Energy Efficiency Survey Aboard *USS Princeton* CG-59

Based on surveys aboard during 11–15 December 2000 and 29 January–2 February 2001

Amory B. Lovins, CEO (Research), Project Director (ablovins@rmi.org)
Chris Lotspeich, Senior Associate, Survey Team Leader (chrislot@rmi.org)
Ron Perkins, Jim Rogers, P.E., and Edwin Orrett, P.E., Consulting Engineers
Rocky Mountain Institute, 1739 Snowmass Creek Road, Snowmass CO 81654-9199
970.927.3851, fax 970.927.4178, www.rmi.org; PictureTel videoconferencing available

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EXECUTIVE SUMMARY

This report describes the findings and recommendations of Rocky Mountain Institute (RMI)'s unclassified survey of energy efficiency potential aboard *USS Princeton* CG-59. Energy efficiency seeks to deliver the same service with less fuel and uncompromised or improved warfighting capability via improved technologies or operational practices. RMI's reconnaissance focused on hotel loads in cruise condition, and excluded radars, weapons, and C^3I systems. This report is intended not as a definitive analysis, but to indicate areas for further investigation, also in new ships. It finds potential savings much larger than those the Navy has achieved (15% nonaviation) or expects (19% in CG-47).

The cruise-condition electric load is 2 MW in a brief observation, but may be 50+% larger under the range of seasons and conditions. The potential for reducing it is about 20–50%, much of it retrofittable. This could reduce fuel use by up to 10–25%, depending sensitively on improving turbine operating modes and efficiencies. The largest electric savings would be realized in motors, pumps, fans, chillers, and lighting. If the identified electrical savings were combined with potential improvements (not examined in detail) in electrical generation and in propulsion, *Princeton*'s total fuel use could probably be reduced by about 50% with modest effort, or by roughly 75% with more intensive effort.

VALUE OF SAVED ELECTRICITY ONBOARD

Diesel Fuel Marine is used in roughly equal quantities to propel the ship and make electricity. The FY2002 shipboard *delivered* fuel price averages ~$54.33/bbl or ~$1.29/gal. Generating each MWh in the Gas Turbine Generators (GTGs) burns roughly 182 gal of fuel, worth $235, and costs about $270 in all—*roughly ten times the fuel cost of a typical onshore civilian fossil-fueled power station.* Most electrical savings are thus lucrative.

CG-59 ENERGY SAVINGS: PRINCIPAL RECOMMENDATIONS

END-USE EFFICIENCY AND LOAD MANAGEMENT PRINCIPLES

- *First* reduce loads and energy use, *then* select the optimal energy supply.
- Specify premium-efficiency equipment.
- Use measured, not rated or estimated, efficiencies.
- Turn off unnecessary equipment.
- Minimize parasitic loads.
- "Rightsize"—match equipment and output to the measured loads served.
- Optimize sizing, and the dispatch of multiple units, for best efficiency over the pattern of various loads, not for any single loadpoint.

LOW-COST AND NO-COST RECOMMENDATIONS

- Decrease chiller lift and reduce chilled water flow rate.
- Optimize seawater cooling system flow rate.
- Reset chilled water temperature to 1 F˚ below the highest zone temperature.

POTENTIAL RETROFIT OPPORTUNITIES

- Improve motor, pump, and fan efficiency comprehensively via whole-system design.
- Use Variable-Speed Drives (VSDs) on variable loads.
- Improve duct and pipe pressure drops and entering/leaving conditions.
- Improve power factor and understanding of its importance.
- Improve electrical power generation efficiency. Options include:
  - Operate one gas turbine generator (GTG) rather than two in low-threat conditions.
  - Add a more efficient generator better matched to the load.
  - Explore efficient new generation technologies such as microturbines or fuel cells.
- Improve propulsion power efficiency. Options range from split-/trail-shaft operations (feasible now) to adding smaller turbines or fuel cells (more feasible in new ship design). Hull and propulsor improvements are important too, but were not examined.
- Improve pumping efficiency. Options include:
  - Add VSDs to all pumps, particularly fire pumps, seawater (cooling) pumps, chilled water pumps, and steering gear hydraulic pumps.
  - Large fire pumps constantly circulate seawater that is discharged overboard. Turn them off, seal and pressurize the fire main with fresh water (or seawater flushed daily), maintain pressure with a small pump, and set fire pumps to autostart.
- Improve fan efficiency.
- Improve space cooling systems equipment and operations. Options include:
  - Run one lead high-efficiency chiller to double efficiency, and control the backup chillers with automatic startup systems.
  - Cool Combat Information Center equipment directly, not the space it occupies.
  - Improve space conditioning controls (*e.g.*, on fan coil units).
- Thermal integration. Options include:
  - Reuse “waste” heat, matching onboard waste heat flows to potential uses (galley, HVAC, laundry, hot water).
  - Explore absorption chillers (and desiccants) that use waste heat for cooling.
- Improve the energy efficiency of potable water (PW) production and heating
  - Use waste heat for PW production and heating, *without* making steam.
  - Conserve up to 25–50% of the PW to save energy.
- Improve lighting efficiency and quality.
  - Use more efficient technologies and lighting designs, including white paint.
  - Consider light-emitting diodes for colored and white lighting.
- Improve air compressor efficiency.
- Upgrade systems monitoring, sensors, and controls.

RMI recommends making integrated whole-system life-cycle design and assessment routine, and systematically applying fleetwide the NAVSEA energy conservation program’s recommendations and training, supplemented by these findings. This report invites rigorous scrutiny, prompt assessment, and if upheld, decisive action. That might start with experiments in highly integrated energy design for enhanced economy and warfighting capability—perhaps one intensive retrofit and one new ship design.

INTRODUCTION

Project background and RMI work with DOD

This project—conducting an energy-efficiency survey aboard a warship—grew out of Rocky Mountain Institute's (RMI's) longstanding relationships with and work for the Department of Defense and particularly for the Navy. RMI's cofounder and CEO (Research) Dr. Amory Lovins has been involved in national-security-related issues for more than 30 years. Together with RMI co-founder and CEO (Strategy) Hunter Lovins, he has published numerous papers and books on energy and national security issues. The Lovinses conducted a study for DOD of the vulnerability of centralized energy systems, which formed the basis for the subsequent book *Brittle Power: Energy Strategy for National Security*—still the definitive unclassified work in this field. Its Foreword was written by ADM Tom Moorer, former Chairman JCS, and R. James Woolsey, former Under Secretary of the Navy. In the 1990s, after coordinating the nongovernmental participants in the Greening of the White House, RMI led the 1994 charrette (an integrated, intensive, transdisciplinary, whole-systems design workshop) for the "greening" of the Pentagon building. Dr. Lovins and other RMI staff have also briefed or advised the Services' staff and war Colleges, senior leadership including JCS staff, and SECNAV.

After Dr. Lovins's 1995 brief to the Resource Requirements Review Committee under ADM Lopez, the Navy asked RMI to help raise the resource efficiency of its shoreside buildings and facilities. During 1996–98, RMI helped NAVFAC to launch and support a fundamental reform of how the Navy designs all its facilities ashore. RMI trained NAVFAC architects in integrated design, reviewed eight pilot projects, and participated in related work at installations including Camp Lejeune, NC, and the Washington Navy Yard. RMI's integrated design approach let NAVFAC and its contractors achieve energy savings often severalfold larger than previously, but at comparable or lower capital costs. This led Dr. Lovins to wonder whether similar improvements might be available afloat.

This shipboard energy efficiency project has its origins in that hypothesis growing out of RMI's NAVFAC work; the Institute's relationship with Third Fleet; and Dr. Lovins's participation in a 1999–2001 Defense Science Board (DSB) panel mentioned below.

Dr. Lovins first met then-CAPT Denny McGinn about a decade ago when, about to skipper *USS Ranger*, he heard Lovins lecture at the Naval War College. They renewed their acquaintance during 1999–2000 when VADM McGinn—then COMTHIRDFLT (now Deputy CNO)—became aware of RMI's involvement with NAVFAC and high-level briefings to senior Naval officers, and of Lovins's participation with Third Fleet on Y2K preparations and other projects (often with Third Fleet Surgeon LCDR Eric Rasmussen MD FACP). RMI has provided both formal and informal support to Third Fleet, which has been designated as the test battle lab for "Navy After Next." In summer 2000, VADM McGinn led a Third Fleet delegation to seek consultation at RMI from Dr. Lovins, Mr. Lotspeich, and other staff on a DARPA project exploring the future of ubiquitous computing and the Navy. In spring 1999, VADM McGinn invited Dr. Lovins to conduct a field survey with other RMI experts to test the hypothesis that new techniques and design integration could raise NAVSEA's targets for improving hotel-load efficiency. Third Fleet nominated *USS Princeton*. In conversations at the Pentagon on 19 June and 11 September 2000, SECNAV also expressed to Dr. Lovins considerable interest in what the RMI Team could discover about hotel-load improvements, within the context of the expanding Navy–RMI collaboration on a variety of technical and policy topics. This opportunity was further discussed with a SSG/NWC group that visited RMI on 17 November 2000.

Meanwhile, during 1999–2001 Dr. Lovins served on VADM (Ret.) Richard Truly's Defense Science Board (DSB) panel examining the scope for improving energy efficiency in all DOD land, sea, and air platforms. The Panel submitted in January 2001 its report *More Capable Warfighting Through Reduced Fuel Burden*. The Panel's work confirmed the importance of hotel loads, highlighted indications that there is considerable scope for improving their efficiency, and identified resulting potential warfighting and fiscal benefits. The DSB report mentioned this project, but came too early to report its results.

Project approach and objectives

RMI's research and consulting work concentrates on the economic, environmental, social, and security benefits of resource efficiency. RMI's proven approach combines end-use / least-cost analysis; integrated whole-system design; advanced technology; harnessing market forces; and organizational behavior and incentives. Together, careful attention to these opportunities can often make very large resource savings cost less than small ones. For further discussion of RMI's analytical approach and key design principles, please see Appendix D. The RMI Team is experienced in energy and resource efficiency assessments, and implementation in a broad range of civilian and governmental facilities, including industrial process plants and commercial, residential, and institutional buildings, as well as in hybrid-electric ground vehicle design.

The objective of this project is to test the hypothesis that potential energy efficiency improvements in hotel loads, practical and cost-effective to implement aboard a typical surface combatant, may be considerably larger than NAVSEA's current estimates and goals. This is in part based on Dr. Lovins's casual observations in the past few years aboard the aircraft carrier *USS John C. Stennis*, the Third Fleet command ship *USS Coronado*, and (briefly) a submarine and a cruiser. He suspected that the hotel-load retrofit potential is probably substantially larger than NAVSEA believes, and that in new ships, including DD-21 where hotel-load efficiency could have major benefits for the design of the entire platform, the potential is much larger still.

All of RMI's recommendations and suggestions aim to increase operational effectiveness, and at a minimum, *in no way to reduce combat effectiveness or resilience*. Moreover, RMI's experience ashore suggests that with highly efficient end-use, the quality of the services provided would generally improve; existing ergonomic, reliability, physical space, or infrastructural (*e.g.*, power and cooling adequacy) constraints could often be corrected; and the economics should be attractive. This analysis supports the Office of

Naval Research's (ONR's) interest in ship design and energy use, and pursues ONR's objective of improved operational effectiveness, resource efficiency, and cost reduction.

Project proposal and execution

In November 2000, RMI proposed to ONR to conduct an unclassified onboard survey of hotel-load energy efficiency potential aboard a typical surface combatant. Hotel loads comprise onboard equipment and processes that consume energy other than for propulsion, and for launch in the case of a carrier. (Combat systems—weapons, radars, C^3I—were not to be considered, so their efficiency potential would and does remain unknown to RMI and is not considered here, although analogous civilian systems often show important efficiency potential.) RMI planned to observe, measure, and analyze energy and efficiency potential, focusing chiefly on HVAC, lighting, pumping, desalination, cooking, refrigeration, and electronics systems. The study would consider both retrofit and new design (*e.g.*, DD-21) opportunities. ONR subsequently provided grant #N00014-01-1-0252 to fund this project, pursuant to the Long Range Scientific and Technology Program, as referenced in Broad Agency Announcement BAA 00-018. The subject vessel selected by Third Fleet was the gas-turbine-propelled *Ticonderoga*-class Aegis cruiser *USS Princeton* (CG-59), based in San Diego. She has the 6th-lowest underway fuel intensity of the 27 in her class, and burns nearly $6 million of fuel per year.[1]

The RMI Team (biographies in Appendix L) made three visits to CG-59. First, a three-person team consisting of team leader Chris Lotspeich and technical specialists Ron Perkins and Jim Rogers, joined by NAVSEA engineer Frank Showalter, acted as observers and measurement survey planners aboard *Princeton* during an 11–15 December 2000 float. The Team provided an outbrief of preliminary findings to the crew and NAVSEA representatives, and subsequently prepared a measurement plan that was approved by *Princeton* and participating NAVSEA personnel. Second, RMI Team member Ron Perkins conducted measurements and installed sensors aboard CG-59 at pierside during 25–26 January 2001. Third, an RMI survey team consisting of Chris Lotspeich, Jim Rogers, and Edwin Orrett completed the measurement survey aboard *Princeton* during a 29 January–2 February 2001 float, and drafted a preliminary report that was reviewed by the ship's Chief Engineer. The report was drafted and review copies were circulated in May 2001. Final edits based on the many helpful comments received, chiefly from NAVSEA, were entered at the end of June 2001.

Naval considerations

RMI's technical experience in resource efficiency consulting and research has been primarily in civilian industrial facilities. This project is the first RMI has conducted aboard ship. Although this imposed a steeper learning curve on RMI Team members than they usually face in unfamiliar industries, it also helped them to bring a fresh perspective and analytical approach to marine architecture and Naval procedures. The opportunity to observe *Princeton*'s crew and systems while underway was invaluable, and allowed the

[1] $5.8M based on the FY98–00 SECAP data and the $1.29/gal FY02 *delivered* fuel price estimated at p. 18.

Team to understand better the unique cultural issues, standard procedures, and military considerations of the Naval operational context.

Within that unique context, of course, Naval procedures may conflict with optimal energy efficiency, usually for very good reasons such as battle-readiness and survivability. A warship, after all, is neither a civilian vessel nor a factory, even if many of her mechanical systems are similar. Simply stated: unlike warships, factories typically are optimized for cost more than for performance. Their processes may be critical and hazardous, but factories are not designed to move fast, go far, hit hard, and survive being hit by a missile from any vector.

Nonetheless, the RMI Team offers several recommendations gleaned from shoreside civilian experience—including experience in critical applications—with the potential to reduce Naval costs and improve operational effectiveness. This report discusses some of these factors, and where appropriate notes the relationship between a recommendation the Team would make in a shoreside facility and its applicability to a warship. Some of these Naval considerations and the Team's observations are briefly summarized below. The RMI Team requests the pardon and solicits the instruction of readers with Naval experience if any of these impressions seem obvious, naive, incorrect, or biased.

Operating conditions: Shipboard energy use is often assessed under four different operational modes: shore (dockside), anchor, cruise (yoke), and battle. Each of these conditions has different energy consumption implications for each of several types of shipboard systems, depending on its function. For example, a ship's propulsion, weapons, and radars might use more energy in battle mode than in cruise mode or at anchor, while certain auxiliary or HVAC systems might use more energy in battle mode than at anchor—but use more energy still in cruise mode than in battle mode. This report concentrates on energy use under cruise condition. With rare if any exception, under battle conditions, combat effectiveness should take priority over energy efficiency if the two objectives conflict.

Marine architecture: Ship design considers factors and priorities rarely addressed ashore. Marine architecture typically seeks to reduce total mass and optimize its distribution for increased speed and stability. Equipment volume and packaging are important due to space limitations, often resulting in devices and systems that are seemingly crammed into small spaces. These factors significantly affect the volume, routing, and accessibility of piping, ductwork, and wiring. The commonly resulting reduced pipe, duct, and wire diameters, tight bends, and frequent turns combine to increase friction, resistance, pressure drop, and energy use. Warship design further differs from civilian marine architecture in key aspects related to combat effectiveness and casualty resilience, notably by prioritizing mass reduction for increased speed; increasing the amount, sizing margins, and redundancy of onboard equipment; and dispersing around the ship redundant mechanical and electrical systems' generation and distribution capacity, for increased resilience. These factors can further reduce energy efficiency.

Redundancy for survivability: As is typical on Naval vessels, many of CG-59's mechanical systems (*e.g.*, propulsion, electrical generation and distribution, pumping, HVAC) are constructed with redundant capacity situated in dispersed locations. Often two or more work-producing devices (*e.g.*, generators, pumps) are run in parallel at partial loads and reduced energy efficiencies, sharing a load that usually could be served by one of those devices operating at full capacity. In general, this is done so that a combat or accident casualty will not reduce the function of the ship's systems, even if one of the devices is rendered inoperable—since the other device, or a backup unit, can pick up the full load smoothly and rapidly. Although this redundancy reduces energy efficiency in several systems, often drastically, it is well-founded in Naval procedures intended to improve the ship's combat effectiveness and survivability. The RMI Team believes that it might be possible in certain cases to modify these traditional practices so as to maintain this resilience yet also increase energy efficiency, as is noted in the report.

Naval standard operating procedures: Naval operational guidelines and (in RMI's terms) SOPs (*e.g.*, EOSS, PMS, etc.) help simplify, speed, standardize, and institutionalize optimal operating and maintenance procedures for complex technical systems, and often have been developed over many years of experience. Crews have limited ability to deviate from most of these guidelines. NAVSEA notes that ship's engineers may be reluctant to practice energy saving strategies because the Engineering Operating Sequencing System (EOSS) Manual does not include them. NAVSSES Philadelphia has been tasked to revise the EOSS to allow ships to use energy conservation techniques listed in the ENCON Guide.[2] Some SOPs occasionally conflict with more energy-efficient alternative methods, including some RMI Team recommendations. Where applicable, this report notes instances where a new approach might offer benefits. In other cases, RMI recommendations may unknowingly conflict with existing procedures, as the RMI Team was not able to review and assimilate all of the relevant SOPs. As with other aspects of this report, the Navy will doubtless decide whether these recommendations are appropriate.

Implementation of NAVSEA energy conservation recommendations: The Navy has long worked to improve energy efficiency. Experience indicates that ships can reduce fuel usage by 10–30% through procedural and operational modifications (10–15% for diesel and gas turbine ships and 15–30% for steam ships). NAVSEA's Incentivized Energy Conservation (ENCON) Program was established in the early 1990s to make ships more fuel efficient. NAVSEA calculations show that the surface fleet consumed over $600 million of [apparently nonaviation] fuel in FY1999, and that during that year, energy efficiency saved $26.3 million in avoided costs (or 4.2% of surface-fleet fuel expenditures). The potential energy savings attainable, with full implementation of the ENCON program and NAVSEA initiatives, ranges from $60 million to $90 million per year. In recognition of the need to provide crews with an incentive to save fuel, ENCON provides cash awards to ships, equal to up to 40% of the fuel savings achieved. Of the remaining savings, the instruction allows 10% for additional training and ENCON program administration. The remaining 50% of the fuel savings can be used by the CINCs to improve ship readiness. Shipboard Energy Conservation Assistance Teams (SECATs) train CHENGs, Main Propulsion Assistants, and Oil Kings that fuel and maintenance cost savings can be realized by going to single generator operation when practicable. SECAT self-help software includes the Ship Energy Conservation Assistance Program (SECAP), which generates fuel

[2] "EOSS Revisions," in the "ENCON Elements" section of www.navsea.navy.mil/encon/Frontpage.htm..

consumption curves and includes step-by-step procedures for conducting test runs for various plant alignments. SECAP software can be downloaded from the Internet, and provides CHENGs with the ability to quickly determine best transit speeds, plant alignments, and fuel consumption costs for any given transit time and distance.[3] It did not appear to the RMI Team that CG-59's crew, nor those of other ships the Team has visited, was fully implementing the ENCON recommendations (Appendix K).

MIL-SPEC and MIL-STD parameters: Military specifications and standards define in detail the minimum performance characteristics and attributes of equipment and materiel procured by DOD. Non-MIL-SPEC devices and components may not currently be available as options for Navy use, even if equivalents are widely used in the civilian world. In recent years DOD has continued to expand the use of commercial off-the-shelf (COTS) technology. Some RMI recommendations may unknowingly include equipment that is not available in MIL-SPEC versions. Perhaps this report will provide some useful suggestions for equipment that might be purchased as a COTS option, or evaluated, developed, or specified in MIL-SPEC versions.

Shipboard vs. shore-based engineering support: Warships are highly self-reliant due to their technical complexity and mobility, and Naval shipboard organizational culture is renowned for being adaptive and resourceful. Nevertheless, in practice it is generally impractical for warships to carry a comprehensive complement of spare parts and technical specialists. Vessels therefore rely heavily on shore-based engineering support for more complex or extensive repairs, maintenance, and technical support. Ships are maintained and supported by such organizations as the Combat Homeport Engineering Team (CHET) and NAVSEA; these organizations have more continuity and familiarity with a given ship than does its given crew at any particular time. This arrangement has many practical benefits. But to a certain degree, a ship's crew remains a bit "behind the curve" on best practices with regard to onboard mechanical systems, while for their part the shore-based support staff might not always be as well versed in the operational particulars of a specific ship underway. These tradeoffs do not appear to present major drawbacks, but close coordination between ship's engineering crew and shore-based support personnel requires ongoing effort. Coordination between these groups is facilitated by those shore-based staff with shipboard experience; interaction while the ship is in port; and increasingly, e-mail connections to ships at sea (CG-59 is among the first ships with extensive e-mail access for the crew).

Manpower, turnover, and training: Recruitment, training, and retention of qualified men and women is a perennial issue for the Navy. (RMI uses the term "manpower" with equal reference to both genders, although *Princeton* remained an all-male ship during this project). Officers change assignments and regularly (typically every 1–2 years or so), as do enlisted personnel (although less frequently, often staying in an assignment for up to 3–4 years). Turnover of personnel presents a challenge to the organizational memory of ships' complements, despite logs, manuals, SOPs, ongoing training, and the presence of "old-

[3] See www.navsea.navy.mil/encon/Frontpage.htm. SECAP software can be downloaded from either www.navsea.navy.mil/encon/SECAPDescription.htm or www.seaworthysys.com. The ENCON program contact is NAVSEA's Pehlivan Hasan (202.781.3801/ PehlivanH@navsea.navy.mil.).

timers" in key positions (particularly Chief Petty Officers). Automation also presents opportunities to reduce manpower levels in certain areas. RMI has no opinion on optimal staffing levels aboard ship. Relatively higher levels of turnover undermine staff effectiveness to some degree in any organization. As in civilian facilities, the RMI Team noted cases in which it appeared that there were different opinions among Naval personnel about SOPs or technical matters; usually the most experienced or knowledgeable person was quickly identified, consulted, and deferred to. In a handful of cases, personnel did not appear to be aware of, or to use, normal and optimal operating procedures for mechanical equipment's energy efficiency in a civilian environment. Some of these cases might have reflected lack of experience or intimate knowledge of the systems; others might have involved such constraining factors as EOSS or other Naval practices with which RMI is not very familiar. This report notes these issues and instances where applicable.

Generalization of officer skills: In a basic sense, by job description and organizational culture U.S. Naval officers tend to be generalists, while enlisted personnel and especially Chief Petty Officers tend to be specialists.[4] Officers move from one area of responsibility to another assignment in a new discipline with regularity, and might serve in several functional areas—engineering, weapons, supplies, etc.—during their service. They often rely on more specialized and experienced Chiefs and other technicians for detailed knowledge of a particular topic or system. Overall this tradition of varied assignments has served the Navy well, and creates well-rounded leaders with broad direct experience of a range of shipboard functions. But there are trade-offs. Officers have commented that often they are moved on to a new assignment just as they finally begin to feel comfortable with the area they have worked in for the past year or two. One officer with experience as a liaison in a European navy said he preferred the career-long specialization and topical mastery that other navies employ; *e.g.*, once a weapons officer, always a weapons officer. Chiefs have found themselves contradicting the stated opinion of an officer on a given topic with which the officer is less familiar. In a few cases it appeared to the RMI Team that engineering officers were not well versed in certain techniques and technologies that are common in civilian facilities engineering, and may not always have noticed opportunities for their subordinates to improve systems operations.

Cost of fuel and power: The Navy must buy fuel, and from that fuel make electrical power. More efficient use of that electricity reduces fuel use, cost, and associated emissions and signatures. Fuel delivered at sea costs significantly more, especially in remote sites. Cost reductions allow the Navy to stretch its limited budget, financing operational readiness from eliminated waste. Equipment retrofits and optimal operating procedures can reduce fuel use in existing vessels. In new ship designs in particular, energy-saving integrated whole-systems design techniques can reduce capital as well as operating costs. Optimal systems operations can also extend equipment life and reduce O&M costs.

[4] One CG-59 officer had this familiar quotation pinned up on his wall: "A professional naval officer should be able to change a diaper, plan an invasion, deliver a speech, butcher a hog, design a building, write a sonnet, balance accounts, build a wall, set a bone, comfort the dying, take orders, give orders, cooperate, act alone, solve equations, analyze a new problem, pitch manure, program a computer, cook a tasty meal, fight efficiently, and die gallantly. Specialization is for insects." — Robert A. Heinlein, USNA '20.

Logistical requirements: Increased energy efficiency and reduced fuel use can increase time on station, extend operating range, and reduce the number and frequency of in-port and underway replenishments, increasing the Navy's tooth-to-tail ratio. This both saves money and reduces vulnerability to interdiction of fuel supplies. This report also addresses potable water efficiency, with attendant benefits of extending limited supplies of fresh water and the energy required to produce, deliver, and when membrane treatment systems are introduced, dispose of it.

Signatures and emissions: Increased electrical and fuel efficiency can reduce both signature emissions (*e.g.*, heat, noise, perhaps magnetics), making the ship harder to detect, and decrease its environmental impacts (*e.g.*, combustion emissions).

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Besides ONR, other organizations and agencies supporting this effort—directly and formally or indirectly and informally—include SECNAV, Deputy CNO, NAVSEA, Third Fleet, and the DSB panel. Financial support for this project came solely from ONR.

How to read this report

This project seeks both to identify important opportunities for improvement aboard CG-47 class vessels (specifically CG-59) and also to suggest topics for further, more detailed investigation by the Navy. Although measurements and technical analysis are vital to this study, overall this report is qualitative rather than exhaustively quantitative. The scope of work and budget did not permit a detailed and systemic measurement of all of the shipboard systems under consideration, nor for detailed cost-benefit analyses or engineering schematics. *The survey team conducted a general assessment of potential areas for improvement that it estimated to have a high probability of being cost-effective from a life-cycle perspective* (including system capital costs as well as operating costs).

Information was gathered from four main sources: shipboard instrumentation, logs and manuals; interviews with crewmembers and NAVSEA personnel; previous research on CG-47-class vessels' energy use that was made available to the Team; and limited RMI Team measurements using instrumentation and sensors brought aboard CG-59 for this project. Certain subsystems were measured and analyzed by the Team, but most data came from available information. Wherever practicable, this report identifies information sources and analytical methods. While this report provides specific technical and operation recommendations, overall it should be read as strategic advice rather than as an engineering analysis upon which procurement and operational decisions should be based without further evaluation by qualified Naval authorities. It is hoped to serve as a roadmap for some, but not all, of the salient opportunities meriting closer study by the Navy.

The first section of this report provides a brief overview of CG-59 electricity use. The second section begins by exploring the economic value of saved electricity and fuel aboard ship, including comments on cost-benefit analysis. Energy efficiency recommendations follow, divided into sections that progress from the general to the specific. Generic load reduction measures are described, then low-cost and no-cost recommendations. Retrofit opportunities are discussed in detail, both at the whole-ship level and in system- and device-specific terms. The report comments on both retrofit and new ship design opportunities throughout, and offers recommendations both for clean-sheet design (*e.g.*, DD-21 or similar programs) and for institutional next steps The Appendices begin with information specific to CG-59, and then provide an overview of relevant RMI perspectives, guidelines, and methods for resource efficiency in technical and organizational systems. The appendices conclude with Team member biographies (App. L), information sources and bibliography (App. M), and a glossary of terms and acronyms (App. N).

This report was written by Chris Lotspeich with significant input from Team members and editing from Dr. Amory Lovins, who also drafted the Abstract and Recommendations. The Team contributed to the full range of research; in particular, Mr. Perkins worked on HVAC measurements; Mr. Rogers on pump, fan, and lighting analysis; Mr. Orrett on fuel and water use analysis; and Dr. Lovins on economic analysis. The Team worked closely with Naval personnel, but responsibility for the conclusions is RMI's alone. As the editor melding (and hence risking distorting) the various authors' contributions, Lotspeich is responsible for any remaining errors or unclarities. Readers' suggestions for improvement are requested and welcomed.

OVERVIEW OF CG-59 ELECTRICITY USE

This study concentrates on potential reductions in electric load on a CG-47 class cruiser, primarily of hotel loads, and particularly under cruise conditions. The RMI Team did not measure all of CG-59's loads, but used available research for an overview of shipboard electricity use. The Navy had previously conducted several relevant energy studies of CG-47 class ships. One study of CG-60 provided the following representative overview of that ship's *calculated* summer loads under four operating conditions. This table shows both current loads and the projected loads following Shipalt 588, the all-electric conversion from using steam for potable water production and heating to using reverse osmosis and electric water heating. (CG-59 has not yet undergone the all-electric conversion.)

CALCULATED ELECTRIC LOADS FOR CG-60 (KW)

CONDITION	SHORE	ANCHOR	CRUISE	BATTLE
Current load	1,814	2,092	3,248	3,492
Load post all-electric conversion	2,639	2,963	4,247	4,163

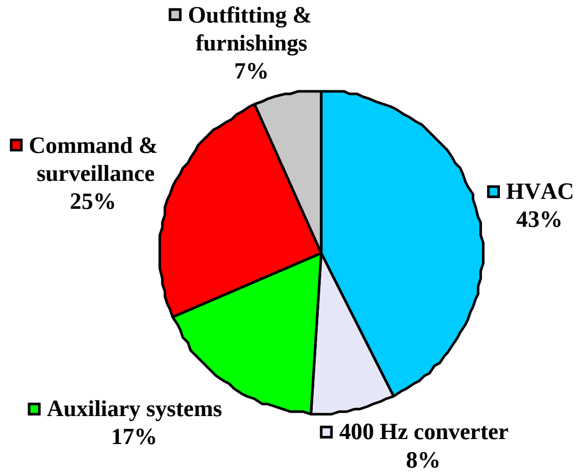
NAVSEA provided the following representative overview of a CG-47 class ship's electric load under summertime cruise conditions, broken down by major system. This table includes a NAVSEA composite rough estimate of shipboard energy efficiency potential, if current energy-saving programs, initiatives, and opportunities were fully implemented. It shows a summer cruise load *55% greater* than the 2.0-MW winter cruise load RMI observed aboard CG-59; the reasons are unknown, but *if the observed loads relied on in this report are anomalously low, the potential savings in this report could be understated.* Moreover, note that *NAVSEA thinks it can save ~8% of ship's electricity in three systems the RMI Team didn't survey*—propulsion, power generation, and combat/command.

CG-47 CLASS SUMMER CRUISE CONDITION LOAD AND EFFICIENCY POTENTIAL[5]

System	Average kW	Efficiency potential	Load after efficiency
Propulsion	345	14.5% (50 kW)	295
Electric plant	511	15.5% (79 kW)	432
Combat/command	780	16% (125 kW)	655
Auxiliary machinery	322	14% (46 kW)	276
HVAC	840	33% (277 kW)	563
Outfit and furnishings	321	6% (19 kW)	302
Total	**3,119**	**19% (596 kW)**	**2,523**

Fuel use for propulsion and electric generation is discussed at pp. 32–49. NAVSEA calculations of typical CG-47 total fuel use, in gph and gpnm, are in App. C.

[5] "Electrical Energy Efficiency," presentation to DSB Task Force on Improving Fuel Efficiency of Weapons Platforms, presentation handouts, Andrew Bigley, NAVSEA (215.897.1190 / BigleyAW@nswccd.navy.mil).



A ROUGH ESTIMATE OF CG-47 ELECTRICITY DISPOSITION[6]

The RMI Team used a Navy energy study of CG-58 to calculate components of a CG-47 class ship's electricity usage, assuming a load factor derived from that study's different calculated and measured loads. The pie chart above shows the heating, ventilation and air conditioning (HVAC) systems' large share of calculated MWh usage (see also App. B). Many of the Team's energy efficiency recommendations are for HVAC systems. In view of the many uncertainties about end-use allocation, including load factors (see App. M), such attempts to decompose energy use should be considered indicative, not dispositive.

CG-59 joins an oiler for an underway replenishment. Chris Lotspeich photo.

[6] Based on calculated CG-47 class data, unattributed report, 16 June 2000, times 0.724 load factor [derived from measured load from CG-58 on 90˚F day divided by calculated load (or 3,120/4,307 = 0.724)].

CG-59 ENERGY SAVING RECOMMENDATIONS

These recommendations primarily apply to CG-59 as a representative typical surface combatant, and distinguish between retrofit and new-construction opportunities. All the comments and suggestions apply to cruise (yoke) operating conditions, but have not been analyzed for and may not apply to battle conditions where energy consumption is not a priority. However, our recommendations should not reduce and may improve warfighting capability and casualty resistance.

VALUE OF SAVED ELECTRICITY ONBOARD

Onboard electricity is expensive. The FY02 DESC (Defense Energy Supply Center) standard cost of F76 logistics fuel is $0.83/gal ($34.86/bbl)., excluding the cost of delivery onboard. In FY1999, handling and delivery costs after receipt from DESC added a 15–85% premium to the standard fuel price to pay for "delivery to aircraft at an air station, delivery to ships in port, and delivery to ships at sea by oilers" but not inflight aircraft refueling.[7] Dr. Alan Roberts, a senior Naval advisor to the DSB task force mentioned above, states that in that analysis, 70% of F76 fuel was delivered to ships by oiler with an estimated delivery cost of $26.88/bbl, and 30% pierside from fuel depots with an estimated delivery cost of $2.18/bbl.[8] Weighted-average delivery cost[9] thus raises average shipboard fuel cost to $34.86 + $19.47 = *$54.33/bbl or $1.29/gal.* Delivery cost isn't normally counted (save in annual fuel cost calculations for some life cycle cost studies[10]), but was strongly recommended by the DSB Task Force on Fuel Efficiency of Weapons Platforms. It found that omitting delivery cost was severely distorting design, investment, and operational decisions throughout DOD, harming both economy and warfighting.[11]

Onboard electricity is especially worth saving because it is inefficiently generated from this costly fuel. At a nominal underway cruise-mode GTG efficiency of about 14.6% under current operating procedure including air bleed for masking (Fig. 1, p. 34), generating each MWh burns roughly 182 gal of GTG fuel (Fig. 1 and Table 1, p. 34).[12] Just the delivered fuel cost of that MWh is thus 182 × $1.29 = $235—***roughly ten times the fuel cost of a typical onshore civilian fossil-fueled steam power station*****.** Thus:

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[7] *More Capable Warfighting Through Reduced Fuel Burden*, report of the Defense Science Board Task Force on Improving Fuel Efficiency of Weapons Platforms, R. Truly, co-Chair, Draft, January 2001, p. 20.
[8] Dr. Alan Roberts, Office of CNO (Roberts.Alan@hq.navy.mil), personal communication, 3 April 2001.
[9] The weighted average fuel delivery cost is calculated as ([0.70 × $26.88] + [0.30 × $2.18]) = $19.47.
[10] Ken Kenyon, NAVSEA SECAT team (ckenyon@csc.com), personal communication, 27 June 2001. The DSB report, however, did not find this to be a widespread, let alone a universal, practice.
[11] *Op cit.*, note 7 above.
[12] The calculation, following Table 1 but applying the 14.6% conversion efficiency estimated from Fig. 1 at an underway load of ~1 MW per GTG with bleed air (from Fig. 2), is: (7,487 gal ÷ 35.38 MWh) × (12.6% ÷ 14.6%) = 182 gal/MWh. Ken Kenyon, NAVSEA SECAT team (ckenyon@csc.com), notes that this "would appear to be a conservative number. Referring to the nomogram for this class in the SECAP program, this is approximate[ly] the fuel burned with one GTG operating and no bleed air. For two GTG operating the nomogram indicates over 250 gal/MW[h]." Pers. comm., 27 June 2001. Subject to check, this higher figure appears to reflect the difficulty of reading a graph accurately. RMI's figures are derived from *Princeton* personnel's data and the Allison Gas Turbine Model Specification No. 828-D provided onboard.

