The lead *Zumwalt* (DDG-1000) class destroyer pictured at speed in the Atlantic Ocean whilst undertaking acceptance trials on 21 April 2016. A cruiser-sized vessel of radical appearance, *Zumwalt* incorporates numerous technical innovations that are likely to have a significant impact on future US Navy surface combatants. *(General Dynamics Bath Iron Works)*

3.3 SIGNIFICANT SHIPS

ZUMWALT (DDG-1000)

PAST AND FUTURE TENSE

Authors:
Edward Feege & Scott Truver

As America's newest destroyer *Zumwalt* (DDG-1000) made her way towards the Atlantic Ocean and her initial sea trials in December 2015, observers on the banks of Maine's Kennebec River could be forgiven for wondering if they were gazing upon a relic of a past era – or the harbinger of things to come.

A cruiser in all but name, the 15,800-ton *Zumwalt* 'land-attack destroyer' was conceived in the 1990s, when the US Navy's greatest challenge was to operate and fight in the world's near-shore, littoral environs. That primarily translated into the projection of power ashore, and supporting operations against 'rogue' nations. This was a tall order, and one that assumed that the United States could concentrate more on the plethora of shorter-range 'green-water' threats closer to shore than on 'blue water' threats represented by the Soviet navy that had imploded with the fall of the Berlin Wall.

The *Zumwalt* class traces its origins to 1990s plans to supplement existing multi-

mission *Arleigh Burke* (DDG-51) class destroyers and *Ticonderoga* (CG-47) class cruisers with a cheaper single-mission combatant – the DD-21 – focused on littoral warfare. Although the DD-21 design was ultimately scaled back, the new warship is still considerably larger and more expensive than the ships that were intended to form the 'high end' of this force mix. As a result, orders were reduced to just three ships in favour of renewed production of the DDG-51 type; *Donald Cook* (DDG-75) is shown here. *(US Navy)*

That situation changed during the next decade. As if overnight, the US Navy was faced with a myriad of 'anti-access/area-denial' (A2/AD) challenges from rising – or recovering – powers such as China and Russia and from regional powers and non-state actors that were gradually improving their arsenals. Increasingly, assured access by sea to key areas of the world was no longer certain. Given this shift, and growing programme costs, the DDG-1000 class no longer looked as critical, or as affordable, as originally envisaged. The US Navy's enthusiasm for these ships waned, and Service and Department of Defense officials ultimately decided to limit the number of ships in the class to three, down from thirty-two when the requirement for a new destroyer was first conceived.

The fact that *Zumwalt* and her two sisters survived at all was testament to the promise that the warships held for the future US Navy, not the littoral-focused service of the 1990s. The ships in the class have numerous features that push the state of the art in American naval combatants. But the key to DDG-1000's survival, and possibly the US Navy's future, lay in only a handful of areas, particularly shipboard electrical power.[1]

The CG-47 class cruiser *Monterey* (CG-61). Continued investment in 'high end' multi-mission combatants such as the CG-47 design was the US Navy's preferred option at the end of the Cold War but budget constraints resulted in a two-tier force structure

plan. The proposed DD-21 design – from which *Zumwalt* emerged – formed the 'low end' of this mix. *(US Navy)*

PROGRAMME ORIGINS

The *Zumwalt* class had its genesis in the aftermath of the victory of the United States and its coalition partners over Iraq during Operation 'Desert Storm' and the first Gulf War. In 1992, then-Chief of Naval Operations Admiral Frank Kelso commissioned the '21st Century Destroyer Technology' Study to establish the requirements for a new surface combatant to be built in the mid-to-late 2000s. The study was influenced by several aspects of the post-'Desert Storm' world, including the lack of a well-defined threat and a corresponding framework for American operations. Fiscal constraints, that had been growing more stringent since the end of the Cold War in 1989, also loomed large, as did the navy's experience in the war with Iraq and its overwhelming focus on projecting power ashore.[2]

A graphic of the approved *Zumwalt* design, dating from around the time funding for the first two ships was approved under the FY2007 budget. The design featured fewer missiles and a lower magazine capacity than the initial DD-21 project but otherwise kept many of its predecessor's features. *(US Navy)*

In a nod to the fiscal environment the navy was facing, the study participants concluded that the preferred option – a surface combatant force consisting solely of high-end, multi-mission warships – would not be realistic. Instead, they recommended a

two-tier 'family' of ships, with multi-mission warships comprising the 'high' end of the force, while other combatants – focused on one particular mission – made up the 'low' end. The requirements for this Surface Combatant (SC)-21 family of ships concept was blessed by the Joint Requirements Oversight Council – the Vice Chairman of the Joint Chiefs of Staff, the second highest-ranking US military officer, and the four chiefs of the military services – in June 1994. The navy subsequently performed a formal analysis of alternatives, which established the force architecture it would require to meet its war-fighting requirements, and the performance it demanded of the ships within the force. Planners determined that a focused-mission, land-attack combatant would be the first of the SC-21 family of ships to be ordered.[3]

Rear Admiral Daniel J Murphy, the navy's Director of Surface Warfare, laid out the key parameters for this all-important power-projection mission in an article in the US Naval Institute's *Proceedings* journal in June 1997, viz.

- Surface fire (gun) support for US forces ashore at ranges of up to 75 miles (120km) inland.
- Interdiction fire to break up armour and troop concentrations at ranges of 200 miles (322km) inland.
- Deep strikes against enemy command-and-control nodes, air defences, and ballistic missile forces at ranges of 1,000 miles (1,600km) or more.[4]

The proposed DD-21 design featured a number of characteristics intended to help it fight and survive in a challenging littoral environment, including a drastically reduced radar cross-section achieved by use of a tumblehome, wave-piercing hull design. This feature survived into the recast DD-(X)/DDG-1000 design and is one of a range of

technologies tested in the Advanced Electric Ship Demonstrator (AESD) *Sea Jet*. A 41m, roughly quarter-scale model of an actual destroyer, *Sea Jet* is operated by the Naval Surface Warship Center Carderock MD from its acoustic research detachment at Bayview ID. *(US Navy)*

US Navy efforts to meet these ambitious requirements led to concepts for two significantly different combatants: A Maritime Fire Support Ship and the DD-21 land-attack destroyer. The former concept – an austere missile carrier, equipped with 512 vertical launching system (VLS) missile tubes and manned by a small crew – was also known as the 'arsenal ship'. The arsenal ship concept was first relegated to the status of technology demonstrator and then ultimately cancelled in 1997.[5]

That left DD-21, a warship able to help achieve maritime dominance but with a focus on land attack. Its capabilities in the former mission area – which included anti-submarine and anti-surface ship warfare – would allow the new class of thirty-two DD-21s to replace the aging *Spruance* (DD-963) class destroyers and *Oliver Hazard Perry* (FFG-7) class frigates. Its capabilities in the land-attack arena would allow it to close a gap in the ability to provide surface fire support to US Marine Corps and other forces ashore. That shortfall had worsened when the Navy retired its last two Second World War-era *Iowa* class battleships after 'Desert Storm'.[6]

Two views of *Zumwalt* under construction at Bath Iron Works (BIW) in Maine on 15 October 2013, shortly before float out. The ship rests on a wheeled transfer system that allowed movement into the floating dry dock used for launch. The middle section of the second ship in the class, *Michael Monsoor*, is positioned astern. The images clearly show the tumble-home, wave-piercing hull design – used to reduce radar cross-section and therefore improve survivability in a littoral environment – that has survived from the

original DD-21 land-attack destroyer concept. *(General Dynamics Bath Iron Works)*

Simply put, the DD-21s would be able to fight and survive in the challenging littoral environment and deliver high-volume gun and missile fires in support of ground and air campaigns ashore. Some of the key ship characteristics that would facilitate this capability would include:

