "A", "B" or "C", but because naval ships must be designed for shock and other considerations, the US Navy developed and adopted a new designation of "N". Sorathia indicates “that N-Class divisions are designed to protect against structural failure and prevent the passage of fire and smoke when exposed to a rapid rise hydrocarbon pool fire exposure for the designated test period in accordance with NAVSEA 05P4 Test Method 02-2006 after shock testing in accordance with MIL-S-901.” In other words, the structure must be able to prevent the passage of fire and smoke when exposed to a hydrocarbon fire after shock testing. This rating system would suitability simulate a naval vessel in such as *Belknap Sheffield* and *Stark* suffering shock then fire.

Because aluminum looses strength when heated, class “N” barriers protecting aluminum structure are required to preclude the material’s core from rising more than 200°C above its initial temperature during the classification period, a minimum of 30 minutes.

The designations also have a time period associated with the temperature rise of the free material side, making designations such as N-30 and N-0. N-30 barriers protecting aluminum structure would preclude the core of the material from rising above 200°C and the unexposed skin from rising 140°C for 30 minutes. The N-0 designation would maintain the core temperature requirement for 30 minutes, but has no free surface temperature requirement, hence the zero.

Fire Protection in Practice

Insulation typically takes three common forms: spray-on, blanket and panel.

Spray-on passive fire protection systems are used extensively in civil engineering and offshore applications. These coatings can be applied very cost-effectively and have the ability to easily vary thickness according to anticipated heat exposure, FIGURE 5. This insulation can be applied over complicated geometry with a minimum of labor, but does not typically appear in naval application because it does not adhere sufficiently to survive shock events.

FIGURE 5 – Worker spray-coating aluminum structure with fire insulation.

Another form of passive fire protection are high-temperature insulation blankets made of mineral wool or silica aerogel and reinforced with a non-woven, glass-fiber batting. Silica aerogel have very low thermal conductivity and could be made in a flexible, environmentally safe, and easy-to-use.

Blanket type fire protection materials offer the shipbuilder flexibility in covering complicated stiffener geometry locating fasteners intermittently where convenient. Seen in FIGURE 6, these materials can be manufactured with reflective surface finishes allowing lower radiant heat gain from an adjacent fire.

The final product form found in industry is stiff panel insulation, but because of the complex geometry associated with ship structures and the difficulty in forming the material to the necessary shapes it is challenging to utilize.

Advanced technology offers to further simplify and lighten fire protection systems. Hiltz describes organic and inorganic intumescent materials that expand (swell) when heated and form a porous (foamed) material that acts to insulate the substrate below them. Additionally, some of the newer fire resistant non-combustible and non-toxic building materials release water vapor when exposed to the heat of fire. This water cools the fire and curtails its development and spread.

FIGURE 6 – CDR Curt Renshaw, commanding officer of *USS Independence* (LCS 2), addresses guests in ship's mission bay, 8 April 2010. Note the blanket type fire insulation protecting the aluminum structure.

Ultimately, the question facing the naval architect when considering aluminum ship construction is whether the cost and weight of the additional fire protection is worth the light-weighting effects of the material. Lamb addressed this question directly. He describes the additional weight associated with incorporating fire insulation into an aluminum ship, comparing with an 'equivalent' steel ship.

It was found that an aluminum ship requires approximately 40% more insulation weight, but the overall seaframe weight is still reduced by approximately 22%. This weight directly translates to lower propulsion power requirements, increased range and/or improved speed. Additionally, it is shown that though upfront acquisition costs are 7% higher, total ownership costs are less than the equivalent steel ship based on fuel savings, paint requirements, etc.

