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West Bethesda, MD 20817-5700

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Machinery Engineering Directorate
Technical Report

21st Century HVAC System for Future Naval Surface Combatants – Concept Development Report

by

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Energy Conversion Branch, Code 985

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Thermal Management Solutions, Inc.

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14. ABSTRACT
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15. SUBJECT TERMS
HVAC, Air Conditioning. VAV, Automation, Intermediate Temperature Heat Sink, Cooling Coil

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EXECUTIVE SUMMARY

Thermal Management is a critical requirement for today's and future warships. On DDG 91, approximately 25 percent of the ship's thermal load is removed via the Heating, Ventilation and Air Conditioning (HVAC) system. Projected Next Navy's thermal loads are 2-5 times those of today's ships. It is expected that much of the increased load will be rejected via the HVAC system or directly to the chilled water system. The current HVAC architecture will have major ship design implications in weight, volume, energy usage, acquisition costs and overall operational maintainability. Advancements in the technology and the architecture of the HVAC system of future surface combatants are needed.

In this report, a revolutionary new architecture, the 21st Century HVAC system, is described for future shipboard HVAC systems which will enable flexible thermal management at the ship level while providing a comfortable ship environment, rapid and redundant damage control capability, energy efficiency, reduced size and weight, and reduced manning. Four major thrusts are pursued: Automation; Integration with Damage Control and Firefighting Systems and other System Level Networks; Design Paradigm Shifts; and Advanced Component Development. Some concepts enable other concepts and/or greatly enhance the benefits of other technologies. Bundling of these technologies/paradigms together into a cluster is an integral part of this architecture.

- Automation - Air flow to compartments are currently based on a static (worst case) condition for the compartment. Varying airflow in response to actual thermal load, manning and/or equipment status is needed to reduce manning and improve energy efficiency. The automation entity adopts modern building's HVAC features like direct digital control and variable air volume systems. Automation efforts of foreign Navies are shown within. As these systems become more intelligent, ship level diversion of cooling to vital needs can be accomplished. Non-vital needs will be served to ensure crew and equipment safety, not necessarily comfort when cooling is diverted. Diversion of cooling may be able to mitigate some of the new cooling growth especially if some of the future loads are sporadic, not continuous.
- Integration with Damage Control and Firefighting Systems and other System Level Networks – Sharing information from other shipboard networks is essential. The Damage Control Community has several initiatives to locate personnel within the ship. With this knowledge, replenishment air and lighting can be controlled at the ship level, thus reducing the total HVAC load. Integration with the firefighting system could be utilized to de-smoke damaged compartments. Information of overall heat-generating equipment status could be exploited to improve the overall effectiveness of the HVAC system.
- Design Paradigm Shifts – The current HVAC system requirements and paradigms were challenged and new paradigms generated. New paradigms suitable for the advanced technology components and overall HVAC system were generated. On the airside, velocity limitations within ductwork and various HVAC components were revised upward. Water flow normalized to cooling load was revised downward while the distribution supply temperature was also reduced. Adopting these new paradigms will have a dramatic impact on the size and weight of air/water distribution system while minimizing the impact of fan/air conditioning plant electrical requirement by adopting advanced technologies.

- Advanced Component Development – Today's HVAC component technology is dated. Next generation fan, cooling coil and ducting offered the most benefits at the ship level. Coatings could be applied to ductwork to reduce frictional losses. Improved fan aerodynamic performance and utilization of permanent magnet motor at higher and varying speeds provides dramatic size, weight and power reductions. Cooling Coils with enhanced surfaces and increased airside velocities would also provide these dramatic benefits.

A spiral development process is envisioned for the deployment of the21st Century HVAC system. Technologies and paradigms were selected for one of three Flights based on overall risk factors. Performance and physical attributes goals were developed at the component level for each Flight. Low to moderate risk technologies were applied as a 21st Century Flight 1 system, which can be available (designed, developed and demonstrated/qualified) within 5-7 years for implementation into new ship designs. The Flight 2 system addresses moderate to high risk technologies with significant benefits and will require 10-12 years to fully demonstrate before implementation into new ship designs. The Flight 3 system addresses high risk technologies with aggressive goal and revolutionary benefits with longer term implementation schedules.

