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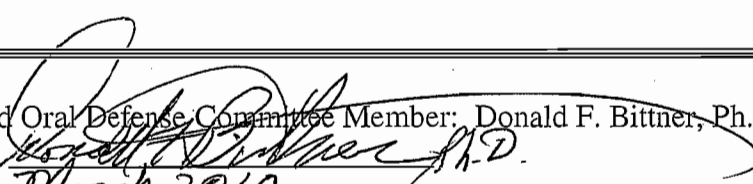
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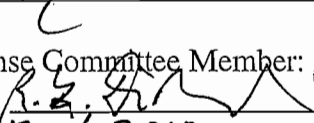
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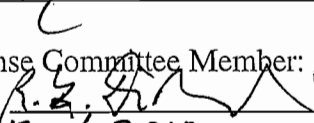
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EXECUTIVE SUMMARY

Title: Electromagnetic Aircraft Launching System: Do the Benefits Outweigh the Costs?

Author: Lieutenant Commander Stephen D. Hartman, USN

Thesis: The benefits of the Electromagnetic Aircraft Launching System outweigh the costs associated with it.

Discussion: Since the beginning of flight, engineers have been looking for ways to power assist aircraft into flight. The evolution of the catapult has gone from weighted bags to spinning flywheels to hydraulic driven and, finally, to steam driven catapults. The next evolution of the catapult is on the horizon. The Electromagnetic Aircraft Launching System (EMALS) is attempting to replace a proven technology in the steam catapult.

The current catapults installed on aircraft carriers are steam-powered, direct-drive, flush-deck type catapults used to launch aircraft from the carrier deck. The steam catapult has been a proven technology since 1950. It is a system made up of a myriad of subsystems that are heavily reliant on complete system operability for each launch. As the system ages, much like any equipment that gets older, it is requiring more and more maintenance and money to keep it at its operational level.

The U.S. Navy is currently in the process of building the next generation of carrier, the *USS Gerald R. Ford* (CVN 78). This ship will incorporate advanced design and new technologies. The new carrier will be manned by less personnel and have a significantly reduced cost of ownership over a 50 year lifespan as compared to a Nimitz class carrier. One of the most significant advances incorporated on the new carrier is the EMALS.

The EMALS is an advanced system that incorporates technology that has been around for many years in other applications such as magnetic levitation (MAGLEV) trains. State-of-the-art systems make up the components of the system. There are several benefits the EMALS has over the current steam system. The EMALS brings significant reductions in weight, space and manpower requirements. Stress put on aircraft airframes are also reduced. However, EMALS has come under some heavy scrutiny and intense criticisms due to cost overruns and schedule delays.

Conclusions: The U.S. Navy has put large amounts of money into the development of the EMALS. It is the launching system of the future. The EMALS should continue to be developed and any further discussion of refitting *USS Gerald R. Ford* is a wasted effort. The U.S. cannot afford to cut back on its ability to project power. The benefits of the EMALS do outweigh the costs associated it.

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PREFACE

The operations and functions of the steam catapult onboard U.S. Navy carriers holds a distinct fascination in all people. The first time someone witnesses a launch from the deck it is an awe inspiring event. This was truly the case with me. As a Catapult Officer onboard USS Dwight D. Eisenhower (CVN 69), I was fortunate enough to not only witness this event on a daily basis, but to become intimately knowledgeable about its entire system.

New technologies come with new challenges. The Electromagnetic Aircraft Launching System (EMALS) brings these new challenges to an already dangerous and unforgiving environment. The EMALS system has also bore the scrutiny associated with higher costs. The costs associated with this may be too much to overcome with current technology. I will attempt to answer the question if the benefits of the new EMALS outweigh the costs associated with it.

The approach of this paper will look at the systems of the steam catapult and the systems EMALS in order to offer a comparison. While the major systems will be looked at, not every system will be intricately examined. Sources and information are all from open source articles as recent as February 2010. There is much challenge associated with writing on such a contemporary topic. There is no way to tell what systems or service requirements may change after the publication of this paper.

There are issues that are not addressed in this paper, but that are still of considerable importance. I do not discuss the aspects of acquiring a ship with still unproven or even developed technology. I did not detail the aspect of training a new rate to maintain and service

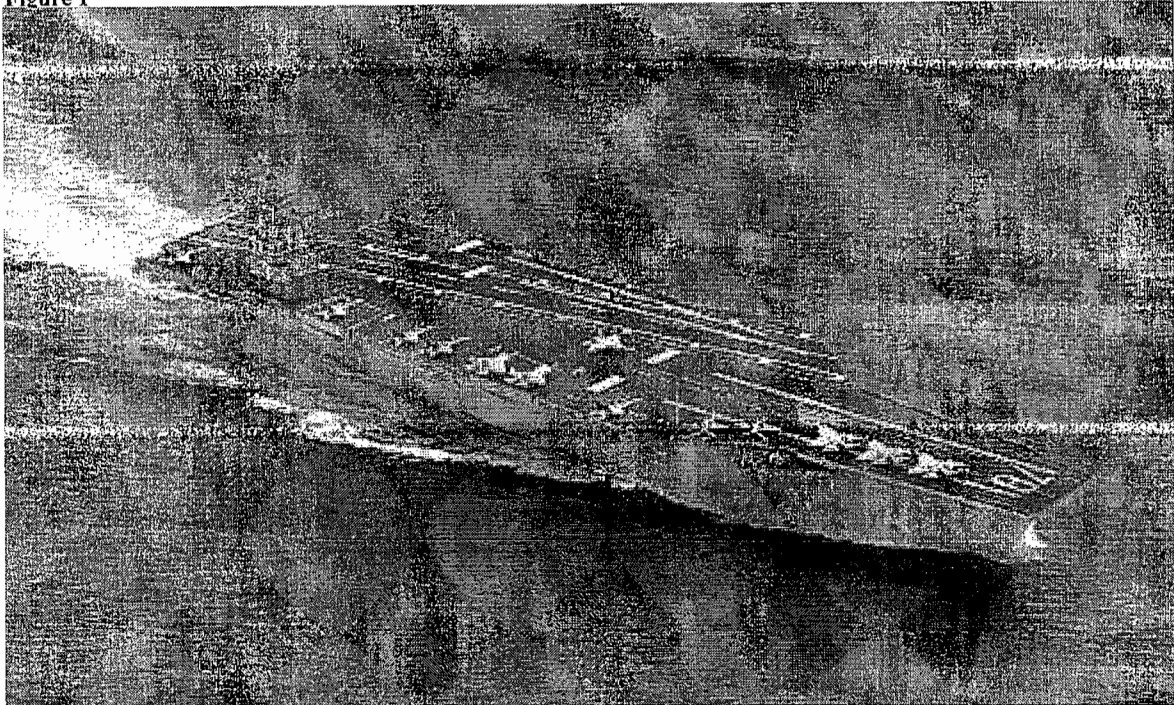
the new technology. Also, due to no significant testing done on Electro Magnetic Interference (EMI) with relations to ordnance, flightdeck communication, or navigation equipment, I was unable to research its effects.

