Naval Railguns

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Abstract—Compared with propellant guns, railguns can fire at higher velocities and do not require gun propellant but use ships' fuel. These features lead to important advantages, including shorter time of flight (important for ship defense), higher lethality on target (important for direct fire), and very extensive range capability (important for support of troops on shore). Such extended range capability also supports the sea-basing concept in which a forward-deployed battle group is able to operate far enough off shore to be safe while providing a long reach for distant targets.

In this paper, the characteristics of the railgun systems needed for these applications are identified and discussed, leading to a definition of the most important science and technology objectives for near-term research programs.

I. INTRODUCTION

Guided missiles have adopted many roles in modern navies, but there is continued interest by ship operators in maintaining gun capability. Gun applications fall into three categories—ship defense, direct fire, and long-range indirect fire to support troops ashore. In these roles, guns are generally complementary to missiles. The advantage of guns is that the rounds fired are smaller and less expensive than missiles, so hundreds to thousands of rounds can be carried, compared with tens of the more expensive and larger missiles.

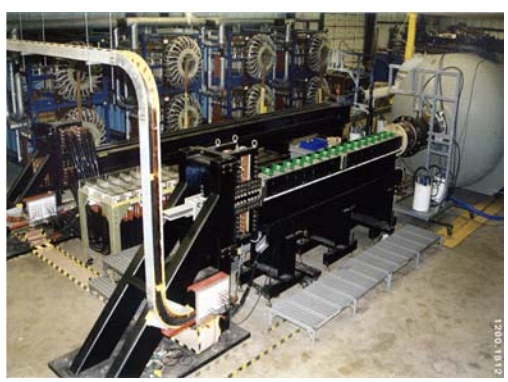

Fig. 1. IAT EM railguns and power supplies.

After two decades of increasingly promising R&D, much of which was undertaken by the Institute for Advanced Technology (IAT) at The University of Texas at Austin (UT), the US Navy has embarked on a program to develop electromagnetic (EM) railguns for naval use. Present Navy Mk 45 conventional powder guns launch 5-inch diameter projectiles at velocities of ~0.85 km/s and muzzle energies ~11 MJ. In contrast, small projectiles are routinely launched from subscale (40–60 mm bore) EM railguns at velocities up to 2.5 km/s and 2 MJ muzzle energy at IAT (Fig. 1).

Larger integrated launch packages (ILPs) have been launched many times from the UK electric gun facility at > 2 km/s and ~ 7 MJ [1].

The IAT has assisted the Navy to consider EM railguns through support for the Strategic Studies Group [2], by holding a Workshop on Electromagnetic Launchers at the IAT in November 2001 [3], and by assessing the technology status and requirements for the Office of Naval Research (ONR) [4].

Since 2003, the IAT has supported the Naval Surface Warfare Center, Dahlgren Division (NSWCDD) through an indefinite delivery, indefinite quantity (IDIQ) contract under which four delivery orders have been placed. The largest of these delivery orders included a substantial subcontract to IAP, Inc., of Dayton, Ohio, for the design of a 32 MJ laboratory launcher for NSWCDD and the fabrication of a 1 m test section. This test launcher will be the largest EM railgun yet built, providing accommodation for a 10 m long EM launcher barrel with a bore diameter up to 155 mm (round or square). The facilities for housing this launcher are in development at NSWCDD.

II. Future Naval Relevance

The railgun offers several advantages for naval use. The ultimate Navy railgun technology goal is to develop a long-range Sea Strike railgun capable of reaching over 300 km with a muzzle energy of 64 MJ at a launch velocity of 2.5 km/s. This railgun could be used for long-range shore bombardment with a greater range and capability than the present Mk 45 gun or the Advanced Gun System now in development, even with advanced rocket-assisted launch of the gun projectiles. The railgun would provide enhanced support for forces ashore (see Fig. 2) and improve naval interdiction capability to ranges in excess of 200 nautical miles with low latency [5].

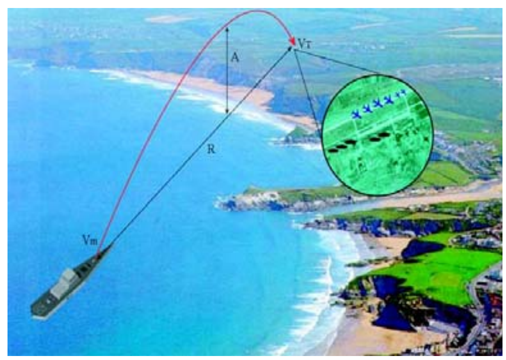

Fig. 2. Long-range shore bombardment concept.