- At an illustrative 5%/y real discount rate, a 20-year stream of just the GTG fuel cost has a present value of $11,636 for a 1-kW load in continuous duty during GTG operating hours (which the RMI Team found to be a typical load profile under cruise conditions for much onboard equipment)[13]. In conditioned space, removing the heat costs ~34% more.[14] Thus *eliminating one watt of continuous onboard electrical load in conditioned space saves fuel with a present value (at constant FY02 fuel prices) of ~$15.61*. That's about the typical cost of *generating* an average watt from photovoltaics (solar cells)—the costliest generating option on today's market.[15] (To be sure, that's not very practical—a CG-47 class cruise-mode load of 2 MW in typical temperate latitudes, without the efficiency improvements described in this report, would need over 21 acres of 13%-efficient solar cells—but the cost could still beat GTGs.)
- These figures don't count the generator's capital cost or O&M cost, nor distribution losses to the load terminals, so the actual value of the electricity is even higher—approaching $20 per continuous watt. A typical 2.5-MW GTG has a capital cost of about $3 million and a 40-year present-valued maintenance cost of about $3.4 million[16]. While these together are probably only about one-eighth of lifecycle cost—fuel cost dominates—they raise the cost of an onboard MWh from $235 (fuel only) to *~$270 total*[17]. (Lower loads make the GTG run cooler and under lower mechanical stress, extending its life and reducing variable O&M costs.) Assuming a 96% electric distribution efficiency typical of factories, *a delivered MWh costs about $281, typical of photovoltaic power costs today, and the 20-year present value of an avoided continuous watt in conditioned space is about $18.66*—worth close attention.
- Even that doesn't include the warfighting or environmental costs of wasted electricity—*i.e.*, the foregone benefits of these kinds that are available from reducing onboard fuel use, such as from reduced signatures or from greater operating range without entailing sustainment via vulnerable fuel logistics, or from reduced emissions.
- A busbar MWh at an onshore civilian thermal power plant typically costs not $270 but only about $20–30 (total fuel, operating, and capital cost). The typical civilian industrial customer ashore in the U.S. in 2000 paid a $44/MWh retail utility tariff—less than *one-sixth* the cost of generating electricity aboard CG-59. Thus *the conventional*

[13] $235/MWh × 3,974 h/y × 20 y × 0.623 discount factor × 0.001 kW/MW. The 3,974 h/y is "effective operating hours" for the CG-47 FY96–00 class average. It is calculated from actual operating hours (2,602 h/y underway + 1,160 not underway = 3,762 total) by adjusting the 1,160 hours not underway by the ratio of 14.6% to 12.6% GTG efficiency, normalizing all GTG consumption to GTG cruise-mode efficiency. Thus the GTGs' effective duty factor is 3,974 / 8,766 = 0.45. The class average operating hours and CG-59's comparable typical (FY99) hours—2,545 underway, 1,296 not underway (port/anchor), 3,841 total—were kindly provided by Ken Kenyon, NAVSEA SECAT team (ckenyon@csc.com), pers. comm., 27 June 2001.
[14] At the observed cooling-system efficiency of ~1.2 kW/t (p. 58), the chiller and chilled-water pump energy add about 34%, not counting condenser-water pumping and air handling energy.
[15] Photovoltaic arrays in 2000 cost ~$3.5 per peak watt with 0.19–0.26 capacity factor so without power conditioning or storage, typical U.S. PV DC output cost ~$14–17. This cost is falling rapidly with volume.
[16] "Fuel Cells for Marine Applications," presentation handouts by Mr. Harry Skrutch (703.602.0706), Execution Manager, Ship's Service Fuel Cell program, Naval Sea Systems Command, presentation to DSB Task Force on Improving Fuel Efficiency of Weapons Platforms, 20 October 2000, p. 19.
[17] Back-calculated: if ref. 16 used (say) a 5%/y real discount rate, a ~$3.4M 40-year present value corresponds to $198k/year or, for 2.5 MW @ 3,974 effective h/y (note 13), $20/MWh. Conservatively using a 5%/y real fixed charge rate, a $3M capital cost would be charged at $150k/y or $15/MWh.

civilian shoreside economics that yield short (~1–2-year) simple paybacks for most energy-saving retrofits in industry should yield 6-fold faster paybacks aboard ship, such other things as duty factors and retrofit costs being equal. Conversely, onboard savings six times as costly as they are ashore could still pay back comparably quickly.

- Making CG-59's ~2 MW for 3,974 effective h/y at $270/MWh costs $2 million/y[18]; this would rise proportionately if actual average loads are higher (pp. 16, 36, 45, 124).
- Onshore civilian industrial and commercial electricity savings typically cost less than $10 per MWh to achieve—often much less. Against CG-59's ~$270 / 0.96 = $281/ MWh delivered cost, a saving costing $10/MWh pays back in 5.3 months.
- Importantly, however, because of the current parallel-units GTG operating practice, discussed starting on p. 32, *about 75–80% of the potential GTG fuel saving from saving electricity can't be captured unless this operating practice is changed.* If this serious problem is not corrected, the economics of saving electricity aboard ship will be more like those in civilian businesses ashore, rather than manyfold more favorable.

COST-BENEFIT ANALYSIS CONSIDERATIONS

The RMI Team did not examine Naval cost-benefit analytical methods. However, a number of the Team's recommendations that are typically cost-effective in shoreside civilian settings (at manyfold lower electricity costs) were responded to informally by Naval personnel as being too costly. This led the Team to suggest that the Navy reconsider its cost calculations, in certain cases. The following guidelines have proved useful ashore:

Use empirical, not estimated or theoretical, costs.

Don't assume that high efficiency costs more up front—it may not. For example, there is no empirical correlation between the price and efficiency of the commonest kind of induction motor (1800-rpm TEFC NEMA Design B) up to at least 300 hp, nor of most industrial pumps (p. 50) and many rooftop chillers. Motor, pump, fan, and chiller efficiencies are particularly important to Naval electrical efficiency.

Optimize for lifecycle cost, not first cost.

Even if efficiency does cost more up front, it can usually pay for itself quickly, except in equipment operated quite infrequently.

Optimize *whole-system* cost, not component cost—for multiple benefits

Look for the cheapest overall cost of owning and operating the *entire system* of which the device is a component. Paying more for one component often downsizes or eliminates others, reducing total capital cost as well as operating cost. Optimizing components for single benefits, not whole systems for multiple benefits, "pessimizes" the system (p. 93).

[18] Class average: (2,602 UW h/y × 2.01 MW) + (1,160 NUW h/y × 1.53 MW × (14.6%/12.6%) = 7,365 effective MWh/y; that total × $270/MWh = $1.99M/y, if the conditions observed were representative. If the average underway load were 3.119 MW (p. 16, summer cruise condition), that would be about $3 million/y.

CG-59 pulls over a fuel line from an oiler. A single complete filling of CG-59's tanks would incur a delivered cost of about $0.85 million. CG-59 uses approximately $5.8 million worth of delivered fuel in a typical year, and is more efficient than three-fourths of the Navy's 27 hulls of this class. Chris Lotspeich photo.

FIRST THINGS FIRST: END-USE EFFICIENCY AND LOAD MANAGEMENT

An important principle of resource-efficient design is first to reduce loads and necessary energy consumption, then to optimize the size, type, and efficiency of energy supply. This can reduce the required capacity (hence the size, weight, and cost) of supply systems (including fuel), or permit more efficient operating modes for existing systems. Generalized energy-saving recommendations include:

Specify premium-efficiency equipment.

Premium-efficiency equipment might not cost more up front, but even if it does, the additional initial investment is usually paid back very quickly in reduced operating costs.

Use measured, not rated or estimated, efficiencies.

Measured efficiency under the actual conditions of installation and use often falls short of rated efficiency. (It was often difficult for the RMI Team to determine the rated efficiency of motors, pumps, and fans due to the lack of nameplate data and lack of ready availability of file data. The RMI Team did not measure the actual efficiency of any motors, but did infer from its measurements the approximate efficiency of one chiller, which was lower than rated—please see p. 56.)

Turn off unnecessary equipment.

This can be as simple as turning off the lights when one leaves a room. Sensors and controls can help inform or automate such decisions (*e.g.*, motion sensors for lights in infrequently occupied spaces). Several systems operate redundant equipment on parallel or standby status (*e.g.*, fire pumps, GTGs, CHs) so that one component can assume the full load instantly in case another component (or the primary system) goes off-line. This is not always necessary despite warships' need for system resilience. For specific examples, please see p. 24.

Minimize parasitic loads.

Parasitic loads arise when unnecessary work is required because of how a system is designed or operated. Just as barnacles on ship's hull induce unwanted friction, fouled pipes—and sharp-angled pipe bends, pipes and ducts that bend too close to a pump or fan—add friction and thus increase pumping energy and add heat, much of which must then be removed all over again. Oversized or inefficient CHW pumps likewise heat CHW with some of their wasted energy; inefficient fans unnecessarily heat the air they move; these and inefficient motors add more heat to conditioned space. At least a sixth of the indicated chiller load the RMI Team observed is parasitic, not native (p. 56, n. 62).

"Rightsize"—match equipment and output to loads served.

Excess capacity in equipment that is oversized relative to the work required (*e.g.*, in motors, pumps, fans, chillers), beyond the safety margins required by prudent engineering practice, often makes equipment run inefficiently at partial loads. Variable-speed drives or other control systems can allow power devices to use only as much energy as is necessary to do the job. It is often worth serving small but frequent loads with a small device optimized to that task, reserving big equipment for the rarer occasions when its capacity is actually required. (This study focuses on cruise condition; each equipment sizing decision must take into account all ship operating conditions and commitments before recommending a retrofit of smaller equipment for efficiency.)

Optimize for efficiency over integrated load, not for any specific load.

It is often worth sacrificing efficiency at an infrequently used loadpoint in order to improve it under the conditions more commonly experienced. Fuel is used year-round under all load conditions, not just at a single loadpoint, so the total fuel used per year can be reduced by optimizing integrated efficiency over the entire load range. This may change unit sizing or characteristics, or encourage the dispatch of multiplex unequal units.

CG-59's bridge. Chris Lotspeich photo.

LOW-COST AND NO-COST RECOMMENDATIONS

Turn off unneeded equipment.

Observations
CG-59 consumed electricity at an essentially constant rate of about 2 MW while underway; this load varied little regardless of time of day or activity on board. (See discussion below at p. 35.) The air-conditioning CHs showed a similar load pattern. A significant fraction of this energy is wasted overboard or converted to parasitic cooling load. Apparently two significant drivers to the size and the constancy of this load are (1) background loads caused by redundant systems, and (2) equipment that lacks VSDs (yet serves variable loads) and is effectively oversized and operating inefficiently. Parallel systems and backup equipment are often operated simultaneously for redundancy, even when this might not be necessary for survivability. Using autostart systems on backup devices, or maintaining devices in standby modes with rapid ramp-up times, might allow a primary device to operate at a higher utilization factor and meet the same operational requirements while both conserving energy and maintaining resilience. Crew members were generally resistant to turning off backup systems because critical ship functions depended on uninterrupted service. This seemed to be compounded in some cases by low confidence in automatic controls and lack of detailed knowledge of the support systems' functional capability. *Turning backup systems off (in autostart mode) could save perhaps 575 BHP or 429 kW of electricity, or 21% of the ship's total current electrical energy use.*

Recommendations
Consider the following opportunities:

- *Turn off main fire pumps*. Rework fittings and the control system to maintain fire system pressure with a VSD-equipped lead pump and a backup pump in automatic startup mode, or small jockey pumps instead of the large fire pumps. See discussion below starting on p. 50.

Serving loads with one piece of equipment run efficiently at a higher output rather than sharing it among two pieces run inefficiently at lower outputs can achieve major savings. For example:

- *Run one SW pump instead of two.* See discussion below starting on p. 52.

- *Run one chiller instead of two*. One chiller running at closer to full capacity is more efficient than two running at partial capacity. If one chiller fails, the time it takes for a backup unit to come online is brief but not problematic (particularly with automated start-up controls), because the thermal lags of the systems being cooled are typically much longer than chiller startup/rampup time. See discussion below starting on p. 56.

- *Run one GTG in routine cruise conditions instead of two*. This would be facilitated by, and would become more important with, load reduction and load management.

Running a GTG at partial load significantly reduces its efficiency. See discussion below starting on p. 35.

Increase chiller lift and reduce CHW flow rate.

Resize the CHW pump to be smaller and more efficient. This may save more energy than the higher chiller lift uses. Reduce or eliminate flow restriction devices such as balancing valves, pressure reduction valves, and contorted piping.

Optimize SW cooling flow rate.

Minimize bypassing and non-productive pumping.

Reset CHW temperature to 1 F˚ below the highest zone temperature.

For example, raise the setpoint from ~44˚F to ~46–47˚F. A zone is defined an area controlled by sensors and thermostats modulating chilled water control valves.

CG-59 at dusk. Chris Lotspeich photo.

POTENTIAL RETROFIT OPPORTUNITIES

General recommendations include:

Improve motor, pump, and fan efficiency comprehensively.

Observations
The Navy generally uses "squirrel-cage" induction motors for shipboard applications. Shipboard motors are rugged and specified to meet shock requirements, and as a result are reported to have efficiencies in the 90% range. For a given motor specification, it is generally most economical to specify *the most* efficient of the premium-efficiency class of motors, fans, pumps, and similar devices, rather than poorer-performing "high-efficiency" models (which generally represent the least efficient new motors available). Even modest increases of a few percentage points in efficiency can be very cost-effective in high-duty drivepower applications. For example, a large continuous-duty motor ashore uses its capital cost equivalent in electricity roughly every month. At the onboard fuel prices calculated above but a similar motor cost (perhaps an incorrect assumption), that would be about every week. At the ~$270/MWh total estimated electricity cost aboard CG-59 (p. 19), *each one percentage point* of efficiency gain in unconditioned space is worth *$127/hp* in 20-y present value, or *a thousand dollars per 100-hp motor per year*.[19]

It was difficult to determine the efficiency of CG-59's motors, as the nameplates did not list NEMA or other rated efficiency. No motors from major manufacturers were noted. This may be because motors are rebuilt to MIL-SPEC by vendors that then omit such information from their new nameplate. NAVSEA staff report that older ships tend to have more rebuilt motors. CG-59 has a motor census indicating location application, horsepower, and other characteristics—but not rated efficiency. The RMI Team has not been able to obtain rated motor efficiencies from NAVSEA or vendors. Moreover, both part-loading and maintenance practices—such as repeated repainting, which inhibits the escape of heat—could yield actual efficiencies well below rated efficiencies. (However, commendably, the Navy is the only large organization in the country that uses internally (*e.g.*, aboard *USS John C. Stennis*) the excellent Thumm method for rewinding—not standard burnout ovens, which irreversibly increase iron losses.)

One obstacle to improving motor efficiencies in the fleet (*e.g.*, via retrofits) is concern about negative effects on shipboard electrical systems. More efficient motors typically have lower impedance and higher inrush currents, which upon start-up produce spikes in power demand that exceed average operating loads by as much as 10× (compared to nominally 6× in standard-efficiency NEMA Design B motors). The Navy prefers to maintain power generation capacity margins of ~10% (better if possible) on surface combatants, to reduce the risk that demand spikes from equipment lighting off might trigger automatic load-shedding responses, or worse yet damage shipboard electrical systems.

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[19] (1/0.90) – (1/0.91) × 3,974 h/y × 20 y × 0.623 discount factor × 0.746 kW/hp × $0.27/kWh ÷ 0.96 distribution efficiency) = $126.85 present value per hp, or, *e.g.*, $12,685 present value for a 100-hp motor. The equivalent annual values are $10.18/hp-y, or $1,018/y for a 100-hp motor—all for *each* percentage point.

However, civilian best practice—if only to reduce wear and tear on mechanical and electrical systems—is to equip any motor of 10+ hp with a solid-state soft-start device that limits inrush current. This feature is already included in many modern VSDs.

Another obstacle to increased motor efficiency is perceived higher costs. Apparently many senior decisionmakers believe that more efficient motors are more expensive, and that existing motors work fine. The Navy faces budgetary constraints on fleet maintenance. However, the RMI Team believes that, in general, maximally efficient motors would probably reduce life-cycle costs substantially and may *not* even increase capital costs. Research using the Motor Master 3.02 database indicates that, in the U.S. market, there is no correlation between motor cost and efficiency up to at least 300 hp. Naval life-cycle costing and return on investment criteria were not examined by the RMI Team.

Recommendations

Specify, and retrofit to, the most efficient (or very nearly so) of the premium-efficiency class of devices wherever possible. They are almost always the best buy. Every civilian motor on the U.S. market is listed in DOE's free MotorMaster software, with a search engine that can identify the best buy for the application. The MIL-SPEC process should be reexamined to see how necessary it is for various motor applications onboard, especially in light of the availability of specially reliable and rugged types of civilian motors off-the-shelf. Where MIL-SPEC is really required, the data on the nameplate legally required for civilian motors, notably efficiency and power factor, should be carried forward to the new nameplate. Similar considerations apply to pumps and fans.

The Team suggests that life-cycle costing and return on investment criteria be reviewed to optimize decisions with regard to both capital and operating costs as well as whole-systems benefits. Any economic optimization in motor, pump, and fan purchasing should use a refined version—including all costs, not just fuel—of p. 19's onboard power cost estimate. *All design should be integrated across whole systems (Appendices D–E).*

Only field-testing can reveal actual efficiencies at actual loadpoints and thus the potential for improving sizing and efficiency. NAVSEA should consider conducting some spot-checks to prospect for oversizing.[20] See also Appendix E.

Use Variable-Speed Drives (VSDs) on variable loads.

Observations

VSDs allow motors, fans, and pumps to use only as much energy as is required to serve the load in real time. They also reduce wear, startup surges, and maintenance costs. Apparently there aren't any VSDs on *Princeton*, even though many of the applications would seem to merit them and they are widely used in critical civilian applications. VSDs

[20] For example, see the method described in K.K. Lobodovsky, "Field Measurements and Determination of Electric Motor Efficiency," *Energy Engineering* **86**(3):41–53, Association of Energy Engineers (Atlanta), 1989. This test method requires no dynamometer—only about a half-hour, simple measurements (V, A, true W, Ω, T, and slip), and the ability to de-energize and unload the motor. Yet it quite accurately measures the actual loadpoint and efficiency-at-loadpoint, using a combination of IEEE 112B Methods E and F.

nowadays are very rugged, reliable, compact, affordable, and consistent with high power quality. They are typically designed so that in the very unlikely event of failure, they default (or can easily be bypassed) to constant-speed operation rather than an open or short circuit. The Navy uses motor controllers that are *not* VSDs in many shipboard applications, and they are generally considered highly reliable, although in civilian environments, VSDs run drivepower systems more efficiently than such motor controllers can.

MIL-SPEC VSDs are under development and have been used in limited applications on other Navy ships (*e.g.*, a VSD was applied to a 300 kW motor generator set on the aircraft carrier *USS John F. Kennedy* and is approved for that application on other CVs[21]), but progress has been slow. Broader VSD use has been hindered by the limited range of MIL-SPEC options and relatively high material procurement costs (despite lower drivepower system life-cycle costs), particularly under perceived budgetary constraints.

NAVSEA has been investigating VSDs for several years, and coordinates an interdepartmental VSD Team. NAVSEA staff have held discussions with major motor manufacturers about development of MIL-SPEC VSDs. Apparently most of the large manufacturers indicated that the military market is too small to give them an incentive to overcome the economic barriers to entry. These barriers include concerns about cost and return on investment (despite life-cycle economic benefits); negative impacts on shipboard power harmonics and power quality (an issue routinely resolved in demanding civilian applications); differences between MIL-SPEC and civilian standards and specifications; and manufacturer reluctance to retool production lines for relatively small runs to meet MIL-SPEC requirements. The cumbersome process of MIL-SPEC qualification for COTS technologies has retarded VSD adoption, which may even then be approved only for specific applications (*e.g.*, gensets but not other motors). To address some of these concerns, NAVSEA has MIL-SPEC-qualified a modular-design Alstom COTS drive for use in varied applications. The rectifier modules allow scalable application by adding more modules to larger motors. In FY01 NAVSEA will be testing a similar module for LM 2500 GTM cooling fans at a land-based engineering site in Philadelphia.[22]

Recommendations

Wherever practical, specify and retrofit VSDs on drivesystems (*e.g.*, motors, pumps, fans) serving varying loads, rather than switching, throttling, bypassing, or wasting flow.

Improve duct and pipe pressure drops and entering/leaving conditions.

Observations

Each bend in a pipe or duct increases friction, heat, vibration, turbulence, noise, and pumping or fan power requirements. For example, ventilation and exhaust fans are located in four places around the ship. Some supply fresh air to AHUs, and some ventilate turbine enclosures and engine room spaces. Many of these fans are connected to ducts via

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[21] Cutler-Hammer (www.ch.cutler-hammer.com/nc/) provided the VSD for this application; this firm also makes motor controllers and other control systems for the Navy.

[22] Andrew Bigley, Branch Manager, Electric Power Systems Branch, NAVSEA Philadelphia, Code 934 (215.897.1190 / BigleyAW@nswccd.navy.mil), personal communication, 9 May 2001.

sharp-angled bends. The same, or worse, is true of pumps and pipes. The best answer is to redesign pipe and duct layouts to minimize or eliminate bends in the first place. For example, some pumps observed on Navy vessels would incur only about one-fourth as many pipe bends if installed in a different orientation in the first place. According to one ONR staffer, preferably—but not always—larger shipboard rotating machinery is oriented with the shaft running fore-and-aft to minimize bearing loads due to ship motions (*e.g.*, gyroscopic effects). This preference, along with limited space, may take precedence over the desire to minimize sharp bends.[23] Yet for smaller units, it may be overdone.

Bends, especially sharp bends, in pipes and ducts are especially harmful when they occur too close to the entry or exit of a pump or fan. They reduce the machine's efficiency far below its rated value. For optimal efficiency, centrifugal pumps need smooth entry and exit pipe transitions such as long-radius reducing elbows at the suction inlet and at least four pipe diameters of straight pipe at the pump's discharge (some engineers recommend at least eight diameters[24]). Centrifugal fans have even more elaborate hydrodynamic rules about entrance and exit conditions.[25] Marine architecture and warship design uniquely constrain pipe and duct layout, but RMI suspects there is nonetheless room for improvement, perhaps in some retrofits and certainly in new ship design. Constrained geometries can also influence fluid-moving equipment choices: for example, a vaneaxial fan may look no more efficient than a backward-curved centrifugal fan under free-flow laboratory conditions, but the vaneaxial fan's installed (*in situ*) efficiency is far less sensitive to constrained entering and leaving conditions than is the efficiency of the centrifugal unit.

Ductwork in CG-59's hangar bay. Note the convoluted entering conditions, including a 270° bend in airflow. Jim Rogers photo.

[23] Scott Littlefield, Deputy Director, Naval Ship Science and Technology Office, Office of Naval Research (703.588.2358 / littles@onr.navy.mil), personal communication, 11 June 2001.
[24] See E SOURCE Technology Atlas *Commercial Space Cooling and Air Handling* (1995 ed.), p. 245, www.esource.com.
[25] *Ibid*, pp. 130–1.

Pipe and duct sizing are also very important, because friction falls as nearly the fifth power of diameter. Even a modestly larger size can greatly reduce friction. So can reduced flow through the same size—perhaps via reduced cooling loads due to more efficient equipment in the conditioned space, for example. This can then reduce the size, weight, cost, and energy usage of the fan or pump, hence of its motor and associated electrical equipment. Similar compounding benefits are available from close attention to smooth pipe and duct interior surfaces; minimizing fittings, valves, and dampers; and selecting those units so as to minimize friction. All these shifts in design philosophy are likely to minimize whole-system capital cost as well as operating cost. See Appendix D.

Recommendations
Some retrofit improvements are possible in existing applications on CG-59. For example, the air intakes for the GTGs drop vertically in a rectangular shaft, at the bottom of which the GTG intake air makes a 90° turn into the turbine chamber. Placing fairings, baffles, or similar curved surfaces ("turning vanes") in this shaft to smooth out the directional changes in the airflow would reduce friction and turbulence, lowering both fanpower requirements and noise, as well as improving airflow into the GTG. (There may also be opportunities to precool GTM and GTG intake air to improve turbine efficiencies, for example with absorption chillers run on waste heat or, in climate zones where marine air does not approach saturation (or downstream of a heat-driven desiccant in any climate), with turbine-inlet evaporative cooling; please see p. 63 below.)

In new installations, naval architects and mechanical engineers should place a high priority on systematically minimizing fluid flow and its friction. This can leverage large upstream savings in equipment size, cost, weight, fuel, and signatures. In civilian design, the best approach is to lay out the pipes and ducts first, *then* the equipment they serve. Used as far as possible, this approach is likely to pay dividends in naval architecture too.

Improve power factor.

Observations
PF (Appendix J) was difficult to determine, as the RMI Team did not observe any PF indicators or DDIs on any CCS control panels elsewhere, and CG-59's engineering staff did not seem certain what the ship's electrical system PF was. (Navy ships in general seem to lack PF indicators.[26]) Apparently the ship's nominal PF is 0.8. This is suboptimal, and requires the ship to generate more power than it needs. In the civilian world, facilities attempt to maintain PFs as close to 1.0 as is practical (typically in the 0.90–0.95 range). The same electrical engineering principles should apply aboard ship.

Section 5.1.6.3 of MIL-STD-1399 (Navy) Section 300A, dated 13 October 1987, states: "Shipboard electric power systems are designed to operate with an overall p.f. of 0.80 lagging to 0.95 leading for 60 Hz power systems and 0.80 lagging to unity for 400 Hz power systems." MIL-STD-1399 is considered an interface standard, characterizing the

[26] Personal communications with CG-59 engineering staff while aboard, and with Andrew Bigley, NAVSEA Branch Manager, Electric Power Systems Branch, NAVSEA Philadelphia, NSWC 934 (215.897.1190 / BigleyAW@nswccd.navy.mil), 9 May 2001.

power that equipment must deal with at the interface with the shipboard distribution system. It is not a power quality specification.[27] Some of CG-59's engineering staff believed that PF of 0.8 is a Navy standard (one officer reported that "The Navy pays to keep it at 0.8.") A NAVSEA energy staffer reported that the Navy specifies shipboard equipment to operate at a shipboard PF of 0.8, which is what shipboard systems tend to operate at without correction (*e.g.*, banks of capacitors, such as might be found in a civilian electrical system). This source wasn't sure whether there was a Naval standard for PF, but didn't believe there's a standard saying that ships should *not* operate as close as possible to unity PF.

All Naval and NAVSEA personnel questioned about this agreed that in principle it is better for PF to be as close as practicable to 1.0. So long as power factor remains generally slightly lagging rather than leading, this is sound practice because it reduces the losses in and capacity of generators and distribution equipment, stretches equipment life, and improves voltage regulation. Ashore, PFs below 0.8 or 0.9 often incur penalty charges from the utility, which must generate and transmit extra power but cannot charge for it; on CG-59, the ship *is* the utility. Power factor below unity therefore requires the GTGs to burn more fuel—increasing cost, pollution, and signatures—to generate power that merely heats the distribution system and cannot do useful work.

For example, a PF of 0.8 instead of 0.95 increases distribution-system losses by 42%. Conversely, a PF of 0.95 instead of 0.8 effectively increases distribution capacity by 20%. Low PFs also often indicate equipment problems; by increasing shipboard distribution losses, heat up distribution equipment, shortening its life; and add needless cooling and air-handling loads to conditioned space. All these civilian design considerations are especially important aboard ship, both because of mission-critical equipment sensitive to power quality and because the very high costs estimated on p. 19 above put a special premium on avoiding the unnecessary generation of reactive power and associated distribution losses.

Recommendations

Install PF display indicators if they are lacking (*e.g.*, on CCS control panels). Increase the ship's PF above 0.8, aiming closer to 1.0. This need not incur the space, weight, and cost of capacitors: just improved inductive loads, such as premium-efficiency motors and electronic (rather than magnetic) lighting ballasts, would greatly improve PF *as a free byproduct* of profitably saving energy.[28]

Each GTG is rated at 2.5 MW *at 0.8 PF*. Presumably, if the load's PF improved, the generator could generate less reactive power but more real power from the same fuel at the same torque input and hence at the same point on the turbine's performance-*vs.*-load curve. If so, the turbogenerator set's efficiency in terms of *real* power per unit of fuel input could improve. This should be checked with the manufacturer as a potential further benefit of increased PF.

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[27] Ken Kenyon, NAVSEA SECAT team (ckenyon@csc.com), personal communication, 27 June 2001.
[28] See E SOURCE, *Drivepower Technology Atlas*, 1999, pp. 273–286, www.esource.com.

Specific recommendations include:

Improve electrical power generation efficiency.

Observations

Electrical power used aboard *Princeton* is generated by gas turbine generator systems (GTGs). Three such systems are aboard, and two were operating in parallel at all times with one in cold reserve during the RMI Team's time afloat. Each GTG includes one Allison 501-K17 constant speed gas turbine that drives a load-following generator capable of delivering up to 2.5 MW (~3,300 BHP). Power is varied by adjusting fuel flow to the turbine. When underway, some high-pressure air is bled from the turbine's compressor to the ship's bleed air system, *e.g.*, for use in the Prairie and Masker Air Systems. The ship pays a fuel penalty for this bleed air, but the masking benefits are important.

Normal and parallel GTG operations: NAVSEA uses the term "redundant" when talking about parallel plant operation, and "normal/alternate" when talking about split plant operation. Under cruise and battle conditions, GTGs are typically operated in parallel under a load-sharing control scheme, both to maintain redundancy for fight through resilience and to be able to serve pulsed or spiking loads (*e.g.*, the acute power draw of the SPY-1B radar). Operating two generators in parallel also provides additional capacity for transients, and reduces harmonic distortion by lowering the internal source impedance. During normal generator operation, one generator is designated as the standby generator, indicating it is aligned and ready to start.[29]

GTG loss and power system resilience: Battle conditions impose special restrictions on single GTG operations. This study focuses on cruise conditions, but the 60 Hz power distribution and load-shedding aspects of the system provide insight into the risks related to generator failure during various GTG operational alignments. Depending on the systems operating and their loading level, combat systems can be operated using one generator (*e.g.*, the SPY radar has high- and low-power modes). But the normal load during combat may exceed the capacity of one GTG. The three GTGs feed three switchboards and five load centers (LCs). The LCs are distributed in zones to increase fight through resilience. The power distribution system includes three buses on a ring, with automatic bus transfer (ABT) for critical systems and manual bus transfer (MBT) for noncritical systems. Each critical piece of equipment or system is fed from an ABT that will switch to alternate power when normal power is lost. In parallel operation on a live ring bus, the ABTs would not need to switch. When the GTGs are operating in automatic mode with one standby generator, if there is loss of power to the bus (dead bus) the standby generator will automatically start and be available for use in approximately one minute. If the GTGs were in split plant mode—where one switchboard or LC would feed the normal supply, and another switchboard or LC would feed the alternate supply—the ABT would switch if normal power were to be lost. During parallel plant operation, if one GTG were to be lost, the other would continue to feed the bus, preventing any power interruption to combat systems. If the remaining load exceeded the capacity of one generator, the pro-

[29] Frank Showalter, NAVSEA (215.897.7260 / ShowalterFE@nswccd.navy.mil), personal communication, 25 April 2001.

tective circuitry would shed non-vital circuits. CG-59 is one of two ships with the Turbine High Overload Recovery (THOR) system, providing three stages of automatic load-shedding of noncritical systems.[30]

GTG fuel use: The primary benefit of shipboard electric load reduction is GTG fuel conservation. Diesel Fuel Marine (F76) is used to fuel the GTGs. This is provided to the turbines directly from four service tanks (two forward, port and starboard, and two aft, port and starboard) that have a combined volume of 81,852 gallons. The four 21,500 BHP (16-MW_{mech}) propulsion turbines (GTMs)—each seven times larger than each GTG—are also fed from these tanks, via the same fuel lines. Fuel is typically drawn from two service tanks simultaneously (one forward and one aft, one port and one starboard) to maintain the ship's trim. When a service tank is drawn down to approximately 50% full, suction is shifted to the appropriate standby service tank and the half-drained tank is refilled from storage, after ensuring that fuel quality standards are met. The maximum volume of F76 carried by *Princeton* is 659,158 gallons, costing $0.85 million at $1.29/gal delivered.

There are two means for determining fuel expenditure aboard *Princeton*. One method, deemed the most accurate by veteran senior crewmembers of the Engineering Department, is sounding the tanks. This is routinely done at midnight and whenever suction is shifted from one service tank to another; the result is expressed in the ship's Daily Fuel & Water Report (24-h volumes of fuel and potable water expended). Senior engineering personnel also created a special log for our study by doing hourly soundings during a 19-hour period while underway. The other method for monitoring fuel usage is to record readings manually from analog fuel gauges in CCS (while making appropriate adjustments for replenishment of tanks). This is less accurate than sounding, for two reasons. First, the rolling motion of the ship introduces errors akin to those of trying to infer the fill state of a car's fuel tank by reading its gas gauge while going up and down hills. Second, the dials are hard to read accurately, due to logarithmically compressed sections of the scale and variability in interpreting values across the curved face.

Although overall fuel consumption is measurable, there is no routine means for identifying fuel used by individual turbines, nor even for GTGs vs. GTMs.[31] Thus the very large savings in propulsion fuel that the Navy has already achieved by real-time fuel-flow gauges that permit optimization of speed against the requirements of each mission have no analogy in the use of fuel to generate electricity. Nevertheless, an ideal opportunity was presented for determining the thermal efficiency of the GTGs during the RMI Team's time aboard when *Princeton* was moored at the wharf at NWS Seal Beach for 40 hours, with no shore power, and with its propulsion turbines secured. All fuel expended was therefore used solely by the GTGs to generate electricity. The efficiency of electrical generation in this situation was determined as follows:

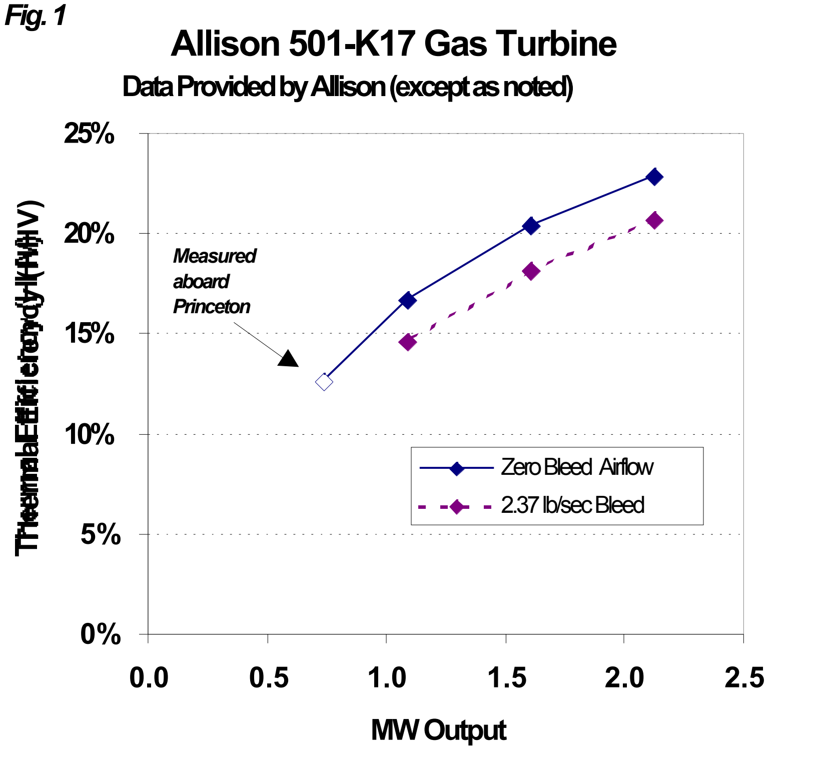
[30] *Ibid.*; also interviews with CG-59 crew.

[31] The RMI Team did not determine that the ship's systems could not directly measure GTG fuel use in time to make use of portable fuel meters. Fuel meter availability was noted by Ken Kenyon, NAVSEA SECAT team (ckenyon@csc.com), personal communication, 27 June 2001.

Table 1 Efficiency of Gas Turbine Generators (Dockside; Minimal Electrical Load)			
Fuel Consumed:	7,487 gal	9.58×10^8 BTU	24-hr volume from Daily Fuel and Water Report, 30 Jan 01. Assumptions: chemical energy is 18,400 BTU/lb (HHV); density is 6.98 lb/gal.
Electricity Generated:	35.38 MWh	1.21×10^8 BTU	Energy output recorded from DDI hourly log. Conversion factor is 3,413 BTU/kWh.
Thermal Efficiency:	12.6%		Output BTU / Input BTU (HHV)
Average Load per GTG on Line:	0.74 MW		29% of Full Load (max: 2.5 MW per GTG)

Data provided by Allison indicate a thermal efficiency of ~13% is not unreasonable for this powerplant (see Fig. 1): it is caused by operating at an inefficient portion of the GTG's performance curve.

Fig. 1



The Team also monitored actual energy demand aboard *Princeton* both at the dock and while underway, by recording data reported by the DDI each hour. As indicated by Figure 2 on p. 36, this reveals three things:

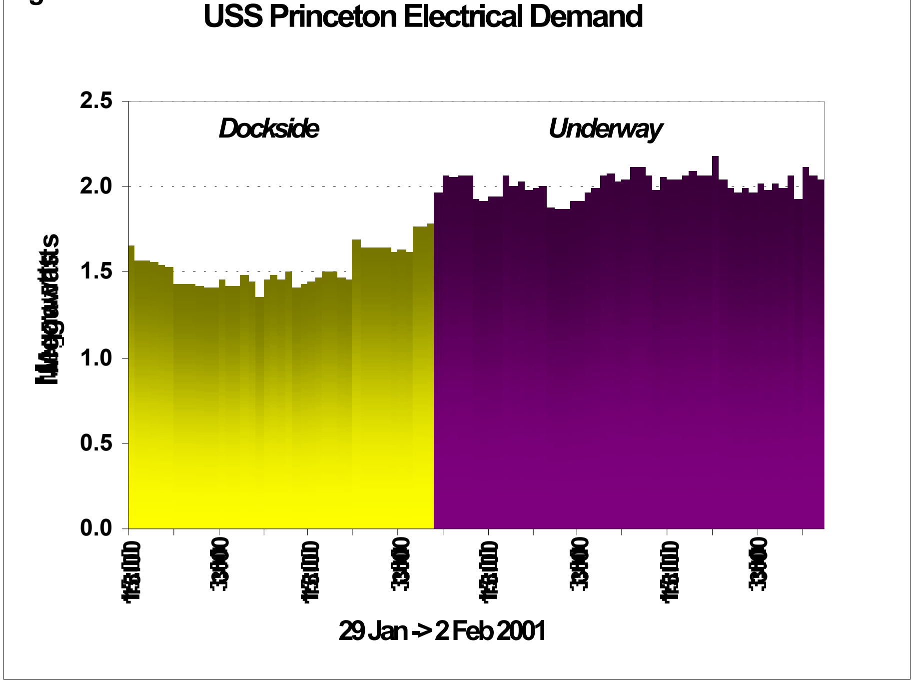
- Electrical demand underway is greater than when at the dock (average demand of 2.01 MW vs. 1.53 MW), because more systems are operational.
- There is no obvious correlation between time of day and energy demand: while underway the load is especially steady—its standard deviation from the mean is only 4 percent. This implies, correctly, that very few significant loads (actually none) use variable speed controls, and that many significant loads are left on all the time.
- Even while underway, the GTGs operate at only 40% of their rated capacity. This is on the low end of their thermal efficiency curve—an efficiency of less than 15% with air bleed, or around 16% without.