No piece of writing is ever done solely. This is particularly true with this paper. My military faculty advisor, LtCol B.J. Payne (USMC) and my friends and colleagues in conference group ten made the academic year enjoyable and intellectually stimulating. Then there are my three civilian faculty advisors: Dr. Robert Bruce, who taught me more than I ever thought possible about all subjects related to military history; Dr. Pauletta Otis who was instrumental in teaching issues of culture I never thought important; and Dr. Donald Bittner for his advice and wisdom on writing this paper.

I especially owe the largest bit of gratitude to my wife, Lisa. Her love, patience, support, and courage has not only carried me through eleven years of demanding service, but proved invaluable in the research and writing of this and all other projects. Finally, my boys Brian, Jackson, and Nathan, also deserve a special thank you. I tried to find a balance between writing and spending time with each of them. They understood that the writing was important, but still asked me to throw the ball to or play a game with them. Those were just the kind of excuses that I needed to take a break.

PROLOGUE

Figure 1



Artist Rendition CVN 78 Source: GAO Report GAO-09-326SP

The *USS Gerald R. Ford* is the future of Naval Aviation. The single most important advanced technology being implemented onboard is the Electromagnetic Aircraft Launching System (EMALS). This is the replacement for the steam catapults currently in use by the U.S. Navy. The catapult provides the carrier with its purpose to exist. Without it the carrier simply cannot do what it is intended. EMALS will allow the carrier to perform at a level not yet seen.

Introduction:

On November 12, 1912 the United States Navy made its first successful catapult launch of an aircraft off the deck of a ship from a modified coal barge at the Washington Navy Yard.¹ Three years later, on November 5, 1915 the first successful catapult launch occurred from a moving ship by Lieutenant Commander Henry C. Mustin on the *USS North Carolina*. (Figure 2, APPENDIX A) In the early days of naval aviation, the force required to launch the planes into the air was minimal. Light and unarmed aircraft did not require much push to reach minimum takeoff speed. The U.S. Navy began to launch planes by methods such as the use of compressed air pushing a piston to a flywheel driven catapult.² By the time of World War II, the Navy had put catapult technology on hold as the current fighters and shipboard bombers could takeoff via a deck run of the larger carriers. Herbert and Ada Friedman illustrate this point in their 2006 article, "Shot in the Dark."

Unfortunately, no one seemed interested. The Navy was still thinking in terms of big, fast fleet carriers, which at first could get along quite well without catapults. As late as April 1943 the captain of the *Enterprise* asked to have its catapult removed. The advent of the smaller, cheaper, quickly built jeep carriers—115 of them, as against 30 fleet and light fleet carriers—changed all that. They made almost all their launches with flush-deck catapults, and their success led the Navy to take a second look at catapults for fleet carriers as well, as a space-saving measure.³

The Navy had begun to look at the flush-deck mounted catapult in order to save space. These predecessors to the modern catapult were hydraulically driven where a steel cable attached to a trolley would be wound by a hydroneumatic engine. As planes became heavier, the hydraulic catapults were operating at ever-increasing pressures. The system limitations of the hydraulic catapult finally became apparent in May 1953 when the port side catapult onboard *USS Bennington* (CVA 20) burst, with the hydraulic vapors igniting and causing multiple explosions, causing over 300 casualties: 103 Sailors killed and 201 injured.⁴ The incident on the *Bennington*

was the worst accident in naval history not involving enemy action or another ship.

Another more reliable method of launching aircraft was thus required. Fortunately for the U.S. Navy, the Royal Navy was also developing catapult technology. By 1950, Commander Colin S. Mitchell, of the Royal Navy, had designed and built a steam catapult. Although refined over the next 50 years, this in essence is the same catapult technology still in use today on every Navy aircraft carrier.

The next evolution of the catapult is currently in its testing phase. The Electromagnetic Aircraft Launching System (EMALS) is attempting to replace a proven technology in the steam catapult. With the new technology comes, among other things, a higher price tag. The question then becomes, what are the benefits and the costs of EMALS? This paper looks to determine if the benefits of EMALS outweigh the costs associated with it.

Steam Catapult

In order to understand the benefits of a new system, it is imperative to be familiar with the one used at present time. The current catapults installed on aircraft carriers are steam-powered, direct-drive, flush-deck type catapults used to launch aircraft from the carrier deck. These catapults, known as C-13 Mod 1 or 2, consist of two rows of slotted cylinders side-by-side in a trough under the flight deck. Pistons within these cylinders attach to a shuttle that tows the aircraft. Steam pressure forces the pistons forward, towing the shuttle and aircraft at ever increasing speed until takeoff is achieved. Each catapult consists basically of the same major systems:

(1) Steam System. The Steam System delivers the steam required to operate the catapult from the ship's engineering spaces. The steam system portion of the C-13 Catapult is operated and maintained by ships' engineering department personnel. This constant-pressure system uses a capacity selector valve (CSV) to control the steam pressure to the catapults for launching.

(2) Launch Engine System. The Launch Engine System consists of most of the major components that are used in applying steam to the launch engine pistons during the launch sequence and stopping the launch pistons at the completion of the launch.

3) Retraction Engine and Drive System. A rotary retraction engine system provides the necessary ability to retract the shuttle and the launching engine pistons after the catapult has been fired. It is also used to advance the grab forward and aft.⁵

(4) Hydraulic System. The Hydraulic System supplies hydraulic fluid for the operation of the hydraulic components of the catapult such as raising the jet blast deflectors.

(5) Lubrication System. The Lubrication System provides a means of lubricating the catapult cylinders prior to firing and also provides lubrication at other times by way of manual lubrication. It accomplishes this by injecting lubricating oil through the cylinder covers with a spray pattern that ensures even lubrication of the cylinder walls before passage of the launching engine pistons.

(6) Bridle Tensioning System. The Bridle Tensioning System provides a means of tightly connecting the aircraft to be launched to the catapult shuttle.

(7) Control System. The Control System consists of the panels, lights, and switches that are used to operate the catapult throughout the various sequential operational phases.

The main component of the steam catapult is an assembly with two cylinders and two power pistons for each catapult. The spear-shaped pistons, which are forced at high speed through the cylinders by steam pressure during the launching operation, are solidly interconnected by the shuttle assembly. The vertical arm of the assembly extends upward through a slot in the flight deck. A spreader is attached to the shuttle that serves as the hook to which the aircraft's tow bar is connected. The shuttle is a small roller-mounted sled which moves during the launch on tracks installed directly below the flight deck.

The power to move the shuttle and its aircraft load comes from steam piped to the catapult from the steam system. This steam is held under pressure in large tanks, known as accumulators, located beneath the launching engine. Steam is passed to the receivers through the flow control valve. From the receivers, the steam is transferred at the instance of launch into the power cylinders. Steam pushes directly on the pistons and propels the piston-shuttle assembly through the cylinders. Launch valves control the amount of steam that is applied to the pistons. A sealing strip closes the slot in each cylinder as the pistons are pushed forward, preventing steam from escaping the cylinder slots through which the shuttle connectors moves.