An intermediate goal may also be to establish the capability for a multi-shot, direct-fire system with notional muzzle energy of 32 MJ at 2.5 km/s for ship defense (see Fig. 3). The short time of flight and high lethality on target with such a railgun would greatly enhance ship survivability against present and projected future high-speed maneuvering missile and surface threats [6]. This 32 MJ direct-fire system would lead to the 64 MJ indirect-fire system.

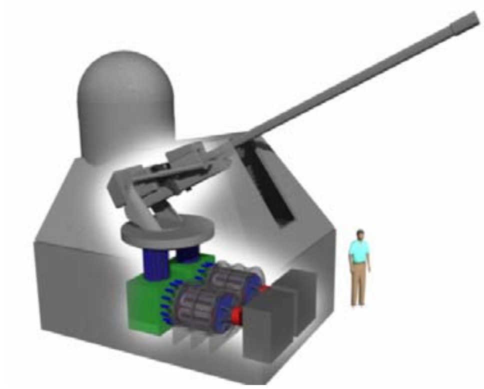

Fig. 3. Railgun ship-defense concept.

For long-range shore bombardment applications, the absence of a gun propellant magazine in the gun installation would enhance ship and personnel safety and survivability in the event of battle damage. The use of inert hypervelocity rounds reduces the need for propellant production, storage, loading, transport, and re-arming in favor of additional ships' fuel, thereby reducing cost and crew size. Gun-launched rounds would also be smaller and less expensive than missiles, thereby permitting deeper magazines—so tens of missiles can be replaced by thousands of gun rounds. The EM gun would be able to fire a mix of rounds at velocities that can be selected by varying the electrical power provided to the breech of the gun—hypervelocity kinetic energy rounds, flechette rounds and high-explosive rounds could all be used, both for ship defense and for long-range applications.

The electric gun is also synergistic with a ship electric propulsion system, as well as future shipboard radars, electric protection systems and sensors, superconducting homopolar motors, and electrically driven laser weapons. Large modern warships require substantial power to enable high speeds to be achieved. However, full power is only needed at top speed*; at lower speeds, much of the installed power could be made available for electric weapons that have a high power demand and high firing rate.

III. Electric Gun Requirements

The potential benefits of electric guns come with the complication that the gun firing rate is linked to the main power supply on the ship. This means that the relationship between ship performance and gun firing rate has to be evaluated more carefully than in a conventional gun system, where the gun operation and ship performance are intrinsically independent—although often closely linked in practice. In the discussion below, it is assumed that the use of electric power for ship propulsion will *always* have priority over gun operation. This is probably the worst-case situation for the electric gun, since there *may* be instances where the gun could take priority over propulsion. One objective for this study is to start to identify a path toward a "smart" system, which would allow the ship's captain to optimize the choices available in order to maximize the tactical situation.

There are at least three options for the interaction between the onboard electric power and the electric gun:

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* On average, full power is used only for about 2% of the ship operating time.

a) The electric gun can only use excess power that is available after other needs, such as propulsion, radars, etc., have been met.

b) The electric gun subsystem can include sufficient stored energy to fire every round that is loaded in the magazine.

c) The electric gun system can include an intermediate buffer energy storage system that stores sufficient energy for a limited number of shots.

Each of these options has advantages and disadvantages.

In some ways, option (a) is the simplest approach for the ship's driver, because propulsion will always have priority. Conversely, it is the worst for the gunnery officer, because only electric power left over from other demands would be available for firing. Because the ship's captain has to integrate all requirements, decisions would be complicated.

Option (b) would be ideal if it could be achieved. However, the amount of energy needed would be immense. For example, a 64 MJ muzzle energy system operating at an efficiency of 40% would need 160 MJ energy input per shot. Thus, for a magazine holding 2000 rounds, the energy storage system would require 320 GJ. No presently available options would provide this amount of energy storage for a ship.