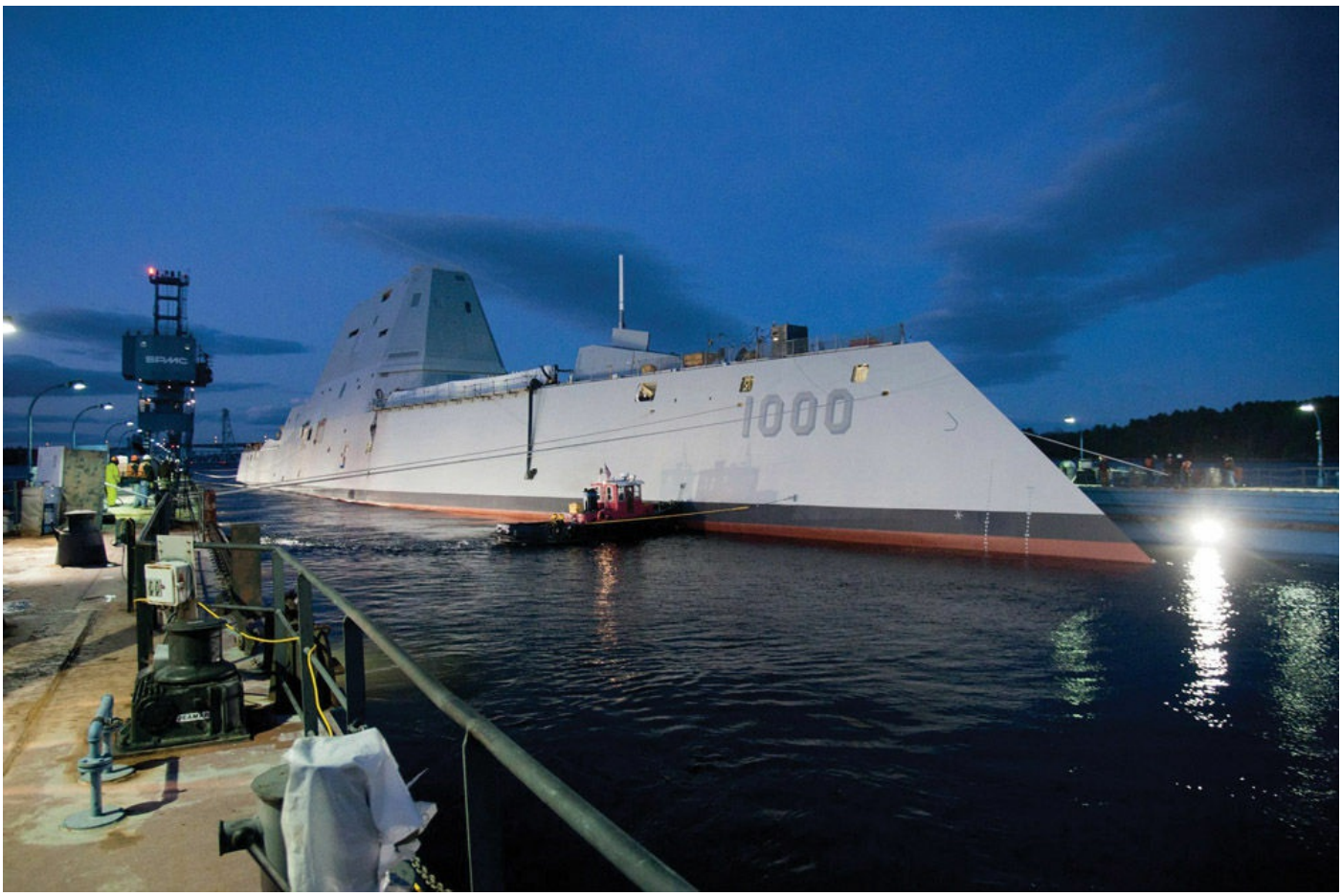
- A 1,400-round, twin 155mm vertical launch gun system (referred to as a VGAS, which later evolved into the Advanced Gun System, or AGS).
- Two 64-cell VLS packs 'capable of launching any missile in the 21st Century surface navy inventory'.[7]
- A drastically-reduced radar cross-section (RCS), achieved in part through the use of a tumblehome, wave-piercing hull design that scatters and diffuses radar reflections away from enemy receivers. This would be combined with a significant reduction in the ship's acoustic signature, which the navy announced would be achieved in large part through the use of quiet, electric-drive propulsion.
- A new radar geared towards ship self-defence, and a sonar optimised for underwater detection of submarines and mines in the littoral environment.
- A crew size of 95–150, smaller than that of any US Navy surface combatant then in service.[8]

And as Rear Admiral Murphy noted, the intent was to do all of this cost-effectively – the

unit cost of the fifth ship in the class was not to exceed US$750 million in FY1996 dollars.[9]

In 1998, the US Navy, in consultation with its private-sector vendors, devised a plan under which two industry groups would compete to design and provide life-cycle support to the ships in the DD-21 class. The 'Blue' team was centred on General Dynamics and its Bath Iron Works (BIW) shipbuilding subsidiary, along with Lockheed Martin as the team's system integrator. Similarly, the 'Gold' team included Northrop Grumman and its Ingalls Shipbuilding subsidiary, paired with Raytheon, which would be that group's system integrator. Ultimately, the navy expected that both teams would split the actual construction of the planned destroyers.

As the programme moved forward, DD-21 also acquired a name. In July 2000, the US Navy announced that the first ship in the class would be named for Admiral Elmo R Zumwalt, the Chief of Naval Operations from 1970 to 1974. But even at this stage, however, events were conspiring to drastically reduce the class's size and budgetary impact.



A picture of *Zumwalt* being floated out on 28 October 2013. Note the raised 155m gun barrel of the forward AGS mounting. The two AGS mountings, which provide the class's main land-attack capability, have been a significant driver of overall ship size. *(General Dynamics Bath Iron Works)*

THE GREAT TRUNCATION

As preliminary designs for *Zumwalt* moved forward, the US Navy realised that the requirements for its new destroyer class were driving up the ship's size and costs. DD-21's estimated fullload displacement grew from an initial 9,000 tons to between 16,000 and 18,000 tons. This was driven in part by a combination of the low-RCS tumblehome hull and the outfit of guns, VLS and missiles the ship would carry. In comparison, the Navy's *Ticonderoga* (CG-47) class cruisers had a full-load displacement of only 9,600 tons. That said, inside-the-lifelines volume was cheap; it was what was going to be installed that soon generated 'sticker shock'.

With time, the navy gained a better appreciation of the technical risks associated with the development of DD-21's electronics, weapon systems and propulsion. Consequently, the US$750 million price tag for a fifth ship in the class looked increasingly unattainable. Cost growth in ship programmes is not unusual, but the potential magnitude of that growth – and the impact burgeoning DD-21 costs might have on other US Navy programmes – increasingly pointed to the need for a course correction.

That came in November 2001, when the Navy announced that the DD-21 had been replaced by a new DD(X) Future Surface Combatant Program. This programme included a 'family' of ships, including a DD(X) destroyer, a multi-mission CG(X) cruiser to handle air and missile defence, and a smaller littoral combat ship (LCS) to deal with submarine, mine and fast attack craft threats closer to shore.[10]

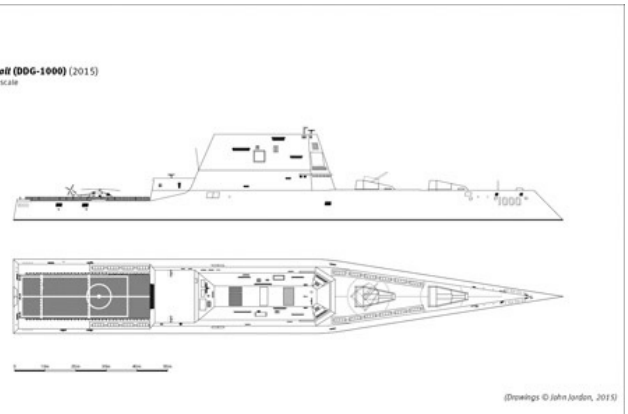
DD(X) essentially would be DD-21 – but smaller. DD(X)'s armament, sensors, low-RCS features, crew size, advanced automation, electric drive and other features would be similar to its predecessor. But in a nod to affordability, the number of VLS cells would shrink from a planned 128 on the DD-21 to eighty on DD(X), while magazine capacity for DD(X)'s AGS mounts would also be reduced. However, DD(X) would add new dual-band radars – an X Band (NATO I/J Band) multi-function radar and an S-Band (NATO E/F Band) volume-search radar – giving ships in the class an area air-defence capability not originally planned.

Table 3.3.1.

ZUMWALT (DDG-1000) PRINCIPAL PARTICULARS

Building Information:	
Fabrication Commenced:	11 February 2009[1]
Launched:	28 October 2013
Commissioned:	15 October 2016 (planned)
Builders:	General Dynamics Corporation's Bath Iron Works yard, Bath ME, USA.
Dimensions:	
Displacement:	15,761 tons full load displacement.[2]
Overall Hull Dimensions:	186.0m x 24.6m x 8.4m (sonar).
Equipment:	
Missiles:	20 x Mk 57 4-cell VLS modules. Can accommodate most current and planned US Navy vertically-launched missiles. Will initially be equipped with BGM-109E Tomahawk land-attack cruise missiles and RIM-162 ESSM.
Guns:	2 x 155mm Advanced Gun Systems (AGS). 2 x 30mm Mk 46 GWS (yet to be fitted).
Aircraft:	2 x MH-60R Seahawk helicopters or 1 x MH-60R and 3 x MQ-8 Fire Scout series UAVs.
Boats:	Internal bay for up to 2 x 11m RHIBs.
Countermeasures:	Unspecified ESM/ECM system. Space reserved for AN/SLQ-25 Nixie torpedo-defence system.
Principal Sensors:	AN/SPY-3 multi-function radar. Navigation radar. AN/SQQ-90 integrated undersea warfare suite comprising AN/SQQ-60 MF and AN/SQQ-61 HF bow arrays and AN/SQR-20 towed array.
Combat System:	Raytheon Total Ship Computing Environment (TSCE) linked to Common Display System (CDS) workstations.
Propulsion Systems:	
Machinery:	Integrated Electric Propulsion. 2 x Rolls-Royce MT30 gas turbines each rated at 35.4MW and 2 x Rolls-Royce RR4500 gas turbine generator sets each rated at 3.9MW produce a total of 78MW ship power. Propulsion through 2 x GE Power Conversion Advanced Induction Motors each rated at 33.6MW producing a total of c. 90,000hp through two fixed shafts.
Speed:	Designed maximum speed is in excess of 30 knots.
Other Details:	
Complement:	A typical crew comprises c. 147 personnel plus an additional 28-strong aviation detachment. Accommodation for 186 personnel.
Class:	Three ships have been ordered: *Zumwalt* (DDG-1000), *Michael Monsoor* (DDG-1001) and *Lyndon B. Johnson* (DDG-1002).

Notes:
1 Official keel laying was 17 November 2011.
2 There are significant variations in quoted displacement figures for the class. The quoted figure is from the US Navy's Naval Vessels Register as of June 2016.