After firing, the pistons are stopped at the end of its launching run by a water brake. The brake consists of two six-foot cylinders at the forward end of the catapult with fresh water pumped into them. The tips of the piston spears ram into the water-filled cylinders. As the spear tips penetrate the water, pressure builds up and stops the assembly in an instant.

The catapult cylinders are preheated by using an internal heating system which prevents shock and minimizes possible damage to the launching engine when superheated steam is admitted through the launching valves into the launching cylinders. This process of warming up the catapult also keeps the elongation in a ready launch state.⁶ The piping for steam supply must also be warmed up before use.

Steam Catapult Shortfalls

Although the steam catapult in use on U.S. Navy carriers is built with some redundancies, such as backup safety equipment and alternate modes of firing, the entire system itself is heavily reliant on all components operating smoothly on every shot. At any given moment during the launch sequence, if a hydraulic pressure drops or a water system springs a leak, the catapult operators or launching officer will suspend the launch.⁷ The single-point failure throughout the system is designed to save the life of the pilot being launched and the catapult launching crew;

however the inefficiency of the system slows down critical launch times that could impact mission success.

Perhaps the most dangerous failure of the steam catapult is the hangfire. A hangfire occurs when the launching officer has given the signal to fire and the fire button has been pressed but the launch valves fail to open. Danger presents itself in that the catapult can still fire at any moment. The most common cause of a hangfire is the catapult crew failure to move the launching pilot latch to the safe zone.⁸ After the catapult is rendered electrically and mechanically safe from launching, this problem is corrected. The next most common and most dangerous cause of a hangfire is the loss of low pressure air.⁹ It is the low pressure air that actuates the fire solenoid which opens and allows hydraulic fluid to pass, opening the launch valves. At any given moment before the catapult is rendered safe, an accidental launch could occur without enough power to launch the plane.

The steam catapult has been a proven technology for many years. As the system ages, much like any equipment that gets older, it requires more maintenance and money to keep it at its operational level. The U.S. Navy is looking for new and fresh technology to replace the aging system.

Future of the carrier

*"A U.S. Navy aircraft carrier is a symbol that is recognizable throughout the world. It represents American power. It is a reminder of America's global interests, and global reach."*¹⁰

-Secretary of the Navy, Dr. Donald C. Winter
16 January 2007

The CVN 21 Program is the future aircraft carrier replacement program for current Nimitz class aircraft carriers. The Gerald R. Ford, ordered from Northrop Grumman Shipbuilding Newport News on September 10, 2008, and scheduled to be delivered in 2015, will

be the premier forward asset in a major combat operation. This new class ship promises to bring improved warfighting capability, quality of life improvements for Sailors on board and reduced acquisition and life cycle costs. The Ford class ships will share the same approximate dimensions as the Nimitz class ships and will still feature four catapults. (See Appendix C)

Each ship in the new class will save more than \$5 billion in total ownership costs during its 50-year service life, compared to the Nimitz class.¹¹ Approximately half of the total ownership cost for an aircraft carrier is allocated to costs of manpower for operations and maintenance of the ship. The Ford class ships are being designed to operate effectively with nearly 1200 fewer crew members than current aircraft carriers. By improving the ships design, ship's crew will be reduced by approximately 800 and the embarked air wing will be able to operate with 400 fewer personnel.¹²

USS Gerald R. Ford is the first aircraft carrier designed with all electric utilities. This will eliminate steam service lines, thereby reducing maintenance requirements and improving corrosion control efforts. A few of the additional features of the advanced ship design will be the new A1B reactor, Electromagnetic Aircraft Launch System, Advanced Arresting Gear, and Dual Band Radar. These advanced technologies offer enhanced capability with reduced manning requirements.

The Gerald R. Ford class is designed to maximize the striking power of the embarked carrier air wing. The ship's systems and configuration are optimized to maximize the sortie generation rate (SGR) of attached strike aircraft, resulting in a 25 percent increase in SGR over the Nimitz class.¹³

The new ship's configuration and electrical generating plant are designed to accommodate any foreseeable requirements during a 50- year service life. The Gerald R. Ford class is the beginning of a new era for the carriers of the U.S. Navy in both technological and operational aspects. The technological advances of the new carrier class builds upon the Navy's

legacy of improving innovations stretching back to the first aircraft carrier. There are currently three ships planned for the Ford class. CVN 78 is due in 2015, CVN 79 will deliver in 2019, and CVN 80 scheduled for delivery in 2023.

Electromagnetic Aircraft Launching System

Of the new systems incorporated in the Ford class carriers, the one that will have the most significant impact on the daily operations is the Electromagnetic Aircraft Launching System (EMALS). The electromagnetic aircraft launching system will use electricity to propel the launch shuttle down the catapult track vice a steam driven piston. EMALS adopts an approach similar to an electromagnetic rail gun, in order to accelerate the shuttle that holds the aircraft.¹⁴ By achieving a uniform acceleration throughout the move down the catapult track, this approach will effectively provide a smoother launch. The pilot will no longer have the initial hard jolt of the catapult shot, but a gradual buildup of speed. This smooth acceleration will also limit the initial stresses put on the aircraft.

There are far lower space and maintenance requirements associated with EMALS, because it eliminates most of the steam catapult's piping, pumps, motors, control systems, and other subsystems. "Ancillary benefits include the ability to embed diagnostic systems, for ease of maintenance with fewer personnel on board."¹⁵ Offering up to 30% more launch energy potential to cope with heavier fighters, EMALS will provide a more efficient, flexible, and safer means to launch aircraft from the carrier.¹⁶ EMALS is critical to meeting sortie generation rates and reducing manpower on the ship.

EMALS, a multimegawatt electric power system, will be powered by the ship's updated and robust electrical system. It will consist of six main subsystems: a launch motor, prime power interface, a power conversion system, a state-of-the-art launch control system, energy storage, and energy distribution system.¹⁷ The system's design incorporates the same shuttle for

launching as the steam system and will fit into the same area as the steam troughs on current U.S. Navy aircraft carriers.

The launching motor is developed in a linear induction motor configuration. It is a compact, integrated flight-deck structure that converts electrical current into the electromagnetic forces required to accelerate the aircraft along the launch stroke. The design takes into account the range of conditions experienced in the flight-deck environment. Just prior to the end of the launch, the electric current will reverse the motor to brake the shuttle to a stop without the use of a water brake. The linear induction motor will translate electrical energy into motion by generating a magnetic wave that will move the shuttle down the catapult track as well as providing launch, braking and maneuvering energy through one component. The prime power interface is the link between the ship's electrical distribution system and the catapults energy storage generators. The shipboard energy stores will use the inertia from the rotor of an electrical generator to power the catapult and are recharged from ship's power between launches. The power conversion system receives power from the energy store and converts this power to traveling wave of energy of the appropriate voltage and current to drive the shuttle along the launch stroke. It is a solid-state component that regulates the voltage and frequency of the electrical pulse supplied to the shuttle. The energy distribution system delivers the power from the conversion system to the launching motor. This will provide a reliable and consistent power source and regulate power distribution.¹⁸

The launch control system monitors the health of the system and informs the operators of any failures provide feedback by way of a closed loop feedback and monitoring system. This will allow more precise end speeds to a wider range of aircraft, such as the F-35 Joint Strike Fighter, EA-18, and Unmanned Ariel Vehicles, and provide operators better control of the aircraft speed as it launches off the catapult, reducing the risk of a weak catapult launch.