ALUMINUM ARMOR

Early Aluminum Armors

Material scientists looking for lighter options for armor soon found that aluminum could provide a solution for some threats at lower areal densities than steel. The community quickly identified 5083-H131 (MIL-DTL-46027) as a solution. 5083-H131 is a non heat-treatable, strain hardened aluminum magnesium alloy. The material is readily wieldable and was found to exhibit excellent resistance to fragmentation threats. These positive characteristics drove 5083 incorporation into the US Army's M113 Armored Personnel Carrier and the M109 Paladin Self Propelled Howitzer.

In the 1960's, industry was working to develop aluminum armor alloys with higher strength and protection levels against ball and Armor Piercing (AP) threats. 7039-T64 (MIL-DTL-46063) was developed to fit these requirements. It is an aluminum magnesium zinc alloy that is heat treatable to a hardness higher than 5083-H131. It does exhibit higher protection levels against ball and AP threats, but also exhibits some loss in performance against fragmentation threats. Unfortunately, it also proved to be susceptible to stress corrosion cracking, and therefore fell out of common use. The upper half of the Bradley Fighting Vehicle is made from 7039-T64.

In the late 1970's, industry worked to develop an armor alloy that overcame the disadvantages of 7039-T64. The result was 2519-T87 (MIL-DTL-46192), an aluminum copper manganese alloy that achieved strengths between that of 5083-H131 and 7039-T64. This alloy exhibits better performance than 5083-H131 against fragmentation threats, and matched the ball and AP resistance of 7039-T64. It therefore came into common use.

The 2519-T87 presented good resistance to stress corrosion cracking, but unfortunately, poor resistance to general corrosion. This alloy also exhibited a dramatic drop in ballistic performance in the regions of welds, due to lower properties in the heat affected zones. This alloy was proposed for use in the Marine Corps Expeditionary Fighting Vehicle.

Mainly due to the corrosion issues with 7039-T64 and 2519-T87, 5083-H131 became the most widely used aluminum armor alloy in the late 1990's and early 2000's with little additional development of aluminum armor alloys occurring.

Advanced Aluminum Armors

The conflicts in Iraq and Afghanistan created a demand for light weight armor systems with improved ballistic and blast performance. This need became acute as forces began to encounter increasing numbers of Improvised Explosive Devises (IEDs), mines, and other blast threats. Producers were being asked to improve armor performance while maintaining or improving other vehicle capabilities. This drove a significant need for light-weight armor development. Several new aluminum materials have become available to support this need.

This discussion is particularly important for naval architects as lower intensity conflict (pirate operations, terrorist activity, etc.) and war-fighting trends are emphasizing access to the littorals, hence the Littoral Combat Ship (LCS) designs currently being procured by the US Navy. These shifts and issues are making ships more susceptible to ballistic and blast threats normally associated with land combatants. It stands to reason that solutions initially developed for the urgent need in Iraq and Afghanistan could be leveraged by the marine community.

CR56-H131

CR56-H131 is a variant of 5456-H131 that has been developed to meet the ballistic requirements of 5456-H131 (MIL-DTL-46027), while maintaining consistently higher properties. TABLE 1 shows a comparison of minimum design properties of 5083-H131, 5456-H131, and CR56-H131.

TABLE 1 – CR56-H131 Design Minimum Properties (*inclusive of that size)

Alloy	Gauge (inch)	TYS (ksi)	UTS (ksi)	% Elong
5083-H131	0.5-2.0* 2.0-3.0	37 35	45 44	8 9
5456-H131	0.5-2.0* 2.0-3.0	37 35	45 44	8 9
CR56-H131	0.5-2.0* 2.0-3.0	45 45	51 51	7 8

The higher strength of CR56-H131 makes it an excellent alloy for both structural applications and ballistic protection. The ballistic performance of CR56-H131 is roughly equivalent to 5083-H131 against Fragment Simulating Projectiles (FSP), but the higher strength results in increased ballistic protection against AP threats. CR56-H131 consistently meets or exceeds the minimum ballistic requirements set forth in MIL DTL 46027.