This last point might seem to imply that saving one unit of electricity can save about 6–7 units of fuel input to the GTG (actually a bit more because of avoided distribution losses). That would be very valuable leverage for saving fuel, cost, and signatures. However, that leverage is not actually available, because the current practice of operating two GTGs in parallel at all times (said to be required for reasons discussed below), each serving half of the electrical load, comes at the price of fuel efficiency, which worsens as the load is further reduced. This relationship is expressed by Figures 3 and 4 on pp. 36–37.[32] The severe penalty exacted by operating the GTGs at ever lower loads and efficiencies means that end-use electrical savings of, say, 20% or 50% will respectively save only 5% and 12% of the fuel input to the GTG. That is, *under the current operating practice, about three-fourths of the fuel that should be saved by saving electricity is not saved,* because reducing the already-low load on the generators makes them even less efficient than their already unimpressive performance. This means that *even heroic improvements in electrical end-use efficiency will yield only modest fuel savings unless the way of generating electricity is also addressed.*

CG-47 class cruiser emits a plume of engine exhaust. Chris Lotspeich photo.

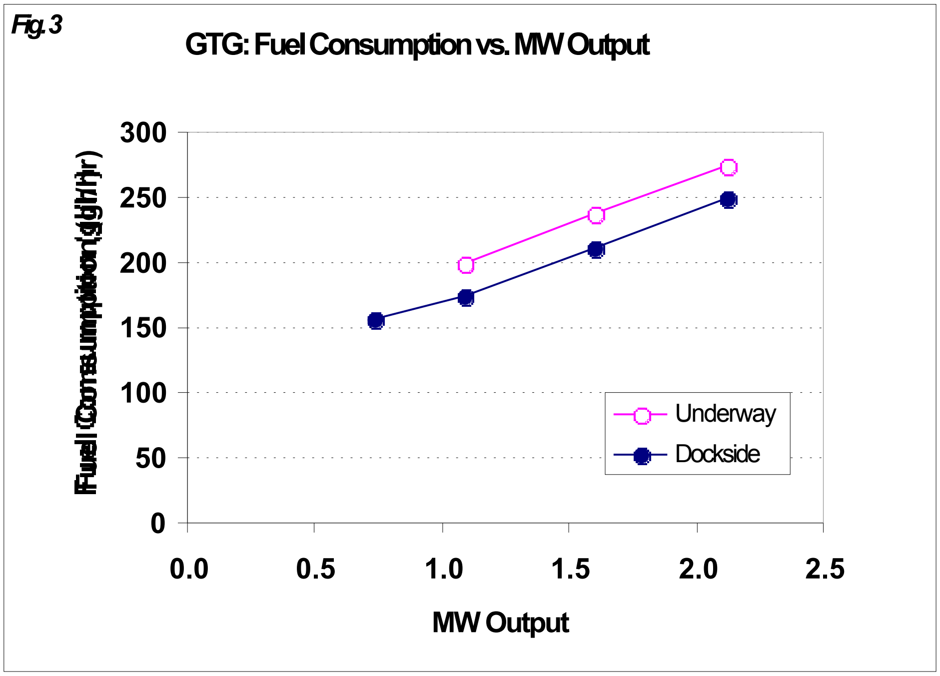
[32] Figure 3 is plotted for one of two GTGs operating in parallel. The deviation between the lines labeled "Dockside" and "Underway" is due to the air bled from GTG compressors to serve the Prairie/Masker Air systems. This alone requires approximately 60 gal/h of fuel (per Note 4 of a document provided aboard entitled "Nominal CG-47 Class Fuel Consumption Curves," Enclosure (1): "60 gph for prairie/masker air from 2 SSGTGs").

Fig.2

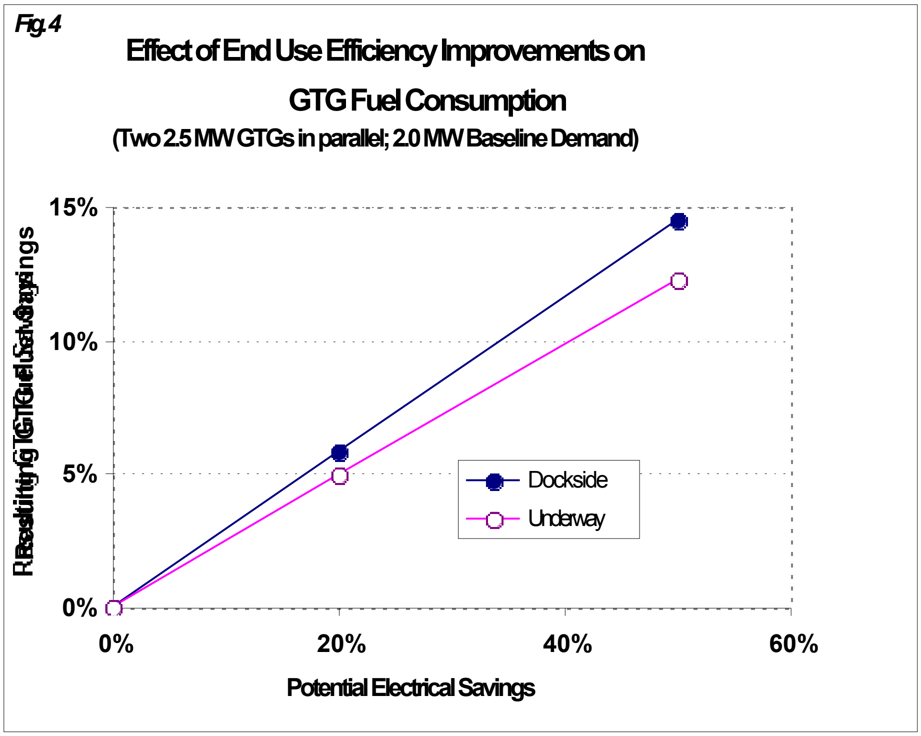


USS Princeton Electrical Demand
Dockside
Underway
Megawatts
2.5
2.0
1.5
1.0
0.5
0.0
29 Jan -> 2 Feb 2001

Fig.3



GTG: Fuel Consumption vs. MW Output
300
250
200
150
100
50
0
0.0
0.5
1.0
1.5
2.0
2.5
MW Output
Underway
Dockside



Recommendations
The analysis of end-use efficiency improvements must be integrated with supply-side efficiency improvements. *Treating these two opportunities sequentially and in isolation will sacrifice about three-fourths of the fuel savings that could otherwise be achieved by saving electricity.* Among the most important opportunities we found aboard *Princeton* is to combine two approaches: save much of the electricity, and (if possible) seek highly reliable ways to operate one GTG at 80% load rather than two units at 40% load.[33] This combination will increase the operating turbine's efficiency by more than two-fifths, thus reducing the fuel-saving leverage of saving electricity; but it will also operate on a less steep portion of the turbine curve (Fig. 3), where the electrical savings will incur far less part-load turbine-efficiency penalty. Alternatively, the Navy might rethink the power plant entirely.

The opportunity to combine these electric end-use and generating efficiency improvements with analogous propulsion-power improvements is analyzed at pp. 44–49, and is shown in Table 4 on p. 49 to have the potential to increase by 4–5-fold—to a potential saving on the order of perhaps three-fourths of the ship's total fuel use—the savings available just by "trailshafting" the GTGs or just by saving one-fifth of the electrical load.

[33] This is well within NAVSEA's margin policy, which permits loading to 90% of rating.

The Team therefore suggests that the Navy explore and contrast at least three scenarios:

1. Consider operating one GTG instead of two during routine operations.
2. Replace or supplement one (or more) of the existing GTGs with one or more generators which have capacities and efficiencies better matched to the load.
3. Consider replacing the "rightsized" GTG with an even more efficient and reliable new technology such as a fuel-cell generator.

These suggestions are discussed below in more detail.

1. CONSIDER OPERATING ONE GTG INSTEAD OF TWO DURING ROUTINE OPERATIONS.

The current 2.01 MW load, and air bleed to serve Prairie/Masker air, together requiring 398 gal/h of F76, would need only 299 gal/h if met with a single GTG (25% savings), because the GTGs are more efficient at higher loads. If required for redundancy until a second GTG can be started if the primary unit fails, a source of instantaneous backup power would be added (batteries, ultracapacitor bank, flywheel—at least for critical loads). It is already common practice to operate only one of the four propulsion turbines ("trailshaft" mode) to save fuel when under low-threat conditions and when not facing critical maneuvering situations. The RMI Team suggests that the same reasoning and an analogous procedure apply to GTG operation.

If pulsed radar loads are requiring dual GTG operation for voltage regulation (sharing the pulsed load to reduce the chance of tripping critical equipment on transient low voltage), then the Navy should consider adding a mechanical flywheel instead—angular momentum is much cheaper than fuel. If necessary, the pulsed radars could be isolated from other loads by a separate motor-generator set with a big flywheel, or could be buffered by ultracapacitors or a ferroresonant transformer, depending on the pulse dynamics. (Fast solid-state transient eliminators or even superconductive storage loops, both of which are in commercial use to stabilize electric utilities' transmission and subtransmission systems, may also be appropriate.) Preliminary estimates of potential fuel savings from single GTG operations are shown on Table 4 on p. 49. Single GTG operations under current conditions (Strategy 1) offer an estimated 14% savings in total fuel use underway; single GTG operations plus a 20% load reduction (Strategy 2) offer an estimated 18% saving.

NAVSEA staff have already explored many of these issues, and significant considerations and questions remain (and should continue to be explored, in the Team's opinion). Some Naval personnel have long recognized the drawbacks of operating two GTGs at partial loads, and have explored the benefits and challenges of single-GTG operations. The Team will attempt to summarize and characterize these issues below.[34]

Doctrine: Apparently ship COs (and possibly CHENGs) have the discretion to go to a single-generator alignment, if and when they feel conditions warrant (e.g., peacetime

[34] This discussion benefited greatly from the input of Dr. Alan Roberts (Roberts.Alan@hq.navy.mil) at the Office of the CNO, and NAVSEA's Andrew Bigley (BigleyAW@nswccd.navy.mil), Bill Stoffel (StoffelWH@nswccd.navy.mil), and Jack McGroarty (mcgroartyjj@nswccd.navy.mil).

cruise conditions, independent transit in open ocean). There may be Type Commander or Squadron doctrines that dictate dual GTG operational alignment requirements for other more critical conditions (though neither the RMI Team nor NAVSEA personnel that the Team questioned are aware of any such directives). One NAVSEA staffer noted that, even given the prerogative to do so, it would be unlikely that a CO would consider going to a single generator if there were any kind of potential threat, in areas of restricted navigation, operating in close formation, etc. As noted above, ship's engineers may be reluctant to practice energy saving strategies because the EOSS Manual does not include them; NAVSEA is to revise the EOSS to allow ships to use energy conservation techniques listed in the ENCON Guide.[35]

NAVSEA support for energy conservation: Both the NAVSEA Incentivized Energy Conservation (ENCON) Program and Shipboard Energy Conservation Assistance Teams (SECATs) train CHENGs, Main Propulsion Assistants, and Oil Kings that fuel and maintenance cost savings can be realized by going to single generator operations when practicable.[36] SECAT self-help software includes the Ship Energy Conservation Assistance Program (SECAP), which generates fuel consumption curves and includes step-by-step procedures for conducting test runs for various plant alignments. SECAP enables CHENGs to determine quickly the best transit speeds, plant alignments, and fuel consumption costs for any given transit time and distance. The SECAP software package can be downloaded from www.navsea.navy.mil/encon/SECAPDescription.htm or from www.seaworthysys.com. SECAP indicates potential fuel savings from single GTG operations. This tool, if fully exploited, is a classic example of sound energy management.

Fight through capability: The primary consideration of single GTG operations is ensuring fight through capability, so that the ship's combat systems suffer no reduction in capabilities due to a casualty or power interruption, even for very brief periods. As one NAVSEA staffer put it, ships run two GTGs "because of the low confidence levels that exist and the dangers that can occur when a ship goes dark, even for just one minute." It is technically possible to operate combat systems with only one GTG online, but fight through capabilities are lessened. If one GTG goes down, it takes approximately 90 seconds to bring another one online.[37]

Motor generators/Static Frequency utilization is currently used on Navy ships to power up critical combat system loads. Combat systems also require redundant power feeds, primarily for critical operating scenarios (*e.g.*, high threat conditions), as a single load cannot be separated for redundancy via a single motor genset. If the ship's electrical system were to be damaged, there are automatic bus transfer switches (both very fast ABT's currently being implemented in the fleet, as well as existing ASCO types) to switch

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[35] "EOSS Revisions," "ENCON Elements" section, at www.navsea.navy.mil/encon/Frontpage.htm.

[36] See www.navsea.navy.mil/encon/Frontpage.htm. The ENCON program contact is NAVSEA's Pehlivan Hasan (202.781.3801/ PehlivanH@navsea.navy.mil).

[37] In contrast, the 1-L Otto engine of a Honda *Insight* hybrid-electric car restarts from idle-off to full rpm in <0.1 s via a compact 10-kW 25-ft-lb permanent-magnet pancake motor run by batteries (an ultracapacitor could run it instead). The concept is scalable, and ship's electrical loads could meanwhile be met by a small electric storage device. The aim would be to make GTG startup time limited by shaft shear, not blade stall.

power feeds to keep combat system up and operational. These distribution considerations are relevant to power storage device options, as discussed below.

Generating capacity: DDGs and CGs draw electrical loads in cruise mode that would allow them to run on one GTG. NAVSEA requires a 10% reserve generating capacity, and currently certain equipment could light off and increase the load close to that margin, or risk exceeding it. One NAVSEA staffer noted that often a vessel's power demand seems to increase as the ship ages, and therefore the ~20% margin that may exist during single generator operation on a new ship would gradually decrease over time. The RMI Team's observations suggest that reducing cruise mode loads—via end-use efficiency, motor soft-start devices, and improved power factor—would markedly increase the capacity margin, and perhaps also the security and comfort margin, of single GTG operations.

Fuel and cost savings and trade-offs: A NAVSEA engines group position paper presented to SURFPAC Command in 1998 explored the potential fuel savings of single GTG operation.[38] The paper concentrated on single GTG operations during low threat conditions such as deep water peacetime voyages, as loss of power during transit at sea would not have as serious effects as it might under higher threat conditions. One author of the study noted that allowing one GTG to remain in operation—spinning and synchronized—but at a no load condition would not provide any benefit, because the 2.1 gal/min required to operate the GTG at no load would eliminate the fuel saving of single-GTG full power operation. There are also the other operational factors that would lead to increased maintenance. Nonetheless, the study recommended that ships with GTGs should operate only one GTG during transit. In addition to fuel savings, operational maintenance on one GTG is eliminated, operational hours are reduced, and program overhaul costs are decreased. The study proposed a detailed investigation into the actual operating times and possible ramifications of single-generator operations during transits, but that proposal was not requested nor funded.

Alignment considerations for linked GTGs: Keeping a second GTG ready to take up load instantly can be achieved by means other than fuel-intensive idling. Ideally, one GTG in single operation mode could instead be linked via a clutched shaft to an adjacent backup GTG. This practice would allow the primary GTG to maintain the backup GTG in a no load standby condition by spinning it synchronously, thus avoiding the backup GTG's fuel use and startup delay. Apparently, such an in-line alignment is a key aspect of the benefits of trailshafting propulsion turbines, which connect in pairs to a common spinning shaft. However, CG-47 GTGs are neither aligned end-to-end nor situated near each other, which complicates this synchronized approach. This might in principle be overcome by using an electrical rather than a mechanical coupling.

Energy storage devices and systems: If linking CG-47 GTGs together mechanically is not practical, then an energy storage system might help bring a standby GTG online quickly and/or meet critical loads until a backup GTG can safely carry the load (see discussion below). For example, perhaps a flywheel could be coupled to the shaft of each GTG, with a dedicated (ideally synchronous) electric motor engaged to keep a standby GTG rotating

[38] Contact Jack McGroarty (mcgroartyjj@nswccd.navy.mil) at NAVSEA.

(with its flywheel) in readiness for instant load takeup. The RMI Team did not assess the practicality of this approach, nor the extent to which resulting windage and bearing loads might burden an otherwise unloaded GTG.

The Navy has considered various energy storage systems (*e.g.*, batteries and flywheels) for shaving peak loads and surviving severe load transients that might support both fight through capability and single GTG ops. In the 1980s, research was done on a Battery Energy Storage System (BESS) specifically to address the problems of dual GTG operations. However, up-front retrofit funds for implementing this system were not found.[39]

Because combat systems cannot tolerate power outages longer then a few milliseconds, much emphasis was placed on high speed, full power switching capability in the BESS program. The same requirement for high-speed load transfer would apply to other technologies for electrical storage such as flywheels. It would also be vital to ensure that control systems would shed non-critical loads as necessary during unplanned GTG transfer events while energy storage devices serve critical loads.

Flywheels offer potentially inexpensive energy storage. The newest types typically use carbon-fiber rotors and largely or wholly passive magnetic bearings. One NAVSEA staffer[40] reported that the Navy is looking into bidirectional flywheel energy storage devices that would power up off the ship's bus at steady state power conditions and provide power during high power consumption transients. The Navy currently employs flywheels on pulsed power applications for minesweeping generators and as an energy storage device on AOE-6 class auxiliary oilers. These machines have been designed with the flywheels on the generator shaft to enhance the inertia constant and help with the pulsed power duration or transient loading. In this staffer's opinion, retrofitting a Navy GTG with a flywheel for energy storage would be a significant effort. However, that opinion was probably based on traditional metal flywheels or on since-superseded carbon ones.

Naval research now focuses more on carbon fiber flywheels. Spinning in a vacuum at high speed (10,000–40,000+ rpm), they can maintain a small footprint and generate high rotational energy. Large iron flywheels are seen as a greater Naval retrofit and design challenge due to their bulk and potential impacts on weights and moments. Some of the perceived shipboard safety issues revolve around flywheels' high speed, including failure modes (flywheel burst, bearing failure, containment, fiber combustion), imbalance, loss of vacuum, shock and vibration requirements, and bearing loads and gyroscopic effects during high sea states. These issues appear, however, to have been resolved by the RMI Team's colleagues at AFS Trinity Flywheel in Livermore, CA (www.afstrinity.com).[41] This firm is shipping samples of several models to mainly military customers. Flywheel gyro effects are normally handled by either gimbals or double counterrotating wheels; the latter is used in Trinity's MPMF model. It stores 3 MJ, *e.g.*, 750 kW for 3 s, in 11 ft^3 and a total package mass of 500 lb, and can be combined modularly in one location or many.

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[39] Contact Dr. Alan Roberts at the Office of the CNO (roberts.alan@hq.navy.mil).
[40] This flywheel section is largely paraphrased or quoted from NAVSEA's Andrew Bigley (215.897.1190 / BigleyAW@nswccd.navy.mil).
[41] Contact Fred Schwartz (fschwartz@afstrinity.com), head of AFS Trinity business development.

In addition to these safety issues, the conversion of the high rpm outputs to useable electrical energy is sometimes considered to be a challenge. Modern flywheels like Trinity's overcome this with ironless Halbach Array permanent-magnet generators coupled to efficient high-frequency power electronics to yield DC or any desired output frequency. A NAVSEA informant described more traditional approaches: flywheel systems, in his view, could use a gear (not desirable for several reasons), or convert to DC and distribute. Flywheels would probably require high-frequency generators (which he felt are only now emerging from R&D); *e.g.*, a 15,000–18,000 rpm flywheel would feed a ~1,000 Hz genset. Thus the ship would have to rectify the output and invert it, requiring significant control systems. Current ship designs utilize 60 Hz power, so the DC would have to be converted back to 60 Hz via power electronics. In RMI's view, however, the required power electronics should be readily available from superflywheel, switched-reluctance motor, and other high-speed (*e.g.*, homopolar) motor inverter technologies and vendors.

Shipboard power system design is moving away from copper wire and towards silicon-based power distribution, which may facilitate the use of flywheels or similar devices. Future ship designs may potentially utilize DC Zonal Electrical Distribution Systems, which in principle would allow flywheel output power to be rectified, put out to the ship's bus, and then inverted via local inverters. NAVSEA is also involved in the R&D of high-frequency alternators that would be small and lightweight. Such alternators, currently being developed for high-speed electromagnetic trains, would be linked to a flywheel in rail or shipboard applications.[42]

2. REPLACE OR SUPPLEMENT ONE (OR MORE) OF THE EXISTING GTGS WITH ONE OR MORE GENERATORS WHICH HAVE CAPACITIES AND EFFICIENCIES BETTER MATCHED TO THE LOAD.

More modern generators would probably be inherently more efficient thanks to technological advances since the original GTGs were procured. Importantly, these units should be sized and selected *after* end-use efficiency improvements have permanently reduced the ship's load, making the new generators smaller than the GTGs. If such alterations are conducted, consider using that opportunity to improve generator and/or turbine efficiency at the same time. (For related discussion, see Strategy 3 shown in Table 4 on p. 49.)

If it hasn't already done so, the Navy might consider using modular microturbine generators in scalable clusters or packs. Critical loads could rely on one or more dedicated microturbines and noncritical loads with one GTG, thereby increasing the generating capacity reserve margin to allow single GTG operations with assured fight through capability. One COTS option is Capstone microturbines (www.capstoneturbine.com). In 30- or 60-kW sizes, they are ~26–30%-efficient (about twice as efficient as *Princeton*'s GTGs), are very compact and quiet, have low NO_X, can burn diverse liquid or gaseous fuels, and could be dispatched modularly to fit the load profile (they come in up to 10-packs, and are hot-swappable). Capstone had shipped 1,400+ units through April 2001 and is rapidly

[42] Andrew Bigley, NAVSEA (215.897.1190 / BigleyAW@nswccd.navy.mil), personal communication, 9 May 2001.

increasing production. Current cost is ~$900/kW and falling, probably by about threefold over the next few years. Such devices present a modular, highly resilient architecture, dispatchable stepwise to sustain high array efficiency over a wide range of loads.

3. THE "RIGHTSIZED" GTG COULD BE REPLACED BY AN EVEN MORE EFFICIENT AND RELIABLE NEW TECHNOLOGY SUCH AS A FUEL-CELL GENERATOR.

Extending this logic, fuel cells are electrochemical devices akin to a refuelable battery. Most designs run on hydrogen, which is either extracted or "reformed" from a hydrocarbon fuel or electrolyzed from water. Some fuel cells types could either use F76 directly, or draw hydrogen from a fuel processor that itself could be thermally integrated with existing turbines. Fuel cells are highly thermally efficient, converting 50+% of the fuel's chemical energy into electricity; efficiency might rise as loads decrease. Although they are more expensive, larger, and heavier than an equivalent gas turbine, fuel cells need less fuel, pollute less, and use less cooling. The Navy has been researching fuel cell technologies, and ONR is already making good progress developing molten-carbonate onboard fuel cells with private industry.[43] For example, FuelCell Energy, Inc. is developing a fuel cell for DDG-51 class ships, designed to operate on the same F76 DFM in use today, specifically to replace the same GTG system that is used aboard *Princeton*.[44] (For related discussion, see Strategy 4 shown in Table 4 on p. 49.) Solid-oxide fuel cells have also been demonstrated[45] that can switch on the fly between logistics fuel and natural gas.

CG-59 reverses propellers during a high-speed turn. Chris Lotspeich photo.

[43] Fuel cells being investigated by the Navy for marine service use diesel fuel and have excellent thermal efficiency (~50%) and turndown characteristics. For example, see "Fuel Cells for Marine Applications," presentation handouts by Mr. Harry Skrutch (tel 703.602.0706), Execution Manager, Ship's Service Fuel Cell program, Naval Sea Systems Command, presentation to DSB Task Force on Improving Fuel Efficiency of Weapons Platforms, 20 October 2000. See also Abens, Ghezel-Ayagh, Steinfeld, and Sanderson (FuelCell Energy, Inc.), and Cervi (Naval Surface Warfare Center), *Development of a Ship Service Fuel Cell*, paper presented at Fuel Cell Energy Seminar 2000, Portland, OR: October 2000, http://www.ercc.com/site/products/marine.html. However, NAVSEA's current contract to develop a 2.5-MW hotel-load fuel cell for surface combatants—the same size as current GTGs—should be reviewed as to unit size, in light of the scope for and desirability of reducing those loads first, and of modular architecture.
[44] Sandors Abens, FuelCell Energy, Inc., 3 Great Pasture Rd, Danbury, CT 06811, pers. comm., 19 Feb 2001.
[45] Contact Benson Lee, 216.541.1000 / tmi@stratos.net.

Improve propulsion power efficiency.

Observations

Although this study is nominally limited to the efficiency of hotel loads, this report identifies the need to expand the analysis to include the efficiency of the electrical generators that serve those loads. To understand better the value of reducing hotel loads in relation to the ship's total fuel use, and therefore mission readiness, the Team spent one day collecting data to estimate an approximate energy balance for the entire ship.

NAVSEA offers fuel consumption data for most Navy ships. SECAP software includes Baseline Fuel Rates for PACFLT. These are defined by three year average underway (UW) and not underway (NUW) fuel rates for each active, fossil fueled ship listed in the Navy Energy Usage Reporting System. NEURS also reports three year average UW and NUW steaming hours. Class averages are used for ships with <3 y operating time. PACFLT data were for FY 98–00 data. CG-59's estimated total fuel use is shown below:

NEURS three year average fuel rates for CG-59[46]

Ship	Fleet UW bbl/h	Fleet UW gal/h	NUW bbl/h	NUW gal/h	UW h/y[47]
CG-59	28.62	1,202	6.05	254	2,398

GTM fuel use cannot be directly measured in isolation from GTG fuel use with the ship's systems; NAVSEA's free meter installation had not yet been applied to CG-59.[48] The Team's first step was to estimate fuel used by each of the major end-uses: propulsion, electricity generation, and compressed air (for the masking systems). As noted above, the amount of fuel used to generate electricity can be determined by working backward from generator output data, which are routinely logged hourly, but only in conjunction with measurements made over a 24 h period at dockside when only the GTGs were running. Air obtained from the GTG compressors reportedly requires 60 gal/h.[49] The difference between these two terms and total fuel consumption is ascribed to propulsion.

All these data came together during one 19-hour period when *Princeton*'s crew sounded the fuel service tanks hourly to measure total hourly fuel consumption. The ensuing estimate for propulsion fuel consumption was checked for reasonableness by comparing fluctuations in fuel use with those in GTM shaft horsepower (the latter is logged hourly by the DDI system). After adjusting for variations in the timing of fuel tank soundings by

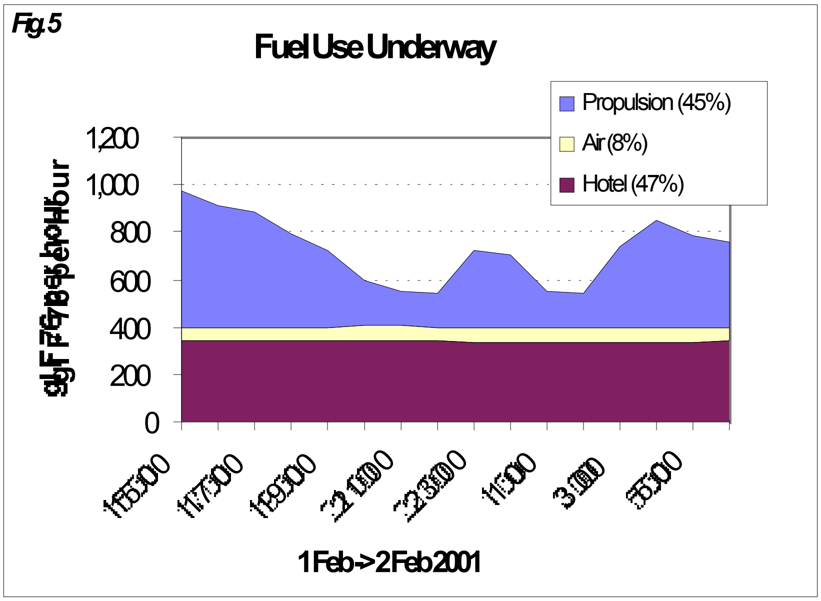
[46] See www.navsea.navy.mil/encon/BaselineFuelRateTable.htm. CG-59 has the second-lowest underway fuel consumption rate of the 14 PACFLT hulls of this class, 11% below the PACFLT class average, or 7% below the LANT class average, for FY98–00.

[47] Reportedly the SECAP 3-yr-average UW hours data for *all* SURPAC ships is not correct and needs to be updated. Ken Kenyon, NAVSEA SECAT team (ckenyon@csc.com), pers. comm., 27 June 2001. It seems internally consistent to interpret the stated 7,194 UW h/y as a three-year *total*, so we divided it by three.

[48] The RMI Team determined that the ship's systems could not directly measure GTG fuel use only too late to use portable fuel meters instead. Machalt 370 A provides fuel meters for the main engines of gas turbine ships. CG-59 can request them at its next port visit to a Navy Operating Base. The ENCON program covers the installation of fuel meters at no cost to the ship. Ken Kenyon, NAVSEA SECAT team (ckenyon@csc.com), personal communication, 27 June 2001.

[49] "Nominal CG-47 Class Fuel Consumption Curves," provided by *Princeton* personnel.

using three-hour moving averages, GTM fuel and power fluctuations were found to track closely, consistent with the fuel disaggregation model. Figure 5 presents the result.



The ship was operating at relatively low speed throughout this period (generally ≤12 knots; powered shaft speed averaged 58 rpm).[50] For this period, the GTGs, servicing both the hotel and air loads, consumed more fuel than the GTMs (55% *vs*. 45%). For this to occur in cruise mode, albeit at modest speed, confirms the importance of electrical loads, including hotel loads, although *no claim is made that this spot observation is typical.*

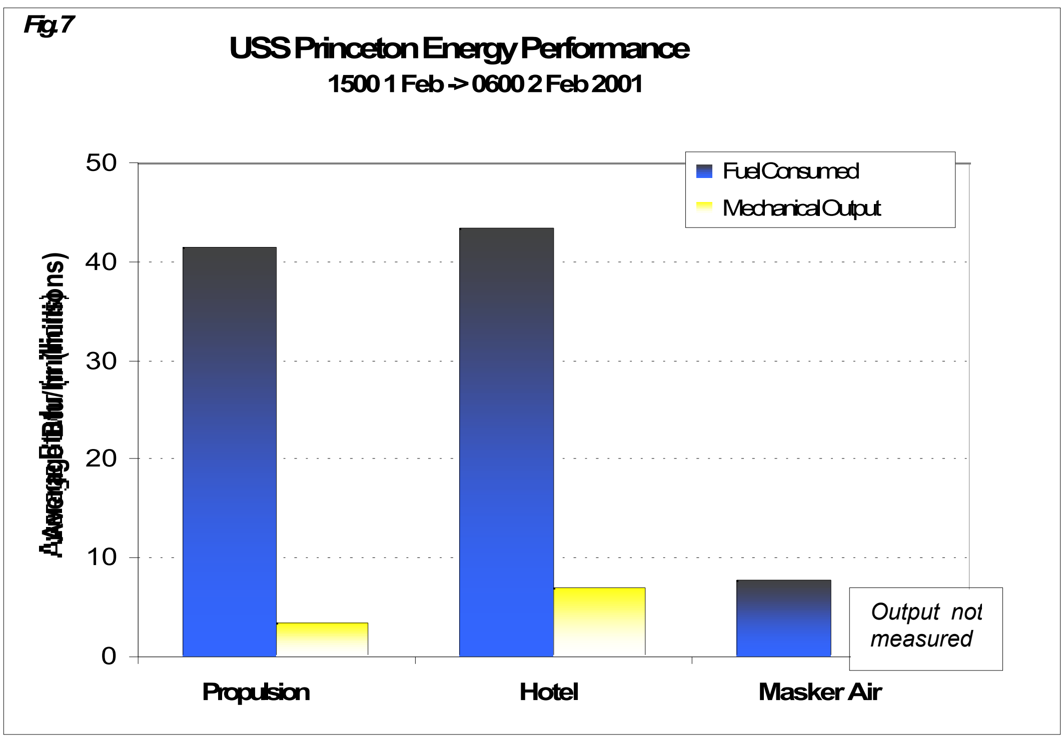
From the hourly propulsion fuel and shaft horsepower data, the thermal efficiency of the propulsion plant was determined to be approximately 8% (see Table 3 below)—half the typical as-used average efficiency of a car engine. This is lower than the 13% measured for the GTGs, but is not unreasonable because the GTMs were operating at an average of only 4.3% of their full load (vs. 29% load for the GTGs). With this information, the overall fuel efficiency story, at least for this portion of time underway for which the requisite data are available, is presented on Figure 7. This shows that *roughly 88% of the fuel consumed during this [possibly unrepresentative] cruise period to propel the ship and run its generators was converted directly to heat without doing useful work en route.*[51]

The powerful General Electric LM-2500 marine turbines aboard *Princeton* are designed for high-speed operation. Data provided by *Princeton*'s Engineering Department gives another sense of the relative fuel use of hotel and propulsion loads: the latter dwarf the former as ship speed increases.

[50] Approximately half the time, the ship was operating with a "Split Plant" (one GTM per shaft); the balance of the time with "Trail Shaft" (one shaft powered by one GTM with the driving propeller at 70% pitch, and the other shaft trailing in the over pitch condition, turning freely without power).

[51] As information required to determine the useful energy (and waste heat) associated with the Prairie/Masker air system is unavailable, this portion is excluded.

Table 3 **Efficiency of Propulsion Turbines (Average Shaft Speed = 58 rpm)**			
Fuel Consumed:	4,869 gal	6.23 × 10^8 BTU	Volume from hourly tank soundings. Assumed fuel energy is 18,400 BTU/lb (HHV); density is 6.98 lb/gal.
Energy Output:	20,400 SHP-h	5.19 × 10^7 BTU	Energy output recorded from DDI hourly log. Conversion factor is 2,547 BTU/SHP-h.
Thermal Efficiency:	8.3%		Output BTU / Input BTU (HHV)
Average Load per GTM on-line:	890 SHP (Shaft Horsepower)		4.3% of Full Load (max: 21,500 SHP per GTM)



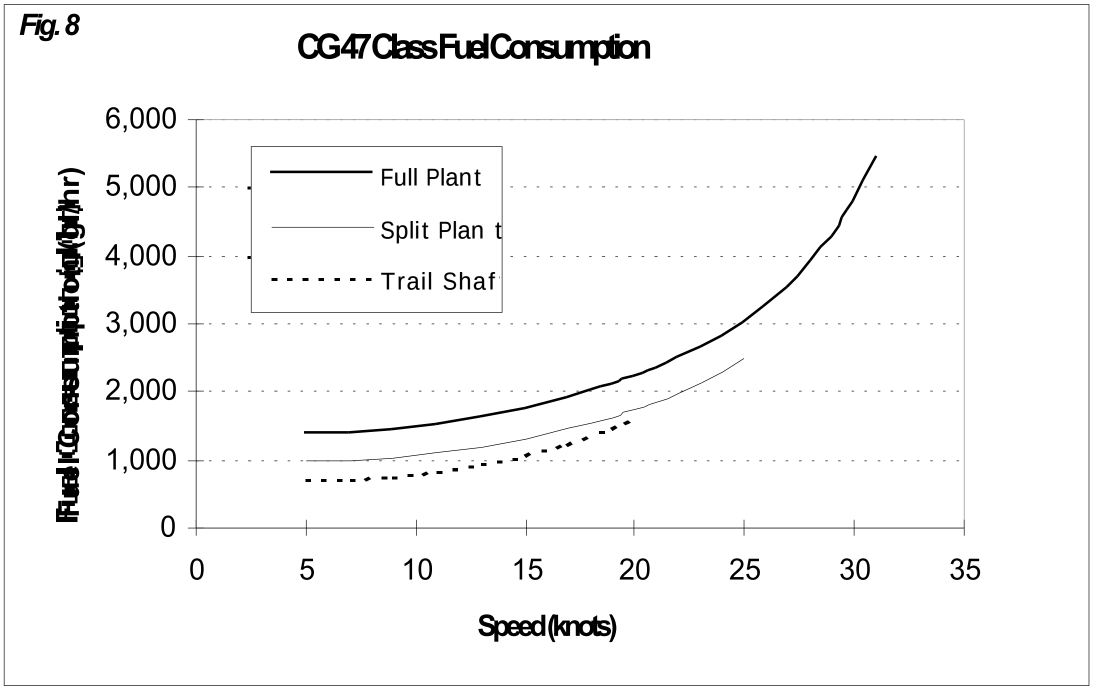


Fig. 8

NAVSEA data available from the ENCON Program also indicate specific fuel use under varied GTM alignments and speeds in gal/h (GPH) and gal/nautical mile (GPNM).[52]

Recommendations

This analysis, particularly as summarized by Figure 7, reveals a large opportunity to improve overall energy efficiency when operating below a nominal speed of 10–15 knots. Although the Split and Trail Shaft operating modes help to mitigate the propulsion turbines' inherent inefficiency at low ship speed (and therefore low turbine power levels), a considerable opportunity remains to reduce propulsion fuel use at low speeds. The Team did not determine the percentage of time this class of ship cruises at low speed, its propulsion plant efficiency at other speeds, and similar parameters. Lacking this baseline information, and knowledge of ship design and the ramifications of different powerplant choices, the following suggestion is offered to improve thermal efficiency alone.