Benefits vs. Steam

Current steam catapults are inefficient and are maintenance intensive; however recent development of EMALS systems design will reduce maintenance and increase reliability. The EMALS will require 20,000 cubic feet of space, a 50% reduction in the total size of the system, mostly below the flight deck, compared to the 40,000 cubic feet for a steam catapult system which requires separate and heavier components to accomplish its tasks.¹⁹ The major reduction in space required for the EMALS below the flight deck is due to its drive mechanism. Powered by the ships own electrical source, the EMALS will not require hydraulic or pneumatic power. Additionally, since there will be no cylinders for the shuttle and piston assembly to pass through, the catapult track itself will not require lubrication. Current steam powered catapults require massive amounts of lubricating oil in the cylinder that is expelled into the environment with each shot. Designers of the EMALS also state, "Another advantage of EMALS is that it would reduce manning requirements by inspecting and troubleshooting itself. This would be a significant improvement over the present system, which requires substantial manual inspection and maintenance. The EMALS, however, will require a transition of expertise from mechanical to electrical/electronic."²⁰ EMALS promises to be more reliable with 1,300 mean cycles between failures which, combined with the closed loop feedback and monitoring system, will allow operators to address potential problems before they become dangerous.²¹ Due to the reduction in size and more operability of the catapult systems, fewer personnel will be required to operate the new catapult. The limiting of manpower for the systems also eliminates required space for berthing.

The limits or negatives of the steam catapult system are apparent. Through the inevitable growth of larger and faster aircraft, the steam catapult, if retained, would have to be upgraded to a larger and heavier version to maintain a safe operating capability. EMALS would negate the

need for any further modification to the steam catapult. The EMALS launching engine is capable of a higher thrust density, as proven by the half scale model that demonstrated 1322 psi over its cross section. This is compared to the relatively low 450-520 psi of the steam catapult.²²

The present steam catapult has a relatively high peak-to mean acceleration profile, meaning there is a significant initial shock to reach top speed before deceleration. This results in high stresses upon the aircraft airframe and generally poor performance. With an electromagnetic system, the acceleration profile is smooth and flat compared with that of a steam catapult profile. (See APPENDIX B) The result of this reduced initial jolt is reduced stress on the airframe. EMALS engineers have explained this, "To quantify the effects of a reduced peak-to-mean, a Fracture Mechanics analysis was conducted on the airframe [4] with both the steam catapult and EMALS peak-to-means. The results from this analysis show a peak airframe life extension of 31% due to the reduced stresses on the airframe."²³ This becomes more important as the Navy is purchasing fewer new aircraft while maintaining an aging fleet of Hornets and Super Hornets which will continue to fly off the new ship. The EMALS operates as a closed-loop system that constantly monitors itself. It will continuously adjust the speed and power to create a launch profile tailored to each type of aircraft. Steam catapults are simply open-loop systems, with no sensors or feedback once the launch sequence is initiated.

As robust of a system as it may be, the EMALS is not without its drawbacks. One of its major problems noted is the effect of electromagnetic interference (EMI) on electronic equipment. There would be sensitive aircraft equipment as well as ordnance sitting directly on top of the launch motor.²⁴ The ship's own equipment could also be affected by the electromagnetic emissions. Another challenge is being able to continually operate a completely electrical system in a highly corrosive sea environment.

Costs and Issues

As a new and emerging technology, EMALS has come under heavy scrutiny and intense criticisms. Since the mid-1990s the U.S. Navy has planned to produce the EMALS system. Design changes and unexpected problems with respect to the EMALS system has resulted in production delays that could now jeopardize the on-time delivery of *USS Gerald R. Ford* (CVN 78).

In April 2004, General Atomics was awarded a System Development and Demonstration contract to design, build, and test a full scale shipboard production of the EMALS. With the original contract worth \$145 Million, another \$20.5 Million contract followed for construction of a land based support facility.²⁵ The EMALS system is supposed to be ready for installation on CVN 78 by 2011. However, by March 2006, design problems were already appearing. "General Atomics in San Diego, CA received a not-to-exceed \$6 million modification to a previously awarded cost-plus-award-fee contract (N68335-04-C-0167) for acceptance and incorporation of two Engineering Change Proposals for the Electromagnetic Aircraft Launch System (EMALS)."²⁶ The proposed changes include one for the Center Deck Display, and one for a revision to the Launch Control System Motor Controller. This seemed to be the beginning of some ever increasing issues the Navy is facing with EMALS and other systems that could affect the on-time delivery of CVN 78.

In 2007, the Navy faced the potential of seeing EMALS terminated. The Navy charged General Atomics with building a system in which each of the four catapults on the carrier weighed 530 tons. Yet each launcher being produced was about 100 tons overweight, making the total system 400 tons overweight.²⁷ The system, as built was going to take up too much space. The Navy corrected the problem by changing EMALS from having stand-alone electrical equipment for each catapult to systems that could be shared by all four catapults on the ship.²⁸

Electrical systems and inverters were thus reconfigured for shared use among each of the catapults. Additionally, there was an initial problem with the EMALS energy storage device. The component employed steel clips, which caused an arcing of electric fields. The storage device was redesigned so that it employed more traditional plastic clips.²⁹

Many problems with technology are often discovered during the development phase. This becomes more of a teething issue with the growth of new technology than a showstopper for the program. However, these issues prompted the Navy to coordinate with the ship builder, Northrup Grumman Shipbuilding, to change the building order for the program. This allows the builder to concentrate on other parts of the ship, while EMALS has time to mature before installation.

The issues surrounding the EMALS program became very troublesome by the end of 2007. A Government Accountability Office (GAO) Report in August 2007, questioned whether the Navy would be able to meet cost goals for its next-generation aircraft carrier.³⁰ The report stated that EMALS program had finished its system integration phase over 15 months behind schedule and substantially above budget. Delays resulted from technical challenges, as well as difficulties meeting detailed Navy requirements.³¹

Though some progress has been made on many of EMALS' individual components, some major systems still faced technical challenges. This centered on failures with the prototype generator that stores the high power needed to propel the launchers. The prototype generator malfunctioned during integrated and follow-on testing. However, General Atomics was able to correct the problem through redesign of the prototype generator.³²

The 2007 GAO Report, titled "Navy Faces Challenges Constructing the Aircraft Carrier *Gerald R. Ford* within Budget," identified some issues with the EMALS contractor General Atomics:

(1) The contractor has also faced challenges meeting the complex requirements involved with Navy ships. Because they operate at sea and must meet unique survivability requirements naval vessels, especially carriers, have more stringent requirements than general land based systems.

(2) General Atomics has never produced a shipboard system, particularly one as highly integrated into the ship as EMALS, and underestimated the effort needed to meet Navy requirements. Converting EMALS design into producible and affordable components, with established test and quality controls, proved challenging for a contractor traditionally involved in projects aimed at research and development.