CR56-H131 is produced in both plate and forged products. Because the material is strain hardenable, specific processes have been developed to guide forging operations to ensure the correct amounts of work have been incorporated into final products thus ensuring uniform properties and protection. This process has been successfully employed to forge three-dimensional parts including doors, V-hulls, hatches and various fittings.

C79A-T651

As part of the effort to react to the needs of Iraq and Afghanistan, 6061-T6 was evaluated and certified for use in armor applications to increase armor supply options. MIL-DTL-32262 was developed to specify and control the use of 6061-T6 armor plate, and is based on matching the ballistic performance of 5083-H131 armor.

In much the same manner as CR56-H131 was developed as a variant of 5456-H131 with improved properties, C79A-T651 was developed to achieve higher strength design minimums than 6061-T6. TABLE 2 provides a comparison of C79A-T651 properties to those of 6061-T6.

TABLE 2 – C79A-T651 and 6061-T6 Property Comparison (*inclusive of that size)

Alloy	Gauge (inch)	TYS (ksi)	UTS (ksi)	% Elong
6061-T6	0.5-2.0* 2.0-3.0	37 38	38 35	10 10
C79A-T651	> 0.5	56	57	11

As the higher strength of CR56-H131 makes it an excellent choice for armor applications that also require structural performance, the same is true for C79A-T651. Again, the improved strength of C79A-T651 results in improved ballistic performance over 6061-T6.

C79A-T651 is available in both plate and extruded forms. Unlike CR56-H131, C79A-T651 is a heat-treatable alloy and therefore does not retain properties during welding and cannot be used in welded form for armor applications. This is also the case with 6061-T6.

7085

The 7085 aluminum chemistry is a commercially available aerospace alloy developed to attain high strength, fracture toughness, and good corrosion resistance. Two tempers were developed to optimize either ballistic or blast performance. 7085-T7E01 was developed for the plate product, to achieve higher strength and superior protection against AP rounds. 7085-T7E02 was developed to achieve a ductile response in blast and ballistic protection equivalent to 7039-T64. 7085 armor products (MIL-DTL-32375) are referred to as “ArmX$^{\text{TM}}$ AP Armor” and “ArmX$^{\text{TM}}$ Blast Armor” respectively. TABLE 3 compares the properties of 7039 and 7085. 7085 is available in plate and forged product forms.

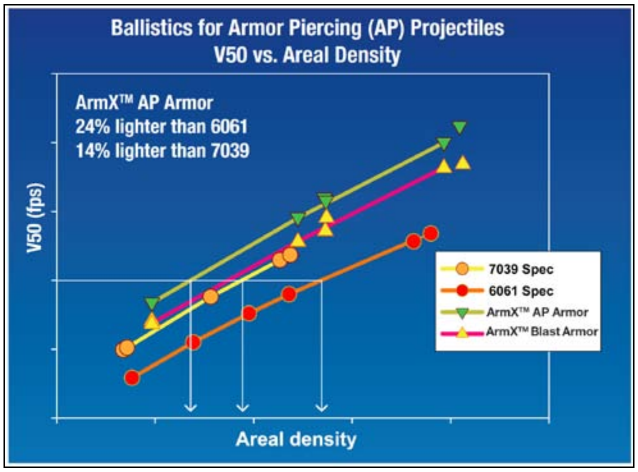

FIGURE 7 – Relative Ballistic Performance of 7085-T7E01 (ArmX$^{\text{TM}}$), 7085-T7E02 (ArmX$^{\text{TM}}$), 7039 and 6061 against the Armor Piercing Rounds

FIGURE 7 relatively compares the ballistic performance of 7085-T7E01 and 7085T7E02 (ArmX$^{\text{TM}}$ AP Armor and Blast Armor) to 7039. 7085-T7E01 clearly exhibits a significant increase in ballistic protection against the threats tested. Test data has shown 7085-T7E01 up to 14% better than 7039-T64 and 24% better than 6061-T6 against AP threats. Additionally, the material has been shown to perform 5% better than 6061-T6 and 5083-H131 against FSP threats.