US Navy planners believed that those changes would bring the new ship's displacement below 15,000 tons and decrease costs. Nevertheless, DD(X) – still named *Zumwalt* – would be the largest surface combatant to serve in the US Navy since the

nuclear-powered cruiser *Long Beach* (CGN-9) of 1961. Moreover, the estimated cost of the fifth ship would remain over US$1 billion. These stubbornly high programme costs led the navy to reduce its acquisition plans to twenty-four ships, a fall of eight from DD-21. And that was not the end of the shrinking horizons for DD(X). Between 2001 and 2005, the number of ships in the programme was cut again, first to between eight and eleven, and then to between five and six ships.

Aware that these costs were still excessive for a ship focused on a single mission, the navy also reclassified DD(X) as a multi-mission combatant, now designated DDG-1000, in April 2006. Now six ships would follow the first ship in the class. The US Congress funded the first two ships of the class in 2007, with funding split across two fiscal years.

Even with this progress, further programme cuts were made in 2008. This time, however, the navy's leadership emphasised *Zumwalt*'s shortcomings in light of a changing strategic environment. Service officials announced that the class would be limited to three ships, and that the resources thus freed up would be devoted to the construction of additional *Arleigh Burke* (DDG-51) class destroyers, which formed the backbone of the service's surface warship force. As Chief of Naval Operations Admiral Gary Roughead explained, changes in the threat environment drove the Navy's decision:

> The world has changed markedly since we began the march to DDG-1000 in the early 1990s. Between 1990 and 2006, for example, approximately one new nation developed a ballistic missile capability every three years and then in July of 2006 the terrorist group Hezbollah, not a nation, launched an anti-ship missile against the Israeli ship *Hanit*. DDG-1000 did not address these important changes and challenges. In addition, while it has been optimised for littoral anti-submarine warfare, the growth of the worldwide submarine fleet – a growth projected by business sources to be 280 submarines over the next two decades – does not allow us to diminish our deep-water capabilities. For these reasons, I made the difficult decision to truncate DDG-1000, to take advantage of the technologies, to learn from them, but continue the DDG-51 line because it has the right capabilities and provides greater capacity where we need it.[11]

Cutting the class size meant that upfront development costs would be spread across three ships, not the thirty-two first envisioned. That in turn, caused an eighty-six per cent jump in unit cost, which in 2010 led to a breach under the Nunn-McCurdy provision of US acquisition law.[12] With the breach, the Under Secretary of Defense for Acquisition, Technology, and Logistics Ashton Carter (in 2015 confirmed as Secretary of Defense) stepped-in to determine the cause of the spike. Carter's office also worked with the US Navy to bring the programme back in line with acquisition law if possible, or terminate it if costs and performance could not be brought back under control.

The navy and the Office of the Secretary of Defense (OSD) agreed that the breach

mainly was a function of cutting the size of the class. The programme was re-authorised to proceed, but with changes imposed. One was a design alteration – the ship would no longer feature a dual-band radar. The S-band volume-search radar was foregone, although the option to back-fit it at a later date was retained. That left the *Zumwalt* class *s*hips with only an X-band multi-function radar, dubbed AN/SPY-3. With those decisions, the final structure of the class was in place.[13]

Names of the second and third ships were announced in 2008 and 2012. DDG-1001 eventually was named *Michael Monsoor* in honour of a Navy SEAL and Medal of Honor winner killed in Iraq in 2006. DDG-1002 was named after the 36th President of the United States, Lyndon B Johnson.

An April 2016 view of *Zumwalt* on trials from General Dynamics' Bath Iron Works yard. Although a Northrop Grumman-led team won the initial detailed design contract for the class, all three members of the class have been built at the General Dynamics' facility. *(US Navy)*

BUILDING THE *ZUMWALT* CLASS

In April 2002 the navy awarded the Northrop Grumman-led Gold team a US$2.88 billion contract to conduct preliminary design work on DD(X) and to build and test engineering development models of key systems to reduce the risks associated with the new technologies slated for the ship. The navy subsequently brought much of the Blue team into the fold in a bid to ensure that both Northrop Grumman's Ingalls Shipbuilding and General Dynamics' Bath Iron Works could both bid on the detailed design and construction of DD(X), beginning in FY2005.

In 2004, the navy and the OSD agreed on an acquisition strategy that would see Northrop Grumman's Ingalls yard in Mississippi build the first ship in the DDG-1000 class. General Dynamics' BIW would build the second ship at its yard in Maine. The remaining ships in the class – not yet truncated at three ships – would be split between both shipbuilders. The navy's leadership changed its mind in 2005, and asked for permission to hold a winner-take-all-competition between the two shipbuilding groups. But OSD reticence and the opposition of congressional delegations from Mississippi (home to Ingalls) and Maine (home to BIW) scuppered that approach. The navy then switched to a dual lead-ship approach, with each yard building one ship of the pair authorised in the FY2007 budget.

The navy's announcement limiting the class to three ships resulted in further changes. Three-way navy and industry talks took place in 2009, after which the service announced that GD/BIW would build all three *Zumwalt* class ships, while Ingalls would build a greater percentage of the additional DDG-51 destroyers also announced in 2008. Ingalls also would provide components for the DDG-1000s, including deckhouses made of composite materials. By that point, fabrication had already begun on *Zumwalt*.

The distinctive deckhouses of the first two *Zumwalt* class ships are constructed of composite materials to reduce weight. They were the most significant of a number of components for the ships' provided by Ingalls shipbuilding business. The third ship, *Lyndon B. Johnson*, uses a more traditional steel structure. *(US Navy)*

CLASS CHARACTERISTICS

The mix of littoral combat-driven systems, combined with numerous state-of-the-art systems – some of which may be included in future warships – makes the DDG-1000 and its sisters a rare breed of warship. Some of the key attributes of these ships are discussed below. See also Table 3.3.1 for further technical details.

Stealth and Survivability: One of the more striking aspects of the DDG-1000 design is the hull and superstructure, all shaped to lower the ship's RCS. Designers originally targeted a DD(X) RCS fifty times smaller than that of the *Arleigh Burke* (DDG-51) class ships. The decision to rely upon a tumblehome hull with a wave-piercing bow was a key part of this process. However, this type of hull shape also offered less internal volume than a more conventionally-shaped hull of the same size and displacement. Recovering internal volume that otherwise would have been lost – and adding reserve space and weight that could be used to adapt DDG-1000 for future systems and missions – led to the increase in the ship's size and displacement. At c. 15,800 tons, *Zumwalt* has a greater displacement than any other current US Navy surface combatant. The DDG-1000's tumblehome hull and wave-piercing bow might also create sea-keeping problems under more extreme conditions, as *Zumwalt*'s first prospective commanding officer, Captain James Kirk, noted:

> In extraordinary seas – wave heights greater than 20 feet, the ship can, if not sailed

with care, experience undesirable righting motions. To address these concerns, extensive model testing at Naval Surface Warfare Center Carderock, Maryland, has been conducted, and a safe operating envelope across these higher sea states, which are expected for no more than 400 hours over the 35-year service life of the ship, has been developed.[14]

This aerial view of *Zumwalt* gives a good impression of the ship's overall stealthy design, particularly the use of careful shaping of external surfaces to reduce radar cross-section. It is interesting to note the dividing line – just above bridge level – between the steel and composite deckhouse structure, as well as how the composite hangar has also been attached to the steel structure aft. Other details include the two stealth enclosures for the 155mm AGS mounts forward of the deckhouse. The launch cells for the Mk 57 VLS that forms the Peripheral Vertical Launching System are grouped around the edges of the deck. *(US Navy)*

Indeed, during the December 2015 tests, which totalled 100 hours and ranged across the Gulf of Maine, US Navy and Bath Iron Works personnel tested the *Zumwalt* at full power – more than 30 knots – and ran the propulsion plant through more than a dozen different configurations. The tests also subjected the ship to a series of sharp turns (full rudder swings) to determine stability and overall manoeuvrability. This was to address concerns of observers who predicted that the ship would 'turnturtle' during a sharp turn or in heavy seas. Naval architect Ken Brower told *Defense News* in 2007: 'The trouble is that as a ship pitches and heaves at sea, if you have tumblehome instead of flare, you

have no righting energy to make the ship come back up. On the DDG-1000, with the waves coming at you from behind, when a ship pitches down, it can lose transverse stability as the stern comes out of the water—and basically roll over.'[15]

Those concerns have now seemingly been laid to rest. 'The faster it goes, the faster it responds', according to Rear Admiral (select) James Downey, *Zumwalt* programme manager, in January 2016 noting that the ship was able to stop in only 90 seconds.[16] The innovative tumblehome hull design had no issues with the eight- to ten-foot swells it encountered, and manoeuvrability was not affected at all.