(3) The contractor received the majority of the Navy's requirements after they had already designed most of the system themselves.³³

Through 2007, the contractor had demonstrated the feasibility of using magnetic fields to launch aircraft on a land-based test designed to simulate a flight deck. Still, challenges arose that led to schedule delays and cost growth. (Table 4 Appendix E) To meet ship installation dates for EMALS' components, the contractor eliminated all schedule margins. These margins are built in lead time to allow for addressing unexpected issues. As a result, the schedule could no longer allow for any unanticipated testing or production problems. Ship and system redesign had already created a one-year delay in the Ford's schedule. Without this delay, it would have been unlikely that EMALS would have met the ship's original installation date.

It soon became clear that General Atomics and their industry partners did not have the right amount of personnel to manage and control production for the EMALS. They required an additional 80 engineering personnel. This helped contribute to cost overruns of the system. While the contractor believed that problems during system integration had been resolved and EMALS' delivery schedule can be met, challenges still remained and demanding tests lay

ahead.³⁴

The contractor needed to demonstrate a shipboard-ready system and produce a shipboard-ready system. In order to stay on schedule, the program had to shift a number of key test events, including its maintainability testing, to the production phase. With no margin for delays, any problems that may be encountered during testing would still prevent an on-time delivery to the shipbuilder.

In the beginning of 2008, Navy Secretary Donald Winter had been briefed on whether EMALS should be terminated. However, in the end, the program was directed to continue forward and the Navy requested a \$37 million reprogramming increase in FY-07 primarily for additional systems development.³⁵ During the spring of 2008, the situation with the management of the EMALS program needed a change. The U.S. Navy made the decision to take the program, which had been under NAVAIR's Air 1.0 organization, and move it into the Program Executive Office Tactical (PEO T) aircraft. According to Capt. Randy Mahr, program manager for aircraft launch and recovery equipment, PEO Carriers (PMS 378), this happened for a couple of reasons. "PEO T has all the other aircraft programs and we have a lot of experience in PEO T managing large complex integration programs like [EMALS]."³⁶

In an effort to speed up production times and limit delays, the U.S. Navy also decided to change the relationships of the program. They brought the ship builder, Northrup Grumman Shipbuilding, into the buying process.³⁷ Prior to this, the program manager would buy everything from General Atomics for both development and production, and pass those components along to PMS 378, which would then, in turn, hand those parts off to Northrop Grumman Shipbuilding. The Navy, while maintaining control of development, made the decision to pass the production responsibility for CVN-78 to the two contractors to figure out how to make that work.³⁸ The Navy has effectively eliminated itself as the middle man in an

effort to save time. As of now, Northrop Grumman Shipbuilding will buy the production EMALS components directly from General Atomics. The money still flows from PMS 378, but instead of flowing through the program office it now goes directly to the shipbuilding contract.

In April 2008, the first full-size test motor generator completed factory acceptance testing. Problems with developing the motor generator had delayed the program by several months, as testing was originally scheduled to start in February 2008. *A Defense Industry Daily* article describes the motor generator and its capacity as:

The motor generator weighs over 80,000 pounds, and is 13.5 feet long, almost 11 feet wide and almost 7 feet tall. It's designed to deliver up to 60 megajoules of electricity and 60 megawatts at its peak. In the 3 seconds it takes to launch a Navy aircraft, that amount of power could handle 12,000 homes. This motor generator is part of a suite of equipment called the Energy Storage Subsystem, which includes the motor generator, the generator control tower and the stored energy exciter power supply.³⁹

In September 2008, General Atomics completed the first round of high-cycle testing. This placed the motor through 10,000 cycles over the course of two months, and produced confidence in the performance of the generator. However, this did not slow down the criticisms of the new system.

By the beginning of 2009, Naval leadership again considered the possibility of replacing the EMALS with a steam catapult system for the *USS Gerald R. Ford*. After reviewing the program's cost and schedule delays and weighing the feasibility of reverting to a steam catapult, the Navy has decided to proceed with the EMALS. Vice Adm. Barry McCullough, the deputy chief of naval operations for integration of capabilities and resources, testified at an April 1, 2009 House Appropriations defense subcommittee hearing on shipbuilding. He stated, "Right now, both through the reduction in personnel required to man the launching system, the increased operational availability and the reliability of the EMALS system, there's still lifecycle

savings over what we have if we went back to steam catapult.”⁴⁰ Confidence amongst the contractors and within the service remained high that the EMALS system would be successful. Additionally, the cost and production delays associated with redesign and installation of the steam system for the ship would have proved excessive: estimated possible delays of 18 – 24 months and costs of around \$2 billion for such a conversion.

In March 2009, another GAO report was issued stating that EMALS was one of three technologies intended for CVN 78 which presented the greatest risk to the ship’s cost and schedule.⁴¹ The other two were the advanced arresting gear and dual band radar. The GAO continued to report that it would take seven months after installation on the ship has begun until EMALS will be able to demonstrate the performance of a ship-board ready system. This assumes there would be no further delays with the program.

On June 5, 2009, the Navy added another \$24 million to the budget for a revamped research, development, test, and evaluation (RDT&E) effort for EMALS. With this, FY-09 spending on developing the troubled program exceeded more than \$168 million. The funds were approved by the Department of Defense with a document stating, “Additional scope of work has resulted from complex ship integration, a re-planned test and evaluation program to reduce risks for CVN-78, incorporation of the production assessment review findings, and the escalated costs of steel, copper and other materials.”⁴² Besides the reprogrammed funds, the Navy received \$24 million for EMALS in the FY-09 supplemental spending bill. This brought its total of extra dollars requested above the program’s budget to about \$85 million.⁴³ In September 2009, EMALS finally completed Phase 1 of Highly Accelerated Life Testing (HALT) and the second phase System Functional Demonstration (SFD). “The HALT gauges the EMALS launch motor’s ability to operate in simulated at-sea environmental conditions on board the carrier. HALT also supplies the system’s engineers with the data necessary to verify EMALS’ peak

performance, even in extreme conditions.”⁴⁴ SFD testing simulates full-scale launching capabilities of EMALS by integrating and testing all power components system with the launch controller. In November 2009, NAVAIR hosted a ribbon-cutting ceremony for the EMALS full-scale catapult test site at Joint Base McGuire-Fort Dix-Lakehurst, NJ. Also that same month, the keel was laid for the construction on CVN 78 in Newport News, VA.

The next step for the EMALS will be the first launch of an F/A-18 Hornet from land. This event is currently on schedule for summer 2010. Testing of each separate component has already been completed. So far, the development team has tested moving the shuttle a maximum of 10 meters at a maximum speed of 9.75 meters per second. These tests are designed to ensure that the system can detect the location of the shuttle and apply the desired amount of force. As testing continues, some of the EMALS components are being built, with their scheduled delivery dates to meet the required dates that CVN-78 shipbuilders have laid out. Thus, the U.S. Navy remains fully committed the installation of EMALS on the next generation of aircraft carriers.