Option (c) provides an intermediate possibility that has some important advantages but also requires a more careful evaluation of operating scenarios. The clear advantages are that much less energy must be stored than for option (b), while the railgun's complete dependency on energy remaining after all other demands have been met is greatly alleviated. The most important issue that has to be resolved is the number of shots' worth of energy that has to be stored. Clearly, that number is between one and the full magazine—but it still leaves a large parameter of space to optimize. The main factors that will determine the amount of energy are the need for salvo fire operation—that is, the need to launch many shots in rapid succession in a burst—the size of that salvo, and the cost and size of the energy store.

The first of these factors will be determined by the type of gun under consideration—e.g., long-range shore bombardment or ship defense (or other application)—and by the future operational needs of this technology. This is not necessarily easily determined, and it will always be prudent to err on the side of a more capable system, within reasonable bounds.

The second factor depends strongly on the energy storage and pulsed power technology to be used, some of which is still in the early stages of development. One important feature of this technology that needs to be evaluated is the use of a modular approach that can provide redundancy against battle damage as well as modularity for upgrades and replacement.

IV. PULSED POWER

Despite the large electrical power capacity on a modern electrically driven warship, the instantaneous power levels needed for a railgun during the few milliseconds of launch greatly exceed the ship's onboard power capability. A dedicated pulsed power system is therefore needed to take available power from the ship, store that energy over a long period, and deliver it in the short (milliseconds) period of the launch. The ship propulsion system would provide tens of *mega*watts, but the railgun would need power to be delivered during launch at a level of tens of *giga*watts. However, the *energy* needed for a launch can easily be provided by the onboard power. For example, transferring 25 MW from the ship's power system for 10 s into an energy storage system would provide 250 MJ (less losses), which is more than enough for any naval railgun envisioned at present.

The dedicated pulsed power system would need to provide a high average current throughout the launch, have sufficient voltage to drive the current into the railgun, and supply the breech energy and instantaneous power needed for the launch. For some missions, energy storage for several shots may be also needed. Other important aspects—such as power conversion, motoring, thermal management, energy recovery, torque reaction, and controls—need consideration.

For a Navy launcher with a muzzle energy of 64 MJ and a barrel efficiency of 60%, the railgun breech energy needed is 64/0.6 = 107 MJ per shot. If multi-shot rapid fire with (for example) a burst of three rounds is required, the total breech energy required would be $3 \times 107 \cong 320$ MJ. At present, only three options exist that could provide this level of energy:

a) capacitors, where the energy is stored electrostatically;

b) pulsed alternators, where the energy is stored inertially and released electrically; and

c) battery-inductive systems where the energy is stored chemically and inductively.

Most, but not all, existing and prior laboratory EM launcher facilities (e.g., Green Farm, Thunderbolt, and Kirkcudbright) have used capacitors. Fig. 4 illustrates a 32 MJ system using 1990s technology with a capacitor energy density of ~ 0.6 MJ/m^3. A 320 MJ system would be ten times larger than this, although some volume reduction could be expected because of improvements in capacitor energy density that are expected with improved modern dielectric materials.

Fig. 4. Thunderbolt 32 MJ facility.

A 320 MJ system would store only three shots' worth of energy for the stated railgun, and thermal management of a high-voltage system of this type under long-term, multi-shot operating conditions has yet to be demonstrated. For these reasons, a large capacitor facility seems inappropriate for shipboard use, although the development of improved capacitors could modify this conclusion.

The preferred solution may be the use of pulsed alternators based on technology under development for the US Army (see Fig. 5). Pulsed alternators store energy inertially after being spun up to speed with an electric drive motor and, when appropriately switched, discharge some of the stored energy in a suitable train of high-current pulses. Since the alternators produce alternating current (ac), an associated converter system is required to rectify the alternator output and transform it into the direct current (dc) required for the railgun. Depending on the size and speed of the rotor, sufficient energy can be stored for multiple shots. Of course, more energy storage means that the machine would become larger, but the size of such machines is much less than capacitor banks. Because there is a substantive torque reaction on the alternator stator when taking a gigawatt-size pulse out of the rotor, pulsed alternators of this type are generally used in matched pairs, as shown in Fig. 5. The number of pairs of machines would depend on issues such as sizing and fit of the alternators within the ship structure, as well as power distribution to the railguns and battle redundancy considerations.