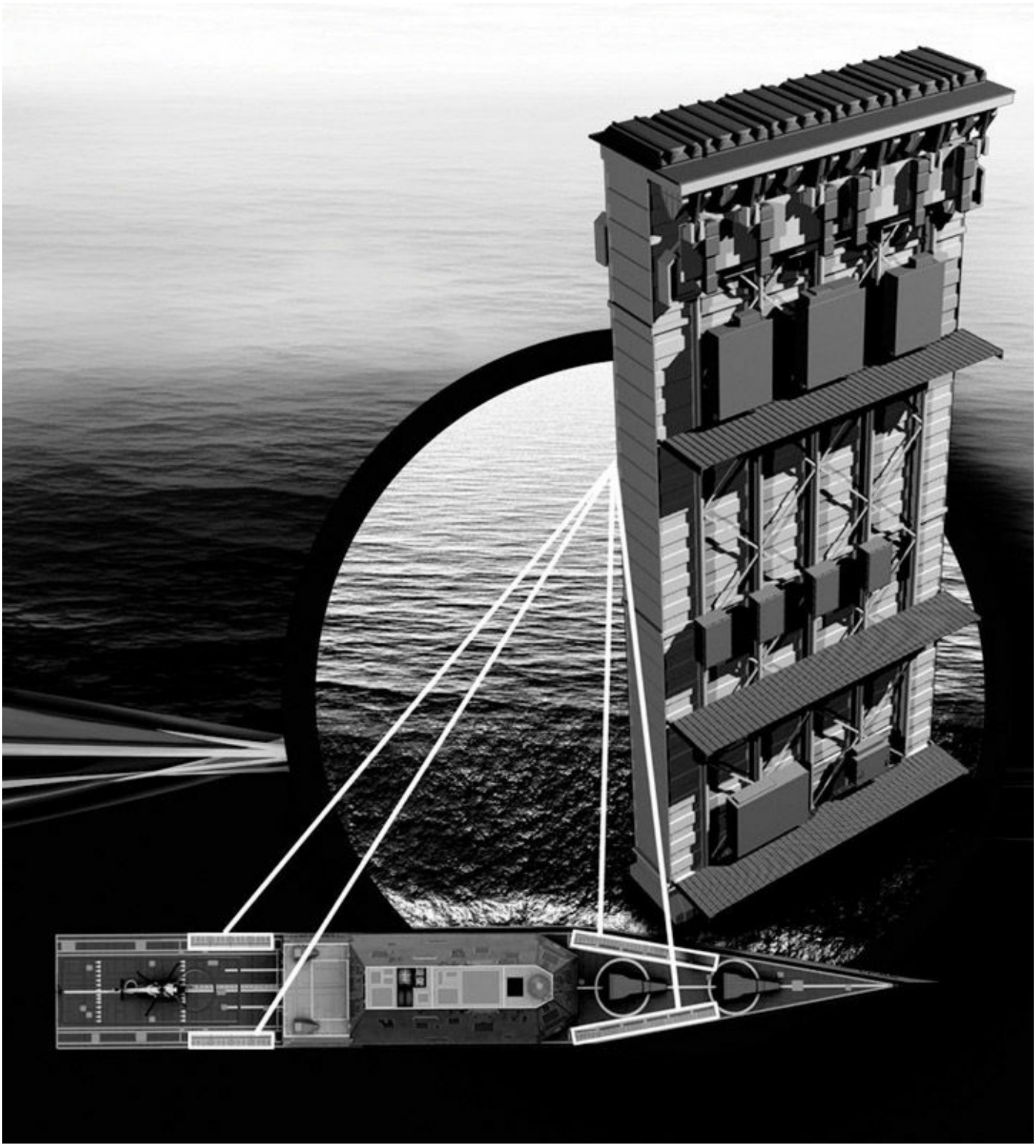
DDG-1000's deckhouse is also shaped to reduce radar and infrared signatures. The first two ships of the class will rely upon deckhouses built with composite materials to effect this reduction and to remove weight. Their deckhouses are formed by panels and beams made of carbon fibre and vinyl ester skins, combined with balsa and foam cores. The ships' helicopter hangars, which are integrated into the overall superstructure, are formed with the same material.[17]

Many of the antennas for the ship's communication systems and sensors are embedded within their composite deckhouses, with the antenna faces flush with the deckhouse surface. However, as a costsaving measure – taken in the aftermath of the 2010 Nunn-McCurdy cost target breach – the navy has apparently chosen to add a mast to the deckhouse design and relocated several antennae from the deckhouse to that mast, as well as to platforms on the side of the deckhouse. The move will increase the ships' RCS, although they still meet their overall signature-reduction targets.[18]

Northrop Grumman and subsequently its Huntington Ingalls Industries (HII) successor built the composite deckhouses at a facility in Gulfport, Mississippi, from where they were transported to BIW by barge.[19] That will not be required with DDG-1002, however, as the navy announced in 2013 that DDG-1002 would have a steel superstructure instead of relying on a composite deckhouse. The service justified the move by noting that it had achieved greater weight savings with DDG-1002's design, and thus could forego the use of the composite deckhouse. The steel structure for the third ship is being built by BIW, which eliminates the transportation and integration costs associated with the previous arrangement.[20]

Two images showing a mock-up of a Mk 57 vertical launch system and its positioning on *Zumwalt* class ships. The Mk 57 system on *Zumwal*t comprises twenty four-cell units. Six of these are located on either side of the forecastle, with a further four on either side of the forward part of the helicopter deck. The system can handle most

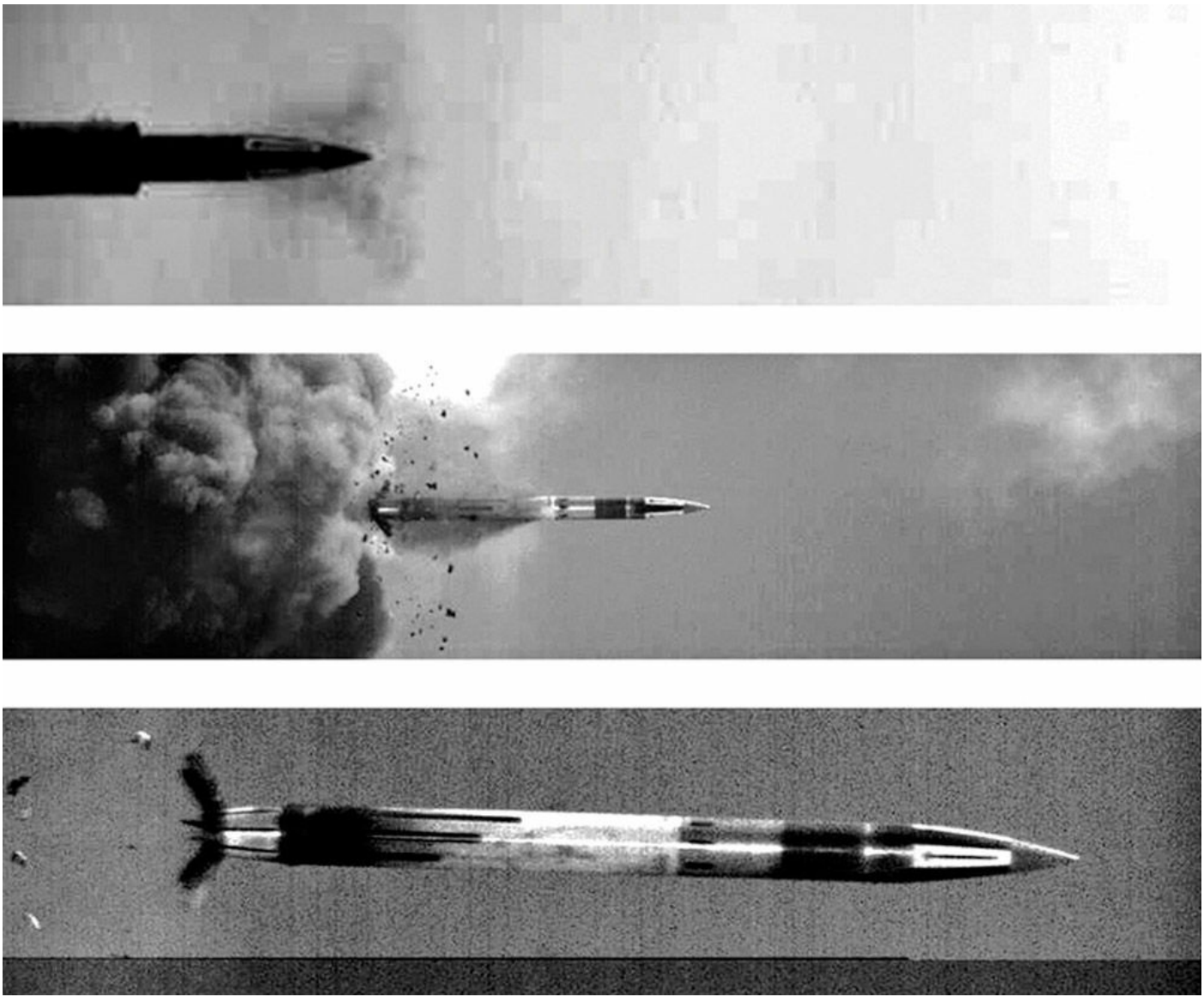
current and planned verticallylaunched missiles in the US Navy's inventory. *(Raytheon, BAE Systems)*



Weapon Systems: Given the *Zumwalt* class was designed around the naval surface fire-support mission, the new 155mm AGS is a central element in DDG-1000's arsenal. The early 1990s retirement of the US Navy's last battleships left only 5in/54-calibre (127mm) guns in the fleet to provide support to US Marine Corps and other troops ashore.[21] That system had a maximum range of only 13nm (24km), compared with the 23nm (43km) range of the battleships' 16in guns when firing unguided, unassisted

weapons. At this short range, any warship providing gunfire support would be exposed to a range of anti-ship missile, rocket and artillery fire from shore defences. Only a longer-range weapon that allowed the firing ship to remain over the horizon from most enemy sensors and weapons would generate a reasonable chance of survival in a contested littoral environment.

For DDG-1000, the answer is the Mk 51 155mm AGS, an integrated gun and magazine weapon system capable of a maximum sustained firing rate of ten rounds per minute to ranges of up to 63nm (117km). The *Zumwalt* class's AGS are located in two bow turrets, each with its own automated magazine and weapon-handling system. The guns themselves incorporate thermal- and erosion-management technologies that help extend their barrel life and minimise infrared signature. Below deck, the magazines, which are unmanned, provide total storage for up to 600 rounds. And the control system for the AGS encompasses both gun and fire control, and is in turn integrated with the overall ship computing environment.