Analysis

The Navy is looking to save money over the life expectancy of the new carrier class. The new carriers are expected to generate savings in two major ways. One is through the vast design and automation changes to different areas of the ship that reduce the number of sailors required aboard. The other is with the reduction in the number of major maintenance overhauls. Through the ships’ projected 50-year lifetime, NAVSEA expects these changes to save \$5 billion per ship.

Nimitz class ships currently receive one Refueling and Complex Overhaul (RCOH), four Drydock Planned Incremental Availabilities (PIA), and 12 Pier-side PIAs over a 50 year lifetime.⁴⁵ Design changes of the CVN-21 program are expected to reduce that to one RCOH, two Drydock PIAs, and eight Pier-side PIAs. The Navy believes this will equate to total life cycle savings of \$1.9 billion in FY 2008 dollars. The Navy has estimated a cost of \$7.9 to 8.1

billion for construction cost of CVN 78. Currently the Navy puts the cost of a Nimitz class carrier at \$4.5 billion. "The \$4.5B figure, they note, represents an average cost across the period of 1968-2008. The actual cost of each ship must consider the effects of inflation, and also the effects of shipyard workload."⁴⁶ If calculated for today's dollars with inflation, the price to build a new Nimitz class would be approximately \$8.5 billion. Investment costs include \$3.6 billion in research and development and nearly \$3 billion for detailed design. With the technology advantages of the Ford class, there are massive savings potential over the Nimitz class. With the design that includes EMALS, and the Advanced Arresting Gear, the Ford class CVN cost savings could be substantial. The Ford class will reduce manning by 1,200 total personnel compared to the Nimitz-class carriers in service. With the reduction in manpower alone, if the Navy saves \$90,000 per Sailor annually on the 800 additional ship's crew members, the life cycle savings in manpower alone is around \$3.6 billion. Reduction of 400 air wing personnel brings an additional savings of \$1.8 billion. In respects to operating costs, the EMALS has the potential to save the Navy money by reducing the excessive wear on the aircraft caused by steam catapults and the energy absorption system for aircraft landings

New ways of evaluating the cost over the life of the carrier have given way to the development of total operating costs. By examining the entire cost from development to operations, the Navy is able to analyze the total cost to build and operate a carrier. This analysis generates the life cycle costs. Total Costs of Ownership (TCO) adds manpower and weapon system costs to the life cycle costs. The bottom line is the TCO of producing and operating an advanced carrier design is more economically beneficial to the Navy and the taxpayers in the long run.

There have been cost growth and teething problems associated with the development of the EMALS. The associated delays have put the delivery of the new carrier in jeopardy. Yet,

the U.S. Navy continues to remain committed to the procurement of the new advanced system. The technology for the equipment has been operating for years in the form of magnetic levitation trains. It is applying that technology to the harsh climate of the flight deck that remains to be demonstrated. If the decision to go forth with a redesign of a steam system, the delays incurred for redesign and the costs associated with implementation would push the new carrier well passed the scheduled delivery date and well over-budget.

If the ship has to be refitted for the older steam system, it will have to be redesigned for more people, account for the changes to weight and balance, and designated catapult sections of the ship would need new plumbing, cooling, and water brakes that comes with the older steam technology. There may potentially even require a design change to the nuclear reactor, since that is from where the catapults would get the steam. Steam will add weight to the new ship as well as more crew. Refitting the ship for steam would make the *USS Gerald R. Ford* a unique design and the only ship in its class. Since the EMALS program will continue, the next ship of the class, CVN-79, would be another first in class ship.

Conclusion

*"...it is necessary for an aerodrome, as it is for a soaring bird, to have a certain considerable initial velocity before it can advantageously use its own mechanism for flight, and the difficulties of imparting this initial velocity with safety are surprisingly great, and in the open air are beyond all anticipation."*⁴⁷

- Samuel Pierpont Langley, Secretary of
the Smithsonian Institution, July 1897

In the early days of aircraft carriers, some propeller-driven aircraft could take off unassisted if they were lightly loaded. However, naval engineers soon realized that they would need a boost for most launches as aircraft became heavier and larger. The launch problem only became more difficult as aircraft entered the jet age. For more than 50 years, the steam-powered

catapult has been the system designed into aircraft carriers to launch aircraft. Although the steam catapult system has worked well and is a proven technology, a new generation of Navy designs is striving to meet goals of lower operating costs, reduce crew requirements, and improve performance. The present steam system has been refined to its technical end and has some inherent limitations that are not likely to be overcome.

The technology involved in EMALS may still be in development, but the basic design of the linear induction motor has been used for years in systems such as Disney's Monorail. The U.S. Navy has committed large amounts of money into the development of the EMALS. It is the launching system of the future. With the potential to reduce manning, provide less stress and possible longer life for aircraft, and less maintenance requirements, the benefits of the EMALS do outweigh the initial costs associated with it. The EMALS should continue to be developed and any further discussion of refitting *USS Gerald R. Ford* to the older steam catapult system is a wasted effort. The U.S. cannot afford to cut back on its ability to project power. Convincing politicians of the viability of the EMALS is of the utmost importance. The system is too far along to consider cancelling for the implementation into CVN 78, especially after construction has already begun.

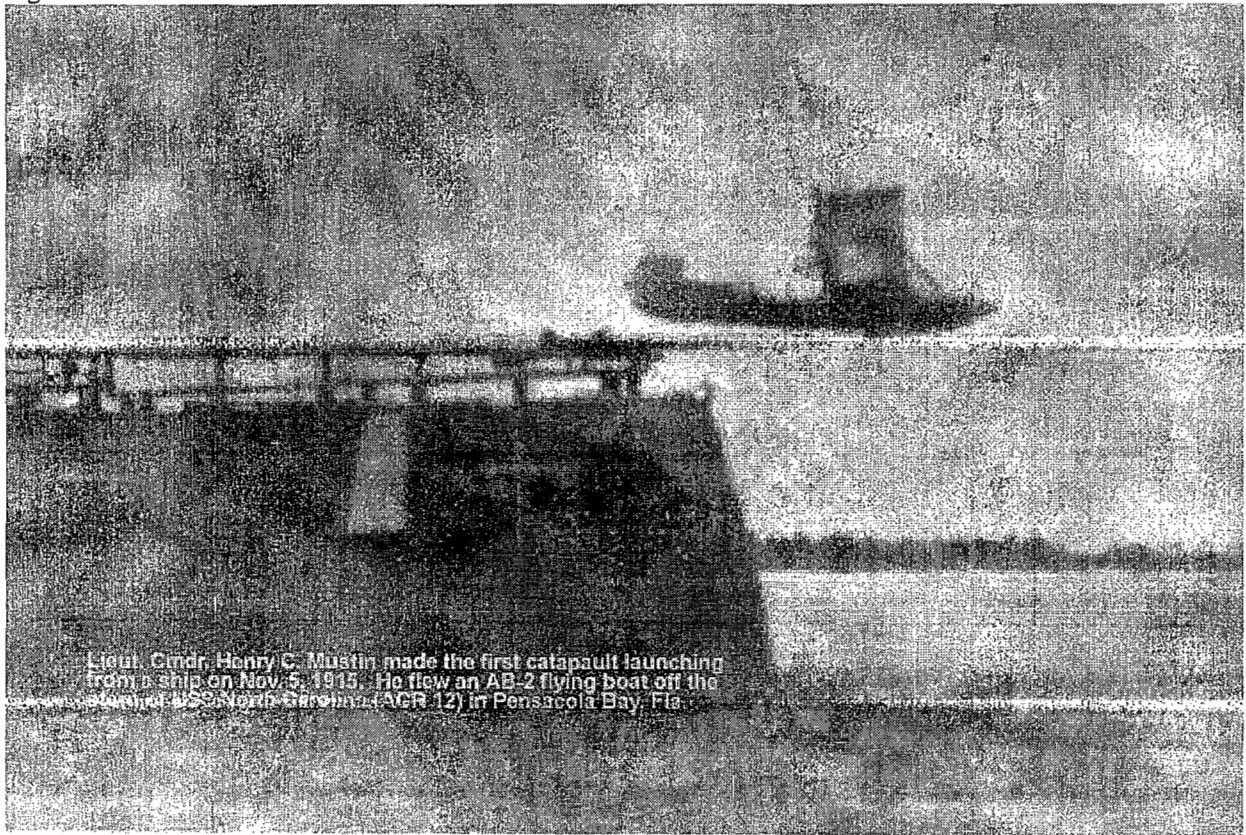
To redesign the ship at this stage would be a disastrous undertaking for the shipbuilder. They would suffer serious delays and a pretty significant cost hit, somewhere in the neighborhood of \$600 million and delays of one to three years. If any other issues arise with the EMALS there may also be a delay, but nothing as significant as the other option. The Navy simply cannot afford to place restrictions on the system at this time.