Several early electric gun systems used homopolar generators before pulsed alternator development took place; one example is shown in Fig. 6. The homopolar generator is a simpler and more rugged machine than a pulsed alternator but cannot produce sufficient voltage to drive a railgun directly. It therefore has to be operated with a pulse-sharpening inductor and an opening switch to divert current into the railgun.

A notable consideration for all types of pulsed alternators is that they require extensive auxiliary subsystems to support the bearings, vacuum seals, brushes, interior evacuation, and inert gas filling of the machine—as well as the diagnostic, control, and

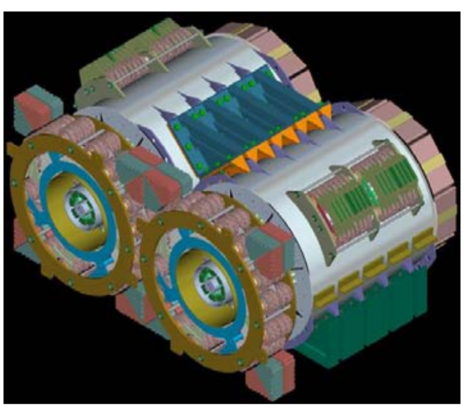

Fig. 5. Pulsed alternators.

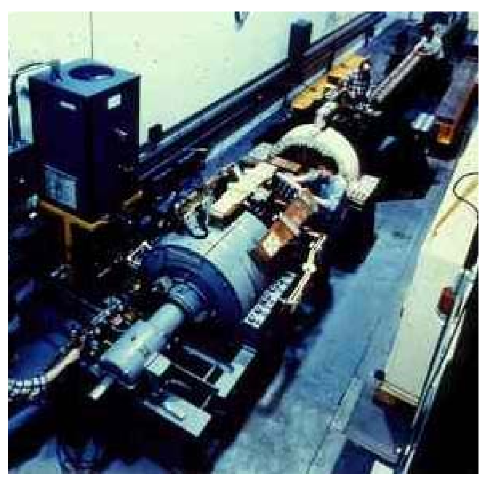

Fig. 6. Sixteen MJ EMACK homopolar system.

safety subsystems. The total system is therefore considerably larger than just the alternator itself, and machine operation is not straightforward, as integrated operation of all the auxiliary systems must be coordinated.

Alternatives that have been considered are storing energy magnetically in inductors and/or chemically in batteries. Inductive energy storage suffers from resistive losses that quickly dissipate the stored energy in a characteristic time τ, given by $\tau = L/R$, where L is the inductance of the inductor and R is its resistance. For room-temperature inductors, τ is typically 0.1 s or less for a system that stores sufficient energy to be of interest for these applications. This implies that the inductor would have to be charged up to its full energy-storage capability within less than 0.1 s of gun firing. This is likely to be a significant operational constraint, so reducing the inductor resistance by cryogenic cooling to liquid nitrogen, hydrogen, or even liquid helium temperatures may therefore be advantageous. If the inductor temperature is low enough that the conductor material becomes superconducting, the superconducting magnetic energy storage (SMES) approach may be used. SMES systems have been developed primarily for utility applications, where they can store sufficient energy to provide a short-term buffer in the event of a transient interruption of power supply in situations where assured power is needed, such as hospitals or critical manufacturing processes. The military also has critical situations where such systems could be used, e.g., flight operations or fire-control radars. Large, liquid-helium-cooled superconducting systems are unlikely to be practical for combat systems, but high-temperature superconducting systems operating at liquid nitrogen temperatures using cryocoolers may be feasible in the future. ONR has programs to develop multi-megawatt superconducting homopolar ship propulsion motors, so there may be substantial onboard cryogenic capability that could be integrated into such a railgun system.

The battery-powered inductor concept is becoming more attractive as improvements in battery technology take place, especially in lithium-ion (Li-ion) batteries in recent years. Batteries are very effective at storing *energy* and are widely used in the Navy. However, they are not capable of delivering *power* at the rate required for a large railgun. One arrangement would utilize batteries to charge up an inductive energy store (one or more large coils) that can then be discharged into the railgun at the required power levels. This pulse compression arrangement ensures that even though the power delivered into the railgun breech might be 10 GW over 10 ms, the batteries could recharge the inductor at a rate of 25 MW over 5 s.[†] This arrangement is smaller, operates at lower voltages than capacitors, and there is no rotating machinery. However, a high-current opening switch is needed to provide the current pulse. Such switches are not readily available, although some research is underway.