The Navy might consider installing a new propulsion power source to drive one shaft (or both) during low-speed operations, assuming the mechanical connections can be made, etc. This might be a small gas turbine—again, designed specifically to support low-speed operation—or a fuel-cell-powered electric motor. (See Strategies 3–4 in Table 4, p. 49.) A retrofit would face space constraints and would probably require significant effort; this approach might be more easily undertaken during major refurbishing, or in new ship design. (The new LHD design incorporates electric motors operating off the ship service system for low speed operations to save fuel.[53]) In any case, the large gas turbines would remain in place to support combat operations and other full-power requirements.

[52] See www.navsea.navy.mil/encon/CG47.htm.

[53] Ken Kenyon, NAVSEA SECAT team (ckenyon@csc.com), personal communication, 27 June 2001.

FOUR SCENARIOS FOR FUEL SAVINGS OF GTG AND GTE OPS AND CONFIGURATION OPTIONS

Table 4, below, provides preliminary estimates of the potential fuel savings associated with four strategies for GTG and GTE operations and configuration, together and in combination. To summarize Table 4:

1. Strategy 1 shows that single GTG operations without reducing electric load can save about 14% of the ship's total fuel use by running the GTGs more efficiently.
2. Strategy 2 assumes single GTG operations and a 20% electric load reduction. This could save 18% of the ship's total fuel use—whereas without single GTG operations, far less would be saved, because most of the hotel-load savings would be offset by even lower GTG efficiency at the lower load.
3. Strategy 3 assumes moderate but more realistic electric load reductions (35%), plus new small gas turbines optimized for both electricity generation and low-speed propulsion. At Standard or lower speeds, this saves about 49% of the ship's total fuel.
4. Strategy 4 combines low-speed fuel-cell-electric propulsion, a 50% electric load reduction (which based on this analysis does not seem unreasonable with a concerted effort), and fuel-cell generation to serve electrical loads. At Standard or lower speeds, this saves about 76% of the ship's total fuel.

These scenarios do not directly include estimated expense and feasibility; Strategies 3 and 4 would be relatively costly and complex retrofits. The Navy has not yet installed nor completed testing and development of all of the technologies mentioned above (*e.g.*, fuel cells). Nonetheless, these strategies suggest the potential to reduce total CG-59 fuel use by about half with modest effort, or by roughly three-fourths when making a more intensive effort to reduce hotel loads while simultaneously installing fuel cells. The latter option would reduce fuel demand by approximately 540 gal/h when operating at Standard speed or less.[54] This level of improved within-the-skin-of-the-ship efficiency would quadruple the cruising radius (at this speed) without additional underway replenishment. Alternatively, every seven hours' cruising at this speed with this improved efficiency will provide one "free" hour of sprinting at Flank 2. External improvements, such as those in the Navy's Bulbous Bow program[55] (akin to smoothing the Hypercar[SM]), Stern Flap, and improved hull husbandry, or better combat systems (p. 16), would add to this potential.

This brief overview does not incorporate other advantages of using fuel cells to serve both propulsion and hotel loads. The enormous reduction in waste heat (by burning 75% less fuel to accomplish the same things done today) translates to reduced fan use for engine cooling, and a 75% reduction in the ship's thermal signature based on heat flux without regard to temperature, which may also decrease. Furthermore, the value to the Navy of reducing fleet fuel demand is surely significant. The logistics to support—and the increased vulnerability during—underway replenishment, for example, suggest a high warfighting value for such dramatic fuel savings. The Defense Science Board Task Force report described on p. 8 and cited on p. 18, n. 7, compellingly supports this approach.

[54] CG-47 class ships today require ~3,850 gph at Flank 2 (p. 47, Fig. 8: fuel consumption at 28 knots).

[55] Bow designed for DDG-51 class ships to save 4% of fuel. Mary Zoccola, **"**Bulbous Bow Saves Fuel**,"** *Wavelengths*, March 1997**,** www.dt.navy.mil/mz/bulbous.html.

Table 4

Potential Configurations to Improve Performance at Standard Speed

LOAD		SCENARIO Today	Proposed	SAVINGS gph	%	Comments
Strategy 1: Operate One Instead of Two GTGs (no change in end use efficiency)						
Propulsion						
	Efficiency	8.3%	8.3%			No change in Propulsion System
	Fuel (gph)	325	325	0	0%	
Hotel						
	Load (MW)	2.01	2.01			Serve entire hotel load with one instead of two GTGs.
	Efficiency	16%	22%			
	Fuel (gph)	338	239	99	29%	
Air						
	Fuel (gph)	60	60	0	0%	Unchanged (insufficient information)
	TOTAL (fuel):	**723**	**624**	**99**	**14%**	
Strategy 2: Modest Hotel Load Efficiency Improvement; Operate Single GTG						
Propulsion						
	Efficiency	8.3%	8.3%			No change in Propulsion System
	Fuel (gph)	325	325	0	0%	
Hotel						
	Load (MW)	2.01	1.61			Improve hotel end use efficiency by 20%, and serve load with one instead of two GTGs.
	Efficiency	16%	20%			
	Fuel (gph)	338	210	128	38%	
Air						
	Fuel (gph)	60	60	0	0%	Unchanged (insufficient information)
	TOTAL (fuel):	**723**	**594**	**128**	**18%**	
Strategy 3: Moderate Hotel Load Efficiency Improvements; Right Size Gas Turbines						
Propulsion						Provide new small turbine to power low speed propulsion
	Efficiency	8.3%	18%			
	Fuel (gph)	325	150	174	54%	
Hotel						
	Load (MW)	2.01	1.31			Improve end use efficiency by 35%, and provide new small turbine (replace one GTG or supplement existing engines)
	Efficiency	16%	22%			
	Fuel (gph)	338	158	180	53%	
Air						
	Fuel (gph)	60	60	0	0%	Unchanged (insufficient information)
	TOTAL (fuel):	**723**	**369**	**354**	**49%**	(Applies at Standard or less speeds)
Strategy 4: High Efficiency Hotel Load; Low-Speed Electric Propulsion; Fuel Cells						
Propulsion						Provide electric motor, powered by a fuel cell, to drive one shaft during low-speed cruising
	Efficiency	8.3%	43%			
	Fuel (gph)	325	63	261	81%	
Hotel						
	Load (MW)	2.01	1.01			Improve end use efficiency by 50%, and install diesel fuel cell (replace one GTG or supplement existing engines)
	Efficiency	16%	50%			
	Fuel (gph)	338	54	284	84%	
Air						
	Fuel (gph)	60	60	0	0%	Unchanged (insufficient information)
	TOTAL (fuel):	**723**	**177**	**546**	**76%**	(Applies at Standard or less speeds)

Improve pumping efficiency.

Generally speaking, CG-59's pumps are oversized and operate inefficiently relative to the work they are meant to do. Most pumps appear to be designed for the worst-case condition, so at all other times they are oversized. Pumping systems often are throttled back to control excessive flow or pressure, which means they are doing more work than is required. Apparently there are no pumps with VSDs, so all of the ship's pumps operate in one of two modes: full-on, or off. Several pumps run continuously when they don't need to. Some systems unnecessarily discharge water overboard (which must be replaced), and some of this water is chilled, wasting chiller energy as well as pump energy.

Pump efficiencies appear not to have kept up with the market. A 1989 Swedish study found, for a given flow and head, an 8–10 percentage point range of rated design-point efficiency among manufacturers, or even among different pumps from the same manufacturer (with 1% price difference). As with U.S. induction motors (p. 27), there was no correlation between Swedish industrial pumps' price and efficiency. The best new pumps in were 3–10 percentage points more efficient than the average new pump, which in turn was 3–5 percentage points better than the average in-service pump. Today's new pumps are often better than the best were in 1989, thanks to supercomputer design optimization.

Compared to CG-59's fans (which have similar generic characteristics), most pumps' flow and pressure requirements are better understood and managed. Nevertheless, there are numerous opportunities to improve energy efficiency by reducing both pump speed and fluid flow. (Recall that power consumption varies as the cube of pump speed, while flow varies directly with pump speed.) As with the air systems, there are numerous bends and restrictions in the piping that create turbulence and decrease efficiency. Significant savings can be achieved simply by reducing pump speed to what is necessary, rather than overpumping or throttling back on flow—a common but deplorable practice analogous to flooring a car's accelerator while controlling its speed by stepping on the brake. As with fans, adding VSDs is the simplest way to achieve the desired speed reduction while saving energy and extending equipment life.

Some specific pumps and pumping systems are addressed below:

FIRE PUMPS

Observations

The most extreme example of large background electrical loads is the fire suppression system. During cruise, anchor, and shore operating modes, two of six 125 BHP electric fire pumps run continuously to maintain pressure to 150 PSIG on the network of seawater (SW) fire main piping. (They were observed actually operating at 175 PSIG.) The fire main system is interconnected with the seawater service (SWS) piping network, in case there is a failure of the two SWS pumps. The SWS system provides water for cooling equipment (*e.g.*, radars), toilet flushing, and other applications. There is no designed flow required in the fire mains if no fire condition exists when the SWS interconnect is in the closed (normal) condition. To keep the fire pumps from over-pressuring and burning up, water is recirculated and ultimately discharged overboard.

This approach uses these large pumps very inefficiently at fractional loads as pressure maintenance "jockey pumps" and to flush toilets and urinals. This is hard on both the pumps and the piping system. Pipe fouling and scaling due to seawater adds unwanted friction and pumping energy requirements. The new pumps are made of titanium. The motor efficiency is rated at 97% (good if actually realized), but the pump efficiency is rated at 70.3%[56] (this is relatively poor; it should be ≥85%). In effect, 2,200 gpm (2 × 1,100) of seawater is pumped at 150 PSIG through the ship's fire main piping and dumped overboard, continuously, for most or all of 3,762 (actual CG-47 class average[57]) operating hours per year.[58] The ship runs two pumps instead of one in case one fails, so that the other will serve the load without interruption of service. (The operators were reluctant to rely on the automatic pump control system to start off-line pumps, even though in principle such a control system should be no less reliable than the automatic bus transfer currently relied upon for the entire ship's redundant power supply.)

This practice draws about 210 kW of electric power[59] (791 MWh/y at 3,762 operating h/y, assumed to equate to cruise + anchor + shore modes). At $270/MWh (cruise mode, p. 19), this costs ~$198,000/y—a 20-year present-valued cost of $2.66 million. Perhaps the worst consequence is the constant seawater abrasion, erosion, corrosion, scaling, and fouling of the fire main pumps and piping. (*Princeton*'s CHENG reported that the pump and first elbow had had to be converted to costly titanium to combat erosion.[60]) Maintenance and replacement costs for the whole system should be factored into this decision. On its face, a multi-million-dollar present-valued electricity cost per two fire pumps, on one ship, would seem to justify careful examination of operational alternatives.

Recommendations

Turn the fire pumps off. Substitute the shore-based technique of sealing and then pressurizing the fire main with fresh water (or seawater, flushed regularly to reduce fouling), maintaining header pressure with a small jockey pump, and placing the main SW fire pumps in "auto" control mode (*i.e.*, start if there is a loss of header pressure). Excessive cycling of the jockey pump would indicate a leak in the fire mains. The starting of a main fire pump would signal a fire, failure of SWS pumps, or a major pipe break. Fire pump reliability and rapid ramp-up times could be ensured with regular testing. This approach would provide a better fail-safe condition than the present practices, and would significantly reduce both maintenance and waste.

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[56] Frank Showalter, pers. comm., 26 Dec. 2000, based on a 1995 Navy standard; 215.897.7260 / ShowalterFE@nswccd.navy.mil.

[57] Ken Kenyon, NAVSEA SECAT team (ckenyon@csc.com), personal communication, 27 June 2001.

[58] Using Kenyon's CG-47 class average.

[59] The kW usage of the two pumps, each @ 1100 gpm @ 150 psi, is given by the pump equation: (2200 gpm × 346 ft w.g. × 0.746 kW/hp) ÷ (3960 gpm-ft w.g./hp × 0.703 pump efficiency × 0.97 motor efficiency). Measurements confirmed that one pump draws 104 kW of power: 168 amps × 452 volts × 1.73 [= √3, the three-phase correction factor] × 0.79 inferred power factor = 105.2 kW, in good agreement.

[60] LCDR Paul Hogue, pers. comm., 2 Feb. 2001.

Add VSDs to operate closer to minimum system pressure (on whatever sized pumps are used). Lower pump speeds reduce flow proportionately and energy use as the cube.

Consider using a pipe and tube cleaning system to reduce sea growth, scaling, and other pressure-inducing buildup. Explore chemical, mechanical, and possibly magnetic methods. Investigate magnetic anti-scaling devices for pipe, boiler, and condenser water treatment. This is a somewhat disputed approach, but appears to have documented successes ashore, and might be able to reduce friction-induced parasitic loads. The scientific basis for using a high periodic magnetic field to cause calcium carbonate to crystallize in a slippery vs. sticky form seems sound, but application success varies and requires experimental verification. Magnetic signature considerations might also have to be taken into account but are probably unimportant compared to other constant and variable fields.

System energy use could potentially be reduced by as much as 20–90+%, depending upon the measures implemented.

SW (COOLING) PUMPS

Observations
CG-59 uses seawater to cool some equipment (*e.g.*, radars). The crew runs two of three 125 hp SW cooling system pumps at full capacity. System pressure was observed at 60 PSIG; the target is 3,000 gpm flow at 50 PSIG. Some SW bypasses equipment; all of it is vented overboard.

Recommendations
RMI recommends adding VSDs to maintain pressure at 50 PSIG (if that is actually the pressure implied by optimized system design). Because of the cube-law dependence of pump energy on flow, reducing pressure from 60 PSIG to 50 PSIG might save as much as ~40% of the electricity.

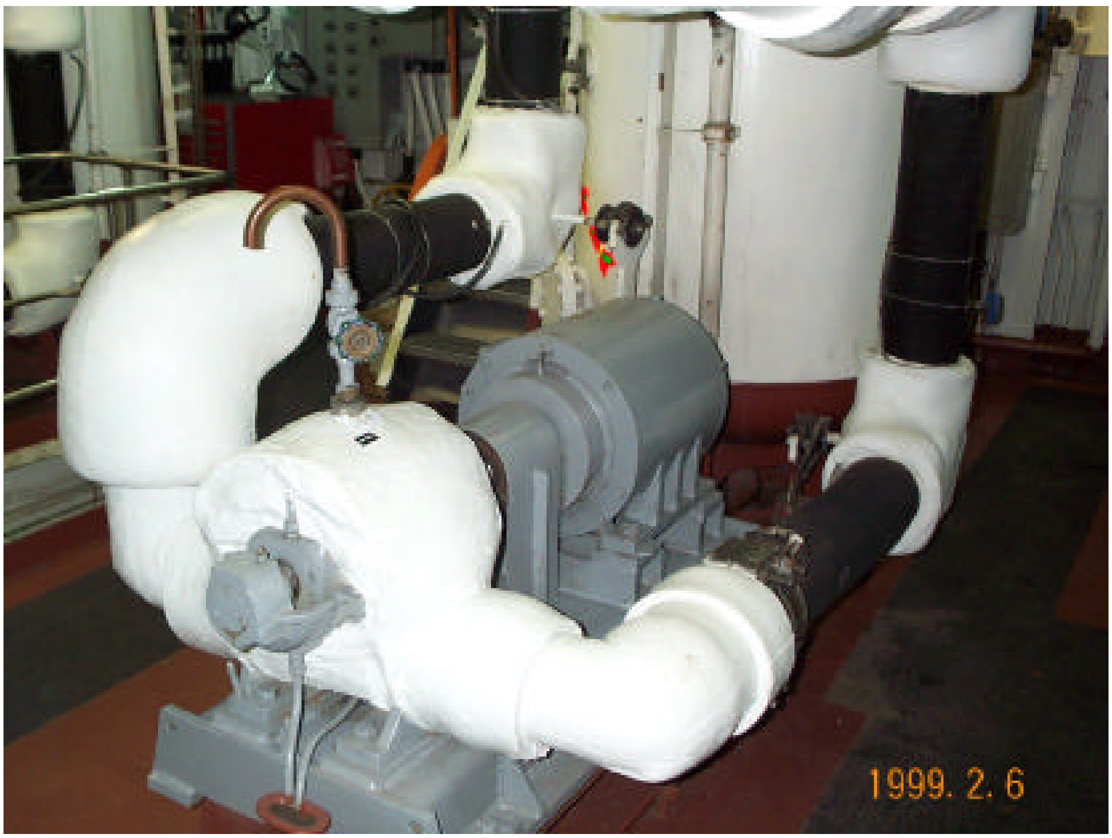
The RMI Team also suggests consideration of a novel cooling strategy, possibly for retrofits and at least for new ship design. In a sense, the hull is one-half of a plate-exchanger HX. Consider adding cooling coils inside the hull for the other "half," to make closed-loop condenser water for process/equipment cooling. Apparently some tugboats use this approach. This would be a significant retrofit project for CG-59 (assuming that the space to do so even exists), and would probably best be explored in new ship design.

CHILLED WATER PUMP

Observations
The 50 hp chilled water pumps (CHWPs) appear to be inefficient. The ship apparently runs two of four total pumps at yoke, with a specified flow of 720 gpm (730 gpm observed) and a specified ΔP of 56 psi (from 82 psig to 26 psig). Based on RMI's observations, and assuming (as there are no data available) a motor efficiency of 90% and a pump impeller efficiency of 80%, the CHWP efficiency would be 0.1 kW/ton. In contrast, best practice ashore is 0.026 kW/ton—fourfold less. A typical shore-based flow rate

is 2.4 gpm/ton (at ARI conditions). Apparently the ship needs 480 gpm (based on 10 F˚ ΔT), but is pumping 729 gpm if the ship's flowmeter is accurate. This system has variable flow, but uses a constant-speed pump. It is overpumped and induces parasitic loads. Increasing the chiller lift, by slowing the CHWP or trimming the impeller, would reduce pumping parasitic load considerably. Since the condenser pumping is provided by the SWS pumps, there are no condenser water pumps. These pumps are horizontal split case pumps. Although pump curves for these units were not available, the fire pump curves show efficiencies of less than 80%.

Operating conditions vary, and cooling must be done in warmer waters (*e.g.*, the Persian Gulf). As the sea water temperature rises, more flow will be required to remove the same amount of heat. The system should be controlled to produce a set amount of ΔT (10 F˚).



Chilled water pump. Note the constrained entering and leaving conditions of the piping, with immediate 90° turns. Ron Perkins photo (camera date was mis-set)**.**

Recommendations
Add a VSD to the CHWPs, trim the impeller, and increase motor efficiency to match and serve the load more efficiently. Balance flow at CIC Fan Coil Units (FCUs) by eliminating or opening balancing valves.

STEERING GEAR HYDRAULIC PUMPS

Observations
At yoke, each of the rudders typically operates on one (of two) 100 hp hydraulic pumps (four total, all of which operate under battle conditions). The RMI Team observed all four operating at yoke. These pumps maintain 700 PSIG hydraulic pressure for steering the ship; an undetermined amount of hydraulic fluid is bypassed when not needed. However, much of the energy is expended on—wasted in—a hydraulic bypass system because the load varies, since most rudder orders (minor and continual fluctuations to maintain a steady course) require relatively little energy to carry out.

Recommendations
Use VSDs on these pumps, set to maintain desired pressure. For example, at yoke set the first pump to maintain pressure at 700 PSIG, and set the second (backup) pump to come on anytime the pressure drops below a certain setpoint (*e.g.,* 650 PSIG).

Improve fan efficiency.

Observations
The GTMs (propulsion turbines) have four 80 hp turbine cooling fans, one per turbine; the GTGs have six 60 hp fans, two per turbine. There are about 78 supply and exhaust fans on CG-59. Of these, 50 are 2 hp or larger and 32 are 5 hp or larger. There are about 138 FCUs with The RMI Team was unable to measure this fan load, but estimated the fan performance in a typical FCU to be about 0.5 kW/ton, at 1/5 hp. The design static pressures range from 5" to 0.5" w.g. TSP.

Many of the supply and exhaust systems need a complete analysis and balancing. Some fans appear to be oversized and either supply too much air or must be throttled back to control excessive air flow—very inefficient either way. All fans on the ship operate essentially in binary mode: on or off. There are no VSDs. By definition, the fan systems are designed for the worst-case condition, so at all other times they are oversized. Some fans run continuously, often 24/7, unnecessarily (*e.g.*, in the galley and scullery). Exhaust fans that unnecessarily vent conditioned air waste chiller and pump as well as fan energy.

Recommendations
One approach is to replace oversized fans with properly sized units. However, that is easier said than done on a Navy ship. Another, often better, solution is to install VSDs on the larger fans that have variable loads, then control the speed to maintain desired parameters (*e.g.*, temperature, static pressure, etc.). The best candidates are the turbine cooling fans. (As noted above, in FY01, NAVSEA will be testing a VSD module for LM 2500 GTM cooling fans at a land-based engineering site in Philadelphia.[61]) Install controls that turn off fans when they are not needed. For example, the galley and scullery could have "Melink" controls that slow the hood fans in the galley when there is no cooking activity. Install premium efficiency motors in units with long run times (FCUs).

[61] Personal communication, Andrew Bigley, Branch Manager, Electric Power Systems Branch, NAVSEA Philadelphia, Code 934 (215.897.1190 / BigleyAW@nswccd.navy.mil), 9 May 2001.

The VSD approach will produce major savings at least cost. If fan speed and flow volume can be reduced by only 20%, the energy saved is 49% because of the cube law (actually a few points less due to inverter losses). If the speed of a fan can be reduced by 50%, the energy savings will be about 87% (ditto). On *Princeton*, and probably other ships, the savings could be even greater because of the turbulent flow conditions in many ventilation ducts as a result of the numerous bends and restrictions. A representative example:

The Outside Make-up Air Fan shown here is one of four units providing ventilation air to the ship. The axial fan motor draws 5 kW,* producing an external static pressure of 1.83" w.g. Not visible in this picture is the fan inlet located 3" off deck. The restricted inlet and outlet, 180° change in flow direction, and short transition to cooling coil section severely degrade the fan system's aerodynamics. The photograph shows the very congested equipment space (not large enough to enter for maintenance or repair). Future designs should use the compartment as the air duct and eliminate ductwork and transitions. The fan should be aimed in the direction of airflow into the ship. In this case, one fan would be pointing downward, and one horizontally exiting through the coiling coil. This arrangement would minimize pressure drop and duct losses, and lower the fan power by at least 2/3 (3.3 kW). The inefficiencies of the system create heat in the air stream and load for the chiller. The suggested fan power and weight reduction would translate into generator, turbine, chiller sizing, and fuel savings. A less familiar concept worth considering is a passive latent heat exchanger (App. H, p. 107, n. 125).

*$[(7.4 + 7.7 + 7.5\text{A}) \div 3] \times 450\ \text{V} \times \sqrt{3} \times 0.85$ inferred PF = 4.95 kW (measured).

Improve space cooling systems equipment and operations.

Space-cooling efficiency is best considered in a far wider context than mere equipment improvements. An optimal sequence, especially for new ship design and to some degree for retrofits, is summarized in Appendix H. Although its further elaboration is largely beyond the scope of this report, it should systematically inform Naval design philosophy.

IMPROVE CHILLER EFFICIENCY.

Observations

Princeton has four 200 ton York centrifugal chillers for space cooling, and runs two of them under cruise conditions with two manually off, held in reserve (she runs four in battle). Each CH draws an indicated ~184 kW, or ~0.9 kW/ton chiller at ARI conditions—among the most inefficient centrifugal chillers the RMI Team has ever evaluated. The rated efficiency is affected by entering CW temperature (SW); the efficiency increases about 1.2% for every degree the CW temperature is depressed below 85°F. At 65˚F CW temperature, the *rated* efficiency of the existing units would be about 0.72 kW/t, while the *best* York chillers would be rated at about 0.45 kW/ton at these conditions. CHW design temperature is 50.6˚F entering and 44˚F leaving, a lift of 6.6 F˚. The chiller's 250 hp motor is oversized.

The RMI Team observed CHs One and Two operating 60% loaded at an indicated 1.1 kW/ton at a CW temperature of 61˚F. One CH could handle the native load if the other one were turned off, but standard procedure is to run two at all times.[62] (The redundancy-for-resilience strategy is to operate two CHs in distributed spaces; the RMI Team on its first float observed two CHs operating in the same space.) Each of the two CHs that are operated in parallel runs at ~40% capacity; it would be more efficient to run one CH at ~60% capacity. The CHs are started manually, taking about 15–20 minutes to position the valves and start the CHW pump. This long start cycle was cited as the primary obstacle to running one lead CH with a lagging backup CH, instead of running two CHs in parallel. If this procedure were automated, as is done at most plants ashore, the CHs could be started automatically or remotely from the Central Control Station (CCS). The CHs are specified with a low lift (6.6 F˚) and require 720 gpm CHW flow to offset the low ΔT (instead of 480 gpm for 10 F˚ΔT).

CH measurement: The RMI Team observed (App. A) that CH Four appeared to be constrained from reaching its full output, perhaps by its current limiter; controls and sensors indicated that the CH had reached 97% of FLA at only 120 tons—about 60% of its rated capacity of 200 tons. The Team was unable to determine why this occurred, and referred the problem to NAVSEA and CG-59's crew for investigation. The Team also suspected

[62] Two chillers were running at 4 F° ΔT and 67% FLA (indicating 60% load at 240 tons), but at least 40 tons of this load appears to be parasitic.

that hydronic problems (*i.e.*, pumping, piping, and distribution) might be reducing the CHW system's effectiveness. If so, such problems might not allow the ship to use one CHW pump to serve the load more efficiently.

Refrigerant replacement: The Navy is eliminating ozone-depleting refrigerants from the fleet. All four of *Princeton*'s AC compressors have been converted from CFC-114 to HFC-236fa. *Princeton* is one of the few ships to have been converted to date, so her systems are not representative of those currently installed on most Navy ships. The balance of the Navy's R-114 plants will be converted over the next 12 years or so. Only the ships currently using CFC-114 will be converted to HFC-236fa. Future ships will be equipped with compressors designed for HFC-134a.[63]

As part of the conversion process, the R-114 compressors are modified to accommodate a smaller impeller and other upgrades. NAVSEA has a parallel R&D program working on compressor efficiency improvements that can be incorporated into the machines during the conversion process. These improvements will not be available soon enough to benefit such early conversions as *Princeton*. One NAVSEA report projects that compressor improvements (*e.g.*, due to numerical optimization methods) that can be made to CG-47 class ships during the refrigerant replacement could increase efficiency by 10%, saving ~57 kW of power during cruise and battle conditions.[64]

Chiller One. Ron Perkins photo (camera date was mis-set)**.**

[63] Bill Stoffel, NAVSEA (215-897-7109 / StoffelWH@nswccd.navy.mil), personal communication, 19 January 2001.

[64] *Ibid.*; see also "Air Conditioning Compressor Improvements," handouts of presentation to DSB Task Force on Improving Fuel Efficiency of Weapons Platforms by NAVSEA's Thomas Bein (beintw@nswccd.navy.mil) and Dr. Yu-Tai Lee (leeyt@nswccd.navy.mil), 21 June 2001.

Recommendations
Turn off all but one CH, doubling efficiency. Retrofit to use one lead high-efficiency CH. Retrofit the CHs to use high-efficiency York Code Pak compressors. Use automatic startup systems to get each CH online in ≤3 minutes. If one chiller fails, the brief time it takes for a backup unit to come online is not problematic, because the thermal lags of the systems being cooled are typically much longer than chiller startup/rampup time.

CG-59 CHILLER PERFORMANCE[65]

	observed kW/ton	**rated kW/ton**	**best practice kW/ton**	**obs'd – best kW/ton**	**Potential savings/ 2 CHs, MWh/y**
Chiller	1.1	0.9	0.45	0.65	1,140
CHWP	0.1	0.07	0.026	0.074	130
CWP	unknown	0.024	0.021	unknown	unknown
Total system	1.2	1	0.5	0.72	1,270

At 96% electric distribution efficiency, the right-hand column implies potential fuel savings, per two chillers, of 241,000 gal/y (at the cruise-mode 182 gal/MWh on p. 18), with an annual energy cost of $357,000 (p. 19) and 20-y gross present value of ~$4.5 million.

EQUIPMENT COOLING SYSTEM

Observations
A closed-loop fresh water cooling system provides cooling for other dedicated refrigeration and electronic equipment. This cooling loop rejects its heat via a shell-and-tube heat exchanger to the SW cooling system. This system appears to be overpumped, based on an observed low temperature rise across the supply and return piping.

Equipment cooling heat exchanger. Ron Perkins photo.

[65] Based on calculations by Ron Perkins; *assumes* a 200-ton total average load and 8,766 h/y operation per year (ship's crew said the chillers are turned off only in drydock), and ignores part-loading and load profile.

Recommendations

Use VSDs on both primary SW pumps and the secondary closed loop pump to reduce power consumption and better match the load being served. Consider using a plate-and-frame heat exchanger, as it would both outperform the shell-and-tube heat exchanger, and require less pumping horsepower (implementation would be easier in new ship designs).

OPTIMIZE EQUIPMENT AND SPACE COOLING REQUIREMENTS (*E.G.*, IN THE CIC)

Observations

In cases where equipment cooling requirements drive space cooling temperature setpoints and energy use, consider the benefits of cooling that equipment directly and lowering the space conditioning requirements. The Combat Information Center (CIC) appears to be the area of greatest potential in this regard. The CIC is maintained at 61–62°F; some personnel regularly wear jackets in the CIC. Keeping the CIC so cold renders the space very sensitive to CHW fluctuations. The reason given for this low target temperature was to meet the cooling requirements of vital electronic systems. The RMI Team did not determine which CIC systems were cooled by the SW equipment cooling loop. Directly cooling electronic equipment is often more efficient and effective than cooling the space around it. In civilian electronics and information technology facilities (*e.g.*, mainframe computer rooms), the prevailing wisdom for many years was that cooling the space was the optimal equipment cooling strategy, but by the late 1980s to early 1990s, direct equipment cooling became generally accepted. Moreover, the target temperature was often relaxed once the equipment's actual engineering-based needs were more closely examined.

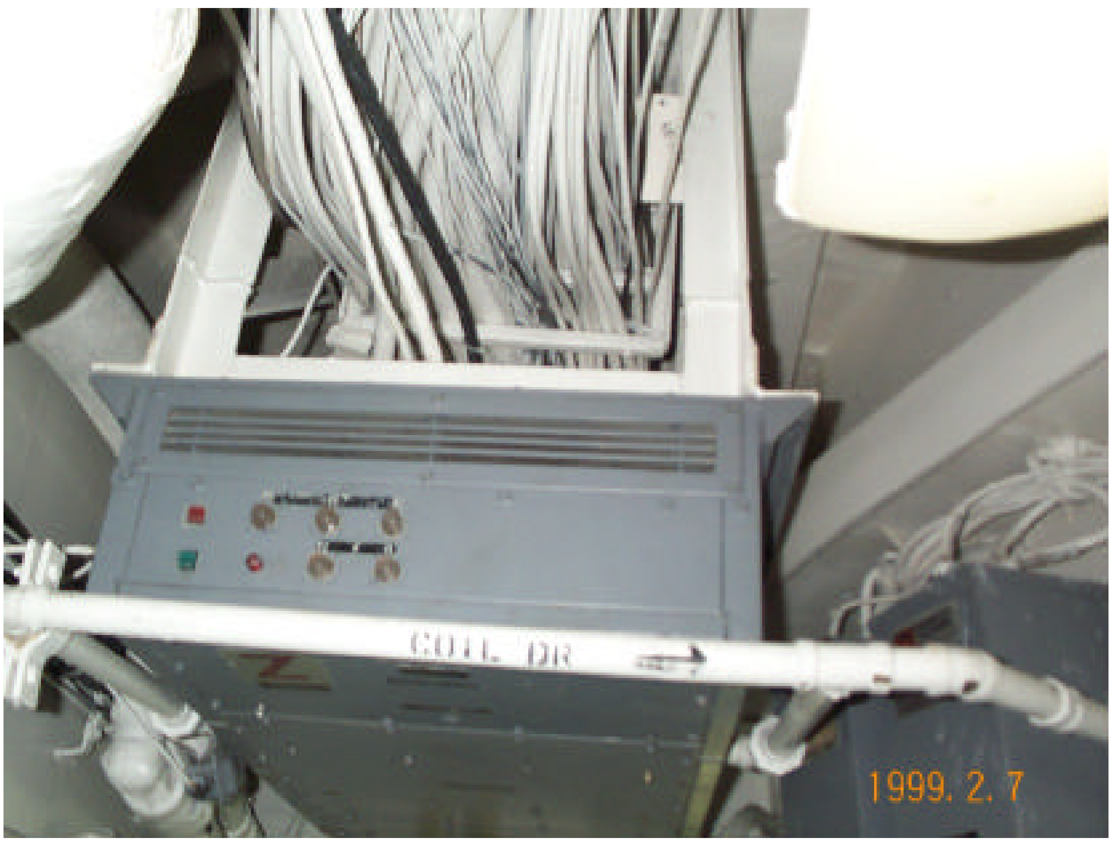
Recommendations

Explore expanded use of direct cooling of equipment that might allow an increase in CIC temperature. More direct equipment cooling strategies might include induction cooling from the floor (*e.g.*, via ducts or raised flooring), or connecting equipment and housings to a dedicated cooling loop (*e.g.*, the existing SW system). Investigate whether heat pumps might remove equipment heat reliably and reuse it for other purposes.

IMPROVE SPACE CONDITIONING CONTROLS

Observations

More than 70 Fan Coil Units (FCUs), linked to the 44˚F water cooling loop, are distributed throughout the ship's spaces, typically suspended from the overhead. Although there are controls on the FCUs, many apparently provide air that is relatively cool (*e.g.*, the logroom [2-268-O-Q] FCU emitted air at 60–61°F).



Overhead fan coil unit. Jim Rogers photo (camera date was mis-set)**.**

Recommendations
Currently, an occupant wishing to control the temperature must either change the setpoint by opening a panel (a cumbersome process) or manually turn off the valve. An automated valve, probably controlled by return air temperature, should be explored instead. It could cost perhaps $300–400 per unit to retrofit, but may well be economic. VSDs providing variable air volume (VAV) are standard ashore, capture cube-law fanpower savings, and should be considered for new installations. Indeed, the design of the entire FCU is ripe for review: an optimized version would have much lower fanpower and noise, closer approach temperatures (~1–2 F˚), low face velocity (≤200 fpm), and useful controls.

Thermal integration: (re)use waste heat.

Observations

In nature, there is essentially no waste: everything is food for something else, and waste is really just a resource out of place. The same is true of thermal resources aboard CG-59. Not only can "waste" heat utilization reduce electrical consumption and save fuel, but it can also help the ship lower its thermal emissions, reducing its IR signature and increasing its survivability. Unfortunately, the Navy is in the process of moving away from recapturing this valuable resource on CG-47 class cruisers.

CG-59's GTMs and GTGs produce high-temperature exhaust. GTM exhaust is cooled for signature reduction by mixing it with outside air (passively, via the Venturi effect with exhaust stack louvers). GTM heat is not recaptured. The ship uses GTG waste heat to make steam for potable water (PW) production via evaporation and condensation, as well as for water heating (see below). However, steam has a high "hassle factor" and significant maintenance costs, so the ship is scheduled to undergo an "all-electric" conversion (Shipalt CG47-00588). This will replace the waste heat boiler and PW evaporator and condenser with an electrically pressurized reverse osmosis (RO) system for producing PW from SW via a membrane system, plus—more significantly—electric resistance heating for water and for certain oil supplies that are currently heated with steam. CG-58 *USS Philippine Sea* has already undergone this conversion. According to the crew, GTG exhaust stack air is ~400˚F now, but after the all-electric conversion it will be ~700˚F, indicating the increased energy use and signature. Electricity use for RO pumping will also increase.

The RMI Team agrees that removing the steam system is a good idea. However, the Team is concerned that the Navy has thrown the baby out with the bathwater—more precisely, with the potable water. The concept of waste heat recapture seems to have been rejected because of understandable problems with *steam* production and distribution. But there are other ways to use waste *heat*, including for PW heating, without making steam. The heat recovery system can be designed to be low-maintenance and reliable.

Recommendations

RMI suggests that the crew or NAVSEA create an inventory of all the heating systems and heat flows on board, and evaluate them as potential waste heat users to be matched with a corresponding inventory of heat requirements at various temperatures. These systems would include cooking, space heating, laundry, and domestic hot water systems. Heat can be very efficiently transferred over long distances via passive phase-change heat pipes if the relative heights are suitable (heat source below load); unlike a runaround loop, this requires only a single pipe, no control, no moving parts except the working fluid, no pump, and no electricity.