The aircraft carrier is the symbol of the sea service today. It is a platform of national interest, paid for with an enormous investment in time, effort, and money. CVN 78 is the aircraft carrier of the future, and the EMALS will propel the aircraft off this ship.

APPENDIX A

Launch Image

Figure 2



Lieut. Cmdr. Henry C. Mustin made the first catapult launching from a ship on Nov. 5, 1915. He flew an AB-2 flying boat off the deck of USS North Carolina (ACR 12) in Pensacola Bay, Fla.

Source: U.S. Navy

APPENDIX B

Catapult Force Profiles

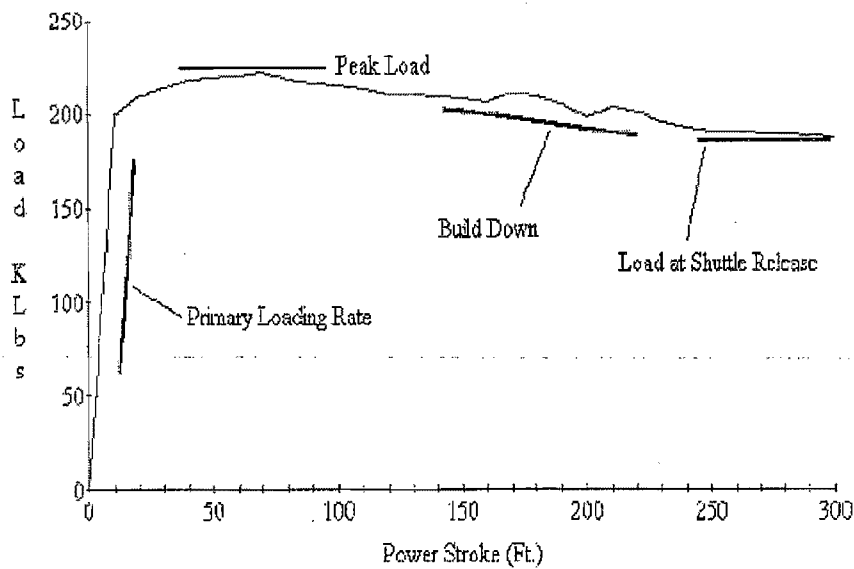


Fig.3. Steam Catapult Force Profile

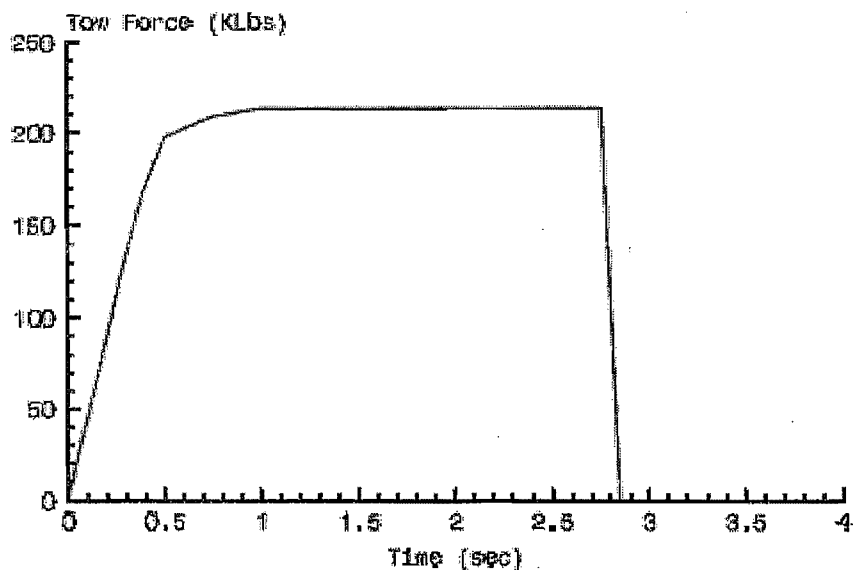


Fig. 4. EMALS Force Profile

Source: Doyle, Michael R., Douglas J. Samuel, Thomas Conway, and Robert R. Klimowski.
 "Electromagnetic Aircraft Launch System - EMALS." *IEEE Transactions on Magnetics* 31, no. 1 (January 1995):

APPENDIX C
Ford Class vs. Nimitz Class

Table 1

Class Type	Ford Class	Nimitz Class
Length	1092 ft.	1095* ft.
Flight Deck Width	256 ft.	252 ft.
Displacement	100,000 tons	101,000 tons
Crew Accomodations	4297	6180*
Catapults	4 EMALS	4 Steam

*Denotes Average of Nimitz class CVN 68 – CVN 76

Source: Naval Vessel Register, http://www.nvr.navy.mil/nvrships/s_CVN.htm

APPENDIX D

Major Events in the Development of Future Aircraft Carriers

Table 2

Year	Events
1993	• Navy establishes a carrier working group to investigate the requirements and available technologies and systems for a new class of aircraft carriers.
1998	• CVN(X) evolutionary design approach established.
2000	• Integrated process and product development contract awarded to Northrop Grumman Newport News. • Design begins on the new propulsion system. • CVN(X) program reaches Milestone 1.
2002	• CVN(X) changes to the CVN 21 program following the Navy's decision to eliminate an evolutionary strategy.
2003	• Construction contract award date shifted from 2006 to 2007.
2004	• CVN 21 program receives approval for Milestone B, the point for entry into the system development and demonstration phase of the DOD acquisition system. • Navy awards a construction preparation contract to Northrop Grumman Newport News.
2005	• Fabrication of the lead ship (CVN 78) begins.
2006	• Construction contract award date shifted from 2007 to 2008. • Construction preparation contract extended by 1 year until 2008. • Secretary of the Navy names CVN 78 USS <i>Gerald R. Ford</i>—initiating the Ford class. • Congress establishes a cost cap of \$10.5 billion for CVN 78 procurement in the Defense Authorization Act for Fiscal Year 2007 (Pub. L. No. 109-364§122 (2006)).
2007	• Navy requests authorization of CVN 78 construction in its 2008 budget request. • Defense Acquisition Board program review (expected). Updated Navy and DOD independent cost estimates were expected in support of the review.
2008	• CVN 78 construction contract award to Northrop Grumman Newport News.
2010	• CVN 78 keel lay.
2012	• Construction contract award for CVN 79.
2015	• CVN 78 delivery.