[†] Assuming 80% overall efficiency.

The IAT is also investigating improvements to an inductor circuit known as the “meat grinder.” The essence of the meat-grinder concept involves charging a multi-coil switched inductor relatively slowly at moderate current over a relatively long period and then discharging it rapidly into the railgun breech using a topological reconfiguration of the energy-storage inductors by rapid switching. A small experimental version of this concept under test at the IAT is shown in Fig. 7 [7].

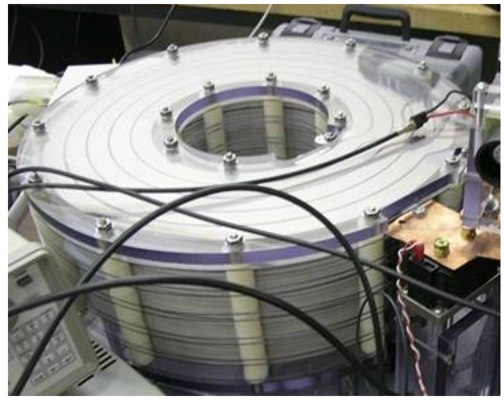

Fig. 7. STRETCH meat grinder inductive current compression system on test.

V. SHIP INTERFACES

Although it is not mandatory, it is most likely that the railgun would be installed on a future naval warship that uses an electrical main propulsion system that runs on liquid fuel. Some ship interfaces for a railgun would be similar to those for a conventional gun. These include the recoil, ammunition storage and loading‡, and thermal management subsystems. However, other aspects would differ, because the energy needed for gun operation would be derived from onboard fuel. It is expected that an electric ship would use dedicated electrical power for the generator-to-motor propulsive power system (up to ~70 MWe) with a standard ship service power system (typically ~10 MWe) for onboard equipment. Such a standard ship service system is unlikely to have a power capability adequate to re-spin the pulsed alternators or recharge capacitors at a rate that matches the high muzzle energies and firing rates demanded by the naval surface-fire support mission (tens of megawatts). Hence, it would be necessary to modify the main propulsive power bus so that a significant fraction of the installed ship electrical power can be used by the railgun when the ship is not at full speed. A new power bus would need to be put in place in order to transmit high power levels to the pulsed alternator recharging system for the railgun. In the case of a capacitor system or integrated pulsed motor–alternators, this power bus would be the solid-state charging power units; in the case of batteries, it would be the recharging power distribution system. Handling these electrical energies and power levels is feasible, but it will require careful evaluation of the control and safety systems.

The concept of operations (CONOPS) for the weapon system is a very stressing and often overriding requirement that plays a large role in determining the optimum pulsed power approach. For example, if the railgun is to be used in a shore bombardment role that requires firing several hundred times per hour for perhaps several hours or even days, a capacitor approach may become intractable due to heat, which would build up within the capacitors because of their inherent internal resistance. This tactical employment may dictate a less efficient solution but one that can more

‡ Note that no gun propellant is needed.

easily incorporate cooling into the energy-storage module. Conversely, if the railgun is to be used in a ship self-defense role, it may need to be able to fire dozens of shots in only a few seconds to successfully defeat a threat to the ship. In this case, it may be necessary for the pulsed power system to store enough energy to fire all the shots required during the engagement without any regeneration from the ship's prime power. This requirement may then favor a system that can deliver the highest energy density, even if it means lower efficiency or even durability. As an example, a deck-mounted ship self-defense gun may need to have pulsed power systems that are closely connected and probably mounted in the same gun housing, as illustrated conceptually in Fig. 3.

Weight is usually viewed as a quantity that must be reduced to the greatest extent possible in weapon systems. In ships, however, the merit of weight depends on location with respect to the ship's centers of gravity and buoyancy. Weight that is below the center of gravity often has little impact, as it can be offset by removal of ballast. Consequently, a pulsed power system that performs favorably is heavy compared with other alternatives may not be at a disadvantage if it can be placed low in the ship. Doing so would not only offset the relatively high (vertical) weight of the gun mount but also improve the ships' sea-keeping performance. For example, it is likely that a large railgun of the type needed for long-range shore bombardment would be a substantial and integral part of the ship in which it is mounted. Indeed, such an arrangement is shown conceptually in Fig. 8.