USE WASTE HEAT FOR SPACE COOLING

Observations
One way to make use of the significant waste heat resource is to use an absorption CH to generate CHW to pre-cool supply air in the turbine intake, to increase the turbine efficiency. This would require space for another CH(s), *e.g.*, in the engine rooms.

Recommendations
Consider replacing one of the relatively inefficient electric CHs with a 500- to 800-ton absorption unit. This unit could also act as a backup to the remaining three electric CHs, or as a baseload machine to keep the electric chillers off line most of the time, avoiding their high fuel cost. The capacity, hence the number and size, of CH units would also be reviewed once the native and parasitic cooling loads throughout the ship had been systematically reduced. This recommendation might be more practical for new ship designs.[66]

USE WASTE HEAT FOR PW PRODUCTION AND WATER HEATING

CG-59 currently uses gas turbine exhaust heat to make steam for PW production, but this is to be replaced with a reverse osmosis unit under the Shipalt 588 all-electric conversion. The RMI Team agrees with the Navy's reasons for eliminating the maintenance-intensive steam production and (especially) distribution system. However, valuable opportunities remain to use waste heat for PW heating in particular, and to augment the PW production process. Opportunities to conserve PW also permit significant energy savings in production, heating, and distribution. These issues are discussed in detail in the next section.

Improve energy efficiency of potable water production, heating, and use

Observations
PW production: The ship currently makes PW from SW by steam-heated evaporation and condensation. Until the all-electric conversion described above is completed, CG-59 is fitted with two 12,000 gpd flash-type distilling systems. These use waste heat from the GTGs to convert seawater to fresh water (95°F distillate). A pressure reducer decreases main steam line pressure from 100 PSIG to 15 PSIG before it is fed into the evaporators. (Perhaps a turboexpander might be considered for this letdown.) There the energy is consumed in the water-making process, in a vacuum created by an air ductor. The system is rated at 500 gph (12,000 gpd)[67] of PW production. Factors including scaling, water temperature, and other engineering dynamics can reduce actual output.

This water is directed to either the potable or the steam-raising feedwater tanks via a flowmeter, or (infrequently) is discharged overboard. The total volume of water expended from the potable and feed systems is tabulated daily (Distiller Plant & Potable

[66] Another potential space cooling option using otherwise wasted turbine heat is a high-temperature desiccant (which could be cascaded with absorption cooling, in either order) for latent cooling. It could also provide excellent sensible cooling if followed by a direct/indirect evaporative cooler—the Pennington cycle.
[67] Personal communication, CG-59 engineering staff, 1/29/01.

Water Log; it also appears in the Daily Fuel & Water Report). As noted above, although the use of waste heat to create water is attractive from an energy standpoint, the steam-driven distilling system is too maintenance-intensive. CG-59 engineering staff indicate that the maintenance burden is mainly in distributing the steam, not in raising it.

The volume of water directed to the two main end-uses (potable and feed) was determined by examining the record for four underway days after shore water was used up.

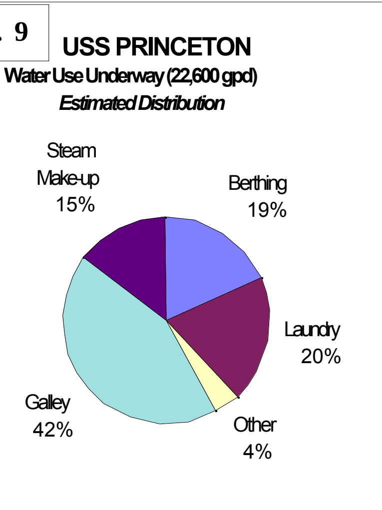
Table 5

WATER DEMAND UNDERWAY

Date	Gallons per Day		
	Feed	Potable	TOTAL
12-Dec-00	3,090	17,440	**20,530**
13-Dec-00	3,580	19,220	**22,800**
14-Dec-00	2,880	19,830	**22,710**
1-Feb-01	4,000	20,290	**24,290**
Average	**3,388**	**19,195**	**22,583**
Std Dvtn	15%	7%	7%

The results, in Table 5, indicate a consistent usage pattern. Since no equipment was available to measure water end-uses, the end-use allocation of PW was estimated (Figure 9) by applying common unit consumption values for showers, sinks, and the laundry; assigning a small amount (5%) to cleaning (*e.g.*, interior and exterior decks; helicopter and radar washdown) and drinking fountains; then assigning the remainder to the galley.[68] Head fixtures (toilets and urinals) are not included because they are flushed with SW.

Fig. 9



[68] Major exterior surface washdown was not included, for it is assumed this occurs only when returning to port, when water use is not a concern. Reportedly there is a Naval standard for calculating water use underway; Ken Kenyon, NAVSEA SECAT team (ckenyon@csc.com), pers. comm., 27 June 2001.

Shipboard PW efficiency improvements should be cost-effective and simple to install and maintain. In the future, water supply will be via RO[69], and wastewater management will incur the cost of membrane treatment.[70] These changes may place a premium on efficient use of PW. For illustration, a CG-60 load study indicated that each of the two RO units alone would draw 75 kW at 0.5 LF under cruise conditions.[71] The conversion also adds two 125-kW water heaters and 97 kW of booster heaters, among many other changes to pumps, fans, ventilation air heaters, etc. Data from a post-Shipalt 588 conversion on CG-58 indicates that, under summertime cruise conditions in 90°F air, the PW-related portions of the all-electric conversion package have a measured peak load of 230 kW and an average load of 77 kW. CG-58's RO unit used 19.5 average kW to produce an unstated amount of PW.[72] If the PW output is the same as the maximum output that an unconverted CG-47's waste-heat boiler recovery system can produce by distillation—24,000 gpd or 16.67 gpm (including 3,400 gpd now used to make steam to drive the evaporators)—then the RO unit uses at least 0.0195 kWh/gal. At the nominal cruise-mode GTG electricity cost of $270/MWh estimated on p. 19, and assuming 96% electric distribution efficiency, the cost of making 1,000 gallons of RO water is thus at least $5.48 plus membrane and equipment maintenance. For comparison, typical municipal water in California costs about $2/1,000 gal—two-fifths as much as the energy to make RO PW aboard ship.

PW heating: PW is currently heated by a combination of waste heat and (in some areas) electric heaters located close to the point of use. Following the all-electric conversion, PW will then be heated by 125-kW electric water heaters; such a heater will use (when energized) 6.4 times as much electricity as the RO unit. Thus PW is valuable, and hot water is especially valuable to save or to reduce in temperature.

Recommendations

PW production: As noted above, the RMI Team agrees with the benefits of converting from costly steam-based PW production to an RO system. RMI has not reviewed the efficiency of the RO unit, where best practice would be to recover backstroke pressure. Consider preheating SW with waste heat (or perhaps graywater discharge) to obtain a significantly greater flux across the low-pressure RO membrane, especially when CG-59 is op-

[69] An example: OffShore Marine Laboratories of Gardena, CA builds systems for the U.S. Navy and other marine clients. Its Model PW 10000, producing 10,000 gpd (35,000 ppm sea water at 77˚F), draws 27 amps at 440 VAC (60 Hz): www.offshore-marine.com/pw1.html.

[70] "In response to the worldwide rising cost associated with the pierside off loading of sewage and graywater, the anticipated future need for U.S. Navy ships to operate for extended periods in littoral waters, and anticipated discharge regulations, the Naval Surface Warfare Center, Carderock Division, in conjunction with the Naval Sea Systems Command, is currently developing shipboard graywater membrane treatment system concepts." Drew J. Demboski, et al., "Evolutions in U.S. Navy Shipboard Sewage and Graywater Programs," Naval Sea Systems Command, Arlington, VA ~1997, p. 1. A follow-up paper: John Benson et al., "Blackwater and Graywater on U. S. Navy Ships: Technical Challenges and Solutions," *Procs. ASNE Day 1999 Annual Meeting and Exposition*, May 1999, www.navyseic.com/propapers.htm.

[71] "Calculated Loads for CG-60", unattributed report (NAVSEA?), esp. Sheet 1, p.5. However, most of the projected 1-MW average load increase is apparently from 1.36 MW connected load of fuel and lube oil heaters. The conversion's calculated loads, too, appear to be higher than the measured loads (Appendix M).

[72] See "Power Monitoring Project, Part One: Summertime Sea Trial," Ingalls Test and Trials, Litton Ship Systems Full Service Center, 20 November 2000.

erating in relatively colder waters. Consider using waste heat to heat PW (if not to support PW production) with methods that avoid the costly problems associated with steam production and distribution.

PW heating: The Navy might reconsider the electric-resistance PW heating strategy for CG-47 class cruisers, as it is a very inefficient means of converting fuel into hot water. (Essentially all the *electrical* energy ends up in hot water, but turning *fuel* into electricity via GTGs is very inefficient.) RMI encourages the use of waste heat recaptured from other uses (*e.g.*, gas turbines) for primary water heating, for example via a heat exchanger, with efficient backup water heaters run on available fuel or electricity.

Other ships heat PW with waste heat but no steam. For example, FFG-7 *Perry*-class frigates have a waste heat recovery system that uses diesel generator jacket water to heat PW (as well as fuel and lube oil), and serves as the heat source for two submerged tube distilling plants. This system does not generate steam. There are also two 300 kW electric heaters in the system to augment the jacket water heat when it is necessary to operate both distilling plants at one time. The PW heater is a 500 gal storage-type heater (in place of the compact instantaneous steam heaters used on ships with steam available). The two submerged tube distilling plants are to be replaced with higher capacity RO units on this ship class also, but the jacket water waste heat system will be retained for heating PW, fuel, and lube oil.[73]

After CG-59's steam distillation system (and therefore the feedwater associated with it) is eliminated by substituting RO, the only remaining use of steam will be to heat water in berthing spaces and the galley (hot water for the laundry is now provided by a 65 kW, 430 gal electric heater). For reasons discussed elsewhere, these few remaining loads may be more simply met with point-of-use electric heaters, or by circulating water that is heated centrally with waste heat (*e.g.*, from an engine, absorption chiller, or heat pump). Replacing the steam system will relieve significant maintenance duties.

Delivery temperatures should be rethought and reset lower to increase safety and crew comfort and to reduce wasted water (*e.g.*, one must now wait for water to stabilize to a comfortable temperature before showering). Faucet water was measured at 134°F in a crew berthing space—a serious scalding risk, and far above the ~110˚F that analyses ashore have found ample for all household uses (except dishwashing, whose 120–130˚F requirement using enzymatic detergent is typically achieved by a 20 F˚ booster heater in the dishwasher).[74] Showers require only 108˚F at the showerhead; higher temperatures tend to be uncomfortable or unsafe, and scalding is a risk above 110˚F, the maximum allowed by Federal law in most hospitals and similar facilities.

In addition to turbine waste heat recapture, alternative water heating approaches include:

[73] Richard Steck (215.897.7912 / SteckRW@nswccd.navy.mil), NAVSEA Fluid Systems, personal communication, 14 May 2001.
[74] Extensive 1991 analysis by RMI (*The State of the Art: Water Heating*) found that this setpoint does not incur a health risk from *Legionella* spp. for the general population; for immune-compromised individuals at special medical risk, even 140˚F setpoints are neither a desirable nor a sufficient way to prevent exposure.

Instantaneous Water Heaters (also called tankless or point-of-use water heaters) use heater elements such as electric coils or gas heaters to heat water passing through the unit. They are tankless or have small tanks, and are located at or near the point of use, reducing line losses. They typically have relatively high electric demand but very low standby losses; require less piping than parallel hot-and–cold water systems; and need only a cold water feed and an energy supply. CG-59 has no tankless water heaters, but does have some small "booster" water heaters (*e.g.*, ~30 gal unit for the Captain's cabin).

Heat pump water heaters remove heat from the air and transfer it into water, with the additional benefit of cooling the air around it. Similar to a water-cooled air conditioner, they work best in warm areas (*e.g.*, kitchens, laundries, boiler rooms), with paybacks typically around a couple of years or less at the far lower energy prices prevalent ashore. Heat pump water heaters don't produce heat, but rather move it—typically providing over 3 kW of heat for each kW of electricity used. They have a relatively slow recovery rate (the time required to heat a full batch of initially cold water), and usually require thermal storage in civilian applications ashore; but conditions aboard ship may be more favorable.

CG-59 HOT WATER USES, SOURCES, AND HEATING ALTERNATIVES

Use	Hot Water Source - Now	Source - Proposed
Galley – Cooking area cleanup	Steam water heater with circulating pump	1. Heat pump water heater 2. Electric instantaneous 3. Electric point-of-use
Scullery - Sink	Uses galley HW	Same as now
Scullery - Dishwasher	Uses galley HW plus steam. Also electric backup	Eliminate steam and use electric
Berthing - Sinks	Steam water heater with circulating pump	1. Heat pump water heater 2. Electric Instantaneous 3. Electric Point-of-Use
Berthing - Showers	Steam water heater with circulating pump	1. Heat pump water heater 2. Electric instantaneous 3. Electric point-of-use
Laundry	Electric HW heater with storage tank	Same plus heat pump water heater
Maintenance Cleaning	Uses galley or berthing HW	Same as now

PW CONSERVATION OPPORTUNITIES

Where practical, conserve PW, especially HW, to save energy and free up PW production capacity for desired uses (*e.g.*, drinking, cooking, maintenance—or Hollywood showers, for quality of life!). To the extent water is conserved or treated and reused aboard, the total volume of water flowing through the ship will be reduced, as will the size and cost of both the supply and discharge treatment systems.

Showers: Vigorous showers needn't require high water flow or high pressure: low-cost COTS high-performance showerheads can give an excellent sensation with only 1.2–1.5

gpm, even at low pressure. More elaborate blower-driven air/mist showers, originally designed for submarines, use only 0.5 gpm, and their 432-W electric blowers use only 1% as much electricity as they save in water heating. The RMI Team observed a few high-performance, low-flow showerheads aboard CG-59, but most showerheads could be usefully upgraded. Reportedly there is a Navy standard that requires all ships to have low-flow showers and spring-loaded shutoff valves.[75]

Galley: This deserves a closer look, including time to measure specific uses. The dish rinsing station in the scullery is a particularly attractive candidate. Instead of using low-pressure PW to flood waste off dishes, better mechanical scraping might be considered, followed by a quick scrub in a periodically replenished basin. All dishes and utensils are thereafter washed and sanitized in a conventional dishwasher equipped with internal water recycling. In addition, modern enzymatic detergents using amylase, lipase, and protease can provide superior dishwashing performance at only 120–130˚F, saving significant water-heating energy. Graywater heat recovery may be worthwhile.

Laundry: Laundries provide an excellent opportunity for reusing water (and heat and alkalinity). The ship's laundry is equipped with three washer-extractor machines manufactured by The Edro Corporation. Two have a 60-dry-lb capacity; the third is 20 lb.[76] Two Fridgidaire "Gallery" tumble-action washers and four Fridgidaire electric dryers, all residential-size, are also provided for individual use by the crew. Hot water (180°F) is provided by a 430-gallon electric water heater.[77]

Edro Dyna Wash washers. Jim Rogers photo (camera date was mis-set).

[75] See App. M, K, #21–22. Ken Kenyon, NAVSEA SECAT team (ckenyon@csc.com), personal communication, 27 June 2001. The RMI Team did not compare this standard to the performance of the best available COTS options. Non-DOD Federal standards for such fixtures fall well short of the best available.
[76] DynaWash machines manufactured by The Edro Corporation, East Berlin, CT, in Oct 1999. Larger machines: model number DW600 PNSWE238 (each has three pockets capable of holding 20 lb dry weight of laundry); smaller machine: model number DX25N.
[77] The Electric Heater Company S/N N1282N. 430V, 3 phase, 85A, 65 kW; installed ~ June 1998.

The laundry load is mostly uniforms and linens, mostly only lightly soiled. Approximately twenty loads are run six days per week in the large machines (ten loads per machine). Assuming ten loads are also run by the smaller machine, the total load is therefore approximately 1,400 lb/workday.

The horizontal-axis residential washers are fairly efficient and appear to have a relatively low usage rate, so are not addressed here as targets for ozonation (see below). However, their 180˚F feedwater temperature appears far too high. Such hot water will greatly reduce the operating life of clothing, and is not necessary for effective cleaning with modern detergents. For example, the *average* Veterans' Administration hospital laundry operates at a peak water temperature of 110˚F; the maximum allowed by the VA is 120˚F; and the VA found that 72˚F laundry, as part of a modern laundry cycle, yielded satisfactory disinfection, whiteness, and stain removal.

The RMI Team suggests that the Navy explore alternative laundry techniques. Ozone systems save water and improve cleaning and clothing life. For conventional laundry processes, lint removal followed by membrane separation is the norm. A vibrating membrane process (to enhance shear forces across the membrane by tenfold) has a small physical footprint and good laundry service examples. These options are discussed next.

OZONE: The greatest energy and water saving opportunity that is appropriate and immediately available is to introduce ozone into the 60-lb Edro washers' washwheels to reduce the energy, water, and chemicals now used by the two 60-lb-capacity washer-extractors. RMI does not currently recommend similarly converting the 20-lb machine, which should remain in its present configuration to handle the heavily soiled items for which there is not yet a parallel example ashore for handling with an ozone system.[78]

The laundry's three principal washing machines presently consume approximately 1,300 gal and 2,900 gal of cold and very hot (180°F) water per day, respectively.[79] Conversion to ozone washing should reduce total water use by approximately 25%, saving approximately 1,000 gpd.[80] More importantly, because ozone performs best in cold water, the volume of hot water required will decline by at least 90%.[81] Approximately 740 kWh/d, worth about $200/d in electricity, will be saved by not heating this volume of water.[82] Net electrical savings for this conversion are estimated at 680 kWh/d, worth about $184/d or $67k/year, after allowing for 60 kWh to produce the required ozone.[83] Additional energy

[78] Experiments conducted by International EcoScience indicate this will soon change. See Ira Krepchin, *Ozone Laundering: A Technology Ready to Clean Up?* E SOURCE ER-99-4 (March 1999), p. 11. NAVFAC's positive experience washing oily rags is even more compelling (see footnote 81 below).

[79] *Ozone Laundering: A Technology Ready to Clean Up?* E SOURCE ER-99-4 (March 1999), p. 9 (Table 3). This reflects usage reported by a traditional laundry processing 2,100 lb/day at a healthcare facility.

[80] The water savings level of 25% is a mean value reported for five sources consulted.

[81] Water heating was eliminated completely when an ozone wash system was tested at the Public Works Center San Diego's Oily Rag Laundry located at NAS North Island. See B. Holden, P.E., UDP-2007-ENV, User Data package for Ozone Oily Rag Laundry System, Naval Facilities Engineering Service Center, Dec. 1999 (https://www.denix.osd.mil/denix/Public/Library/Air/Oilyrag/udp2007.html).

[82] (2,900 gal × 8.35 lb/gal × 104 F° ΔT) ÷ 3,413 BTU/kWh.

[83] *Ozone Laundering: A Technology Ready to Clean Up?* (cited above). Derived from Table 3.

savings will accrue when ships are equipped with membrane technology for both desalination and wastewater disposal (see the membrane filtration discussion below).

The introduction of an ozone washing system provides additional benefits. These include:[84]

- Chemical reduction of up to 65%.
- Wastewater quality improved by the oxidizing power of ozone as it breaks down bacteria and other microorganisms before they reach the drain.
- Increased linen life due to less chemical usage and shorter wash cycle.
- Increased comfort by leaving less chemical residue on the fabric.
- Increased washing machine daily capacity due to shorter wash cycles. As lower doses of chemicals are used, a number of rinses can be eliminated.
- Increased dryer capacity, as less chemical film is left on fabric after washing.

Ozone is a strong oxidant that must be handled carefully. There is considerable experience available to design a system to handle ozone safely during its short life before it decays naturally to oxygen.[85] Developmental and demonstration projects have included the Navy (*e.g.*, International EcoScience's work to develop an ozone washing system for a submarine, and the extensive analysis of Cyclopss Corporation's Eco-Wash Laundry System at Coronado Island, where superior results were demonstrated for cleaning oily rags[86]). As a result of these efforts, an ozone wash system is being installed at the industrial laundry operated by the Navy Public Works Center, Pearl Harbor.[87]

MEMBRANE FILTRATION: Another approach that will save much more water is to clean and reuse wash and rinse water, perhaps leaving the final rinse for fresh water. This may be done together with an ozone wash system, or independent of it (that is, the conventional chemical / hot water wash system is left in place, but with a much lower temperature as noted below). When a membrane treatment system is used to recover water from a conventional laundry process, it also recovers heat and alkalinity. Using a membrane system to treat and reuse water at its point of use will become more attractive as membranes come to be used anyhow where water is both introduced to and discharged from the ship.

One of the most promising technologies for this purpose is a novel membrane filtration system provided by New Logic International, Inc., called VSEP (Vibratory Shear En-

[84] From Vanessa Hill and Marty Ahad, *Ozone Laundry Systems Pilot Study*, Executive Summary, May 2000 (prepared for and published by BC Hydro).

[85] E SOURCE (footnote 78) indicates more than 200 laundry installations to date. Ozone, employed to purify drinking water for nearly 100 years, is also used in tens of thousands of other industrial applications.

[86] See B. Holden, PE, UDP-2007-ENV, User Data package for Ozone Oily Rag Laundry System, Naval Facilities Engineering Service Center, Dec. 1999, https://www.denix.osd.mil/denix/Public/Library/Air/Oilyrag/udp2007.html.

[87] See "Cyclopss Eco-Wash System Sets Sail For Pearl Harbor," www.cyclopss.com/navyins.htm. The article reads in part: "The Navy has proven the Eco Wash system saves energy, water and labor, and reduces pollution for this industrial laundry application. The Navy has a potential need for as many as 100 of these types of systems that sell for approximately $70,000 each."

hanced Processing).[88] This system is achieving water savings on the order of 65–75% for the HCSA Laundry (hospital) in Seattle, WA, and Cal Linen in Oakland, CA. The standard system requires approximately 20 ft^2 and no chemicals. Fouling is avoided by subjecting the entire membrane stack to an oscillating motion that maintains clean filtration surfaces. The horizontal oscillation of the membrane stack, the key to the system's performance, requires a vertical alignment for the equipment, and therefore a height requirement of approximately 11'–14', depending upon the model selected. (The RMI Team did not measure the overhead clearance in the laundry to determine whether this would fit.) Other aspects to be investigated include the nature of the concentrate produced from this system; how to manage it if it is too viscous to flow easily through the ship's drain; and the size and possible location for equalization tanks before and after the membrane system.

Improve lighting efficiency and quality.

Observations

CG-59's total lighting load is less than 10% of total power consumption while cruising, unlike commercial facilities where lighting can be as much as 50% of a building's electric load. However, the ship's lighting electrical load could be reduced by approximately 40% without reducing light levels or quality, and that reduction would also reduce HVAC loads, so it should not be ignored. Ashore, efficient lighting is often a very cost-effective retrofit opportunity and can significantly increase human productivity.

Using data from a load study of CG-60 *USS Normandy*[89], CG-59 has a connected lighting load of approximately 394 kW, of which 175.9 kW is vital lighting and 218.5 kW is nonvital lighting. The CG-60 study assigned utilization factor of 0.33 for vital lighting and 0.39 for nonvital lighting (although the Team thinks these factors seem to be very low). Based on these numbers, total lighting loads under cruise conditions would be 143.2 kW. During the floats the RMI Team was on, the majority of the lighting was on 24/7, and only the berthing areas and darkened ship areas reduced lighting at night. (Darkened ship settings on many fixtures use either the same number, or half at best, of the normal complement of white fluorescent lamps (FLs). A few small areas with local switching also turned off their lights at night.)

Based on this as-used average lighting load, which may be understated to the degree actual load factors are higher, the potential estimated by the RMI Team to save at least one-third of the lighting would save at least 48 kW and probably a good deal more, plus associated HVAC loads to take away the heat of the lights. At the observed HVAC performance of about 1.2 kW/t (COP 2.9), excluding air-handling energy, the "HVAC bonus" would increase direct lighting savings by roughly one-third, raising the 48 to 65 kW.[90]

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[88] New Logic International, Inc.: www.vsep.com.

[89] "Calculated Loads for CG-60," unattributed report, p. 40.

[90] The actual value could differ substantially under different operating and climate conditions, different part-load penalties for the HVAC components, and <100% lighting in conditioned space. It would also decrease with a more efficient chiller system due to reduced parasitic loads fed back from HVAC equipment.

Nearly all lighting is provided by 700+ MIL-SPEC fluorescent fixtures, most of which are about 30" long with magnetic ballasts and T12 FLs, and vary only in the number and color of lamps. All fixtures have a heavy plastic lens, mostly opaque white; a few are clear. The most common fixture has three 20 watt T12 lamps. The fixture variations are single lamp, double lamp and combinations of white and red lamps. The 3-lamp fixtures consume approximately 70 watts each. Newer, more efficient T8 lamps with electronic ballasts would consume about 40% less energy while producing the same light output and improving color rendering and visual acuity. Red lights are used in perimeter and berthing areas during darkened ship conditions, including most of the nighttime period. Red and blue light is provided by putting colored mask sleeves over white FLs to filter out all but the desired color, thereby also reducing lumen output.

Typical overhead lighting fixture. Jim Rogers photo (camera date was mis-set)**.**

Apparently the Navy is aware that these fixtures have "low efficiency, low power factors and harmonic distortion problems."[91] The Navy is currently developing or investigating new lighting and standards and fixtures. The primary difference between the existing fixtures and the new one is improved ballasts. One NAVSEA staffer reported: "All new construction ships are getting the high-efficiency fixtures developed by NSWCCD. The new fixtures have much higher efficiencies and power factor, and they also meet the

[91] Bill Stoffel, NAVSEA (215.897.7109 / StoffelWH@nswccd.navy.mil), personal communication, 10 January 2001.

MIL-STD requirements for harmonic distortion (which the original fixtures never did). The new fixtures are identical to the original except for the ballast, therefore achieving dramatic improvements at virtually no increase in cost. Retrofitting the low- with high-efficiency fixtures is not conventionally considered cost-effective (although any additional fixtures procured through the stock system will also be high-efficiency). [However, that conclusion may merit review, since skilled civilian lighting designers ashore would often reach the opposite conclusion, taking all benefits into account.] At this time there is only one qualified supplier for Navy lighting fixtures and the MIL-SPEC has not been waived for lighting."[92] On existing ships, either the fixtures could be upgraded as they wear out and are replaced, or they could be retrofitted en masse with new T8 (or perhaps even thinner) lamps and electronic ballasts.

The helicopter hangar is the one area of the few areas of the ship with a different lighting scheme: eight 18" × 4' fixtures with six 2' T12 lamps mounted at a height of about 18'. There are also six of the same fixture with red lamps. These could also be upgraded or replaced with fixtures using T8 lamps and electronic ballasts.

There is some task lighting aboard ship. Most racks and desks in berthing areas had fixed fixtures with basic asymmetric reflectors, although several appeared to lack lamps.

Recommendations
Use fixtures with low-harmonics electronic ballasts, and upgrade the lamps to more efficient white T8 FLs. The Navy should continue to investigate further improvements to luminaires, such as imaging specular reflectors. A comprehensive retrofit of reflectors, ballast, lamp, and controls often yields excellent economics ashore, and may have analogies afloat. Indeed, RMI suggests a comprehensive approach to lighting improvements, combining superefficient lamps, ballasts, controls, fixture optics (reflectors and lenses), and—importantly—lighting design.[93] Please see Appendices F and G for a summary of a systematic and comprehensive approach that typically saves 80–90% of lighting energy ashore, with better visibility and esthetics and excellent economics. The high value of saving onboard electricity may make this package attractive for retrofit even in conditions where it wouldn't be cost-effective in a civilian building ashore.

As part of such a whole-system approach, consider—if other circumstances permit—painting interior compartments' overhead, and ideally bulkheads and fittings, matte or low-gloss white rather than gray. Where appropriate, the improvement in cavity reflectance will permit better visibility with far less light.

Explore the applicability of using red or blue LEDs for colored lighting (and indeed, for white lighting). LEDs are rugged, extremely durable, relatively small, very energy-efficient, excellent at optical control (to deliver light in the desired place and pattern), and built to emit only the desired colors. LEDs are gaining favor in many specialized applications such as traffic lights and exit signs. Energy savings in the order of 80–95% are probably possible with red LEDs, but a new light fixture design would have to be devel-

[92] *Ibid.*
[93] See E SOURCE TECHNOLOGY ATLAS, *Lighting* (1997 ed.), www.esource.com.

oped and tested. Investigate whether an LED lamp manufacturer (*e.g.*, Ledtronics, www.ledtronics.com) could develop a lamp that simply replaces the existing red fluorescent lamp. Because LEDs have no fragile cathode, they can have extremely high resistance to shock, increasing survivability.

NAVSEA has cost-effectively installed LEDs that fit into screw-type bulb sockets on the islands of some aircraft carriers, significantly reducing maintenance costs. Apparently NAVSEA has not explored LEDs for use in the standard shipboard overhead fixtures. Reportedly the Navy is developing Neals lighting that might eliminate the red sleeves over the fluorescent tubes.[94]

Battle lanterns: About 700–800+ small (and often portable) yellow battle lanterns are dispersed around the ship. Their 7-V batteries automatically kick in if ship's power is lost. The RMI Team suggests the Navy consider using solid-state circuits with a low draw (and no parasitic draw) instead of the electromechanical relays now used.

Potential productivity improvements: The Navy might consider the potential for increased labor productivity (and possibly better retention and crew health) from improved lighting quality and design. Case studies ashore show 6–16% increases in productivity (including reduced absenteeism) in assembly, retail, and office environments.[95] In short, if people can see better what they're doing, they tend to do more and better work.

Other lighting measures considered: Several other measures commonly employed ashore to improve lighting efficiency were considered but are not recommended as strong candidates for shipboard application. These included:

T5 FLs AND INDIRECT LIGHTING: T5s are very bright and work well in high bay applications where they excel at replacing metal halide. But CG-59 does not have enough high bay areas to justify this. In low bay areas, T5s' use is limited to indirect lighting reflected off the overhead. This would not work on CG-59 because the overhead is too low and cluttered with pipes, ducts and cables.

DAYLIGHT HARVESTING AND REMOTE SOURCE LIGHTING: This lighting technology brings available daylight into a structure without glare, and uses dimming ballasts to reduce light fixture output proportionately and automatically. This approach has apparently been experimented with on hanger decks in Navy carriers; reportedly DDG-78 uses fiber optic remote-source lighting on one area of its hangar deck.[96] However, there are essentially no portholes on CG-59, skylights are out of the question, and other light piping techniques are probably impractical due to structural and space constraints; thus daylight harvesting is not suitable. However, for new ships, simple daylight concentrators and light-pipe or fiber-optic delivery may be worth considering: a concentrating harvester of only a few

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[94] Andrew Bigley, NAVSEA (215.897.1190 / BigleyAW@nswccd.navy.mil), personal communication, 9 May 2001.
[95] See *Greening the Building and the Bottom Line*, 1994/98, www.rmi.org/images/other/GDS-GBBL.pdf.
[96] Andrew Bigley, NAVSEA (215.897.1190 / BigleyAW@nswccd.navy.mil), personal communication, 9 May 2001.

square yards can nicely light thousands of square yards of interior space. This technique is used in Japan to grow gardens many stories underground—and is reportedly worthwhile there at electricity prices lower than those aboard ship. At night or in cloudy conditions, the same delivery system can deliver light from extremely efficient electrically powered sources such as a large metal-halide lamp with the heat filtered out (and perhaps used). Lighting maintenance costs could be nearly eliminated and survivability enhanced.

Occupancy Sensors: These devices automatically turn off the lights in unoccupied spaces. They are not recommended for shipboard use due to high cost and complex controls. The connected load for each occupancy sensor would be very small, and the control would be expensive to install. Also, a delay in a light's coming on during battle conditions is unacceptable. Reportedly NAVSEA has considered various lighting controls improvements, including motion sensors, but has not found any that successfully address concerns about safety and cost.[97]

Improve air compressor efficiency.

Observations
CG-59 has both reciprocating high-pressure air compressors (HPAC) with a rated output of 20 ft^3 of air per hour[98] at 3,000 PSIG, and axial low-pressure air compressors (LPAC) with a rated output of 100 CFM of air at 125 PSIG. Both use desiccant dehumidification (the LPAC has both refrigerative and desiccant dehumidifiers), at least partially to protect rubber gaskets in Leslie valves.

LPAC compressor skid. Jim Rogers photo (camera date was mis-set)**.**

[97] *Ibid*.
[98] As stated in Section 28, p. 99, of CG-59 *Engineering Department Handbook*, undated.

Recommendations
Consider replacing the desiccant dryers with refrigerated dryers. Consider checking the system for leaks comprehensively. Evaluate the efficiency of the compressors when they operate at partial loads (it is probably poor). Investigate using a small "pony" compressor to maintain system pressure during periods of reduced pressure needs, rather than running the main compressors all the time to do so. Investigate the potential advantages of the unique fast (millisecond-timescale) control systems made by Compressor Controls Company of Des Moines, IA (www.compressorcontrols.com) for both axial and centrifugal (but not reciprocating) compressors.

As noted above on pp. 34–35, compressed air is also drawn from the 14th stage of the GTGs and used as bleed air for hull friction sound masking and PRAIRIE prop cavitation sound masking. (The GTMs have a bleed valve at the 16th stage of the turbines, but the bleed air is typically drawn from the GTGs). The air is cooled from ~800°F to ~200°F by a SW HX cooling system before it is released. When the bleed air valve is engaged, the turbine runs hotter; shutting it down when one GTG is producing all of the bleed air reduces turbine temperature by ~100°F, increasing its capacity by about 200–300 kW of load. The ship pays a fuel penalty for this bleed air, but the masking benefits are important. Apparently the volume of air required for masking prohibits economical use of a compressor instead.

Upgrade monitoring and controls.

Observations
As the saying goes, if you can't measure it, you can't manage it. CG-59 has a wide array of monitoring and controls, but there remains room for improvement, including in engineering systems. There are many analog gauges in CCS and on devices (several of which are regarded skeptically by veteran engineering crew). Hourly readings for numerous mechanical systems indicators are recorded, printed out, and stored on paper—but not in automated spreadsheets that would allow for ready analysis, trending, graphing, and other manipulation of the data so it can be effectively interpreted. Some systems' performance (e.g., CHs) are logged manually. There is minimal submetering of systems components; for example, the fuel consumption of any of the GTGs and GTMs cannot be directly measured in operation, as they all share a common fuel line. The lack of graphical capability limits the ability to understand the behavior of complex systems, since the brain has orders of magnitude less bandwidth for numbers than for pictures. Data are not real-time.

In these respects the capable crew lack the ability to view real-time mechanical systems performance(s) at a detailed level of resolution, and thus do not have the opportunity to employ certain advanced management techniques. Nor are they readily able to log, record, trend, and display basic systems performance data over long periods under varied operational conditions (or in real time), which can be a valuable method of identifying problems and potential improvements. Three-dimensional graphical software can be very useful in discovering hidden trends in complex systems' behavior over long periods, and can instantly identify the existence (and, almost instantly, track down the cause) of incipient inefficiencies and failures, greatly improving preventive maintenance. Archived data also support benchmarking, continuous improvement, alignment of performance evaluations with objectives, and the other fundamentals of total quality management.

The Navy is working constantly to improve control systems; indeed, most civilian experts in direct digital controls became experts in the Navy. Full Authority Digital Control (FADC) systems under development help bring intelligence to the component level, increasing operational efficiency (*e.g.*, GTG controls and diesel motor electronic fuel injectors). NAVSEA is conducting R&D on smart motor controllers, lighting controls, and power-saving shipboard network infrastructures for electrical power management and machinery remote command/control/communication.[99] Perhaps casualty control and damage control assessment (DCA) network systems under development that display the status of critical shipboard systems[100] might also support more optimal engineering operational decisions. For example, it might be possible now to use the damage control console to see valve positions in pumped systems.

Yet regardless of the amount and quality of data available, optimal systems management strategies are impotent without the ability to control the systems being monitored. CG-59 has limited ability to vary power or supply outputs to match variable loads, apart from the GTMs and GTGs (and constraints apply even there). The ship typically has to run its equipment in binary on/off mode: most motors, fans, and pumps operate either all-out or not at all. Redundant systems and EOSS procedures enhance resilience and consistency (especially under duress), but also can limit useful, more resource-efficient options (*e.g.*, single-GTG or single-CH operations). Simplified operations can impose significant and costly penalties through increased fuel and maintenance costs.

CG-59's Central Control Station. Chris Lotspeich photo.

[99] "Electrical Energy Efficiency," presentation to DSB Task Force on Improving Fuel Efficiency of Weapons Platforms, presentation handouts, Andrew Bigley, NAVSEA (215.897.1190 / BigleyAW@nswccd.navy.mil), and personal communication, 9 May 2001.

[100] CG-59 XO CDR Bryan McGrath, personal communication, 2 February 2001.

Recommendations
Increase the accuracy, precision, and resolution of sensors and monitoring to improve the ability of the crew to view data in context, with real-time displays and trending over 24-hour and longer periods. Submeter all variable loads ≥20 hp, and include them in the control systems and displays. Convert manual logging to digital data, including spreadsheets and modern graphical displays.

Consider real-time indicators for the following equipment and systems:

GTGs: unit power generated, fuel consumption, phase unbalance, and power factor. The power/fuel relationship should be immediately comparable with the rated turbine performance curves, and should guide decisions on optimal dispatch of generators to maximize whole-system efficiency, just as with propulsion turbines *vs.* ship speed (App. C).