TABLE 3 – 7039 and 7085 Property Comparison (* inclusive of the number)

Alloy	Gauge (inch)	TYS (ksi)	UTS (ksi)	% Elong
7039-T64	≤1.5	51	60	9
	>1.5	48	57	8
7085-T7E01 (ArmX$^{\text{TM}}$ AP Armor)	0.5-1.5*	74	80	11
	1.5-2.0*	73	78	11
	2.0-3.0*	72	77	10
7085-T7E02 (ArmX$^{\text{TM}}$ Blast Armor)	0.5-1.5*	60	68	12
	1.5-2.0*	59	67	12
	2.0-3.0*	58	67	11

It has also been shown that both tempers of the new 7085 armor perform approximately equal to 7039 against FSP threats.

7085 exhibits none of the corrosions issues limiting the implementation of 7039, but offers superior ballistic performance against Armor Piercing (AP) projectiles. 7085 is available in both plate and forgings. Therefore, it can be used as appliqué armor or integrally armored thick section parts such as doors and hatches.

In blast, the high strength of 7085-T7E02 results in low dynamic deflections, combined with high resistance to rupture. This makes 7085-T7E02 a growing choice for blast shield structures, often known as “C-Kits”. The relative performance of 7085-T7E02 against 5083-H131 and 7075-T76 is shown in FIGURE 8.

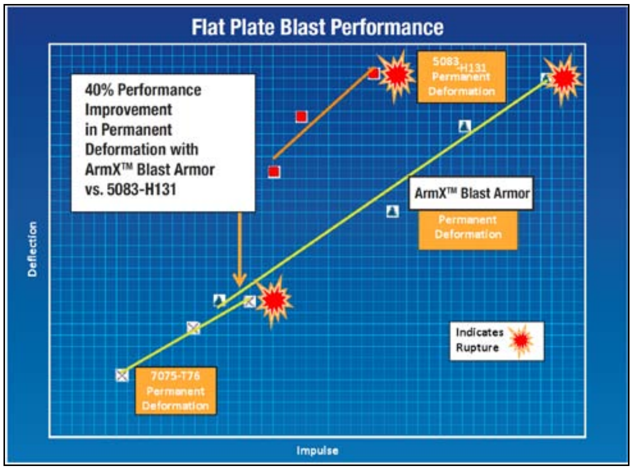

FIGURE 8 – Relative Blast Performance of 5083-H131, 7075-T76 and 7085-T7E02 (ArmX^{TM})

CONCLUSION

Aluminum came into common use in the marine industry by the late 1960’s but as a result of some real and some perceived performance concerns, innovation and implementation stagnated among some communities. Ultimately, through a better understanding of the material and subsequent design improvement, aluminum is a viable weight saving material for critical structures where survivability is a key attribute.

REFERENCES

Altenpohl, D.G., “Aluminum: Technology, Applications, and Environment,” Sixth Edition, The Aluminum Association, 1999

Aluminum Company of America (Alcoa), “Aluminum Afloat,” 1964

Amos, C.W., “Lightweight Armor Design Handbook – Monolithic Armor ”, MTL Technical Report MTL TR 90-40, Watertown, MA, August 1990

Aspen Aerogels, Inc., Northborough, MA 01532; 2006 Aspen Aerogels, Inc. REV 1.0

Binczewski, GJ, “The Point of a Monument: A History of the Aluminum Cap of the Washington Monument,” Journal JOM, 47 (11) (1995), pp 20-25

Greene, E., “Labor-Saving Passive Fire Protection Systems for Aluminum and Composite Construction”, Ship Structure Committee Report SSC-442, dated May 2005

Griffin, T.J., “Ballistic Evaluation of Aluminum Armor”, Aberdeen Proving Ground Report 0807903, August 1959