Simplified macro level HVAC system models (ship, system and compartment level) were developed and applied to estimate the benefits of the 21st Century HVAC System architecture using six legacy design sub-systems of DDG 91 as a baseline. The model results were a 30-50% reduction in weight and volume, regardless of system complexity or function. With a DDG 91 HVAC ventilation and chilled water distribution system weighting approximately 350,000 and 150,000 pounds respectively, these reductions are significant. The benefits of the automation and variable air volume technology were calculated using a simplified Total Ship HVAC Model. The ability to provide cooling and replenishment air appropriate to each space in a dynamic, rather than static, mode was shown to lower the total ship HVAC cooling load by approximately 10 percent at the design condition.

To simulate a Future Surface Combatant, the addition of a portion of the projected thermal load increase was applied to the DDG 91 design. Results from the Total Ship HVAC Model showed dramatic increases in the electrical power requirements of the cooling system, not only that originating from the AC plants but also the fans. Cooling equipment using the HVAC system is inefficient. The chilled water cools the air to 50-55°F which mixes with compartment air at 80°F before entering the equipment. So, the equipment is being cooled by essentially 80°F air. For this reason, an intermediate sink water system for cooling equipment, directly or indirectly in a closed system, was introduced. Implementation of this concept would dramatically lower the power required for Future Combatants with large, new thermal loads by approximated one half of that using Today's HVAC systems.

The 21st Century Surface Ship HVAC Systems Architecture bundles technology advances at the ship level, systems level, and component level. The synergistic potential benefit of these bundles greatly exceeds the benefits of the individual technology. Innovative technology can be applied to develop a new series of HVAC components linked with the new design paradigms resulting in significant weight, space and power reductions for Future U.S. Navy surface ships. It is recommended that development of the 21st Century HVAC System be initiated.

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Abbreviations

AC or A/C	Air Conditioning
AMR	Auxiliary Machinery Room
ASHRAE	American Society of Heating, Refrigeration and Air Conditioning Engineers
BACNET	Building Automation and Control Networks
BOCC	Building Operations Control Center
Btu	British Thermal Unit
CBR	Chemical, Biological, Radiological
C&D	Command & Display
CEC	Cooperative Engagement Capability
CFM	Cubic Feet per Minute
CO_2	Carbon Dioxide
CPS	Collective Protection System
DDG 51	Arleigh Burke Class Destroyer
DDG 1000	Zumwalt Class Destroyer
DDX	Future Surface Combatant
EM	Electromagnetic
EMI	Electromagnetic Interference
ER	Engine Room
ES	Exhaust System
^oF	Degree Fahrenheit
FCA	Fan Coil Assembly
FCU	Fan Coil Unit
FR	Frame
ft	Feet
ft^2	Square Feet
ft^3	Cubic Feet
gal/min	Gallons Per Minute
hp	Horsepower
hr	Hour
HVAC	Heating, Ventilating and Air Conditioning
in	Inch
in^2	Square Inch
k	Unit Prefix (1,000 times unit)
kw	Kilowatt
lbf	Pound Force
lbf /in^2	Pound per Square Inch
lbm	Pound Mass
LCS	Littoral Combat Ship
LP	Low Pressure
LPD 17	San Antonio Class Amphibious Ship
M	Unit Prefix (1,000,000 times unit)
min	Minute
NSWCCD	Naval Surface Warfare Center, Carderock Division

P	Pressure
PWM	Pulse Width Modulation
PZ	Pressure Zone
RAST	Recovery Assistant Secure and Traverse System
rev/min	Revolutions per minute
RS	Recirculation System
sec	Second
SLQ 32	Surface Electronic Warfare System
SNAME	Society of Naval Architects and Marine Engineers
SPY	Surface Radar
SQS 53	Surface Sonar
SS	Supply System
ton	Ton of refrigeration or cooling (12,000 Btu/hr)
TPE	Transfer, Pumpout and Evacuation
VAV	Variable Air Volume
VSD	Variable Speed Drive
W	Damage Control Classification W (William)
(W)	Damage Control Classification Circle W (Circle William)
Z	Damage Control Classification Z (Zebra)
(Z)	Damage Control Classification Circle Z (Circle Zebra)
%	Percent
"H_20	Inches of Water (Pressure)
Δ	Difference