Chillers: tonnage and kW consumed (need ΔT of CHW and CW, and flow), with 5% total system accuracy; this requires accurate and stable temperature- and flowmeters. Flow and power sensors on major pumps will also be desirable to ensure that chiller operation is not optimized at the expense of system efficiency (by losing more on pumping than is gained on the chiller).

POTENTIAL NEW SHIP DESIGN OPPORTUNITIES

This report addresses both retrofit opportunities on a CG-47 and implied new ship design opportunities throughout the Navy. This section briefly summarizes recommendations for clean-sheet design (*e.g.*, DD-21 or similar programs); some weren't previously discussed.

HULL AND SUPERSTRUCTURE

Consider ultralight fiber-reinforced composites with high strength, enhanced ballistic protection, and reduced radar signature. RMI has found that in automotive design, a threefold mass reduction and a severalfold drag reduction open up a new design space: conversion to hybrid-electric propulsion makes the platform's mass, cost, and complexity go down rather than up, permitting radical simplification (www.hypercar.com). Naval architecture is very different, but some useful analogies appear worth exploring.

PROPULSION

Optimize motor size, efficiency, and torque/speed curve, then dispatch to maximize thermal or conversion efficiency and most efficiently meet real-time power requirements. Continue electric drive development using the most modern motor designs (RMI has provided NAVSEA with new technical information on switched reluctance drives).

POWER GENERATION

Maximize end-use energy efficiency to minimize loads before sizing generating capacity. Optimize generator size, then dispatch to maximize conversion efficiency and most efficiently meet loads integrated over the range of operating conditions. Consider modularity, *e.g.*, microturbines and fuel cells. Explore UPS, load-smoothing, and transient-stabilization options including superflywheels and ultracapacitors. Thoroughly integrate production of electricity, heating, and cooling to achieve system efficiencies above 90%.

DRIVEPOWER AND MECHANICAL SYSTEMS

First minimize flow, friction, and resistance. The resulting savings will multiply back upstream, making upstream components successively smaller, cheaper, lighter, and more efficient. Use fat, short, straight, sweet, smooth pipes and ducts wherever possible. Oversized pipes, ducts, and wires reduce flow losses and downsize pumps, fans, motors, and such control electronics as VSDs. Minimize valves and their losses (and likewise in air-handling systems); for example, generally avoid globe valves. Where architectural considerations permit, lay out the pipes and ducts first, then the equipment that they connect. Seek to "untangle" layouts to eliminate bends wherever possible. Do not "dress" layouts to be neat and orthogonal; diagonals, where they fit, often cut cost and friction better.

Specify the most efficient models among the premium-efficiency range of motors, pumps, fans, and other devices. Don't assume this will raise capital cost. ("In God we trust"; all others bring data.) Use VSDs on all variable loads and soft-start devices on all motors ≥10 hp. Optimize device size. Dispatch multiplex unequal units to serve varying loads efficiently. Automate backup device and system startup for fight through resilience.

HVAC

First optimize the human comfort range and minimize unwanted heat gains. Then consider passive heating and cooling by taking advantage of ambient conditions. For example, consider the hull as half of a plate-exchanger HX. Consider adding cooling coils inside the hull for the other "half" to make closed-loop condenser water for process/equipment cooling. Then consider nonrefrigerative cooling—typically combinations of desiccant, absorption, and evaporative, such as the Pennington cycle—run from prime-mover waste heat, and separately sized and optimized for latent and for sensible loads.

To the extent refrigerative cooling is required, optimize chiller size, then dispatch to meet loads most efficiently. Use low-face-velocity (≤200 fpm), high-coolant-velocity coils. Dedicate cooling systems to meet clusters of needs within narrow, empirically defined temperature ranges, to avoid overcapacity or supplying more cooling or lower temperature than is actually required elsewhere. Recapture and use available waste heat.

LIGHTING

Apply comprehensive, integrated lighting design to maximize visibility, productivity, and comfort while minimizing energy use. Provide the right amount and quality of light for the task. Prefer indirect to direct lighting where feasible. Use optically efficient luminaires. Consider daylight harvesting, dimming controls, and resilient, low-maintenance fiber/tube distribution. Avoid magnetic ballasts. Use LEDs for white and colored light.

CONTROLS

Submeter loads and systems extensively with sensors and metrics that accurately indicate physical performance. Link high-quality sensors to multiuse real-time graphical displays that measure, archive, trend, and display data. Automate device controls and backup system startup sequences to optimize energy efficiency and fight through resilience.

MOST IMPORTANTLY—INTEGRATE

Pending discussions proposed by NAVSEA with the Blue and Gold Teams, RMI cannot be sure that the highly integrated whole-platform design approach it developed for automotive design is being applied to DD-21. If not, energy savings would be smaller, and both capital and operating costs higher, than necessary. Inform design by the whole-system marginal value of saving each watt of electricity. In automotive design, that value is understated by an order of magnitude—based essentially on alternator sizing. It omits the cost, bulk, and mass of wiring; ignores mass compounding; and most importantly, omits the whole-platform benefits of peeling a slice off the top of the engine map so that at all times the engine becomes smaller, lighter, cleaner, cheaper, and more efficient. Avoiding this common fallacy probably has useful analogies in Naval architecture.

RECOMMENDATIONS

Based on these observations and findings, the RMI Team recommends that the Navy:

1. Subject this report to rigorous scrutiny. Tear it apart, find and fix its inevitable errors and omissions, make it better (as only your vastly greater knowledge permits), then reassess the broad validity of its general findings. Determine whether next steps then warrant the high priority that the RMI Team would suggest. If the basic conclusions hold up, consider decisive action to accelerate the capture of these opportunities, on the lines urged by the Defense Science Board's Jan. 2001 Task Force report *More Capable Warfighting Through Reduced Fuel Burden.* That compelling analysis found that capturing the vast potential for energy efficiency in all DOD platforms is vital for satisfying the demands of both Joint Doctrine and tight budgets. RMI concurs.
2. Give NAVSEA's fine programs on basic energy stewardship the high priority they have long deserved, while building on them with these additional ideas as merited. Consider the suggested improvements in technical training and operational practice.
3. Expand NAVSEA's efforts to *measure* the disaggregated efficiency of the main on-board *systems* surveyed—drivepower, pumping, air handling, chilling, lighting, and hot water—from end-use back to primary fuel, using physical performance metrics.
4. Intensify efforts to resolve, perhaps with the help of new energy-storage techniques, the longstanding debate over single-GTG operations. Examine the feasibility of more fundamental improvements to electric generating efficiency, such as updated turbine, microturbine or fuel-cell retrofits. Remember that electrical savings without improving GTG operations or technology will save little net fuel.
5. For routine low-threat operations, test the Team's off-plus-autostart, VSD, and other recommendations to modify normal practice, and see if they can be made prudent.
6. Improve Naval energy design philosophy and practice as this survey illustrates. Current design achieves many difficult objectives with great skill. However, greater emphasis on highly integrated energy-efficient design, adapting best civilian practice to the Navy's unique requirements, should be able to improve warfighting and save money to an unexpected degree, creating not conflict but synergy with other goals. The Navy's talented engineers should be able to grasp these opportunities smartly.
7. Consider a prompt intensive retrofit pilot project on a single vessel, based on the following analogy. The sizes and modes of improvement found here are strikingly similar to those RMI found in the Navy's facilities ashore (p. 7). Joint design workshops, invited in 1995 by ADM Lopez and arranged by both uniformed and civilian leadership, tested a new design approach integrating many synergistic techniques, first in one pilot project, then in eight more. Another successful analog RMI helped establish was Pacific Gas & Electric Co.'s $9M 1990s "ACT^2" design/build efficiency test. For Naval vessels, two intensive experiments may be warranted—one retrofit, one new.
8. Consider emulating NAVFAC's next step—indoctrinating in-house and contract design professionals in whole-system thinking. This achieved exceptional energy efficiency at the same or lower cost. Now it's so institutionalized that designers unskilled in such work can't even bid for NAVFAC jobs. Naval architecture is more specialized and complex, but analogous design innovation should be applicable afloat.
9. Please give RMI your feedback to support its own efforts at continuous improvement.

APPENDICES

APPENDIX A:
CHILLER MEASUREMENT SURVEY REPORT

USS Princeton Measurement Phase Trip Report, Thu–Fri 25–26 January 2001

The RMI Team, represented by Ron Perkins, boarded the ship at pier at about 9:30 and found the crew busy with preparations for sea. The Team was escorted to engine room AUX-1 and unpacked three boxes of instruments and sensors. The Team and crew selected chiller #4 for efficiency measurement, because the crew planned to run chillers #1 and #4 at sea and chiller #4 was out of the way. The Team and crew removed the analog thermometers on the chilled water supply and return lines as well as the seawater (condenser water) lines replacing them with hand matched, calibrated thermistors. Thermal grease was used to ensure good conduction and eliminate insulating air pockets. The chiller appeared to be 37% loaded as indicated by the York control panel, and the thermistor temperatures were within 0.6 F˚ of the control panel readings. The Team mounted the Dynasonics flow meter on a vertical section of rubber isolating hose and programmed the data logger. The readings were erratic with abnormal values, and were accompanied by a low signal error message. Evidently the rubber hose contained a layer of reinforcement steel or other material that prevented the sonic waves from penetrating the material. There is no straight section of steel pipe in the space, so the Team abandoned the attempt to measure flow and instead adopted the control panel reading of 730 gpm for calculating load. Calculations from water transport factor formulas indicated that this flow rate is reasonable.

The Team accidentally tripped the chiller off line while attempting to measure power, although this provided a good opportunity to observe what would happen if a chiller went down. Alarms alerted the crew and soon technicians were scrambling around trying to clear the safety cutouts. The chiller was restarted in about 15 minutes. It is interesting that the current limiter control prevents the chiller from ramping up quickly as most York machines have done at other sites ashore. It took about 20 minutes for the chiller to stabilize at about 37% of full load. To reduce the risk of tripping a chiller off line, the Team decided to trust the onboard CT readings to obtain power readings.

Ultimately, measuring the chillers' efficiency proved impractical for two reasons:

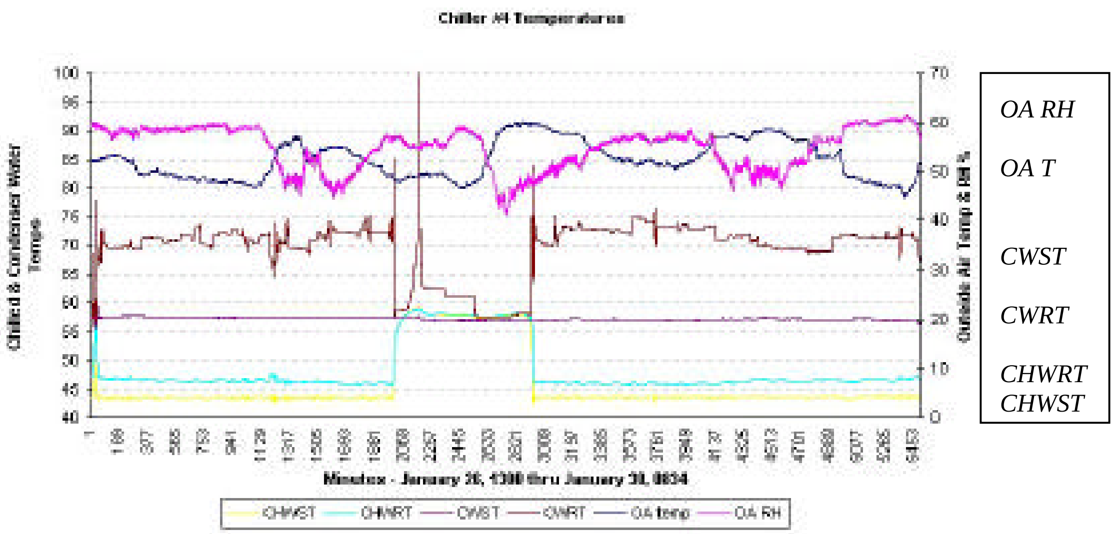
(1) apparently the chillers cannot come to full load, and
(2) hydronic problems might impel the crew to run two chillers instead of one.

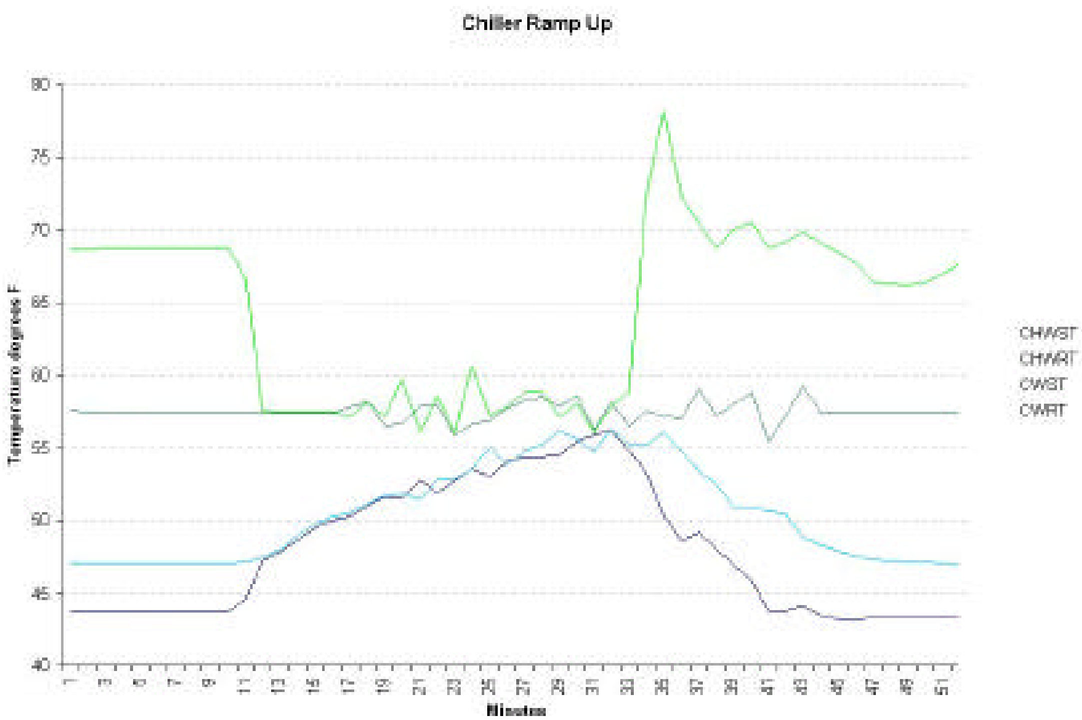
To test the capability of single-chiller operating mode, the Team asked the supervising Chief Petty Officer to turn one chiller off for an hour so chiller #4 could load up. This test began at 9:00 AM. The Chief said they would get a call from CIC complaining about getting hot. That call arrived within 15 minutes. The Team then sent an EM to CIC with a data logger fitted with a temperature and humidity sensor, which measured that it was 67°F and 37% RH in CIC. Before restarting the second chiller, the Team went back to AUX-1 and read the chiller panel and delta sensors. The chiller was still producing 44°F chilled water (at set point) and the load was 120 tons. This is good evidence that 120 tons was the ship's total load on that winter morning (outside conditions were ~63°F and 34% RH). The main propulsion turbines were not running, but they would not load the chillers much because the engine room air is not re-circulated. When the chiller indicated 120 tons, it was using 97% of its full load amps (FLA), indicating that it could not have produced more cooling if it had to, because the current limiter kicks in at 100% FLA. Thus it appeared that the chiller could not produce its rated capacity of 200 tons. The Team does not know why this occurred, and suggests that the Navy investigate further, and test the other chillers to determine whether this applies to them as well.

Because the temperature rose in CIC from 62°F to 67°F while the one remaining chiller was only 50% loaded, the factors described above led the Team to suspect that there was a problem in the chilled water distribution system. The Team turned on a second chilled water pump without starting the second chiller to see if that would reduce the temperature in CIC; it did not. The Team still suspects that this is a hydronic problem, but started the second chiller without taking time for further investigation. Maintaining such cool temperatures in CIC seems to be unusual, as this makes the space very sensitive to chilled water fluctuations, and apparently most or all of the electronic equipment is cooled by a separate system. The Team did not determine other motivations for this approach, and suggests that the Navy might reconsider this space cooling strategy.

The Team continued to measure power, flow, and ΔT at the equipment cooling heat exchanger, the air compressor, and outside air supply fan. The Team did not measure a typical Fan Coil Unit because the chilled water valve was closed (no load) and the fan is 1/5 HP. The insulation was rigid and plastered in place, so the Team was unsure the insulation could be replaced easily and was reluctant to cut into it.

The following chart shows the operating parameters of CH #4 during the monitoring period, measured at one-minute intervals. The top two lines show the outside air conditions in temperature and relative humidity; peaks and valleys are driven by varying insolation. The next two lines down show the seawater temperature (condenser water supply temperature) and the condenser water return temperature. The return water temperature (brown line) varies as the load in the seawater pumps changes due to shifting load patterns aboard ship. These variations cause the flow rate through the condenser to change, and this causes the return water temperature to rise and fall. The seawater (heat-sink) temperature remained quite constant at 57˚F. The bottom two lines (chilled water supply and return temperature) show that the heat rejected through the chiller is relatively constant at 3 F° (about 950 tons at 750 gpm flow rate). The convergence of the bottom four lines at mid-chart indicate when the chiller was off-line. The trends then stabilized as the chiller returned to service.


Chiller #4 Temperatures
Chilled & Condenser Water Temps
Outside Air Temp & RH %
CHWST
CHWRT
CWST
CWRT
OA temp
OA RH
OA RH
OA T
CWST
CWRT
CHWRT
CHWST


Chiller Ramp Up
Temperature degrees F
Minutes
CHWST
CHWRT
CWST
CWRT

APPENDIX B: ELECTRICITY USE OF LARGE PUMPS AND FANS

The following *calculated* data are primarily drawn from connected loads and load factors provided in the CG-60 energy study, representing cruise condition energy use.[101] Measured loads may differ substantially. Available measurements are described in the text. These calculations were part of an *a priori* effort to estimate how much of CG-59's electricity might be going to these particular loads, as summarized in the pie chart.

ENERGY USE OF LARGE FANS

Main engine cooling fans

- 4 fans @ 80 hp (65 kW) each; 2 run @ cruise condition
- (65 kW × 0.52 LF = 33.8 kW) × 2 fans = 67.6 kW

GTG enclosure cooling fans

- 6 fans @ 12.5 hp (9.6 kW) each; 2 run @ cruise condition
- (9.6 kW × 0.9 LF = 8.6 kW) × 2 fans = 17.2 kW

ENERGY USE OF LARGE PUMPS

Seawater pumps

- 3 pumps @ 125 hp (101.4 kW) each; 2 run @ cruise condition
- (101.4 kW × 0.7 LF = 71 kW) × 2 pumps = 142 kW

Fire water pumps

- 6 pumps @ 150 hp (120.5 kW) each; 2 run @ cruise condition
- (120.5 kW × 0.54 LF = 65.1 kW) × 2 pumps = 130.2 kW

Rudder hydraulic pumps

- 4 pumps @ 100 hp (80.6 kW) each; 2 run @ cruise condition
- (80.6 kW × 0.19 LF = 15.3 kW) × 2 pumps = 30.6 kW

Chilled water pumps

- 4 pumps @ 50 hp (41 kW) each; 2 run @ cruise condition
- 41 kW × 0.7 LF = 28.7 kW [× 2 pumps = 57.4 kW?]

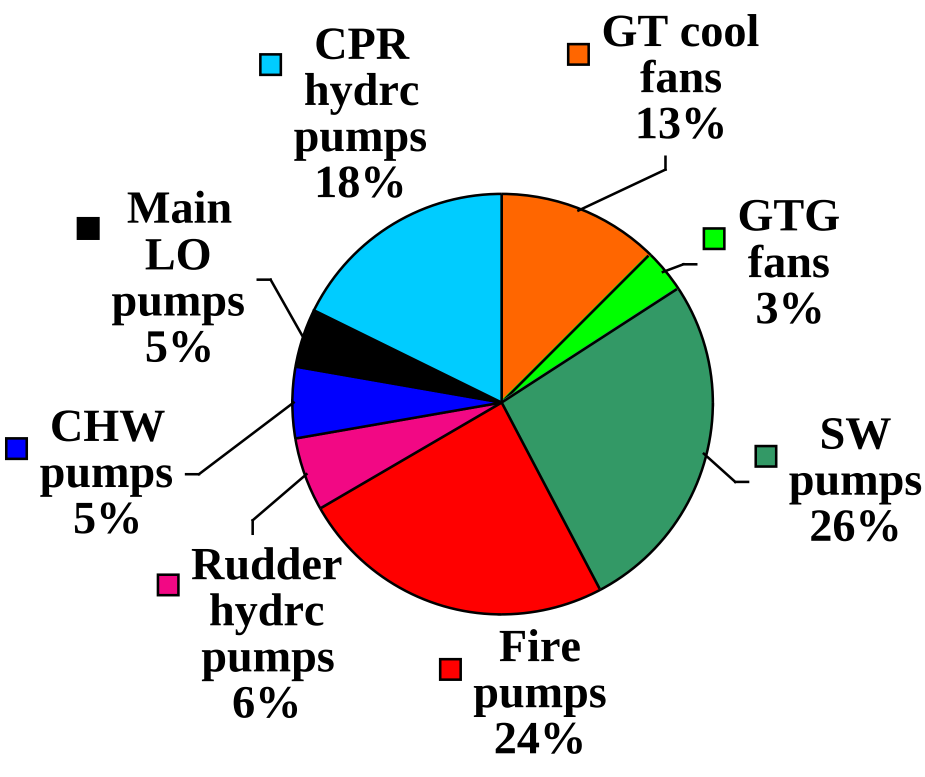
[101] "Calculated Loads for CG-60," unattributed study, sheet 1, pp. 1–54.

Main LO service pumps

- 4 pumps @ 50 hp (38 kW) each; 2 run @ cruise condition
- (38 kW × 0.32 LF = 12.2 kW) × 2 pumps = 24.4 kW

CPR hydraulic pumps

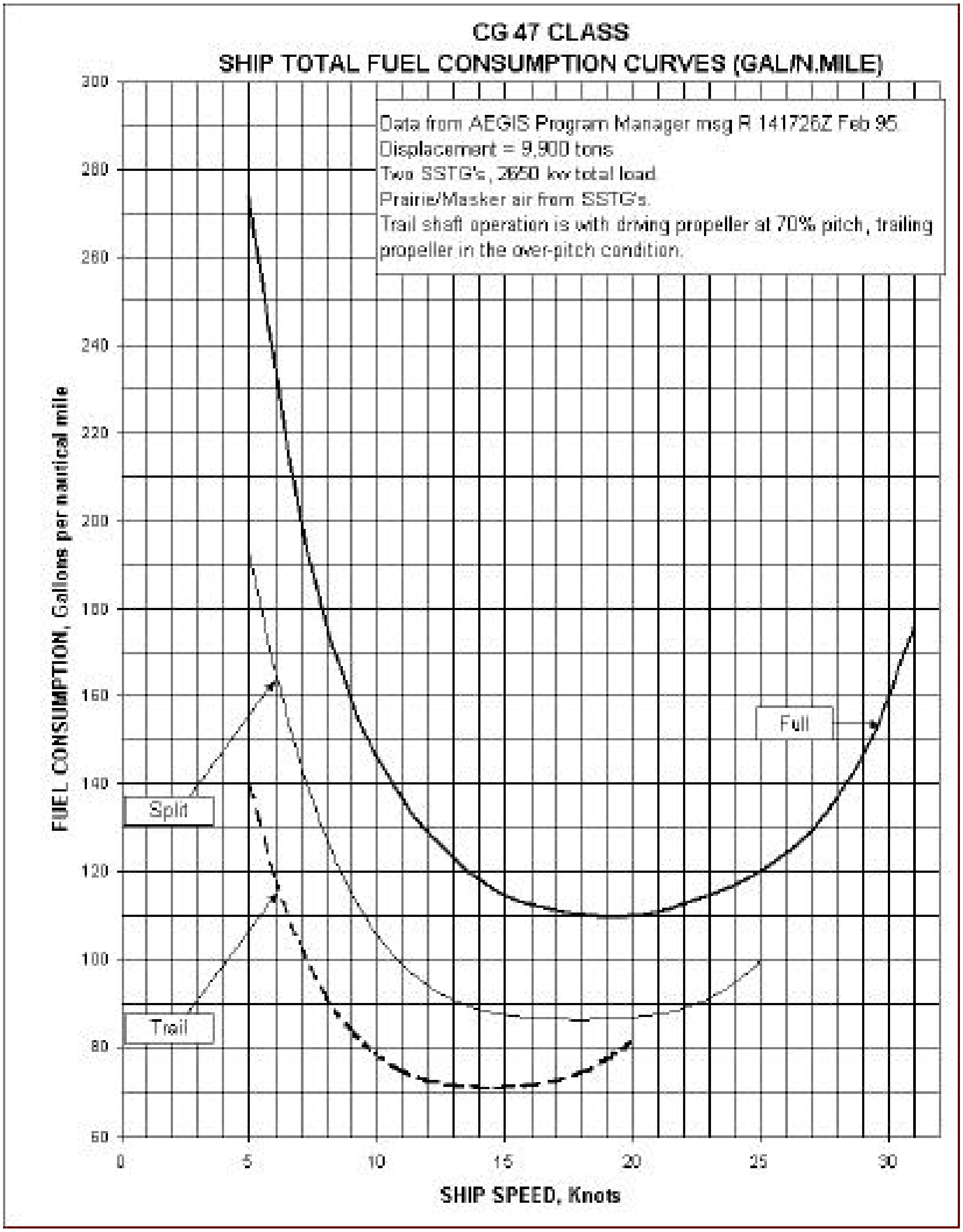
- 2 pumps @ 125 hp (99.1 kW) each; 2 run @ cruise condition
- (99.1 kW × 0.48 LF = 47.6 kW) × 2 pumps = 95.2 kW

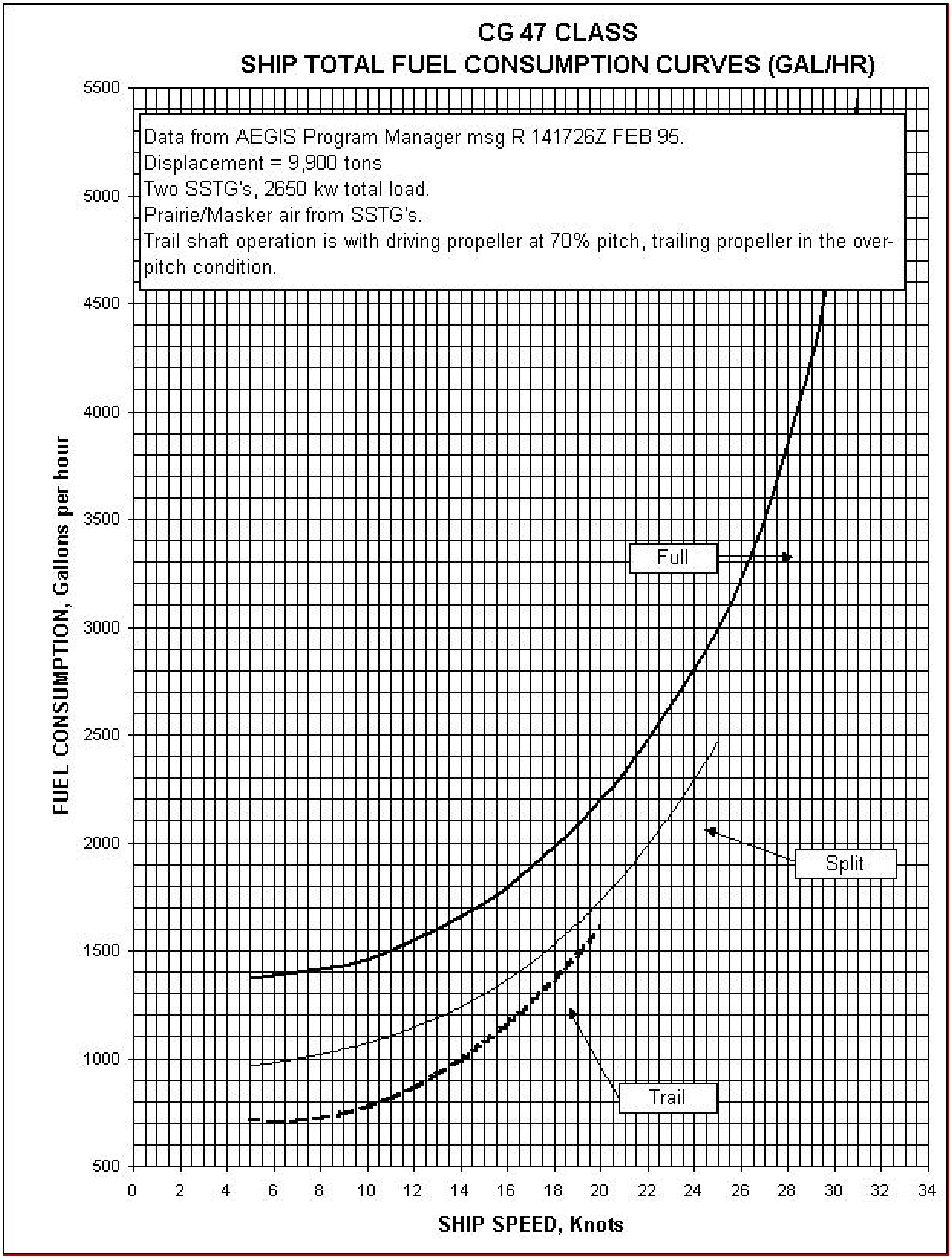


Initially estimated electricity use of large pumps and fans, CG-47

APPENDIX C:
NAVSEA CG-47 FUEL CONSUMPTION CURVES

These charts are from **www.navsea.navy.mil/encon/CG47_files/sheet004.htm**.




CG 47 CLASS
SHIP TOTAL FUEL CONSUMPTION CURVES (GAL/HR)
Data from AEGIS Program Manager msg R 141726Z FEB 95.
Displacement = 9,900 tons
Two SSTG's, 2650 kw total load.
Prairie/Masker air from SSTG's.
Trail shaft operation is with driving propeller at 70% pitch, trailing propeller in the over-pitch condition.
Full
Split
Trail
FUEL CONSUMPTION, Gallons per hour
SHIP SPEED, Knots
5500
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34

APPENDIX D: RESOURCE-EFFICIENT DESIGN PRINCIPLES AND RMI CONCEPTUAL APPROACH

KEY PRINCIPLES

The following principles provide a framework for the RMI Team's approach to resource efficiency in technical systems and facilities:

- Use integrated, whole-system design
- Start at the end-use, so savings compound going back upstream
- Reduce loads first
- Passive before active energy applications
- Use only enough energy needed to do the job
- Reduce resistance, friction, flow, and velocity
- Increase pipe/duct size to cut velocity yet maintain flow
- Fan/pump cube law savings: 1/2 speed = 1/8 energy use

Mechanical systems and equipment

- Chilled water temperatures should generally be as high as possible to help reduce chiller energy use.
- Two-temperature parallel loops are more efficient. Higher-temperature loads can be served by a dedicated chiller and piping system, while a separate cooling loop is served by chillers running at lower temperatures. This way the facilities' loads are segregated into subsystems that enables optimal allocation of total cooling energy, and each chiller and associated equipment can be more accurately sized to serve the load and operate at peak efficiency.
- "Big Pipes / Small Pumps." Increased pipe and duct diameters decrease friction, resistance, pressure drops, flows and velocities in air and water handling. This in turn allows reductions in size and capital cost of the pumps, fans, motors, inverters, and electrical equipment that serve the load, thereby reducing the total cost of the system.
- Pressure drop is proportional to velocity squared. Cutting velocity in half reduces pressure drop by 3/4ths (neglecting minor inverter losses).
- Power is proportional to volume cubed. Cutting velocity in half reduces fan or impeller energy use by 7/8ths (neglecting minor inverter losses).
- Reuse surplus of available low level heat. Make use of available "waste" energy before consuming fuel to accomplish a task.
- Use the best of the premium efficiency motors, pumps and fans with variable speed drives. This is particularly valuable with continuous-duty applications and varying loads. Select best-in-class units using MotorMaster or similar software.

Instrumentation and control systems

TQEM: You can't manage what you don't measure. Submeter with accuracy and precision; link sensors to real-time controls. Archive, mine, and graphically analyze the data. Use metrics that drive continuous improvement. Physical metrics are best (App. I).

DESIGN CONSIDERATIONS

Integrated design methodology allows architectural and mechanical designers and process engineers to optimize the relationships of building envelope and major mechanical and electrical systems. This effort will lower a facility's first cost and increase the efficiency of its mechanical systems. The performance of many mechanical systems is compromised by lack of space, location or orientation. An integrated design approach could have recognized and mitigated these effects at the same or reduced construction cost. Efficient distribution systems and low velocity air handling systems require larger cross-sectional areas (often offset by reduced native and parasitic loads) and smooth, straight, short runs of piping and ductwork. It is much more cost-effective to integrate these elements into the design at the schematic design phase than to try to squeeze them into restricted spaces during the design development phase.

The old saying "Haste makes waste", is confirmed by the second law of thermodynamics' "…entropy is directly related to the rate of change." While brisk execution is important, "fast track" design should *not* become standard procedure, because speed comes at the price of lost efficiency and project value. Designing in haste is generally a recipe for repenting and retrofitting at leisure; so is "infectious repetitis." A concerted effort to *evaluate and improve upon past designs* using operator feedback and careful measurement should be standard practice. Often the perceived need for fast design and construction is caused by lack of planning and preparation. Over time, fast design can inadvertently become a substitute for these vital steps. It should be seen for what it is: a fast track to capital waste in the short term and to operational costs and headaches later.

Maximal savings are achieved by *first* minimizing load at the end-use application, before applying an energy-saving measure such as a variable speed drive. This sequence starts not by making design assumptions but by accurately *measuring* actual performance. The data will reveal opportunities for load reduction (removing restriction points, etc.) and provide a baseline for tracking progress. Then systematically move "upstream" toward the motor, eliminating energy losses at each step. The resulting Resource Efficiency Model typically looks like this:

1. Identify variables that define the system's performance.
2. Calculate how accurately, precisely, and stably it's worth measuring performance. (In general, all performance measurement sensors should be designed to produce ±5% *system-level*—not local single-parameter—accuracy.)
3. *Measure* the system's performance to that accuracy. Managers and operators are flying blind without the valid information that only accurate measurement provides. Measurement promotes insight, credibility, and confidence.
4. Analyze the measurements and identify key steps to cut load and improve results.

5. Reduce load and parasitic losses in the system.
6. Resize motors for ~75–85% load at best available efficiency.
7. Size and select VFD to modulate between 50% and 100% load.
8. Repeat step 3 and evaluate ESM effectiveness.
9. Publicize measured results to all ST energy managers and designers.
10. Repeat from the beginning to achieve continuous improvement.

RMI TEAM CONCEPTUAL APPROACH AND KEY PRINCIPLES

End-use, least-cost analysis

Historically, energy resource discussions have focused on supply. But energy users don't want barrels of oil or kilowatt-hours of electricity *per se*; they want the services that energy ultimately provides: hot showers, cold beer, comfortable buildings, light, torque, mobility, etc. Focusing on these desired services, delivered by the end-use application of energy, allows consideration of a broader range of options than simply the energy supplied by the local grid or pipeline. RMI's end-use, least-cost analytical approach evaluates both demand- and supply-side options to determine the cheapest, cleanest way to deliver each of these services. Often the better, more cost-effective approach is to use less energy more productively, with smarter technologies. Efficient end-use can thus compete with new supply as an energy resource, and leverage bigger savings in resources, cost, and pollution upstream, across the whole system.

Harnessing market forces and using widely demonstrated and synergistic design, technology, and management techniques can deliver energy services at far lower financial and environmental cost. Industry surveys of "demand-side management" efforts to save electricity show saved watts—or "negawatts"—typically cost ~0.5–2.5 cents per saved kilowatt-hour. Most good industrial and commercial programs fall toward the low end.[102]

Resource efficiency provides benefits beyond saving commodity costs. For example, the 6–16 percent labor productivity gains in efficient buildings—due to their superior visual, acoustic and thermal comfort—are typically worth at least ten times more than the energy savings themselves, but are absent from all economic models of whether building proprietors will improve their energy efficiency.[103]

Integrated, whole-systems design

Whole-system design techniques offer some of the most significant savings opportunities. Inventor Edwin Land once remarked that "people who seem to have had a new idea have often simply stopped having an old idea." This is particularly true when designing systems for resource savings. The old idea is one of diminishing returns—that the greater the

[102] See Amory Lovins, "Apples, Oranges, and Horned Toads: Is The Joskow & Marron Critique of Electric Efficiency Costs Valid?" *Electricity Journal*, 7, no. 4 (May 1994) pp. 29–49. Available as Rocky Mountain Institute (RMI) Publication #U94-16 (Snowmass, CO: RMI, 1994).
[103] See Joe Romm and W. D. Browning, "Greening the Building and the Bottom Line: Increasing Productivity Through Energy-Efficient Design," RMI Publication #D94-27 (Snowmass, CO: RMI, 1994).

resource saving, the higher the cost. But that old idea is giving way to the new idea that bigger savings can cost less: that saving a large fraction of resources can actually cost less than saving a small fraction of resources (or saving nothing).