Efficiency is often a key measure of the utility of a system. For a notional shipboard long-range bombardment railgun system, approximately three gallons of fuel would be necessary to generate the total electrical energy necessary for one shot, and approximately two thirds of that energy will be rejected as heat. Given this, one would expect that a pulsed power system operating at half the efficiency of other alternatives would be dismissed out of hand. Quite the contrary is true. A surface combatant carries greater than half a million gallons of fuel and can be easily refueled at sea. Also, Navy ships operate in the world's largest liquid heat sink. Therefore, if the less-efficient pulsed power system performs well in other aspects, such as reliability and energy density, even a substantial penalty in efficiency may have little impact in its overall utility from a ship integration perspective.

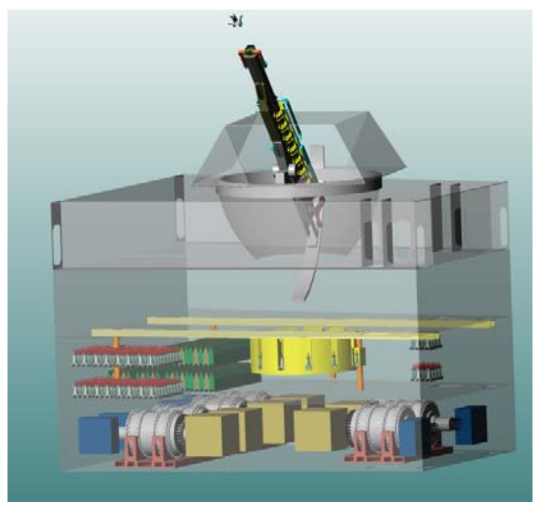

Fig. 8. Ship layout for a long range railgun powered by three pairs of pulsed alternators. (Courtesy NSWC)

VI. CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER STUDY

In the power supply area, further work needs to be done to address the feasibility of the various options:

- Assess the availability and manufacturability of advanced cooled capacitors at large scale
- Evaluate the prospects for development and large-scale production of new high-energy-density capacitor materials
- Undertake the design, development, and testing of industrially producible, cooled, low-risk rotating machines
- Assess the present and likely future capabilities for low-risk, cooled power rectifiers and switching technology for ship applications
- Undertake modeling and experimental evaluations of efficiency-optimized power supply–railgun arrangements
- Evaluate alternate energy storage and power delivery options, including battery or homopolar generator-powered cryogenic inductors and associated switch technology

In the area of ship interfaces, major issues of power distribution, handling, and safety need to be addressed. Power management is the key to the success of the integrated electric ship with high-power electric weapons. Recent studies [8] have shown that there would be sufficient power available to integrate two long-range, indirect-fire railguns aboard an integrated power system (IPS) ship, if it has on the order of 80 MW power available, operates at 10–12 rounds per minute, and maintains ship speed at 10–18 knots during firing, depending on the power plant line-up and configuration. It is concluded that the weight and size estimates for a notional railgun of this capability are within practical limits. Thermal management still appears to be the most challenging engineering task in integration. Further detailed analyses are required to assess optimum IPS interface and transient load management schemes. The properties of either energy storage type (capacitive or rotating machine) need to be examined through detailed electrical analysis, with up-to-date models, parameters, and operational data to provide quantitative representations for power architecture trade-offs. This analysis should include:

- Handling of large disturbances and parallel operation
- Means to implement synchronization and power sharing
- Parameters for power quality and stability as well as schemes for fault handling
- Power buffering and filtering for both capacitive and rotating machine energy storage
- Energy storage location
- Feasibility of bi-directional power flow through power supply

- Detailed analysis of rotating charger drive system, bus interface, drive control algorithms, aggregation properties, and machine limitations

The examination and accurate description of gun-load duty cycles on power and thermal equipment would be necessary to exploit synergism in system resources. This should include the impact of operational duty cycles and the use of power and energy management during engagements on platform systems (especially thermal systems), power generation, and silicon-based power conversion.

Lastly, power management and its impact on survivability and power continuity would be critical during simultaneous operation of gun, mission, and ship service systems.

Acknowledgment

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