A picture of a prototype 155mm Long-Range Land-Attack Projectile (LRLAP) undergoing testing in 2005. LRLAP rounds use rocket assistance and GPS guidance in conjunction with an inertial navigation system to provide extended range and improved accuracy for

the *Zumwalt* class's AGS mounts. *(Northrop Grumman)*

The projectiles that the Mk 51 guns will fire are critical to the effectiveness of the AGS. The rocketassisted 155mm Long-Range Land-Attack Projectile (LRLAP) features a unitary warhead, as well as hardened electronic systems capable of surviving the forces associated with its firing from a gun tube. These include a miniaturised Global Positioning System (GPS) receiver and inertial measurement unit receiver that provide guidance for the round. In addition to their range, these projectiles have a nearly vertical angle of fall during the final stage of their trajectory. This should help limit collateral damage when employed in urban or other crowded environments, according to LRLAP sub-contractor Lockheed Martin.

Missiles also provide an important offensive and defensive punch for the DDG-1000s. The *Zumwalt* class ships are equipped with the Mk 57 VLS, which consists of twenty, four-missile cells able to launch Tomahawk (BGM-109) cruise missiles, the SM-2, SM-3 and SM-6 variants of the Standard surface-to-air missile, and Evolved Sea Sparrow (ESSM, or RIM-162) self-defence missiles. Initially Tomahawk and ESSM will be installed. The systems can also support the Vertical Launch Anti-Submarine Rocket (ASROC), or VLA. In addition, the Mk 57 cells have room to accept future missiles that may be up to 25in (653mm) in diameter – greater than the 21in (533mm) tube limit of the Mk 41 VLS on other US Navy combatants. The Mk 57 uses an open software architecture, which likewise facilitates the addition of new weapons or system modifications, at a relatively low cost in time and resources.

Unlike other US Navy surface warships, the missile cells fitted in the *Zumwalt* class are arranged as a Peripheral Vertical Launching System (PVLS). This arrays the missile cells in rows at the edge of the main deck. The inboard bulkheads of the system are heavily reinforced, so that any magazine explosion would be directed outward. There are twelve PVLS modules (six per side) on the forecastle of the ship, with eight flanking the flight deck aft (split four per side).

In addition to the major weapon systems mentioned above, the DDG-1000 class ships will also be fitted with two Mk 46 Gun Weapon Systems (GWS). Based on the Bushmaster 30mm chain gun – which fires up to 200 rounds per minute, to a maximum range of about 4,000m – the Mk 46 is designed to help the *Zumwalt* class counter swarming small-boat attacks in littoral regions. The US Navy substituted the Mk 46 for the 57mm Mk 110 gun system originally designated for use on board the new destroyers, with the service saying that the 30mm GWS was more costeffective.[22]

An external view of the hull-mounted elements of *Zumwalt*'s AN/SQQ-90 sonar suite. The sonar dome encloses an AN/SQQ-60 mid-frequency sonar and an AN/SQQ-61 high-frequency sonar in one automated system. AN/SQQ-90 also includes an AN/SQR-20 towed array sonar. *(General Dynamics Bath Iron Works)*

Radar Systems: The Department of Defense decision to delete the class's planned S band volumesurveillance radar in response to the Nunn-McCurdy breach left the DDG-1000 class ships without a long-range surveillance and ballistic missile defence capability. In this regard, the *Zumwalt* class ships are inferior to the Navy's DDG-51

class destroyers and CG-47 class cruisers that are equipped with the AN/SPY-1 radar associated with the Aegis weapon system. The disparity with the in-work DDG-51 Flight III destroyers that will be fitted with the AN/SPY-6 air- and missiledefence radar (AMDR) will be greater still. However, the *Zumwalt* class retain the space and weight capacity to accept a long-range volumesearch radar at some point in the future, should the Department of Defense and US Navy ever decide to reverse their position.

Nevertheless, as a modern multi-function active phased array, AN/SPY-3 still represents a considerable capability, particularly in the littoral environment. Operating in the X Band, the SPY-3 has a narrow beam width and wide frequency bandwidth, which are particularly useful for the detection and tracking of low-altitude and low-observable targets. This band is also provides target-illumination capabilities for the ship's ESSM – and other surface-to-air missiles that may be installed – dispensing with the need for separate illuminators found on existing cruisers and destroyers. Installation of the radar is designed to preserve the *Zumwalt* class's low RCS, with three flat transmitting and receiving phased-array antenna faces that provide 360° coverage.

The SPY-3's software also has been modified in an attempt to regain some of the volume-search capabilities lost with the deletion of the S band array. The modification allows the radar to alternate between volume and horizon searches at the operator's preference, although optimising the SPY-3 for one type of search can degrade the radar's capabilities in the other mode. The software alteration underwent testing at the Wallops Island Integration and Test Center in Virginia, and will be further evaluated on board the Navy's Self-Defense Test Ship. However, current 2016 configuration does not provide for area air or ballistic missile defence operations.

This March 2016 view of *Zumwalt* shows how the arrays for the AN/SPY-3 radar and

other sensors are mounted flush with the sides of the deckhouse. Other key features visible include the angled doors in the stern for the internal boat bay located under the large flight deck. The raised safety barriers are fitted in the place of the netting used on other surface combatants and have a radar-absorbing coating to reduce signature. They are raised and retracted automatically. Also of note is the position of the two navigation radars on the superstructure; these will be replaced by two Mk 46 30mm guns when the ship completes fitting out at San Diego. *(Christopher P Cavas)*

Sonar: The AN/SQQ-90 integrated undersea warfare suite onboard the *Zumwalt* class includes the US Navy's first dual-frequency hull-mounted sonar system. It consists of three major components: a hull-mounted AN/SQQ-60 mid-frequency sonar, a hull-mounted AN/SQQ-61 high-frequency sonar array, and an AN/SQR-20 multi-function towedarray sonar. Together with embarked MH-60R Seahawk helicopters, the periscope-detection capability resident in the SPY-3 radar, and the inherently quiet operation of the class's electric propulsion, the SQQ-90 provides the new destroyers with significant anti-submarine warfare potential.

The difficult underwater environment in the littorals, where shallow-water sound reverberations can play havoc with detection and detection ranges, was the major driver for the SQQ-61 hull-mounted array. The sonar array also will provide the DDG-1000s with an 'in-stride' mine-avoidance capability. And for its part, the AN/SQR-20 multi-function towed array sonar and handling system, which is capable of both active and passive operation, promises better coverage and detection ranges, as well as less 'down time' than previous towed arrays.

Commercial-off-the-shelf components, automation and more advanced information processing also allow the SQQ-90 to be operated and maintained with up to one-third fewer people than in service fleet sonar systems. SQQ-90 also benefits from the assembly and integration of its sonar electronics into an electronic modular enclosure (EME). The pretested EME also provides cooling, shock, vibration and electromagnetic interference protection.

A mock-up of the layout of the Common Display System workstations in the *Zumwalt* class's Ship Mission Center (SMC). The Common Display System consoles are identical, three-screen workstations that can be reconfigured to perform a wide variety of tasks necessary for the *Zumwalt's* effective operation. *(Raytheon)*

Total Ship Computing Environment: The sonar EME is just one of several of these modular components that are intended to facilitate shipyard installation and reduce size and weight impacts on the *Zumwalt* class hulls. In total, DDG-1000 will have sixteen EMEs, with each shock-resistant enclosure acting as a data centre holding and supporting the key electronics for all major systems on board the ship. Distributed around the ship, the EMEs then feed the Total Ship Computing Environment (TSCE), an open-architecture, Linux-based information network that ties together the combat management, engineering control, bridge, navigation systems and damage-control systems. In essence, the TSCE provides an internal Internet network for the ship.

This arrangement allows the *Zumwalt* class's systems to be controlled from similar consoles located throughout the ship. The Common Display System features identical, three-screen workstations that can be configured rapidly to allow any type of operation required. In the Ship's Mission Center (SMC) – the DDG-1000 equivalent to the Combat Information Centre (CIC) on older warships – the new displays will allow the heavy, dedicated consoles common to CICs in older ships to be foregone. Instead, the *Zumwalt* class's SMC spaces can be rapidly reconfigured as needed. The CDS consoles are complemented by large flat panel displays in the forward portion of the SMC.

The SMC itself is part of a huge, two deck-high command and control space located

in the second and third levels of the superstructure aft of the bridge. There are nineteen Common Display System (CDS) consoles in four rows; the first two being allocated to war-fighting roles; the third to command and control functions and the fourth to engineering and systems support. Above and to the rear of the SMC is a large, glassed-in high deck for mission planners and command staff. Additional planning spaces – again equipped with CDS consoles – are also incorporated into the design.[23]

The new hardware of the CDS is efficient and ergonomically advanced, but software is the true heart of the TSCE. The design and programming effort required to bring the system into existence has been one of the most complex in navy history. As of May 2016, there have been seven versions of TSCE software, which all told incorporates more than eight million lines of code. The eighth variant was scheduled for approval in 2016.

Automation and Optimal Crewing: A key focus of TSCE has been to increase the operational efficiency of the *Zumwalt* class ships. In the surface warship world, as in many other areas, reduced US Navy budgets have translated into the need to reduced ship life-cycle costs, the largest component of which is manpower. The strategic use of automation to reduce crew size has been a key factor in the DDG-1000 design. Unlike past, unsuccessful navy efforts at reducing crew sizes, however, the human system engineering required to make these reductions intelligently has been 'baked into' the ship's top-level design considerations from the start. These take into account shipboard work, maintenance, combat, and damage control constraints that place limits on when and where manpower can be reduced.