Abstract

A two-phase effort was conducted to define the architecture of a 21st Century Heating Ventilation and Air Conditioning (HVAC) System for Future Surface Combatants and then, in phase 2, to quantify the benefits of that concept. The 21st Century HVAC System is a complete, revolutionary new approach to shipboard HVAC. It features automation at the ship level, variable air volume flow, integration with the damage control and firefighting systems and other ship networks. A complete new catalog of advanced HVAC system components (fans, cooling coils, ductwork) make up this new architecture. New design philosophies/paradigms such as lower chilled water temperatures and flow rates, increased cooling coil face velocities and increased duct velocities are adopted within designs. Simplified macro level HVAC system models were developed and applied in phase 2 to estimate the benefits of the 21st Century HVAC System architecture using six legacy design sub-systems of DDG 91 as a baseline. The model results were a 30-50% reduction in weight and volume, regardless of system complexity or function. The benefits of the automation and variable air volume technology were calculated using a simplified Total Ship HVAC Model. The ability to provide cooling and replenishment air appropriate to each space in a dynamic, rather than static, mode was shown to lower the total ship HVAC cooling load. An intermediate heat sink water system for cooling equipment, directly or indirectly in a closed system, is proposed as an innovative method to dramatically lower the power required for Future Combatants with large, new thermal loads.

Administrative Information

This report describes the work performed by the Energy Conversion Branch (Code 985) of the Machinery Engineering Directorate, at the Naval Surface Warfare Center, Carderock Division (NSWCCD). The work was funded by the Office of Naval Research, ONR 331, Mark S. Spector, PhD.

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The authors also wish to thank Johnson Controls, Inc. for permission to reprint several of their illustrations as shown in Figure 7-15.

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Introduction

Background

The Heating, Ventilating and Air Conditioning (HVAC) System of a combatant ship is a vital part of the overall ship thermal management system. In an earlier study of the thermal load of DDG 51 Class ships, it was determined that about 25% of the total ship waste heat dissipation was via the HVAC system as shown in Figure 1.

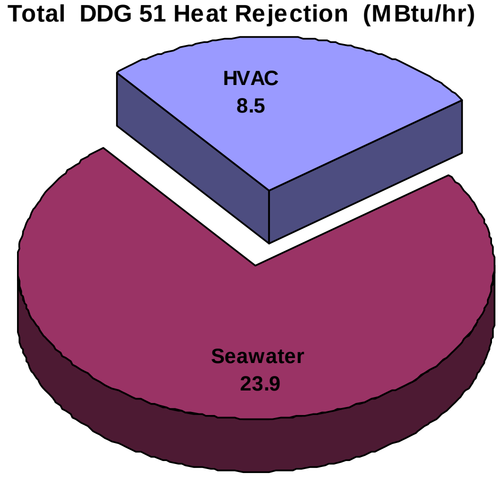

Figure 1 – DDG 51 Class Total Heat Rejection

A fraction (10-15%) of the HVAC system heat dissipation is by direct ventilation to air, the remainder is transferred to the ship's chilled water system and then transferred to the sea via the AC plants. As shown by Figure 2, 77% of the chilled water load originates within the HVAC System.

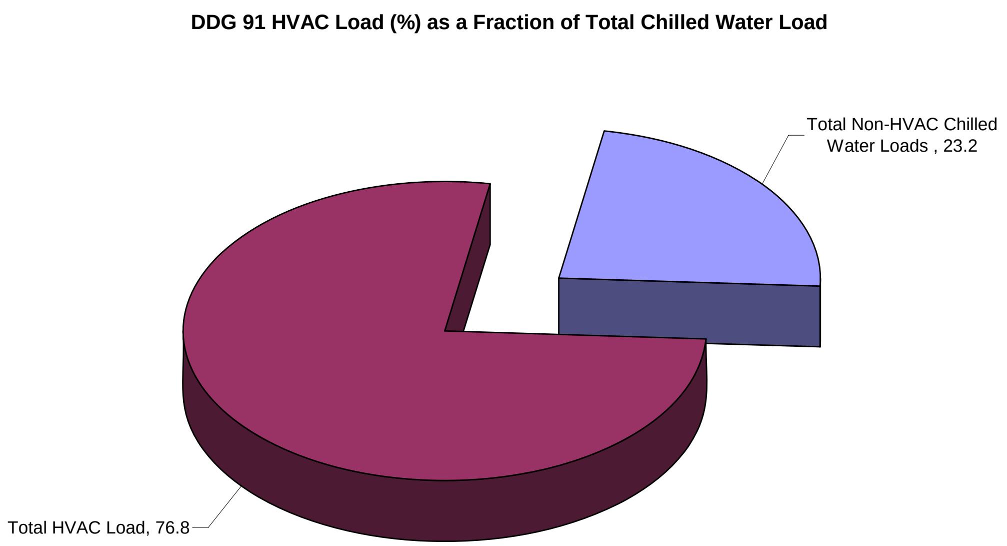

Figure 2 - HVAC Load as a Fraction of Total Chilled Water Load

The HVAC System load consists of the elements shown in Figure 3. Note that a significant portion of the HVAC load is equipment cooling.