Interface Corporation, the leading maker of materials for commercial interiors, applied such an approach to a standard "pumping loop" (a common feature in many factories and most large buildings) in its new Shanghai carpet factory. A top European company had designed the system to use pumps requiring a total of 95 horsepower. But before construction began, Jan Schilham, a Dutch engineer at Interface, realized that two embarrassingly simple design changes would cut that power requirement to only 7 horsepower—a 92 percent reduction. Yet the redesigned system cost less to build, involved no new technology and worked better in all respects.

What two design changes achieved this twelvefold saving in pumping power? Schilham applied techniques pioneered by Singapore engineer Eng Lock Lee of Supersymmetry Services (www.supersym.com.sg). First, Schilham chose larger-diameter pipes, which generate much less friction than smaller-diameter pipes and therefore need far less pumping energy. The original designer had chosen the smaller pipes because, according to the traditional method, the extra cost of larger ones wouldn't be justified by the pumping energy they would save. While this standard design trade-off optimizes the pipes by themselves, it "pessimizes" the system as a whole. Schilham optimized the whole system by counting not only the higher capital cost of the larger pipes but also the lower capital cost of the smaller pumping equipment that would be needed. The pumps, motors, motor controls and electrical components could all be much smaller because of the reduced friction. Capital cost would fall far more for the smaller equipment than it would rise for the larger pipes, because friction falls as nearly the fifth power, but pipe cost rises as only about the second power, of pipe diameter. Choosing larger pipes and smaller pumps—not smaller pipes and larger pumps—would therefore make the whole system cheaper to build, even without regard to its twelvefold reduction in energy use.

Schilham's second innovation was to reduce the friction even more by making the pipes short and straight rather than long and crooked. He did this by laying out the pipes first, then positioning the various tanks, boilers and other equipment that they connected. Designers normally locate the production equipment in arbitrary positions, and then have a pipefitter connect the components. Awkward placement, exacerbated by trade-school training to dress pipes neatly at right angles rather than taking a more direct route or untangling the layout, forces the pipes to make numerous bends that greatly increase friction. In addition to saving on installation, materials and electrical costs, Schilham's short, straight pipes were easier to insulate, saving an extra 70 kilowatts of heat loss and repaying the insulation's cost in three months. A half-dozen further benefits were achieved too.

This small example has important implications. Pumping is the largest use of motors, and motors use three-quarters of all industrial electricity in the United States (or three-fifths of all electricity).[104] Second, the lessons are very widely applicable. Interface's pumping

[104] See E SOURCE, *Drivepower Technology Atlas*, E SOURCE Publication #TA-DP-96 (Boulder, CO: E SOURCE, 1996), www.esource.com.

loop shows how simple changes in design mentality can yield huge resource savings and returns on investment. This isn't rocket science; often it's just a rediscovery of good Victorian-era engineering principles, lately overlooked because of specialization.

Barrier Busting

A common example of breaking down barriers can be found in the behavior of the different parties involved in commercial building construction. Consider four such actors: the owner, the designer, the construction contractor and the tenant. The owner is not likely to specify target levels of energy performance beyond meeting building codes, particularly for a structure intended for lease. The architect probably has not been trained in whole-system, resource-efficient design. If she is familiar with these techniques, she may not wish to struggle with the owner or contractor to explain the benefits of such an approach. In any event, the structure of her compensation typically rewards her for what she spends, not for what she saves. The contractor wishes to capture as much profit as possible from the bid price and has the incentive to install the least expensive components he can find, regardless of how inefficiently they use energy or water. The tenant has no say and is stuck with the utility bills. All of these people are acting in their economic self-interest, within the bounds of their knowledge; yet the outcome is a relatively inefficient building.

For example, the after-tax return on increasing the diameter of wire by just one size in a standard U.S. office lighting circuit typically approaches 200 percent per year. The wire-size table in the National Electrical Code is meant only to help prevent fires, not save money, and hence specifies wire with half the diameter—with four times the electrical losses due to greater resistance—that would be economically desirable. But an electrician altruistic enough to buy the larger (and more expensive) wire would no longer be the low bidder and wouldn't get the job. This example embodies two barriers: a life-safety minimum-requirement code misinterpreted as an economic optimum, and a split incentive between the party who chooses the wire size and the one who later pays the electric bills.

There are numerous remedies for these barriers to achieving efficient buildings. Better awareness of demonstrated techniques for more resource-efficient construction would benefit all the above parties. An integrated design workshop where all the parties involved in the building participate in an intensive, multidisciplinary and facilitated meeting to optimize the plans and specifications often radically improves a building's design. Performance-based fees, which reward the designer in part based upon measured savings in energy and water efficiency relative to pre-agreed standards, can provide the incentive for more efficient design. A former Commander of NAVFAC expressed interest in procuring design services in that fashion; RMI's five successful experiments with such fees indicate that experimentation with them is a realistic and valuable priority for the Navy.

APPENDIX E: MULTIPLE BENEFITS IN MOTOR SYSTEMS

This appendix for more technically inclined readers explains how premium-efficient motors can deliver about 16 different benefits from a single retrofit expenditure.

Motor systems: 16-for-one benefits

What answer you get depends on what question you ask. In car design, if you focus on just the engine of a normal car, you may find it's rated at over 30% efficient. So it is—when run under ideal conditions. Yet the suboptimal way it's typically used cuts its *average* efficiency to about 15%. Some more torque is lost en route to the wheels, and only 1% of the fuel energy ends up moving the *driver*, whose body weighs only about 5% as much as the vehicle does. Electric motor systems in factories and big buildings are similar: the motor itself may be very efficient under ideal conditions, but the way it's usually used is often very *in*efficient, wasting most of the motor's torque before it can do the desired task. Avoiding that inefficiency requires not just an efficient motor, but applying it in an efficient *system*.[105]

When asked how to save some of the three-fifths of U.S. electricity that goes into motors, most practitioners emphasize only two improvements:

- premium-efficiency induction motors, which gain several percentage points' efficiency because they're better designed and built, using a larger quantity and higher quality of copper and iron to reduce electrical and magnetic losses; and
- variable-speed drives (VSDs) using electronic inverters to vary the frequency of the alternating current that drives the motor in order to adjust its speed to what the task requires at the time. The output of many pumps, blowers, and fans is controlled by running them at full speed against a mechanical obstruction like a "throttling valve." Yet pumps' and fans' power consumption varies roughly as the cube of their flow rate, so if only half the full flow were needed, seven-eighths of the full input power, less minor VSD circuit losses, could be saved by removing the obstruction and halving the speed. VSDs' full use could thus save ~20%[106] or ~14% to 27%[107] of all U.S. motor energy, with typical paybacks estimated at about 1 to $2^1/2$ years respectively.

[105] The original analysis is in Lovins, A.B., Neymark, J., Flanigan, T., Kiernan, P.B., Bancroft, B., & Shepard, M. 1989: *The State of the Art: Drivepower*, COMPETKTEK / Rocky Mountain Institute, Snowmass CO 81654-9199. For later, less thorough, but somewhat more up-to-date versions, see Nadel, S., Shepard, M., Greenberg, S., Katz, G., Almeida, A. 1991: *Energy-Efficient Motor Systems: A Handbook on Technology, Program and Policy Opportunities*, American Council for an Energy-Efficient Economy (www.aceee.org), Washington, D.C. and Howe, B., Shepard, M., Lovins, A.B., Stickney, B.L. & Houghton, D.J. 1996: *Drivepower Technology Atlas*, E SOURCE, www.esource.com. Motor data are periodically updated by the comprehensive MotorMaster database sponsored by USDOE (800/862-2086, FAX 360/586-8303, Motor Challenge Information Clearinghouse, Box 43717, Olympia WA 98504-3171).

[106] Fickett, A.P., Gellings, C.W., & Lovins, A.B. 1990: "Efficient Use of Electricity," *Scientific American* **263**(3):64–74, Sept.

So far, so good. But adding 33 further drivesystem improvements—in the choice, sizing, maintenance, and life of motors, in control systems of three further kinds, and in up-stream electrical supplies and downstream mechanical drivetrains—can at least double the savings from these two measures.[108] It can also cut total retrofit cost by perhaps five-fold[109], because of the 35 combined measures, 28 are free byproducts of the other seven that must be paid for, yielding greater savings at no extra cost.[110] In short, whole-system design, by capturing multiple benefits, tunnels through the cost barrier.

Immediately retrofitting an in-service standard-efficiency induction motor to a premium-efficiency model, without waiting for it to burn out, is commonly assumed to be a bad deal: the energy saved by the new motor's higher efficiency is often said to take 10–20 years to pay for the entire cost of the new motor. This comparison counts just the following single benefit:[111]

- The more efficient new motor will need less energy than the inefficient old one to produce the same torque; how much less is conventionally calculated from their full-load rated efficiencies and from how many hours a year they operate.

But in fact, *immediate* retrofit usually pays for itself within just a few years, because the premium-efficiency motor yields many more benefits than just saving energy through a higher "nameplate" efficiency rating:

- Many U.S. motors are so grossly oversized that probably half never exceed 60%, and a third never exceed 50%, of their rated load. This oversizing often makes actual efficiency, operating at the actual loadpoint, lower than the nameplate rating implies. Quite commonly the efficient new motor, properly sized, will be one frame size smaller than the old inefficient motor; sometimes two sizes smaller; occasionally three. Making the new motor even one size smaller makes it cheaper—saving more capital cost than the extra cost, if any[112], of making it more efficient.

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107 Lovins *et al.* 1989, *op. cit.*, updated and supplemented by Howe *et al.* 1996, *op. cit.*

108 Lovins *et al.* 1989, *op. cit.*

109 Fickett *et al.* 1990, *op. cit.*

110 Lovins *et al.* 1989, *op. cit.*

111 Actually this is two benefits, because saving electricity reduces both energy charges and demand charges, but it might be considered just the single benefit of "saving electricity and hence reducing the utility bill."

112 There *is* no such extra cost of efficiency up to at least 250–300 horsepower. However, even if the usual rule-of-thumb were right about how much extra you have to pay for a more efficient motor, making the new motor the right size would typically reduce the payback of immediate retrofit to about three years.

- Motors that are too big—run at below their optimal load—not only become less efficient; they also run faster. When they are running a pump or fan, the faster speed produces more flow that's typically unwanted, but increases energy use as the cube of the flow rate. Making the motor the right size provides exactly the desired flow and eliminates this waste, so the new, right-sized motor will cost less *and save more* than you'd expect just be comparing rated full-load efficiencies for motors the same size.
- The new motor will typically stay highly efficient across a wide range of operating conditions—speed and torque. This "bigger bull's-eye" on the "efficiency map" maximizes energy savings not just at a narrowly defined operating point but through much or all of the range of conditions in which the motor will actually be called upon to operate. It can greatly increase calculated savings compared with a small-bull's-eye motor that operates most of the time at far from its optimal load.
- The efficient new motor, even though it's more fully loaded, will run cooler because it typically halves the losses that route electricity into making the motor hot rather than making it turn. Heat is the enemy of motors: every 18 F˚ of increase in motor temperature cuts the life of the insulation and other oxidizable materials about in half. This also works backwards: every 18 F˚ of *de*crease in temperature makes these key materials last about twice as long. Running cooler therefore stretches motor life, reducing the costs of maintenance or downtime or both.
- Running cooler also decreases electrical resistance in the copper, boosting efficiency.
- Premium-efficiency motors tend to come already equipped with higher-quality bearings than standard-efficiency motors. Three-fourths of medium-sized motor failures are caused by bearing failures, so better bearings mean longer motor life.[113] This means that the energy *plus* maintenance savings of the new motor will, over time, typically more than pay for immediately substituting it for the old motor.
- Cooler operation makes bearing grease last longer. This means either greater reliability on the same lubrication schedule or the same reliability with less frequent lubrication, which reduces maintenance cost. Greater liability reduces, and less frequent lubrication might reduce, downtime, which can range from a minor nuisance to a multimillion-dollar charge, depending on the nature of the process and the function of the motor.
- The new motor automatically eliminates any increased magnetic losses that may have been caused by improper past repair of the old motor.[114] Adding this benefit to proper motor sizing yields direct electrical savings roughly twice as big as would be expected from the new motor's better nameplate efficiency alone.

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[113] Changing to a premium-efficiency motor also makes it easy to add at the factory some "bearing seal isolators" that keep traces of water or other contaminants from getting into the bearing and causing it to fail—cheap insurance that can greatly increase motor life at very low cost.

[114] Normal rewinding methods cook the nonrotating iron parts of the motor in an oven, often causing subtle and irreversible magnetic damage that wastes about $1–3 billion a year worth of electricity in the United States. Better methods that are faster, cheaper, and nondamaging are on the market but little-known. The Navy may have avoided such damage by using the superior Thumm method for rewinds at sea, though RMI does not know whether some outsourced repairs done ashore might not use burnout ovens: the engineering crew aboard *USS John C. Stennis* who were using the Thumm method seemed unaware of its advantages and importance for protecting motor efficiency.

- The high-efficiency motor generally has a better power factor[115] as a free byproduct of its better design. This avoids most or all of the cost of capacitors otherwise needed to compensate for bad power factor, as well as the cost of extra generation and distribution capacity and operating costs to deliver unnecessary reactive power.
- Higher power factor also reduces electrical losses in the wiring within the plant.
- The high-efficiency motor tends to heat up less when exposed to harmonics (multiples of the frequency of the alternating current). This helps it run cooler and more efficiently at variable speed.
- The new motor is more tolerant of improper supply voltage, which is quite common.
- The new motor loses much less efficiency and lifetime if the three phases of its power supply don't have almost perfectly matched voltages—another common condition that can dramatically degrade inefficient motors' power output and their lifetime.
- The new motor's energy savings let it draw less current than the old motor. Losses in the plant's wires, transformers, and other electrical supply equipment vary as the square of current: lower current, much lower losses.
- All the reduced losses, direct and indirect, release less heat into the plant. In air-conditioned space, that means less cooling and air-handling energy and capacity.

The premium-efficiency, right-sized motor thus provides at least 16 important operational advantages; but it needs to be paid for only once. However, many of these savings depend on others.[116] For example, both efficiency and motor life depend on *other* energy-saving improvements too: reducing voltage imbalance between the phases, improving shaft alignment and lubrication practice, reducing overhung loads (sideways pulls) on the shaft that can cut bearing life by at least 5- to 10-fold, and improving housekeeping—not siting motors in the sun or next to steam pipes, not smothering them beneath multiple coats of paint, etc.

Motor choice, life, sizing, controls, maintenance, and associated electrical and mechanical elements all interact intricately. For example, suppose you're replacing an old fan motor with a right-sized, premium-efficiency motor. Most fans are driven by V-belts, which stretch, slip, wear out, require frequent maintenance, and waste about 5–15% of the torque they transmit. It would be better to use a 98–99%-efficient, virtually zero-maintenance belt, such as a "synchronous belt" that doesn't slip because its teeth engage sprocket lugs, doesn't stretch because it has fiberglass or aramid bands inside like a radial tire, and saves so much maintenance that the electricity it saves costs about *minus* a dollar per kilowatt-hour. But such a belt doesn't have much "give," and fans take a lot of torque to start up, so the first time you turn it on, the belt's teeth may well strip with an awful screech. The answer is to use a stretchier but still extremely efficient flat belt, or to equip

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[115] Power factor (Appendix J) is the cosine of the phase angle between current and voltage. It reflects the degree to which the power source must provide out-of-phase current that it must generate and transmit but cannot charge for. Induction motors cause this problem to a degree which, if not adequately compensated by nearby capacitors, may incur a utility penalty charge in civilian facilities ashore, and certainly incur economic and operational penalties afloat even if they are not recognized, charged for, and designed out.

[116] Lovins *et al.* 1989. *op. cit.*

the motor with an electronic soft-start device—often a free feature of the VSD that most fan drives should use anyway.

But there's another catch: if you didn't carefully choose the slip of the motor—a measure of how fast it turns—you may find it's higher with the efficient new motor than with the old one, threatening to waste more energy through extra fan flow than the motor's higher efficiency saves. If so, then you'd better notice it in time to make the new belt sprockets a different size, or electronically adjust the fanspeed with the VSD, so you capture the full savings available from the better motor.

Without going into further detail on all the interactions, the unfavorable ones are far outweighed by the favorable ones. Their collective effect is to make the savings of the whole drivepower package far larger and cheaper than would appear from considering just a few fragmented measures, as most analyses do. The bottom line[117]: retrofitting approximately 35 kinds of improvements, installed in between the electric motor and the input shaft of the machine that the motor is driving, can typically save about half of the drivesystem's energy, even with no improvements further downstream (*e.g.*, in pumps, pipes, flow reduction, etc.). These savings pay for themselves in an average of about 16 months or less at a five-cent-per-kilowatt-hour industrial rate. They're that cheap because if you pay for the right seven savings up front, you get 28 more savings as free byproducts. Seven expenditures, 35 benefits. More tunneling through the cost barrier.

[117] *Id.*, Fickett *et al.* 1990 *op. cit.*, Nadel *et al.* 1991 *op. cit*. The first reference provides the most detailed scoping calculation, although it conservatively omits the overspeeding of underloaded induction motors.

APPENDIX F:
MULTIPLE BENEFITS IN FLUORESCENT LIGHTING SYSTEMS

This appendix for more technically inclined readers explains how dimming electronic ballasts get about 18 different benefits from a single retrofit expenditure.

Dimming electronic ballasts for commercial fluorescent lighting: 18 benefits and counting

A cornucopia unfolds in commercial fluorescent lighting.[118] What do you do to retrofit, say, a ~65%-efficient enclosed two-by-four-foot recessed ceiling luminaire[119]—the most common type of major fixture? The fixture classically uses 180 watts of electricity for its four 40-watt lamps driven by two 16-watt electromagnetic ballasts. Inserting an imaging specular reflector—a very shiny, computer-designed, specially shaped piece of sheetmetal—above these lamps nearly doubles the fixture's optical efficiency. (That's because each exit ray bounces barely more than once off a very shiny surface, rather than nearly three times off a not-so-shiny surface like white enameled sheetmetal.) Half the lamps can then be removed, the rest relocated, and approximately the same delivered light obtained as before. The removed lamps appear to be still there, but they are only virtual images, and virtual lamps require no electricity or maintenance. The avoided maintenance costs end up, over time, paying for half the retrofit package. While being relocated, the lamps can also be replaced, at no extra labor cost, with new lamps whose "tristimulus" phosphors—tuned to red, green, and blue retinal cones—emit up to 18% more light per watt, with more pleasant and accurate color that probably helps you see better. The new lamps are also skinnier, making them up to about 25% more efficient and making it easier to control optically the exact distribution of where the light goes in the room. The two two-lamp ballasts can then be replaced with a single four-lamp high-frequency electronic ballast shared between two adjacent luminaires.

[118] The original analysis is in Lovins, A.B. & Sardinsky, R. 1988: *The State of the Art: Lighting*, COMPETITEK / Rocky Mountain Institute, Snowmass CO 81654-9199. Its fourth update, Audin, L., Houghton, D., Shepard, M., & Hawthorne, W. 1998: *Lighting Technology Atlas*, E SOURCE, Boulder, CO, is considerably more up-to-date (www.esource.com). Fluorescent lighting in the late 1980s was using about half of U.S. lighting energy. The remaining savings are chiefly in incandescent systems and to a much lesser extent in high-intensity discharge lighting. For all lighting retrofits, total cost is typically negative because most replacements of incandescent lamps by compact fluorescents or other longer-lived alternatives are more than paid for by saved maintenance costs (Lovins & Sardinsky 1988). New construction shouldn't use downlights—indirect uplights are more visually effective, attractive, flexible, and cost-effective—and retrofits should consider converting to indirect lighting, but this may not be feasible in some situations such as with low ceilings.

[119] The "luminaire" is the light fixture together with the equipment that produces the light. Its efficiency is how much of the produced light comes out.

This retrofit has two important lessons. First, doing all these measures together as a package saves much more energy, at much lower cost, than fragmenting the package or omitting parts of it.[120] Second, the key to success—the dimming electronic ballast and its control systems—can save electricity in at least 18 ways:

1. The ballast wastes only two watts less per lamp because it's electronic, compared with eight with a standard electromagnetic ballast or 3–4 with a "high-efficiency" electromagnetic ballast.[121]
2. The lamps also produce more light at high frequency (about 20,000–40,000 cycles per second) than at the 60-cycle line frequency. These first two effects can boost light output per watt by upwards of 40%.
3. Because the ballast dissipates so much less heat per lamp, circuitry for four (or perhaps even six) lamps, not just two, can be installed in a single ballast can without its overheating. This in turn means that a single ballast can control at least two adjacent fixtures, reducing capital and installation costs for both the ballast and its control systems.
4. The more efficient lamps and ballasts can make the lampwall temperature—on which efficiency strongly depends—more nearly optimal.[122]
5. The electronic ballast, depending on design, can be less sensitive to or can automatically compensate for lampwall temperature.
6. It can also provide the same insensitivity to or compensation for abnormally high or low supply voltage. This plus effect #5 can reduce by one-eighth the overlighting normally designed in as a precaution to cope with these potential conditions.
7. The electronic ballast can continuously dim the lamps to match available daylight, often saving 50% or more of the lighting energy in the "perimeter zones" around the daylit sides of the building.
8. The same dimming control automatically brightens the lamps as they dim with age and dirt, so they need not be too bright when young, fresh, and clean in order to provide enough light when old, tired, and dirty. This saves at least a seventh of the energy over each group relamping cycle.

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[120] Installing just a reflector duplicates the relamping labor, adds labor for reballasting later, and may save nothing if the reflector is badly designed. Installing a nondimming electronic ballast captures about 3–4 kinds of savings but loses about 14 others; it delivers only one-third the savings of a dimming ballast, but doesn't save enough capital cost to justify that sacrifice. Not switching to the better lamps means unpleasant light, wasted electricity, and a need to change the lamps and ballast later, duplicating labor on both, to correct those problems. (Using 34-watt "energy-saving" lamps also introduces additional technical problems, and reduces light output as much as power input.) Leaving out the controls slashes the savings, and usually requires a costly retrofit later to make computer screens readable and the space reconfigurable. Remarkably, most lighting retrofits make one or more of these mistakes, partly because many utility rebate programs reward specific pieces of hardware rather than integrated packages.

[121] This interim technology uses copper instead of aluminum wire, but is still much less efficient than an electronic ballast. It also runs at line frequency, so it hums and the lamps flicker, and it can't dim. In essentially no applications is it a wise choice.

[122] Mainly for this reason, starting with three 34-watt "energy-saver" lamps and two "high-efficiency" electromagnetic ballasts in a modern louvered parabolic fixture will save, within a few percentage points, the same amount of energy as replacing the less efficient initial equipment assumed in this example.

9. The reduced heat from the lamps and ballasts reduces convective air currents that deposit dust on the lamps and fixtures, so more light output is maintained on the same cleaning schedule, or less frequent cleaning is needed to maintain a given light output.
10. Dimming the lamps stretches their lifetime, saving maintenance costs.
11. It also reduces the rate at which the lamps' efficiency deteriorates, saving energy.
12. High-frequency operation may further slow that loss of efficiency by about 2–5%.
13. The dimming controls permit light levels to be adjusted or "tuned" in different parts of the room according to the tasks being done there (more light over your desk, less off in the corner), and easily changed if the furniture is rearranged. This saves around 12–20% of the energy.
14. Being able to control ambient lighting levels to exactly the level you want will often mean you actually choose, especially if you're relatively young, lower light levels than official standards assume you'll want. Conversely, if you want more light than usual, you can get it without also superfluously providing it to everyone else who doesn't want it. Experiments suggest this better matching to individual preferences may save upwards of 20%.
15. The electronic ballast facilitates smart automatic control occupancy sensors, which turn lamps down or off in empty rooms, often saving 25–50%.
16. An electronic ballast also makes it easier to use timers or digital control circuits to turn off lights automatically after hours (unless you choose to turn them back on).
17. The lamps can be slightly dimmed during peak-load periods, reducing utility peak demand charges for both the lighting energy and the associated space-cooling and fan energy needed to combat the heat of the lights. This valuable peak-dimming is imperceptible because the eye, being able to adjust by a million millionfold between sunlight and starlight, has a logarithmic response that can't detect small changes if they're gradual enough.
18. The electronic ballast can shut down the lamps, and itself, in certain common kinds of failures, rather than wasting energy trying to restart a failed lamp or keeping energized a ballast that's providing no light.

Together, these ballast and control mechanisms can typically save about half the energy per unit of delivered light in the center of a large building, and 70% to 80% or more in a typical mix of core and perimeter zones. The better lamp phosphors and reflector optics cut electricity per unit of delivered light by a further ~15% and ~35+% respectively—a cumulative total saving of about 83% to 91%, all from a whole-system retrofit.

An important example of effects *not* included in the above list of 18 engineering-economic benefits, but vital to users, is that since the high-frequency operation of the lamps eliminates both flicker and hum, fatigue is much reduced, typically requiring less light per person-hour of work to achieve the same visual performance and labor hence productivity.

Such savings are not unusual even in awkward cases, because further opportunities are available from other aspects of the whole lighting system (not just what's in the fixture):

- reducing endemic overlighting (most offices are lit not only far above official recommendations, but at levels that actually violate those standards by making it difficult to read computer screens);
- concentrating local light on the visual task with a user-controllable swing-arm task lamp that lets you spill light evenly across the paper tasks on your desk without also washing out the computer screen;
- making the light more visually effective by bouncing light off the ceiling and walls so it doesn't wash out the contrast between paper and ink, or by equipping overhead downlights with radial polarizers that reduce veiling glare;
- using lighter-colored surfaces to bounce light around better in the room;
- bouncing daylight several times as far into the room (via lightshelves, top-reflective blinds, glass-topped partitions, etc.); and
- improving maintenance, such as replacing lamps all at once before they lose too much efficiency.

In all, 70% to 90% or greater savings on electricity used for lighting are typically available from comprehensive retrofits, with the same delivered light and great improvements in quality and attractiveness. The cost of such a retrofit is typically equivalent, at a six-cent-per-kilowatt-hour commercial tariff ashore, to about a one-year payback if you count saved air-conditioning savings and long-term maintenance savings (from having only half as many lamps and a quarter as many ballasts to maintain). If you didn't count those savings, the payback could be up to about three years. A three-year payback is equivalent to an aftertax annual return on investment of about 32%. At the CG-59 electricity cost of about 27¢/kWh (p. 19), conservatively assuming operating hours no greater than the office norm of ~2,500 h/y, the payback afloat would be more than four times faster.

As with motors, however, achieving both such large lighting savings and such improved quality of service depends on harnessing complex thermal, optical, and electrical interactions between all the components. It requires including all the right parts, and combining them into something greater than their sum. It demands doing the right things, in the right order, at the right time. This isn't as complicated as it sounds, but it isn't simply plugging in one "magic-bullet" gadget and turning it on. Rather, it requires new ways to deliver integrated packages of modern hardware plus managerial and cultural changes.[123] That isn't easy; but neither is expanding electrical supplies.

[123] With motors, for example, an important cultural need is to change lubrication from a low-caste, dirty-hands occupation to a high-caste, white-lab-coat occupation.

APPENDIX G:
OPTIMAL SEQUENCE FOR LIGHTING IMPROVEMENTS

What's the right order for improving office lighting? Most retrofitters start by improving the lighting equipment. But that starts at the wrong end of the problem. Even the most efficient lighting equipment is useless if it lights the wrong place, or at the wrong time, or at the wrong angle so it causes glare. The Illuminating Engineering Society and seasoned lighting professionals would instead recommend the following sequence for, say, retrofitting the lighting in an ordinary office where people main read papers and computer screens:

1. Improve the quality of the visual task.[124]
2. Rearrange the room to make the lighting comfortable.[125]
3. Improve the quality of the light by reducing "veiling reflections"—glare that bounces from the light source off the page to your eye so you can't distinguish ink from paper. This is typically about ten times as important as adding more light. Indirect lighting, which bounces light off the room's surfaces from all directions, can let you see as well with 20 indirect footcandles as with 100 footcandles from glaring direct downlights.
4. Rather than overlighting the whole room to a uniformly high level—which would be as inappropriate as controlling a big building with a single thermostat—get the right amount of light on each of your tasks by adjusting the ambient lighting levels to what you need for walking around and doing non-desk tasks, then filling in on your desk with an efficient swing-arm task lamp.[126]
5. Try to lighten the colors of the ceiling, walls, floor, and furniture so that the light will bounce around better within the space. The smaller the areas of dark colors that soak up light, and the more you lighten those colors (without, of course, making them dazzlingly bright), the less light you'll need to add to the room in order to get a given amount bounced onto your desk.

[124] If you're having trouble reading because the papers have been photocopied on a machine with dust on the lenses and mirrors, clean out the machine first to make the image crisper. If there's glare off the paper, consider using matte paper.

[125] If there's "discomfort glare" from harsh overhead sources, so shading your eyes with your hand like a baseball-cap brim makes your face muscles relax from squinting, control the glare with louvers or lighting redesign. If bright spots are glaring in your computer screen from lights or windows behind you, shade them or change the layout of the room so they're no longer behind you. If you can't read your computer screen because it's in front of a bright window, move the screen or shade the window. If windows are too bright compared to walls, adjust the blinds properly, or use microperforated blinds or diffusing curtains.

[126] You need more light when you're older, or your eyes are more tired, or when you're doing finer or more critical tasks. Task lamps make it easy to get just the amount of light you want, where and when you want it.

6. Harvest and distribute free daylight.[127]
7. Improve the technical efficiency of your electric lighting equipment, for example as described in Appendix F for standard fluorescent-tube fixtures, by using better light fixtures, lamps, ballasts, and controls.
8. Train people how to use these systems.[128]
9. Improve maintenance and management of these systems so they'll stay at top performance and least cost.

Interestingly, most "lighting retrofitters" do only step 7. Doing steps 1–6 first saves more money and yields better results, because smaller, simpler and less equipment will be needed to deliver nicer light.

[127] Modern techniques such as double-curved lightshelves can do this quite evenly and without glare, even as much as 50+ feet in from the nearest window. Lightshafts and atria can bounce soft daylight many stories downward. Special methods, such as lightpipes and fiber optics, can even collect concentrated sunlight on the roof or outside the building, then deliver it as intense daylight far underground. In general, direct sunlight is too strong, producing glare that makes it harder to see, so instead of being "dumped" into the space, direct sunrays should generally be bounced back up onto the ceiling. Glass-topped partitions for private offices can preserve privacy, yet spread daylight better into adjacent rooms.

[128] For example, how to operate Venetian blinds: they're supposed to be not closed like opaque curtains, but tilted so they throw daylight upward onto the ceiling. Then you can still see out, but the outside isn't unpleasantly bright.

APPENDIX H: OPTIMAL SEQUENCE FOR COOLING IMPROVEMENTS

Consider the proper sequence in which to help people feel comfortable in hot weather:[129]

1. Expand the range of conditions in which, according to the official ASHRAE standards, people feel comfortable. There are at least ten ways to do this besides air temperature.[130]
2. Keep unwanted heat out of the room.[131]
3. If you still need to cool the people, first do so passively by "ground coupling" (building on an uninsulated slab that connects the space to the cool earth beneath), ventilative cooling like the Queens Building in Leicester described in www.naturalcapitalism.org/images/other/NCchapter5.pdf, or radiative cooling. Just a shallow roof pond, which stores up heat during the day and radiates it away to the night sky, and a ceiling fan can maintain ASHRAE comfort standards in August in Miami.
4. If still more cooling is needed, use alternative methods: absorption, which turns heat into coolth; desiccant, which turns heat into dryness; or evaporative, which cools dry air by evaporating water, and can deliver either moist or dry cool air into the space.[132]

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[129] Cler, G., Shepard, H., Gregerson, J., Houghton, D.J., Fryer, L., Elleson, J., Pattinson, B., Hawthorne, W., Webster, L., Stein, J., Davis, D. & Parsons, S. 1997: *Commercial Space Cooling and Air Handling Technology Atlas*, E SOURCE, Boulder CO, www.esource.com.

[130] Herman Miller's "Aeron" chair lets you sit not on insulating upholstery but on a ventilative net or mesh, keeping your backside 4–7 F˚ cooler. (In a nice example of design synergy, that "pellicle" also costs less than upholstery, so Herman Miller could afford to include extremely thorough and effective ergonomic adjustments to the chair without making it cost more.) Ceiling fans or other turbulent vertical air movement—not so strong that it would blow papers off your desk—can make you feel about 9 F˚ cooler. "Superwindows" or other ways to block radiant heat from windows can greatly increase comfort. Efficient office equipment similarly radiates less heat at you than inefficient equipment. Appropriate dress codes can greatly increase comfort, and can also reduce the hard-to-accommodate differences in comfort requirements between men in suits and women in skirts and blouses. Just these kinds of measures can together save 20–30% or more of the cooling energy, and can eliminate the need for air-conditioning in many climates—even quite humid ones.

[131] This means designing the building with the right shape, orientation, shading, surface properties, mass, insulation, landscaping, and ventilation design, and then not releasing unwanted heat indoors through inefficient lights and equipment. Many of these improvements can be retrofitted: for example, dark roofs can be changed to lighter colors specifically designed to bounce solar heat away without looking uncomfortably bright to your eye. Shading devices or vegetation can be added where they were originally lacking. Careful control of external and internal heat gains typically lets a refrigerative ton (3.518 thermal kilowatts) of cooling suffice not just for 250–400 square feet of officespace (a typical number in the U.S.), but for about 800–1,000 square feet in a retrofitted building and 1,200 (more in milder climates) in state-of-the-art new offices. As we'll see, that severalfold reduction in required cooling power can save a lot of capital cost.

[132] An experimental office retrofit for Pacific Gas and Electric Company designed a mainly indirect-evaporative cooling system with a whole-system design power of 0.14 kilowatts per ton—25 units of cooling per unit of electricity.

Combining these methods into hybrids, like an absorption chiller whose waste heat regenerates a desiccant to pre-dry the air, or a desiccant to make hot dry air plus direct/indirect evaporative cooling to convert it to cool dry air—can be especially effective. Various combinations of these nonrefrigerative techniques can meet cooling demand anywhere in the world, and can often be operated not by electricity but by waste heat available for free from some other device.

5. To conserve coolth once you've got it, use outgoing air to cool the incoming air through an air-to-air heat exchanger, or to dry the incoming air through a desiccant wheel or passive latent heat exchanger[133], or both.[134]
6. If you really want refrigerative cooling—though the previous methods can make this unnecessary, avoiding potential climatic harm by the refrigerant[135]—then make it extremely efficient. Techniques first proven in East Asia can make big central air-conditioning systems about three times more efficient than the norm, yet less costly to build and more effective and reliable.
7. The fancier systems (#4 or #6) may require controls, which can almost always be improved to save about 20–30% of the remaining energy. Control savings can even rise to 50% with careful training of building operators on simulators analogous to those used in flight training: big buildings are far too complicated for operators to understand intuitively without such help.
8. Peak electric loads and some energy can finally be saved by storing coolth in big tanks in the form of chilled water, ice, etc.

Many practitioners not versed in whole-system thinking pursue these steps in exactly the reverse order—worst buys first. In fact, many air-conditioning retrofitters pursue items 8, 7, and a small part of 6 without ever getting to the cheaper ones before that. Doing this gives up all the potential to reduce the need for costly cooling capacity in the first place. Such reversed priorities maximize expenditure, minimize savings, and destroy synergies between measures. But done in the right order, the savings can be phenomenal. Referring to examples described in this and the Buildings chapters of *Natural Capitalism* (www.natcap.org), imagine combining these steps:

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[133] This ingenious device, invented by Eng Lock Lee and concurrently by several U.S. heat-pipe companies for hot, humid climates, works like this. Precool the air coming into the building (you'll learn how in a moment). This will condense water out of the moist incoming air. Collect that condensate. Run it out of the building by gravity in a small pipe. Evaporate the water into the outgoing air, which, having already been dehumidified, is drier than the ambient air outside. This evaporatively cools the outgoing air nearly to the wetbulb ambient temperature. Capture that coolth with a heat exchanger and bring it back inside passively with a heat pipe. That is the source of cooling that you use to precool the incoming air.

[134] This can be done either passively or with a very small and efficient fan, and can readily be added to most conventional ventilation systems.

[135] Hydrocarbons, ammonia, or other relatively benign materials can be used with appropriate care, but halogenated refrigerants are a problem. Even once manufacturers complete the transition from outlawed ozone-destroying CFCs to interim HCFCs to chlorine-free HFCs, those HFCs will still be greenhouse gases thousands to tens of thousands of times more potent than CO_2—partly because once released, they can stay aloft for millennia.

- Expand the "comfort envelope" to save 20% of the cooling energy;
- Reduce the cooling requirement by 70% by improving the building and its lights, appliances, etc.—less than was saved in two Vancouver office buildings;
- Reduce energy per unit of cooling supplied by passive or alternative methods .
- If remaining refrigerative cooling is needed, save 50% of its energy (60–70% is available); and
- Save 20% from controls, normally near the low end of the range, and nothing from storage.

These savings multiply over each stage in the sequence to 98%. As usual with chains of successive savings, you needn't save much at *each* step in order to get the *total* savings to multiply to a very large level, simply because there are so many steps.

APPENDIX I:
SENSORS, METRICS, MONITORING, AND CONTROL SYSTEMS

Sensors and metrics for continuous improvement of energy efficiency

A key concept of resource efficiency in the field of industrial ecology is dematerialization of goods and services, often achieved by improved design that substitutes information for mass. In facilities management, information can be used to displace kilowatts and other forms of energy use. The most valuable forms of information in this effort are performance metrics, especially those that drive continuous improvement. This puts the focus on the type of question that is asked, for only that which is measured can be effectively managed.