Initial US Navy targets aimed for a DDG-1000 crew size of ninety-five, but subsequent analysis determined that that number was too aggressive. With time, the proposed crew size grew first to 114 and then to 148. Ultimately, that settled at 147, which does not include an aviation detachment of twenty-eight people that will join the ship for training and deployment. Still, the overall manning figure for DDG-1000 compares favourably with that of an in-service DDG-51 Flight IIA destroyer.

Ship designers relied on automation in numerous areas to keep manpower levels in check on the *Zumwalt* class ships. To reduce the potentially large numbers of people needed for damage control, for example, they turned to the Autonomic Fire Suppression System (AFSS). This system combines sensors, cameras and automated fire-sensing and firefighting capabilities. AFSS also makes extensive use of 'smart valve' technology that automatically isolates damage in fluid systems (including the chilled water system and the fire mains carrying water used to fight shipboard fires) and re-routes flows using data sent by the valves themselves. Virtual rather than manual monitoring of potential flooding and fire threats in spaces such as the ships' magazines is another method used to contain manpower.[24]

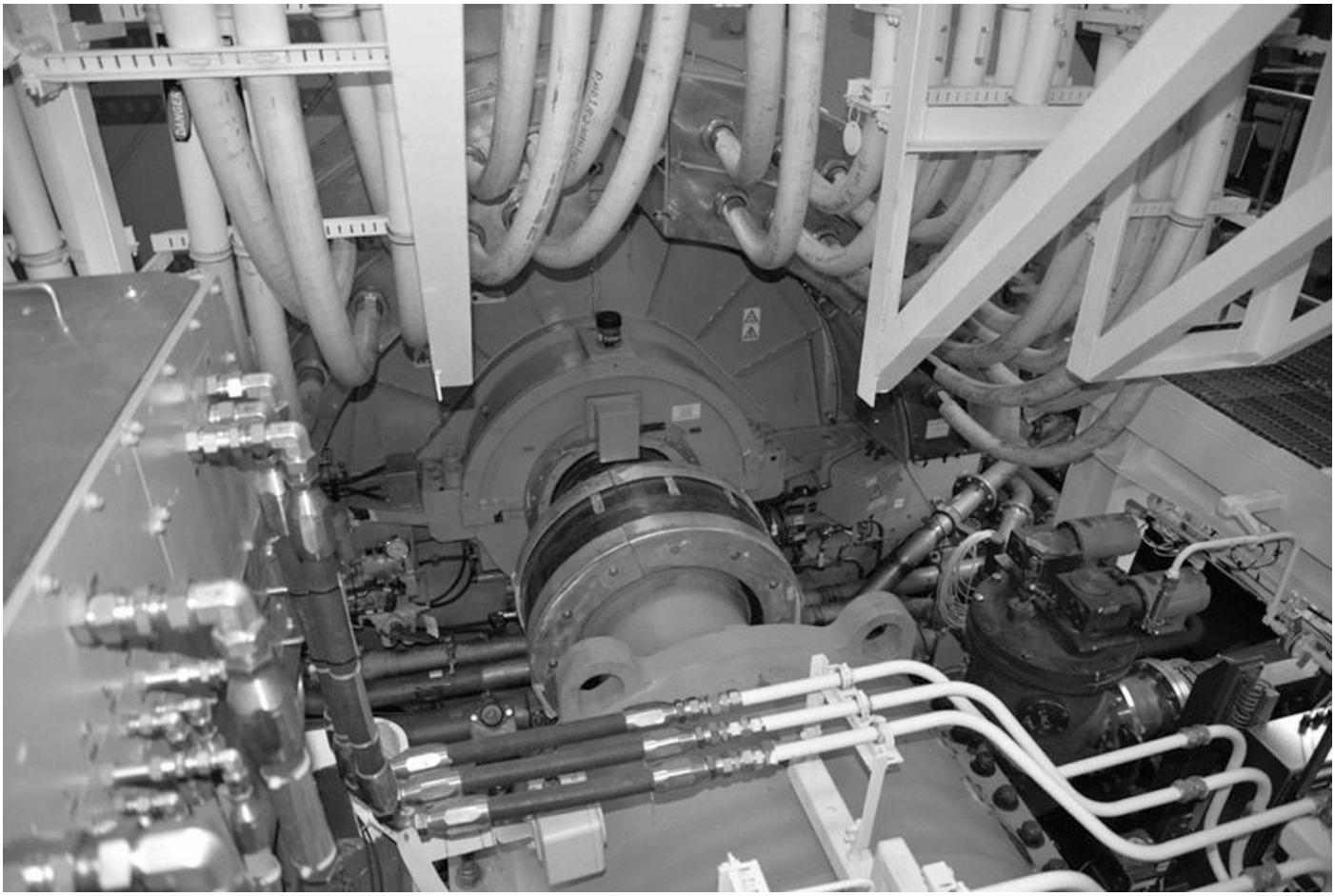
Many of the tasks associated with the manning and monitoring of individual systems – and even controlling the ship itself while underway – also have been automated. The previously-mentioned SQQ-90 sonar suite requires only three people to operate and

support it, compared with the six needed to man its predecessor, the SQQ-89. The ship's engineering plant is controlled by only two people, one of whom – the engineering officer of the watch – sits in the SMC from where he or she can keep tabs on conditions in three main machinery and four auxiliary machinery rooms. Underway, DDG-1000's bridge likewise is manned by only three officers.

The navy expects that network automation will reduce maintenance demands on the *Zumwalt* crews. Moreover, as the navy has done with its Littoral Combat Ships, some of the maintenance burden will be transferred from the DDG crews to shore-based teams, so that 'DDG-1000 will require and have several weeks each quarter dedicated to planned and continuous maintenance availabilities', as Captain Kirk explained. 'Consequently, quarterly and above-preventive maintenance and repairs will be done by off-ship maintainers.'[25]

While DDG-1000 brings together numerous efforts to reduce manning and increase the efficiency of smaller crews, not everyone is sanguine that this endeavour will lead to a crew size that is effective in combat. Noting the *Zumwalt*'s plethora of new systems and design features, the US Defense Department's Director of Operational Test and Evaluation cautioned in 2016: 'These systems and equipment have not been subjected to shock on previous ship classes. Moreover, the previously untried automation and small crew for a ship this size, limit the sailors' ability to conduct repairs to enable recovery from shock-induced damage.'[26] The director's statement reflects the perennial trade-off between critical manpower cost saving – with people costs comprising some sixty per cent of the total ownership costs of a ship – and the equally critical need for a truly optimal (as opposed to a minimal) crew size that can fight and save a ship damaged in combat. The US Navy believes that this time it has the number right, although only operational experience will reveal whether or not this is correct.

Two views of one of the two GE Power Conversion advanced electric motors that draw electrical energy from the *Zumwalt* class's integrated power system to turn the ship's fixed propeller shafts. The images show the heavy electrical cables connecting the huge motor to the ship's electrical grid and the direct connection between the motor and the propeller shaft: there is no need for a traditional gearbox. *(Christopher P Cavas)*



Boats and Aviation: The *Zumwalt*'s size provides ample space for the operation and support of offboard systems such as aircraft and boats. The DDG-1000 class ships will be able to carry and support two MH-60 helicopters for many missions. Alternatively, the ship can carry one MH-60 and three MQ-8 series Fire Scout unmanned aerial vehicles, which also take off and land vertically. The size of its flight deck – almost twice that of the DDG-51 class destroyers, and 20ft (6m) higher above the waterline – also increases the safety of flight operations.

The *Zumwalt* class ships also possess an internal boat bay located under the flight deck. This space has room for two 7m or 11m rigid hull inflatable boats (RHIBs), aligned heel-to-toe. The boats are launched and recovered via a combined extendable stern boat ramp and cradle system. When not in use, the bay is protected by a sliding watertight door.

These boat and aviation capabilities – which reflect the original littoral emphasis of the DDG-1000 design – could be particularly useful in supporting special operations teams from the US Marine Corps or other services. Moreover, each *Zumwalt* will have dedicated berthing and planning spaces for these forces.

Two views of the internal boat bay on *Zumwalt*, which is located under the flight deck. It can house up to two 11m RHIBs, each on its own lifting cradle. Its inclusion in the design is a reflection of the class's origins as a specialised littoral combatant and the desirability of being able to support Special Forces operations. The ship's design also includes separate accommodation for such personnel. *(Christopher P Cavas.)*

Power and Electrical System: One of the greatest assets of the *Zumwalt* class ships is the enormous amount of electrical power they will be able to generate – significantly more than any other inservice American naval surface warship. Two Rolls-Royce MT30 generator sets each provide 35.4MW of electrical power, while two RR4500 auxiliary turbine generator sets (each built around a MT5S turbine) each contribute another 3.9MW. Combined, therefore, these main and auxiliary generator sets can deliver 78MW of total ship power. The generators, along with a ship-wide electrical grid and its controls, comprise the class's integrated power system (IPS).

The MT30 gas turbines at the heart of the IPS are known entities. They are a derivative of the Trent 800 engines developed to power some Boeing 777s. MT30s already serve the US Navy's *Freedom* (LCS-1) Littoral Combat Ship variants, and will power the British Royal Navy's *Queen Elizabeth* class aircraft carriers and Type 26 frigates and South Korea's FFX Batch II frigates, as well as the Italian Navy's forthcoming LHD type amphibious assault ship.