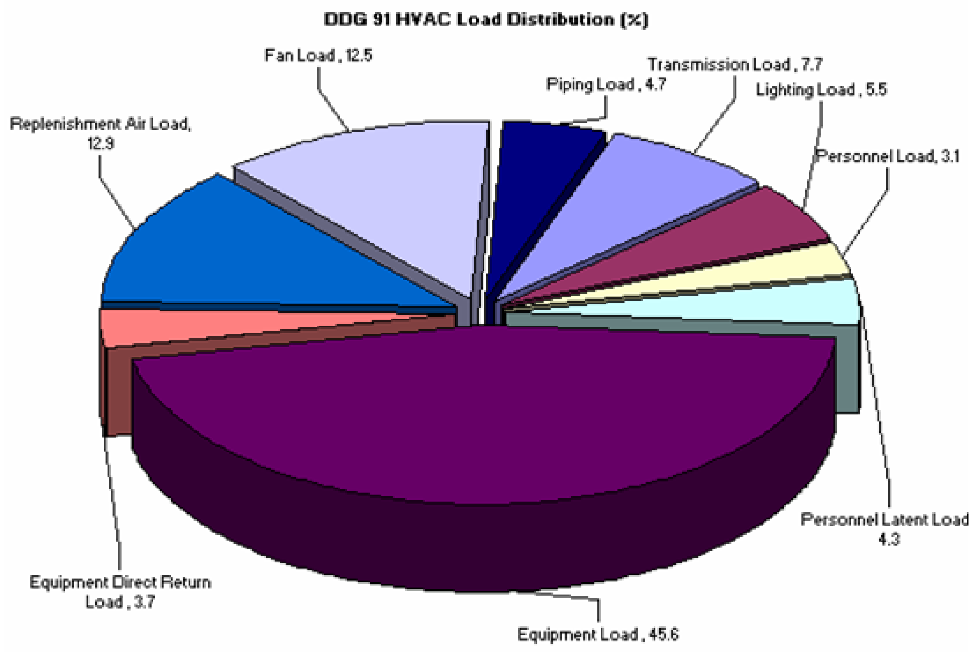

Figure 3 – HVAC Load Distribution

The shipboard HVAC system has changed little over the past 60 years. The design/architecture reflects the thinking of that era – no need for energy conservation, abundant manning – and the naval requirements of that era emphasizing simplicity and dependability. The technology is pre-computer and the electronic revolution that accompanied that technology. There is no automation, no capability for automation, the system air flows are constant, simple thermostats are used to control cooling to the compartment(s), the catalog of mandatory components is dated, and the process for designing and making changes to the HVAC system is institutionalized and thus difficult to change.

Shipboard HVAC System Basics

Shipboard HVAC is a large, complex, vital system which impacts every ship compartment. The HVAC system is divided into zones and integrated with the ship chilled water system. Below is an illustration of the zones on a DDG 51 Class ship, Figure 4.