Currently many manufacturers' internal energy efficiency analysis concentrates on the amount of energy used per unit of product. But such kWh/widget metrics are prone to distortion. Dividing metrics by product output is suboptimal or misleading due to variables including the effects of yield; product complexities; the stage of the product life cycle; myriad tools and processes; and other factors that affect energy usage more than do the efficiencies of utilities usage. Many factors can dramatically decrease a factory's yield, increasing its apparent energy intensity when in fact its technical efficiency has not changed. Consider these everyday analogies:

- If taxis charged only per km traveled, drivers' income would drastically decrease every time they got stuck in traffic—so they also charge for time.
- A hotel can have wonderfully efficient comfort and lighting systems, yet see its energy-per-guest index can soar with any sudden drop in guest arrivals (*e.g.*, Bangkok and Jakarta in their 1998 economic slumps).
- An award-winning hard-disk factory achieved 13.5 kWh/disk drive on existing models. On switching to Giant Magnetoresistive (GMR) technology, this metric shot up to an unimpressive 51 kWh/drive, almost four times worse, not because plant efficiency changed in any way, but only because ramp-up took longer than expected, many vendors' new products needed debugging, and other operational factors drastically decreased yield, so the plant produced far fewer drives than previously.

The remedy is to isolate energy-using subsystems, and apply *physical* efficiency metrics to each individually, so that every metric can be driven toward improvement. This is just like financial cost controls, where numerous line items are each controlled for variance to budget. In engineering as in finance, the key to success is detailed and exact record-keeping so all transactions can be tracked and people held accountable. No factory could run for long without detailed financial data, but many factories' utility plants, and probably all the Navy's ships, routinely run without basic metrics like kW/ton. Applying financial-like standards of accounting to facilities engineering data will yield rich returns.

Monitoring system performance (energy efficiency) is important because it allows comparison of the system to the best known technology in use at the time. The RMI Team typically checks the energy "performance" of a facility by comparing the system kWh as billed by the utility. However, it is crucial to realize what determines the system kWh:

$$kWh = hours \times load \div efficiency$$

Since the hours and load cannot be significantly affected because they are determined by production requirements, the only factor that can be affected by technical improvements is the system efficiency, and it is this factor that should be used to compare systems to the State of the Art.

The objective of heating and cooling system monitoring is to determine, via calculation, the useful thermal energy output of the system. In the U.S., the efficiency of the chilled water plant is usually expressed as kW/ton, which indicates kW of electrical energy consumed per 3.518 kW of *useful* thermal energy produced, allowing easy additive breakdown of the system efficiency into its components. This is inversely proportional to the coefficient of performance (COP), which is used both more commonly in Europe. To convert between kW/t and COP, divide 3.518 by either to get the other.

Sensor type and accuracy

Performance metrics should reflect utilities design, choice of equipment, climate responsive design, operations and maintenance, and the like. Accurate comparison between the actual operational efficiency of a system and the State of the Art requires accurate sensors. These include:

- power transducers to measure kW consumed by individual system components;
- high-accuracy temperature sensors on chilled and CW loops;
- dewpoint sensors to measure compressed-air dewpoint;
- airflow meters to measure cfm per kW of compressed air;
- airflow meters to measure cfm per kW of air handlers and recirculation fans;
- vortex flowmeters to measure cfm per kW for low and high vacuum;
- airflow meters to measure cfm per kW for exhaust systems;
- time-of-flight ultrasonic flowmeters to measure gpm/kW for Ultrapure Process Water plants; and
- drybulb and wetbulb psychrometers at cooling tower and MUAH inlet locations.

We believe that partly because a 10% flow error is about a 30% energy error, the cost of energy implies that the required minimum efficiency measurement accuracy should not be worse than ±5% of the actual conditions. In order to attain this goal, we look for sensors that provide ±1% accuracy (at worst) for each of the three measurements: ±1% of actual power is achievable with modern sensors, ±1% of water flow requires full-bore magnetic flow meters, and ±1% of temperature difference requires that each of the sensors have an accuracy of about ±0.05°F—achievable only with high-accuracy, super-stable thermistors. Such good sensors cost more, but save far more still.

Consider the example of chiller instrumentation. A 1,000-ton shoreside chiller uses ~$300,000/y worth of energy, and thus "eats itself" in financial terms in 1 year. Yet chiller performance generally isn't measured. When it is, measurement always shows sub-optimum performance. The sensors cost around $30,000, or roughly 10% of capital cost of the chiller; that seems high, but it's worth it. Businesspeople have a fiduciary responsibility to manage expenditures. A bank note sorting machine has zero error tolerance; why should chiller be held to a different standard? At high shipboard electricity costs, each of CG-59's *200*-ton chillers, if it runs full-time at (say) half-load, eats nearly $300,000 worth of electricity per year—equivalent to the capital cost of an equivalent civilian chiller about every five *months*.[136]

Facilities Management Control Systems

Many industrial FMCS installations have characteristics that make benchmarking difficult: many of the metrics discussed above are not represented; sensors are not correct or have failed; and it is hard to trend historical data on system performance automatically. The Navy would benefit from an efficiency page or similar display that could collect and trend each ship's systems performance metrics, indicators, and operational targets.

Thorough efficiency measurements should be made possible with an FMCS in order to benchmark one vessel against others, and because efficiency monitoring can lead to large energy savings as engineers recognize poor performance and pinpoint its causes. For example, at one client factory, the RMI Team's measurements revealed chiller condenser tube fouling whose correction represented potential annual savings exceeding $350,000. It would be surprising if ships were free of such currently invisible opportunities.

Disseminating Information

Information can be conveniently harnessed to displace horsepower with thorough and detailed analysis, presentation and dissemination. Performance metrics and other waste-reducing information such as payback criteria, AutoCAD drawings, schematics, and energy-efficient equipment specifications can be conveniently shared Navy-wide with graphical software, videos, Websites, time-series charts, and the like, from actual vessels and their specific systems, both in real-time and with archived historical data. Onboard and ashore, energy efficiency champions and managers can be networked virtually or in person to compare methods and collaborate, sharing and competing in best practices.

Key Value Metrics

What is the dollar value to the Navy of a unit of pressure, a watt of heat, or a one-percentage-point increase in system efficiency? Some firms have relabeled meters and gauges with such financial metrics. A few are used in this report. Dollar-equivalent units can also be incorporated into FMCS and similar systems software displays. Calculating and disseminating this type of information can help engineering crew and officers to understand (and therefore improve) the effect of their decisions on the Navy's bottom line.

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[136] 200 t × 1.2 kW/t (p. 58) × 8,766 h/y × 0.5 assumed LF (without part-load penalty) × $0.27/kWh (p. 19) / 0.96 assume electric distribution efficiency = $296,000/y. A 200-t civilian chiller costs of order $120,000.

APPENDIX J: POWER FACTOR AND PHASE UNBALANCE

The following is from the E SOURCE *Drivepower Atlas*, Chapter 13, "Power Quality."

Power quality is a gauge of how well electric power performs its intended task—rotating a motor, providing heat, energizing an integrated circuit—without causing undesirable side-effects. Measures of power quality can take many forms, including phase power factor, voltage unbalance, harmonics, transients, and outages.

Power factor

In utility circles, power factor is a familiar and long-lived concern. Power factor is an indicator of how much of a power system's capacity is available for productive work—making it an important and constant concern for utilities and large power users alike. Power factor and drivepower are inseparably linked: induction motors require reactive power to operate (to create magnetic fields in their windings) and this reactive power directly manifests itself in reduced power factor.

Industry is concerned about power factor primarily because of the penalties assessed on them (by utilities) if power factor in their facilities drops too low (usually less than 0.85 or 0.90). However, poor power factor in industrial plants can reduce in-plant power system capacity as easily as it does on a utility's grid. [The same is true aboard any ship.]

Power factor concerns are on different scales for utilities and power users: utilities must correct system power factor to efficiently generate and distribute quality power; power users should correct poor power factor to improve capacity and performance of their power systems, as well as to avoid utility power factor penalties.

Phase power factor correction

Lagging power factor can be increased by five methods:

- better-designed, energy efficient motors with high power factor;
- proper sizing of the motor, especially important for induction motors;
- capacitors: their leading power factor counterbalances the inductive load's lagging one;
- electronic controls;
- the use of synchronous motors, which can be designed to provide a leading power factor, adjustable as needed by varying the DC excitation current.

Power-factor correction can increase the capacity of power systems for expansion, as well as reduce utility penalties for poor power factor. Power factor is best corrected as close to the load as possible (load compensation) to gain the maximum benefit in increased wiring and transformer capacity. However, facility-wide power factor correction (bank compensation) may often be most cost-effective from a capital-cost perspective. Phase voltage unbalance is widespread and potentially very harmful to motor efficiency and longevity. Studies show that some 25% of facilities have over 1% voltage unbalance—a level that can cause significant harm to motor systems.

Power factor correction capacitors can interact with harmonics to create harmonic resonance—a dramatic and often damaging increase in the flow of harmonic currents within a plant. Any addition of such capacitors, as well as the addition of adjustable-speed drives or new transformers, should be preceded by a harmonics survey to assess the potential for resonance.

When motors are oversized and operate for extended periods at significantly less than full load, there are three significant operational penalties—reduced efficiency, reduced slip (important if the load is a cube-law type), and reduced power factor.

Reduced power factor is a common problem with underloaded motors. The average standard efficiency 100-hp motor loses about 10 percentage points in power factor from full-load to 50% load and almost 20 more points from 50–25% load. Poor motor power factor affects the user's bottom line in diverse ways because poorly loaded induction motors require a disproportionate percentage of reactive current, creating the "positive VARs" that cause poor power factor. Another benefit of correctly sized motors is that they improve system power factor and reduce the need for and cost of correcting poor power factor within the facility.

The Three Benefits of Power Factor Correction

Why should end users care about this arcane matter of power factor correction? There are three main reasons, listed in decreasing order of importance: to avoid power factor penalties, to free up transformer capacity, and to realize energy savings in transformers and wiring.

Avoided Utility Power Factor Penalties

Much of the cost of poor power factor falls on utilities. Consequently, many utilities assess penalties for poor power factor (typically below thresholds that range from 0.85–0.99) to prod their customers into taking corrective action. The penalties can be a fixed amount, but frequently are an added cost per kVA. In some cases, they can be quite substantial, often exceeding $100,000 annually in industrial facilities. For example, a beef packing plant in southwestern Kansas with a 12-MW load paid $43,200 per year in power factor penalties. [Naval vessels have no penalties—just wasted fuel and money.]

In many cases, the savings the end user can realize by avoiding utility power factor penalties are several times larger than the other benefits listed below. For a customer who is currently paying power factor penalties, the investment in power factor correction equipment will often pay for itself within several months just by eliminating the penalties.

Extra Transformer Capacity

Electric transformers are limited by the total amount of electric current they can provide at a particular voltage. Since improved power factor reduces the electrical current drawn by the facility, it frees some additional transformer capacity, thereby allowing for operation of additional equipment or future expansion, and possibly avoiding the cost of a new, larger replacement transformer down the road. If a facility is limited by transformer capacity, installing power factor correction equipment may be a very economically attractive alternative to a new transformer. If a facility has excess transformer capacity this benefit may be of negligible value.

Reduced Energy Losses

Resistive losses in power circuits are a function of the resistance of the system component (such as a copper wire) times the square of the current—so called I^2R losses. Since improved power factor results in reduced overall current levels, resistive losses in the transformer and copper wires feeding the facility's loads are also reduced. The potential savings in the transformer are far greater than those in the wires feeding the loads.

Some vendors claim that their products can offer energy savings of 10–25% due to power factor correction. In E SOURCE's view, such claims should be viewed with caution, as the energy savings from power factor correction in typical commercial and industrial facilities is less than 5% and typically at or below 1%.

Power Factor Correction Technologies

Poor power factor is usually corrected by installing some form of capacitance on the power system at the customer's service entrance, on a specific offending load, or at a strategic point on the grid that allows the utility to correct the power factor for a particular geographical area. Placed together in a circuit, capacitance and inductance work to counteract each other. But there is a hitch. Inductance varies greatly with the type, mix, and variation of loads. This makes it fans, mine machines, and pit equipment difficult to determine how much capacitance to install. Historically, capacitors of fixed capacity were installed and would be switched on manually when they were needed. In the past ten years, static, dynamic, and rotary power factor correction systems that provide varying levels of capacitance as conditions warrant have become available. Capacitors and other power factor correction technologies are available in nearly all voltage ratings found in facilities and on distribution systems (zero to 69 kV). Larger capacitors are also available for transmission systems. For many applications, particularly residential and commercial utility service, the fixed-bank capacitor will continue to be the most popular correction technology, due to its low cost and the abundance of inventory. For large industrial and grid-related utility applications, the static VAR system is likely to continue gaining in prominence due to its ability to produce large amounts of VARs at higher voltages and its low maintenance.

Voltage unbalance—and the excess heating it causes—pose a serious threat to the longevity of induction motors, seriously stressing their insulation and reducing useful life. Although most of the heating from voltage unbalance occurs in the rotor, it is also significant in the stator. In the phase with the highest current, the temperature rise of the stator coils will increase in percentage by roughly twice the square of the percentage voltage unbalance. Therefore a 3.5% unbalance, in the phase with the highest current, will increase the coil temperature by approximately 2 × (1 – 1.0352), or 14.3%. In the most common insulation system (Class F), in a normal fully loaded NEMA motor, the winding temperature during normal operation may already be, for example, as high as 40°C ambient plus a 115 C° rise, or 155°C. A 3.5% phase unbalance can further increase this by over 30 C°—enough, using the "halving per 10 C° rise" rule of thumb, to decrease expected insulation life by about 88%. A 5.4% unbalance, on the same terms, can cause a 40 C° extra rise, enough to slash insulation life by about 94%. Roughly consistent with this, an earlier assessment of fully loaded 1.15-service-factor Class F motors operating continuously at 40°C ambient temperature found that a 1% unbalance decreases expected insulation life by about an eighth; 3%, by nearly one-third; 3%, by over 90%. For fully loaded 1.0-service-factor motors, "a very serious loss of insulation life [by a third to nearly a half in fully loaded motors] can be expected even with voltage unbalance as low as two percent." The torque produced by an induction motor also declines as a worse-than-linear function of unbalance. Operation with unbalance greater than 5% is not recommended at all because of the steeply rising risk of failed windings. Derating, however, is a last resort and an admission of failure; if at all possible, the unbalance should be permanently corrected.

Reverse, or negative sequence, torques caused by voltage unbalance can have serious impact on both usable torque and motor heating. The negative sequence voltage induced in the rotor is at nearly twice the supply frequency, or about 200 times the frequency induced during normal balanced operation, so rotor heating is further enhanced by skin effect (more of the current flows near the surface of the conductors). For example, a 6.4% voltage unbalance in a typical induction motor can increase rotor losses by 50%, and an 8.85% unbalance by 85%: skin-effect heating increases the rotor resistance to about 3–8 times its value with normal positive-sequence current. The corresponding current unbalance, too, is normally 6–10 times as large as the unbalance in the applied voltage. And the entire motor power required to produce the negative torque is a loss that produces only heat.

APPENDIX K:
NAVSEA ENCON ENERGY SURVEY CHECKLIST

This checklist is posted at http://www.navsea.navy.mil/encon/checklist.htm.

ENERGY SURVEY CHECKLIST FOR IMPROVED FUEL ECONOMY

The purpose of this checklist is to provide a periodic qualitative self-assessment of ship progress in following good energy conserving practices.

The energy survey check list given below is generally applicable to all types of non-nuclear ships. It can be utilized by ship's command to identify the areas where a ship needs better energy conservation practices which will result in improved fuel economy. An area needing improvement is identified with a negative response.

1. Is energy conservation considered: a. When planning ship operations? b. When reviewing fuel and water consumption?

2. Is an energy efficient plant alignment consciously selected for each day's operations in accordance with the POG?

3. Are fuel consumption and economical speed curves maintained to reflect current performance?

4. Are reasonably current fuel consumption and economical speed curves posted on the bridge, engine room and fire room?

5. Are machinery alignment tables and fuel consumption tables available for development of fuel curve data?

6. Are fuel consumption and economical speed curves used for planning ship's daily operations?

7. Are a minimum number of evaporators operated when water supplies are adequate for mission to meet anticipated periods of peak demand?

8. Are the minimum number of ship service generators operated when the total electrical load is below 90 percent rated capacity of the generators in operation?

9. Are the minimum number of fire pumps used whenever possible? Are MD vice TD fire pumps operated when needed?

10. Is a machinery alignment status board conscientiously maintained?

11. Is permission obtained from EOOW for all equipment status changes?

12. Is EOSS validated, properly maintained, and routinely used?

13. Does ship attempt to operate at or near economical speed as much as possible during independent operations or long transits?

14. Does ship attempt to minimize speed change: whenever possible while maintaining station (frequency and magnitude)?

15. Does ship use acceleration/deceleration tables?

16. Are all gauges critical to plant performance properly calibrated?

17. Does ship have personnel trained and certified in gauge calibration?

18. Does ship have an on-condition hull and propeller maintenance program (*e.g.*, when inspection determines need based on significant fouling)?

19. Does engineering department have a valve maintenance program?

20. Is there a program to minimize fresh water usage such as daily announcements for water conservation?

21. Are low flow shower heads installed and in good operating condition?

22. Are faucets in heads spring loaded or metering and in good operating condition?

23. Does ship minimize fresh water leaks throughout ship (e.g;, laundry, showers, galley, etc.)?

24. Is there a program to promote electric load reduction?

25. Does ship secure electrical/electronic equipment when not required to meet ship operational requirements?

26. Are minimum number of A/C units operated when conditions permit?

27. Are A/C boundary doors in good condition and identified with posted signs?

28. Are light fixtures clean and well maintained?

29. Are lights turned off in unmanned spaces?

30. Is the insulation of piping in machinery spaces and throughout ship maintained in good condition?

31. Is crew responsive to maintenance requirements and the need to promptly correct deficiencies?

32. Are interdepartmental zone inspections conducted to uncover deficiencies such as leaks, missing insulation, etc., for tagging and corrective action?

33. Does ship adjust liquid load for slight trim by bow prior to getting underway and does engineering department assure maintenance of trim by the bow?

34. Does ship keep speed at a minimum while independent steaming overnight (6 knots or less)?

35. Is fuel and water usage: a. Documented for trend analysis? b. Published in Plan of the Day?

36. Does ship utilize shore services to: a. Minimize in port steaming? b. Minimize use of its distilling plant?

37. Are ship's personnel aware of the importance of energy conservation?

38. Does ship have an Energy Officer recognized as such with his responsibilities designated in writing?

APPENDIX L: TEAM BIOGRAPHIES AND RMI QUALIFICATIONS

Chris Lotspeich (Team Leader)
Independent consultant; Senior Associate, Rocky Mountain Institute, 1994–2001
PO Box 6203, Snowmass, Village Colorado 81615-6203
Tel: +1.970.948.3280 / Fax: + 1.970.927.4510
Internet: chrislot@rmi.org, chrislotspeich@hotmail.com

CHRIS LOTSPEICH, Senior Associate at Rocky Mountain Institute 1994–2001 and now an independent consultant, focused on the business community for RMI's Natural Capitalism Practice, and also worked on security, energy, and forestry issues. He earned two master's degrees from Yale—in public and private management from the School of Management, and in environmental studies from the School of Forestry and Environmental Studies. He earlier earned a BA in International Politics from Wesleyan University in Middletown, CT, and participated in the politics exchange program with Warwick University near Coventry, England in 1985–86. He was a teaching assistant for undergraduate courses on military and intelligence topics at both Wesleyan and Yale. He served as a wilderness emergency medical technician, firefighter, and hazardous materials technician on volunteer rescue services. He has been recycling coordinator for three Maine communities, a hazardous materials emergency response planner, and a mental health worker. He speaks French and is widely traveled.

Amory B. Lovins (Project Director)
CEO (Research)
1739 Snowmass Creek Road, Snowmass, Colorado 81654-9199
Tel: +1.970.927.3128 / Fax: + 1.970.927.4178
Internet: ablovins@rmi.org / www.rmi.org / www.natcap.org

AMORY LOVINS cofounded and directs research and finance at Rocky Mountain Institute. He also founded and chairs RMI's fourth for-profit spinoff, Hypercar, Inc. (www.hypercar.com), and cofounded its third, E SOURCE (www.esource.com), which was sold to the *Financial Times* group in 1999. At E SOURCE and its in-house predecessor, he led perhaps the world's deepest examination of advanced techniques for efficient use of electricity through integrative design—later expanded into a method for making big resource savings cost less than small or no savings ("tunneling through the cost barrier").

A consultant physicist educated at Harvard and Oxford, he has received an Oxford MA (by virtue of being a don), seven honorary doctorates, a MacArthur Fellowship, the Heinz, Lindbergh, World Technology, and Hero for the Planet Awards, the Happold Medal, and the Nissan, Mitchell, "Alternative Nobel," Shingo, and Onassis Prizes; held visiting academic chairs; briefed 14 heads of state; published 27 books and several hundred papers; and consulted for scores of major industries and governments worldwide.

The Wall Street Journal's Centennial Issue named him among 39 people in the world most likely to change the course of business in the 1990s; *Newsweek*, "one of the Western world's most influential energy thinkers"; and *Car* magazine, the 22nd most powerful person in the global automotive industry, due to his invention of the Hypercar℠ (www.rmi.org/sitepages/pid18.asp). His work focuses on transforming the car, real-estate, electricity, water, semiconductor, and several other sectors of the economy toward advanced resource productivity. His latest book is *Natural Capitalism: Creating the Next Industrial Revolution* (with Paul Hawken and L. Hunter Lovins, 1999, www.natcap.org). His next book will be *Small Is Profitable: The Hidden Economic Benefits of Making Electrical Resources the Right Size* (2001).

His national-security work includes devising the first logically consistent approach to nuclear nonproliferation (technical papers and two books); performing for DOD the definitive unclassified study of domestic energy vulnerability and resilience (*Brittle Power*); co-developing a "new security triad" comprising conflict prevention, conflict resolution, and nonprovocative defense; lecturing at NDU and NWC on least-cost security and on how new technologies will transform missions and force structures; leading for ADM Lopez the overhaul of NAVFAC's design process; supporting similar facilities efforts by USMC; several projects in collaboration with Third Fleet; and 1999–2001 service on a Defense Science Board panel on major fuel savings and their warfighting benefits in all land, sea, and air platforms.

Edwin B. "Ned" Orrett, PE
Owner and Principal
Pacific Technology Associates
210 Fourth ST, Suite B, Petaluma, CA 94952-4201
Tel 707.769.5335 / fax 707.769.5336
pacific@sonic.net

EDWIN "NED" ORRETT is Owner and Principal of Pacific Technology Associates, an engineering consulting firm based in Petaluma, CA Since 1989 Pacific Technology Associates has developed strategic applications of proven technologies that pay for themselves by using less water, energy, and material resources than conventional practice. Areas of emphasis include industrial water and wastewater, municipal water conservation planning, and environmental policy analysis. A Professional Civil Engineer (California Registration C26331)**,** Ned earned a B.S. in Civil Engineering from the University of California at Berkeley in 1971, and an M.S. in Ecology from the University of California at Davis in 1982. He is a member of the honorary engineering fraternities Chi Epsilon and Tau Beta Pi. From 1985–1988 he was Chief Executive Officer of Bio Energy, Inc., which developed a commercial process for recovering nutrients and energy from dairy manure using anaerobic digestion. From 1983–1985 he was Vice President for R&D (and earlier, Manager of Pennsylvania Operations) for National Conservation Corp. / REEP, Inc., where he evaluated energy conservation programs and directed a $1 million residential energy conservation project. From 1975–1978 Ned was a Civil Engineer at Stetson Engineers, Inc. of San Francisco, CA, focusing on a broad range of water-related issues. He has also been a planning consultant and recycling center. Mr. Orrett served as a Civil Engineer Corps Officer in the U.S. Navy from 1971–1975, and was honorably discharged with the final rank of Lieutenant. During his service he was consistently rated in the top one percent of his peers, and was recommended for early promotion. Assigned to a Construction Battalion (Seabees), he was responsible for all construction materials for a 1,000 man construction force at Diego Garcia in the Indian Ocean, and was Officer-in-Charge of all Battalion construction projects in Japan for nine month deployment comprising three sites and 75 men.

Ron Perkins
Chief Executive Officer
Supersymmetry USA, Inc.
P.O. Box 10, Plantersville, TX 77363-0010, USA
Tel/Fax: +1.800.755.2819 / Tel: +1.936.894.2819 / Fax: +1.936.894.3124
Internet: ronaldperkins@msn.com
RR 22154 West Magnolia Forest
Navasota, TX 77868

RON PERKINS has been involved in the design, construction and operation of commercial and light industrial facilities for the past 20 years. He has a BS in Industrial Arts from Sam Houston State University with a minor in Mathematics. He has worked for Todd Shipyards Corporation, Offshore Power Systems, Texas Instruments, Inc. and Compaq Computer Corporation. For eight years, ending in July 1990, Ron Perkins held the position of Facilities Resource Development Manager at Compaq Computer Corporation. He managed a 50-member design team of architects, engineers, contractors and scientists that designed over 2,000,000 square feet of state-of-the-art commercial office and factory space housing Compaq Computer Corporation's World Headquarters in Houston, Texas. Perkins formed a team that researched and applied energy efficient technology. As the result of the team's efforts, Compaq's new buildings cost less to build and were 30% more efficient. In 1991, Ron Perkins joined Eng Lock Lee and founded Supersymmetry USA, Inc. where he provides energy-efficient design consultation for owners, operators and designers of office buildings, manufacturing plants, semiconductor manufacturers, and utility companies. During the past year, Ron's work has also emphasized sustainable design in retail, industry and educational buildings.

James K. Rogers, PE
One Blacksmith Rd, Chelmsford, MA 01824
Tel: 978.256.1345 / Fax: 978.256.2226
Internet: jimrogers@mediaone.net

JAMES K. (JIM) ROGERS is a facilities consultant who specializes in identifying, quantifying and implementing all types of energy measures and facility upgrades for corporate, institutional, government and utility energy efficiency projects and programs. He has been involved in energy efficiency improvement programs for more than twenty years and has managed successful programs for reducing energy consumption and costs for a wide range of operations worldwide. Mr. Rogers has proven knowledge and experience with lighting, HVAC, process and most other energy systems. He was a Vice-president of EUA Cogenex, an energy service company engaged in energy management, conservation and cogeneration for industrial, commercial, and institutional clients nationwide. During his four years at Cogenex he managed energy efficiency projects that totaled 20 megawatts of reductions including the 1.4 megawatt energy efficiency upgrade project at the DOE's Headquarters in Washington. Prior to joining Cogenex, Mr. Rogers spent eight years as Corporate Manager of Energy and Environmental Affairs for Digital Equipment Corporation. In that role he coordinated energy management and environmental compliance activities at the company's major facilities worldwide. Before joining Digital, he spent thirteen years at Raytheon Company where he was Director of Environmental and Energy Conservation for ten years. Mr. Rogers holds a BS in Chemical Engineering from the University of Massachusetts and an MBA from Northeastern University. He is a member of the Association of Energy Engineers and the Association of Energy Service Professionals. He is a Certified Energy Manager, a Certified Lighting Efficiency Professional, a Certified Demand Side Management Professional and a Registered Professional Engineer in Massachusetts. Mr. Rogers has published numerous articles on energy management and environmental control, and lectures extensively at professional meetings and conferences.

RMI Team, 11–15 Dec 2000: (L to R) Ron Perkins, Jim Rogers, Chris Lotspeich.

RMI Team, 29 Jan–2 Feb 2001: (L to R) Jim Rogers, Chris Lotspeich, Ned Orrett.

About Rocky Mountain Institute (RMI)

Rocky Mountain Institute (**www.rmi.org**) is a 19-year-old, ~50-person, independent, entrepreneurial, nonprofit applied research center in Old Snowmass, Colorado. RMI fosters the efficient and restorative use of natural and human capital to create a secure, prosperous, and life-sustaining world. RMI has unique expertise in extremely efficient technologies and design integration for HVAC, lighting, fluid movement, drivesystems, electronics, and most other end-uses of electricity. RMI consults extensively on energy and resource efficiency and integrated, whole-systems engineering and design in industrial, architectural, institutional, automotive, water, energy, and other systems, for private- and public-sector clients, and draws upon a global network of leading technical specialist colleagues for this work. RMI's end-use, least-cost analytical approach seeks to identify the desired task or service to be accomplished by a technical system, and to consider whether more cost-effective and resource-efficient alternatives systems and strategies might be better. Unlike traditional component-based efficiency analyses, RMI's work emphasizes optimizing whole systems for multiple benefits. This often permits very large energy and resource savings to cost less than small or no savings. RMI has spun off four private companies, including E SOURCE (www.esource.com)—the world's most current and detailed source of energy efficiency information, embodied in the *Electronic Encyclopedia* library of technical atlases (to which NAVFAC subscribes)—and Hypercar Inc. (**www.hypercar.com)**, a developer of ultralight hybrid-electric vehicles. RMI's 1999 book *Natural Capitalism: Creating the Next Industrial Revolution* (**www.natcap.org**) offers numerous practical examples of profitable practices that protect the environment.

APPENDIX M: INFORMATION SOURCES AND BIBLIOGRAPHY

PRIMARY DATA AND INFORMATION SOURCES

Data and other information for this report were drawn from several sources, including the following main sources:

Shipboard observations. These included measurements made using both ship's instrumentation and RMI Team measurements of systems performance, as well as ship's logs and crew commentary and estimates. Due to the limited scope of this project and special circumstances of the kinds illustrated in App. A, measurements were mainly illustrative. The RMI Team would recommend a more complete measurement campaign on a suitable ship to fill data gaps and gain understanding of intended *vs*. actual component efficiency.

CG-59 *USS Princeton Engineering Department Handbook*. This little blue manual, prepared and maintained by CG-59's Engineering Department, was an invaluable technical reference.

CG-58 *USS Philippine Sea* load assessment. This is based on the Ingalls Test and Trials report of CG-58's "all-electric" conversion. Researchers measured loads that were 18.4% lower than calculated loads in cruise condition, and 29.3% in OCSOT (All Up Combat System) condition. (Note that the implication—oversized GTGs—will not only cost more, but also run less efficiently all the time because they're even more underloaded.)

CG-60 *USS Normandy* load assessment. This is based on a report of CG-60 energy loads, provided by NAVSEA. CG-60 has not yet undergone an all-electric conversion. The report presents calculated loads, obtained essentially by multiplying the CG-58 measured loads by an assumed across-the-board load factor of 0.9.

CG-68 *USS Anzio* load assessment. This is the Final Report for Class Services Engineering Task TI 2111-2-047, "Measurement of Equipment Loads," conducted under contract N00024-88-C-2111. Measured load data from select equipment under operation were compared to the existing load analysis and found to be roughly 60–70% of the loads originally predicted. The analysts therefore updated load factors to make the actual loads ~75–85% of those originally predicted. (The RMI team infers that this continuing discrepancy reinforces the case for further and more detailed load measurements until the causes of disparities are thoroughly understood and fed back into design methodology.) The study also indicated that for cruise and battle conditions, respective loads would increase by 70 kW and 140 kW on a 10°F day or by 50 kW and 120 kW on a 90°F day.

NAVSEA personnel: As noted in the acknowledgements, many NAVSEA staff were supportive of this research and provided invaluable assistance and information. NAVSEA websites were also useful (*e.g.*, www.navsea.navy.mil/encon/Frontpage.htm).

BIBLIOGRAPHY

In addition to the information sources cited above, the following is a partial bibliography of useful publications:

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APPENDIX N: GLOSSARY OF TERMS, ACRONYMS, AND ABBREVIATIONS

AHU: Air handler.

All-electric conversion: see Shipalt 588 all-electric conversion.

BBL: Barrel (*e.g.*, of oil, which contains 42 U.S. gallons).

BHP: Brake Horsepower; essentially, rated or nominal hp.

CCS: Central Control Station, a ship's engineering control center.

CFS: Cubic foot [or feet] per second.

CG-47: *Ticonderoga*-class Aegis cruiser.

CG-59: *USS Princeton*, a *Bunker Hill*-class Aegis cruiser (*Bunker Hill* class is a subset of the CG-47 *Ticonderoga* class).

CH: Chiller, a machine for making coolth.

CHW: Chilled water, produced by a chiller.

CHENG: Chief Engineer.

CIC: Combat Information Center, the ship's tactical control center.

CO: Commanding Officer.

COTS: Commercial off-the-shelf technology.

CT: Current transformer (a device placed around wires to measure their current flow).

CW: Condenser water, used to transport to a heat sink the heat extracted by a chiller.

DDI: Demand Display Indicator (*e.g.*, a control panel gauge or indicator).

Delta P (ΔP): Pressure drop or pressure difference (*e.g.*, across a coil or filter).

Delta T (ΔT): Temperature difference.

DESC: Defense Energy Supply Center.

DFM: Diesel Fuel Marine (similar to JP-5, but with slightly higher viscosity, lower energy content, and more combustion residues).

DSB: Defense Science Board. This RMI study's director, Dr. Amory Lovins, served on the DSB Task Force on Improving Fuel Efficiency of All Weapons Platforms, which in January 2001 submitted its report, *More Capable Warfighting Through Reduced Fuel Burden*.

EOSS: Engineering Operational Sequencing Systems; equivalent to (shipboard) engineering SOPs.

ENCON: NAVSEA Incentivized Energy Conservation Program (see www.navsea.navy.mil/encon/Frontpage.htm).

FCU: Fan Coil Units, which supply cooled or heated air to many of the ship's spaces.

FL: Fluorescent lamp or light bulb.

FLA: Full Load Amperes.

FPM: Feet per minute.

GAL or GL: U.S. gallon (equal to 3.785 liters).

GPD: [U.S.] gallon per day.

GTE: Gas Turbine Engine for propulsion of the ship. On CG-59 the GTEs are General Electric LM-2500 engines rated at 21,500 BHP each. See also GTM.

GTG: Gas Turbine Generators for electricity. On CG-59 the GTGs are Allison 501-K17 single shaft, axial flow, aircraft derivative gas turbine engines with a rated generation capacity of 2500 kW – 4000 amperes of ship's service 60 Hz electrical power.

GTM: Gas Turbine Module, which provides a controlled environment for the gas turbine engine (GTE) along with connections for controls and support systems for the GTE. See also GTE.

H: hour(s).

HVAC: Heating, Ventilation, and Air Conditioning.

HW: Hot water (potable).

HX: Heat exchanger.

Hz: Hertz (cycles per second, measuring the frequency of alternating current).

JP-5: Jet fuel (essentially a form of kerosene) used in such aircraft as the SH-60 Seahawk helicopters.

kW: Kilowatt, or 1,000 watts, *e.g.*, of electric power (a measure of how quickly electric energy is delivered).

kWh: Kilowatt-hour, a measure of the amount of electricity generated or consumed.

LED: Light-Emitting Diode, a durable energy-efficient lighting technology.

LF: Load factor (or duty factor), the average inferred, assumed, or observed operational utilization of a device or system relative to its rated capacity and full-time usage (8,766 h/y).

LPAC: Low-Pressure Air Compressor.

MIL-SPEC / MIL-STD: Military specifications and -standards, designed to ensure equipment is functional and durable in a wide range of operating and environmental conditions required or assumed to be required for reliable military use.

MW: Megawatt, or 1,000,000 watts, or 1,000 kW, of electric power or generating capacity.

MWh: Megawatt-hour, a measure of electricity generated or consumed; 1,000 kWh.

NAVSEA: Naval Sea Systems Command.

Negawatt(-hour): A saved or conserved watt(-hour). For example, if a system's electrical load is reduced by a kilowatt through end-use efficiency measures, those savings could be considered as equivalent to one thousand negawatts.

NSWCCD: Naval Surface Warfare Center, Carderock Division; Naval engineering and design center, based in Carderock, VA and Philadelphia, PA. Part of NAVSEA.

PMS: Planned Maintenance System, similar to a preventative maintenance schedule.

PSIG: Pounds per Square Inch Gauge; *i.e.*, pressure as read by a meter or indicator.

PW: Potable (drinking-quality) water.

RO: Reverse osmosis, a technology for purifying water (*e.g.*, to make seawater into potable water).

s: Second [of time].

SECAP: Ship Energy Conservation Assistance Program; self-help software to assist personnel in developing underway fuel consumption curves. Available at www.navsea.navy.mil/encon/SECAPDescription.htm or www.seaworthysys.com.

SECAT: NAVSEA Ship Energy Conservation Assist Team, which trains shipboard personnel in energy conservation techniques.

Shipalt 588 all-electric conversion: A common abbreviation of the Shipalt CG47-00588 program to replace steam production and distribution—used primarily for PW production and heating—with RO PW production and electric resistance coil PW heating.

SOP: Standard Operating Procedure.

SW: Seawater.

SWS: Seawater Service.

t: Ton [of refrigeration, equal to 12,000 BTU/h or 3.518 thermal kW of cooling; so called because it is the latent heat required to melt one short ton of ice in 24 hours].

TSP: Total static pressure.

TQEM: Total quality environmental management.

VSD: Variable-Speed Drive, a device that allows drivepower system output to match the load served in real-time. Strictly speaking, it may be electrical or mechanical. Also called Adjustable-Speed Drive (ASD). The most common kind, often used synonymously, is the electronic Variable-Frequency Drive (VFD), also called a Variable-Frequency Inverter (VFI), which supplies electronically synthesized variable-frequency power to a motor.

w.g.: Water gauge, the standard measure of air pressure or water head used by most U.S. mechanical engineers; 1 inch w.g. = 250 Pascals.

XO: Executive Officer (second in command).

y: Year. The average year contains 8,766.3 hours.