In the DDG-1000 class, power from the IPS is used to turn two fixed propeller shafts – capped by two fixed-pitch propellers – via two 33.6MW advanced induction motors. These motors, which together can propel the ship to speeds greater than 30 knots, avoid the need for a physical connection between the turbines and the shafts. The IPS also routes power to ship systems and services through the Integrated Fight Through Power (IFTP) system. This distributes DC power throughout the ship, and allows any available generator to meet any demand for current. The system also will reconfigure itself

automatically if damage occurs to any distribution element. The engineering control system (ECS) oversees this process – along with auxiliary and some damage control systems – and facilitates centralised system monitoring and management. The ECS, in turn, is below the ship domain controller and command and control system in the computer architecture hierarchy – the latter two systems set the 'guidelines' that the ECS follows as it routes power around the ship.

Overall, the ability to flexibly allocate power between propulsion and systems reduces the number of generators required, increases design flexibility, reduces costs and increases the ships' ability to fight if damaged. These are critical features of the IPS, but it is the sheer amount of electrical power that the *Zumwalt* class ships can produce that has captured much of the US Navy's attention. While steaming at 20 knots, for example, the *Zumwalt* still retains 58MW of reserve power. This is energy that can be used, for example, to power advanced naval weapons now appearing on the horizon.

Two images of *Zumwalt* departing harbour for sea trials in very different weather conditions. The ship's integrated power system provides electricity for propulsion, 'hotel' and – potentially – future weapon systems such as railguns and lasers. *(US Navy)*

POTENTIAL GROWTH

In recent years, Department of Defense officials have watched with alarm as Chinese and Russian ‘peer competitors’ have introduced new weapons and systems that approach – and sometimes equal or surpass – the capabilities of corresponding American systems. The department is looking to ‘identify and invest in innovative ways to sustain and advance America's military dominance for the 21st century’ to counter the erosion of the longstanding US technological advantages.[27]

An image of *Zumwalt* at speed during sea trials in April 2016, illustrating how the ram-like bow cuts through the sea. The ship uses an integrated electrical propulsion system to power two fixed shafts and is capable of speeds in excess of 30 knots. *(General Dynamics/Bath Iron Works)*

The electromagnetic railgun (EMRG) and directed-energy weapons such as solid-state lasers are among the futuristic weapon systems that may contribute to this effort. In-service shipboard defensive and offensive missile and gun systems are available only in limited numbers because of cost and magazine-space constraints. Moreover, many of

these weapons often cost many times more than the targets they are designed to kill, setting up an economically-unsustainable contest between the 'expensive and fewer' and the 'many and cheaper.' According to some analysts, even the cost of the AGS LRLAP round has increased significantly as a result of decreased purchases attendant with the truncation from thirty-two to three ships. Both the EMRG and lasers, on the other hand, cost far less than a guided missile: according to one estimate less than US$1/shot for a laser and around US$25,000 for a hypervelocity projectile launched by railgun. Both could theoretically allow a ship to sustain an engagement far longer than current weapons.

The US Navy's EMRG is currently in the second phase of a development programme that began in 2005. Researchers have already achieved 32 megajoule muzzle energy, which – if applied to a shipboard weapon – would be capable of hurling a projectile 100nm (186km) or more. Likewise the AN/SEQ-3 Laser Weapon System has been tested and deployed operationally onboard the interim Afloat Forward Staging Base *Ponce* (LPD/AFSB-15I), in the Persian Gulf. That laser has a 30-kilowatt output, while future naval laser weapons look to generate 100 or more kilowatts.

The US Navy is aiming to use these or similar weapons on future surface warships, including a new, large warship class that could enter service sometime between 2025 and 2030. To field these weapons, these new ships also will be required to generate prodigious amounts of shipboard energy, something that the *Zumwalt* can already do today. Hence, the new DDG-1000 class is a natural choice to test these new weapons as they become available. As Rear Admiral Thomas Rowden, former director of surface warfare (N96), put it, 'We are going to cut our teeth on DDG-1000 and on the IPS we have on that ship … I think a lot of the technologies that we are putting on 1000 to 1002 are going to serve us very well as we drive toward these [new] ships.'[28]

But since *Zumwalt* herself is close to entering service, the last two ships in the class, *Michael Monsoor* (DDG-1001) and *Lyndon B. Johnson* (DDG-1002) are the most likely candidates for newweapon testing. The navy announced in 2014, that the first prototype EMRG would be temporarily placed on board an Expeditionary Fast Transport (formerly designated as Joint High Speed Vessel) for fiscal year 2016 at-sea tests. Longer term, however, the service is hoping to mount an operational railgun on board DDG-1002 – replacing the number two AGS – before the warship makes its first deployment.

Rear Admiral Peter Fanta, in 2016 the director of surface warfare, warned that much engineering and testing remains to be done to determine if this is feasible, but that is the US Navy's goal.[29] The service has no similar plans yet for high-power, solid-state laser testing. But if and when such a weapon becomes available, the *Zumwalt* class ships will again be an obvious choice for their operational testing and deployment.

A picture of *Zumwalt* taken during initial sea trials in December 2015. She was finally delivered to the US Navy on 20 May 2016 and will be commissioned in October of the same year. *(US Navy)*

UNDERWAY, FINALLY!

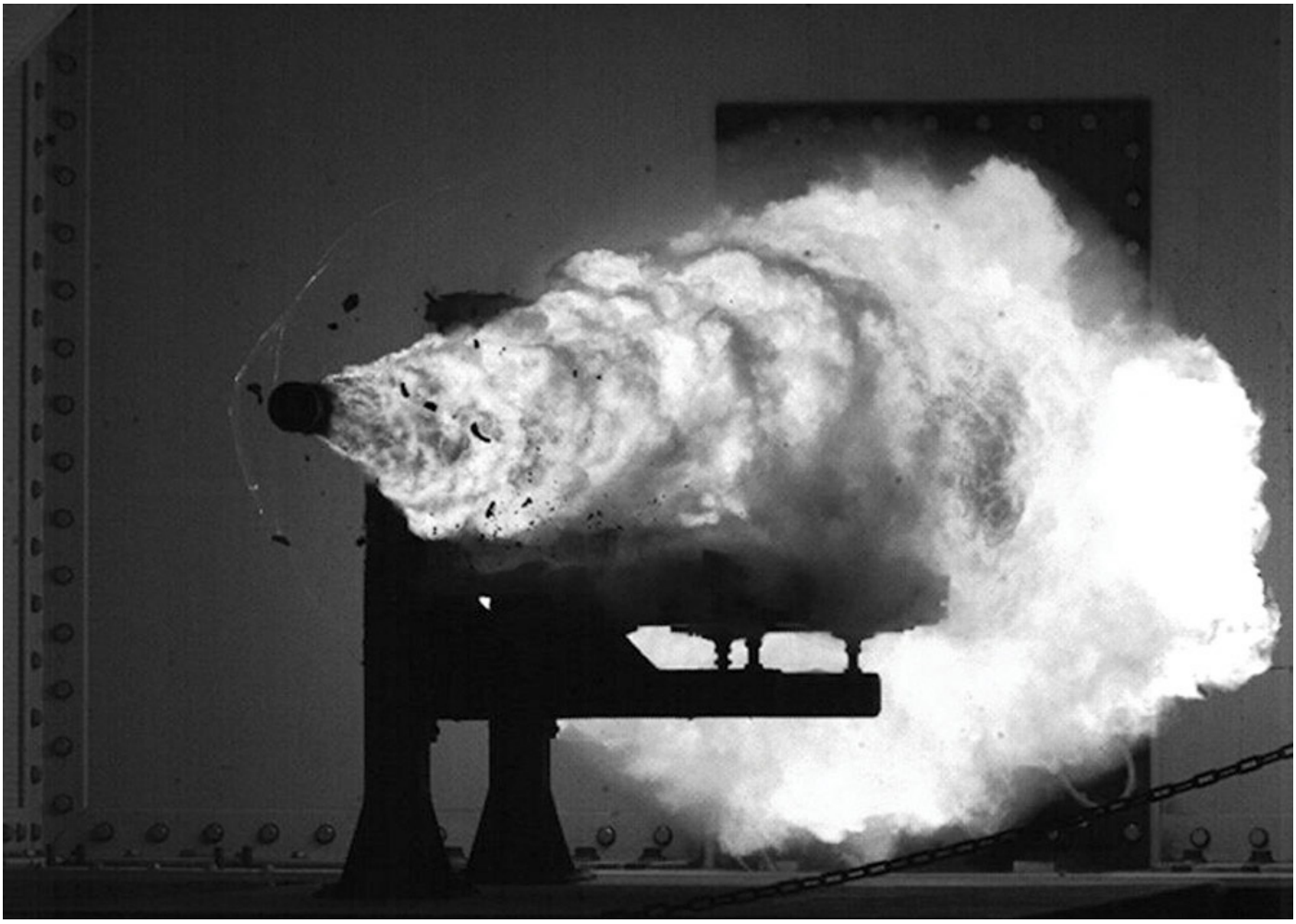
Zumwalt's fabrication began in February 2009. The ship was launched on 28 October 2013 and BIW was initially scheduled to deliver her to the US Navy in the summer of 2015. However, as is frequently the case with first-in-class vessel construction (and even more often the case with complex warships), that delivery schedule slipped. Instead, the Navy took ownership of *Zumwalt* on 20 May 2016, after a final set of acceptance trials the previous month. It plans to commission the ship into the fleet at a ceremony in Baltimore in October 2016. When delivered, DDG-1000 had not yet been fitted with all elements of her combat system and sensors. Combat system activation will be conducted at the ship's homeport of San Diego, California, a decision the navy made to free up space and capacity at BIW, which also is dealing with a thriving DDG-51 construction programme.