International Barrier Technology, Inc., Pyrotite - http://www.intlbarrier.com/products/pyrotite_technology.htm last accessed November 10, 2011

Kelly, J.V., Placzankis, B., “Outdoor Exposure Results for Pretreated and Top Coated Aluminum Armor Alloys 2519, 5083, 7039”, ARL Report ARL-RP-271, September 2004

Lamb, T and N Beavers, “The All Aluminum Naval Ship - The Way to Affordable Naval Ships” INEC 2010

Montgomery, J.S., Chin, E.S., “Protecting the Future Forces: A New Generation of Metallic Armors Leads the Way”, The AAMPTIAC Quarterly, Volume 8, Number 4, 2004

Hiltz, J.A., “New Technologies and Materials for Enhanced Damage and Fire Tolerance of Naval Vessels,” Defense R&D Canada – Atlantic, Technical Memornadum, DRDC Atlantic TM 2010-306, February 2011

NASA, “NSTS 1988 News Reference Manual“ http://science.ksc.nasa.gov/shuttle/technology/sts-newsref/srb.html last accessed November 9, 2011

Placzankis, B., Miller C., Beatty, J.H., “Accelerated Corrosion Analysis of 2519 with Nonchromate Conversion Coatings for DOD Applications”, ARL Report ARL-TR-2401, February 2001

Showalter, D.D., Placzankis, B., Burkins, M.S., “Ballistic Performance Testing of Aluminum Alloy 5059-H131 and 5059-H139 for Armor

Applications", ARL Report ARL-TR-4427, May 2008

Sielski, R.A., "Aluminum Structure Design and Fabrication Guide," Ship Structures Committee Report SSC-452 May 11, 2007

Sorathia, U., "Fire Resistant Divisions in U.S. Naval Ships", Naval Surface Warfare Center, Carderock Division

SwRI Project No. 01.16052.01.620 "Fire Performance Evaluation Tested in Accordance with ASTM E 136.11, Standard Test Method for Behavior of Materials in a Vertical Tube Furnace at 750 degC " – April 14, 2011

US Navy Report, Ser 00/500878 "Investigation to inquire into the circumstances surrounding the collision between USS JOHN F. KENNEDY (CV 67) and USS BELKNAP (CG 26) which occurred on 22 November 1975" dated 7 September 1976 (redacted)

US Navy Report, Ser 00/7S300244 "Formal Investigation into the Circumstances Surrounding the Attack on the USS STARK (FFG 31) on 17 May 1987" dated 23 July 1987 (redacted)

United Kingdom's Secretary of State for Defense Report to Parliament, "The Falklands Campaign: The Lessons" December 1982

AUTHORS' BIOGRAPHIES

Mr. Kyle A. Crum*, the principle author, is a Project Manager with the Alcoa Technical Center where he leads marine R&D. He earned his B.S. from Grove City College in 2004 and his M.S. from the University of Pittsburgh in 2008 both in mechanical engineering. Kyle also serves as a commissioned reserve officer in the United States Navy.*

Ms. Jerri McMichael *is an employee of the Alcoa Technical Center. She obtained her Bachelor's and Master's of Science at Clarkson University, in Potsdam, NY. During her 28 year career at Alcoa she has acted as Defense Technical Leader for numerous land, sea, and air contracts related to military vehicles, including armor development and blast survivability.*

Mr. Miloslav Novak *earned his B.S. and M.S. in Civil Engineering from Czech Technical University in Prague and later also from University of Utah. During his 25 years at the Alcoa Technical Center he worked on various automotive, aerospace, and defense projects as Design Specialist, Consultant, Chief Engineer, and currently acts as Design and Engineering Lead on several projects sponsored by the United States Navy.*

The opinions and views expressed in this paper are those of the authors alone and are presented in their personal capacities. They do not necessarily represent the views of U.S. Department of Defense, the US Navy, or any other agency.