Source: GAO Report, GAO-07-866

APPENDIX E

Key Events and Challenges Related to EMALS

Table 3 Schedule of Key Events Relating to EMALS

2003	2004	2006	2007	2008	2009	2011
Developmental testing of competing systems on a half-length test bed.	Preliminary design competition completed, contractor begins system development.	Follow-up testing and evaluation.	Construction of a land-based test facility completed. Critical design review held.	High-cycle and land-based development and testing on a full-length test bed.	Production start.	EMALS required in yard for carrier construction.

Source: GAO Report, GAO-07-866

Table 4 Challenges Faced by the EMALS Program in Meeting Program Requirements

Weight requirement	The contractor initially designed and tested EMALS in a configuration that minimized the system's weight. After the Navy defined the ship's survivability requirements, the system was reconfigured, separating EMALS components and increasing the use of cabling. EMALS weight increased above its margin, resulting in a reallocation of weight elsewhere on the ship and the redesign of a subsystem. EMALS is now within its revised weight allocation.
Electromagnetic environmental effects requirement^a	Due to the effects of electromagnets, EMALS may interfere with the operations of shipboard systems or ordnance—and potentially harm the ship or personnel. After EMALS' design was stable, a number of electromagnetic effect issues emerged. The program has now taken steps to examine potential interference by hiring an expert and creating an integrated product team to analyze electromagnetic effects. However, tests to understand potential electromagnetic effects have not yet started and the effort required to mitigate these effects remains unclear.
Shipboard requirements	Shipboard requirements evolved during EMALS' design process as the design of the ship became better known. The contractor designed one subsystem component, the power conversion system, to generic shock and vibration requirements while waiting for the Navy's final determination of requirements. The subsystem may need to be reconfigured in order to meet final shock and vibration requirements, but the redesign will not occur until production. According to the contractor, limited coordination with the shipyard contributed to delays in meeting requirements. Initially, requirements were communicated via the Navy, creating a lag in delivery time. The contractor now believes that coordination issues have been resolved through direct communication between the shipyard and the EMALS program.
Systems engineering^b	The contractor underestimated the extent that systems engineering is needed to integrate EMALS into other shipboard systems. The contractor had not previously worked on shipboard systems and lacked the necessary staff to address the Navy's systems engineering requirements. The contractor has now hired additional systems engineers to manage the requirements process.

Source: GAO Report, GAO-07-866

1 On July 30, 1912, Lt. Theodore G. Ellyson attempted a catapult launch from the USS Santee. Ellyson made the Navy's first successful catapult launch on November 12, 1912, from a stationary coal barge, and on November 5, 1915, Lt. Cdr. H. C. Mustin made the first catapult launch from a moving ship.

2 Herbert M. Friedman and Ada K. Friedman. "Shot in the Air." *AmericanHeritage.com*. Spring 2006. http://www.americanheritage.com/articles/magazine/it/2006/4/2006_4_26.shtml(accessed October 12, 2009).

3 Herbert M. Friedman and Ada K. Friedman. "Shot in the Air." *AmericanHeritage.com*. Spring 2006. http://www.americanheritage.com/articles/magazine/it/2006/4/2006_4_26.shtml(accessed October 12, 2009).

4 Dictionary of American Naval Fighting Ships,
<http://www.history.navy.mil/danfs/b5/bennington-ii.htm>

5 The grab is essentially a spring-loaded latch mounted on a wheeled frame just aft of the shuttle that travels along the same track as the shuttle. After launch complete of the catapult, the rotary retraction engine automatically initiates the grab advance to retrieve the shuttle and return it to a "battery" position.

6 Catapult ranges for elongation are 5.5 to 9.0 inches, if less than 5.5 must have Maintenance Officer permission to fire as low as 5.0, elongation readings have to be within 1 inch of each other. As the catapult heats up the cylinders stretch more providing for higher speeds for the aircraft off the catapult. Elongation corrections must be taken into consideration when setting the Capacity Selector Valve for launch.

7 A suspend can be initiated at any one of six location for each catapult. A suspend is triggered by the pressing of a suspend button that electrically isolates the catapult from being able to complete the launch sequence.

8 LCDR Douglas Ramsey, Former Catapult Officer USS Dwight D. Eisenhower, telephone conversation, January 15, 2010.

9 LCDR Douglas Ramsey

10 Remark by Dr. Donald C. Winter during the naming of USS Gerald R. Ford, 16 January, 2007

11 United States Navy Fact File. *Aircraft Carriers – CVN 21 Program*. November 6, 2009. http://www.navy.mil/navydata/fact_display.asp?cid=4200&tid=250&ct=4 (accessed November 29, 2009). For comparison, the total ownership cost for a CVN 68 class ship is \$32.1 billion in FY 04 constant year dollars, and the total ownership cost for CVN 78 is expected to be \$26.8 billion.

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13 United States Navy Fact File. *Aircraft Carriers – CVN 21 Program*. November 6, 2009. http://www.navy.mil/navydata/fact_display.asp?cid=4200&tid=250&ct=4 (accessed November 29, 2009).

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Daily.com. September 29, 2009. <http://www.defenseindustrydaily.com/EMALS-Electro-Magnetic-Launch-for-Carriers-05220/> (accessed October 10, 2009).

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21 M. Doyle, G. Sulich and L. Lebron, "The Benefits of Electro magnetically Launching Aircraft," *Naval Engineers Journal*, (May, 2000): 78-82.

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28 Chris Johnson.

29 Chris Johnson.

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- 31 Government Accountability Office. *Defense Acquisitions: Navy Faces Challenges Constructing the Aircraft Carrier Gerald R. Ford within Budget*. (Washington DC: Government Accountability Office, August 2007),17.
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- 44 NAVAIR Press Release, September 28, 2009. "EMALS completes Highly Accelerated Life Testing, begins System Functional Demonstration launch motor commissioning." http://www.navair.navy.mil/press_releases/index.cfm?fuseaction=press_release_view&Press_rel

ease_id=4189&site_id=15.

45 Planned Incremental Availabilities are times when the carriers are brought to the shipyards for maintenance. Time spent in the shipyards depends on the type of maintenance performed. Pier-side PIAs last 4-7 months. Drydock PIAs last can last 10-12 months. Refueling and Complex Overhaul is the most significant overhaul the ship receives and takes approximately 3 years to complete.

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