The *Zumwalt* class's substantial size and internal volume will facilitate future upgrades, including the introduction of new weapons systems. This image shows the 'Broadway', an extra-wide passageway running along the ship's main deck on the starboard side from the hangar to the forward magazines. As can be seen, it is broad enough for a forklift truck to be driven along. *(Christopher P Cavas)*

The same delay, which a US Navy spokeswoman attributed to 'the challenges encountered with completing installation, integration and testing of the highly unique, leading edge technology designed into this first-of-class warship', has also pushed back DDG-1001's planned launch and delivery schedule. However, that ship was approximately eighty-four percent complete in January 2016, according to the service. She was christened on 18 June 2016.

Ultimately, the last two ships in the class will follow in *Zumwalt*'s wake and will be homeported in San Diego. The basing of all three ships on the West Coast seems to be a direct consequence of the United States' 'Pivot to the Pacific' – a rebalancing of American forces and greater attention to the Indo-Pacific basin, announced by President Barack Obama in 2011 – in response to perceived challenges from China and the rapid growth of Chinese military capabilities.

The *Zumwalt* class's large reserves of electrical power make them eminently suitable for testing new generations of US Navy weapons. One of these is an electromagnetic railgun (EMRG), which has already achieved 32 mega-joule muzzle energy – sufficient for a hundred mile range. These images show the latest 32-MJ version of the weapon and a test of an earlier, lower-powered version. The flame is from the ignition of particle debris. Current plans envisage one of these weapons being installed aboard *Lyndon B. Johnson* (DDG-1002), the third and final member of the *Zumwalt* class. It is *Zumwalt*'s ability to 'midwife' such future technology that provides its real value to the fleet. *(US Navy)*



Ironically, the Pacific theatre may not offer the DDG-1000-class ships a significant opportunity to test their littoral-combat and fire-support capabilities. But the Pacific basin is a theatre where the future of naval warfare – one dominated by new technologies and capabilities – may take shape. Given the programme's significant overall cost and its truncation to just three ships, the *Zumwalt* class's ultimate success may lie less in the capabilities planned for them in the 1990s, and more in their ability to 'midwife' the technologies the Navy will need throughout much of the twenty-first century.[30]

Notes

1. Captain George V Galdorisi, US Navy (ret.) and Scott C Truver, 'The *Zumwalt*-Class Destroyer: A Technology "Bridge" Shaping the Navy after Next,' *Naval War College Review – Summer 2010*, Vol 63, No 3 (Newport RI: Naval War College Press, 2010), pp.63–72.

2. See further Norman Friedman, *U.S. Destroyers: An Illustrated Design History* (Annapolis, MD: US Naval Institute Press, 2004), pp.431–5; and Robert O Work, *Know When to Hold 'Em, Know When to Fold 'Em*: *A New Transformation Plan for the Navy's Surface Battle Line* (Washington, DC, Center for Strategic and Budgetary Assessments, 2007), p.12. A copy of the latter document can be found by searching the CSBA website at www.csbaonline.org. Work has subsequently served as Under Secretary of the US Navy (2009–13) and as of 2016 was the United States Deputy Secretary of Defense.

3. Work, *ibid*. It was decided that around seventy percent of the surface fleet would be full-capability multi-mission combatants, initially the existing *Ticonderoga* (CG-47) and *Arleigh Burke* (DDG-51) classes. The remaining ships would be limited-capability, mission-focused combatants, what became DD-21. After completing the DD-21 programme, the aim was to start replacing the CG-47 class with the second ship of the SC-21 family, a multi-mission CG-21.

4. Rear Admiral Daniel J Murphy, 'Like Thunder and Lightning', *Proceedings* – vol. 123/6/1,132, June 1997 (Annapolis MD: US Naval Institute Press, 1997).

5. Captain Charles S Hamilton, USN, Arsenal Ship Program Manager, *DARPA—Arsenal Ship Lessons Learned* (Arlington VA: Defense Advanced Research Procurement Agency, 1997).

6. Work*, op.cit*., p.15.

7. Murphy, *op.cit*. Some sources suggest that as many as 256 VLS cells were initially planned.

8. Ronald O'Rourke*, Navy DD(X) and LCS Ship Acquisition Programs: Oversight Issues and Options for Congress RL32109* (Washington, DC: Congressional Research Service, 2005), pp.10–11.

9. Murphy, *op.cit*.

10. O'Rourke, *op.cit*., p.14.

11. Admiral Gary Roughead, Remarks to the Surface Navy Association Symposium, 14 January 2009.

12. The Nunn-McCurdy provision requires a number of actions to be taken to avoid termination if a major defence programme exceeds certain cost-growth parameters.

13. Ronald O'Rourke, *Navy DDG-51 and DDG-1000 Destroyer Programs: Background and Issues for Congress RL32109* (Washington, DC: Congressional Research Service, 12 June 2015), pp.33–5.

14. Captain James Kirk, US Navy, 'Ahoy from the *Zumwalt'*, *Proceedings* – vol. 142/3/1357, March 2016 (Annapolis MD: US Naval Institute Press, 2016), p.21.

15. Christopher P. Cavas, 'Is New U.S. Destroyer Unstable? Experts Doubt Radical Hull; Navy Says All is Well', *Defense News* – 2 April 2007 (Springfield VA: Sightline Media Group, 2007). A copy can be found by searching www.defensenews.com.

16. Grace Jean, 'USN Presses on with *Zumwalt* class Destroyers', *ISS Jane's Navy International* – 19 January 2016 (Coulsdon: IHS Janes, 2016).

17. Michael R LeGault, 'DDG-1000 *Zumwalt*: Stealth Warship', *Composites World* – 18 January 2010 (Cincinnati OH: Gardner Business Media, Inc., 2010).

18. Sam LaGrone, 'New External DDG-1000 Mast Reduces Ship's Stealth From Original Design', *USNI News* – 3 March 2016 (Annapolis MD: US Naval Institute, 2016). A copy can be found by searching www.news.usni.org/. The changes are not immediately apparent from early views of the ship on trials but much communications equipment will be fitted only after the ship has been formally delivered.

19. Northrop Grumman decided to spin off its shipbuilding entities – principally the Ingalls and Newport News shipyards – into a new listed group known as Huntington Ingalls Industries in 2011.

20. Sam LaGrone, 'Navy's Steel Deckhouse Decision for Final *Zumwalt* is a Blow to HII', *USNI News* – 5 August 2013 (Annapolis MD: US Naval Institute, 2013).

21. The US Navy has subsequently put into service a longer-range Mk 45 Mod 4 62-calibre 127mm gun.

22. Sam LaGrone, 'Navy Swaps Out Anti-Swarm Boat Guns on DDG-1000s', *USNI News* – 14 August 2014 (Annapolis MD: US Naval Institute, 2014). The 57mm Mk 110 guns are incorporated into both Littoral Combat Ship variants as well as the US Coast Guard's National Security Cutters and the decision was greeted with some surprise. Some commentators suggest that cost and weight-saving considerations – rather than overall effectiveness – were key to the decision.

23. Christopher P Cavas, 'At Sea Aboard the *Zumwalt*,' *Defense News* – 31 March 2016 (Springfield VA: Sightline Media Group, 2016).

24. Captain George V Galdorisi, US Navy (ret.), and Scott C Truver, 'From Minimal to Optimal', *Proceedings* – vol. 137/7/1,301, July 2011 (Annapolis MD: US Naval Institute Press, 2011), p.27.

25. Kirk, *op.cit*., p.22.

26. Director of Operational Test & Evaluation, *FY 2015 Annual Report* (Arlington VA: US Department of Defense, 2016), p.190.

27. Deputy Secretary of Defense Robert O Work, 'The Third U.S. Offset Strategy and its Implications for Partners and Allies', speech, Washington, DC, January 28, 2015.

28. 'In Pursuit of the U.S. Navy's Next Surface Combatant', *USNI News* – 14 January 2014 (Annapolis MD: US Naval Institute, 2014). As Commander Naval Surface Forces, Vice Admiral Rowden has championed increased, distributed lethality throughout the fleet.

29. Christopher P Cavas, 'Navy's Rail Gun Still Headed to Sea, but on Which Ship?', *Defense News* – 10 January 2016 (Springfield VA: Sightline Media Group, 2016).

30. Cost data on the *Zumwalt* programme continues to evolve but currently amounts to significantly over US$20bn. For further detail see Jacob Cohn and Jesse Sloman,

FY2016 Weapon Systems Factbook (Washington, DC: Center for Strategic and Budgetary Assessments, 2016), p.65; Sam LaGrone, 'Navy Requires $450 Million More to Complete *Zumwalt*-Class Due to Shipyard Performance', *USNI News – 6 April 2016* (Annapolis MD: US Naval Institute, 2016). As of FY2015, US$20.8bn had been appropriated to design and construct the *Zumwalt* class and another US$1.2bn was required to complete the programme. Since then costs have increased by around US$0.5bn and the US Navy has indicated a further US$0.4bn is required for post-delivery expenses outfitting. Of this total of c. US$22.9bn, US$9.7bn relates to research and development, US$3.8bn for DDG-1000, US$2.8bn for DDG-1001, US$2.4bn for DDG-1002, US$3.8bn for one-off engineering work and US$0.4bn for the post-delivery work already mentioned.