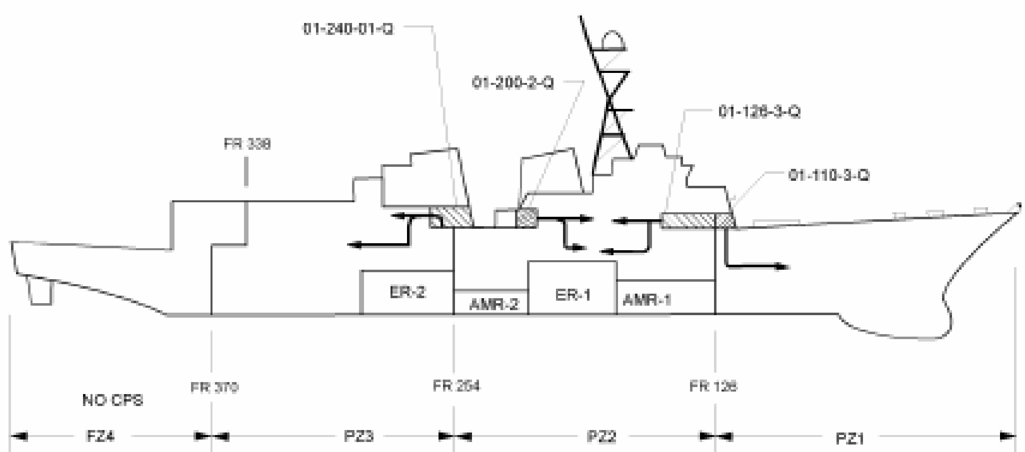

Figure 4 – HVAC System Zonal Structure

In the simplest terms, there are three types of HVAC systems on a ship – supply, exhaust and recirculation. Compartments are either air conditioned or ventilated. In compartments that are ventilated, there is a supply system which brings air to the compartment, and an exhaust system which returns the air to the weather. In air conditioned compartments, the air is recirculated, a portion of the compartment air is exhausted to the weather and a makeup portion of replenishment (weather) air added. In general, air enters the ship via fan rooms where heaters, cooling coils and fans may also be located. On Collective Protective system (CPS) ships, the entering air is filtered through banks of Chemical, Biological and Radiological (CBR) filters. In total protection CPS, designated areas are pressurized relative to the atmosphere. In limited protection CPS systems, the compartments are not pressurized relative to the weather air. Fans, cooling coils, heaters, reheaters are located throughout the ship as necessary. An illustration of a shipboard HVAC system is shown in Figure 5.

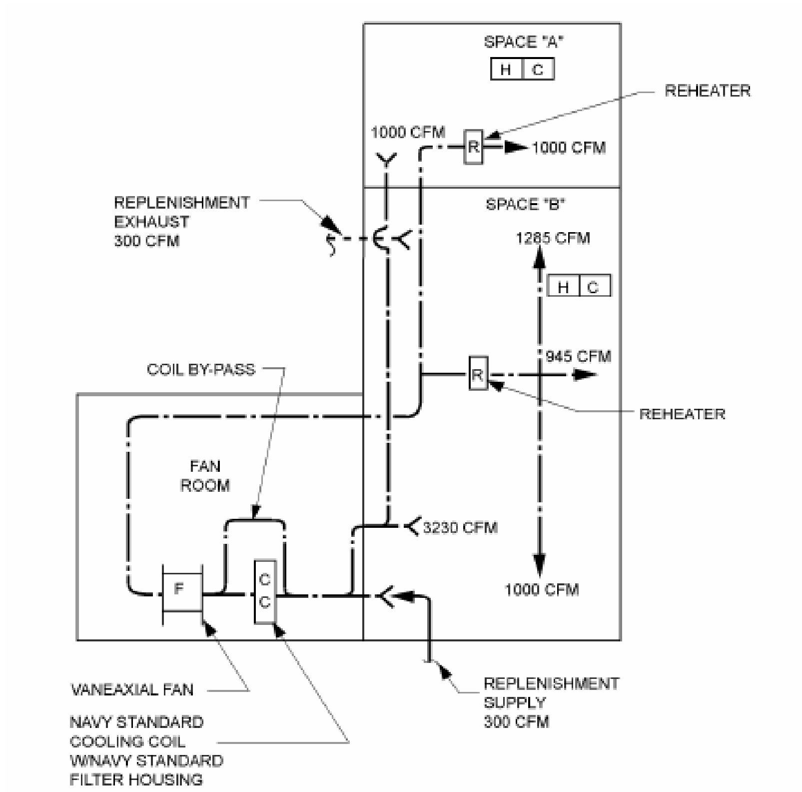

Figure 5 – Typical HVAC Shipboard Recirculation System

As shown above, this recirculation system serves two spaces controlled by two thermostats. If either thermostat calls for cooling, both spaces receive cool air. If either space is cooled below the lower thermostat setting, the reheater for that space is activated. Thus, the air for that space can be cooled and then heated, simultaneously, an obvious inefficiency.

Future Surface Combatant Thermal Loads

Future surface combatant thermal loads are projected to be an order of magnitude higher than that of today's modern surface combatant. It is expected that much of the increased load will be rejected via the HVAC system or directly to the chilled water system. Little of the increased load is expected to be rejected directly to the air or seawater. As shown in Figure 6, there has been a noticeable shift in originally installed

AC plant capacity on Next Navy ships when compared to legacy ships.

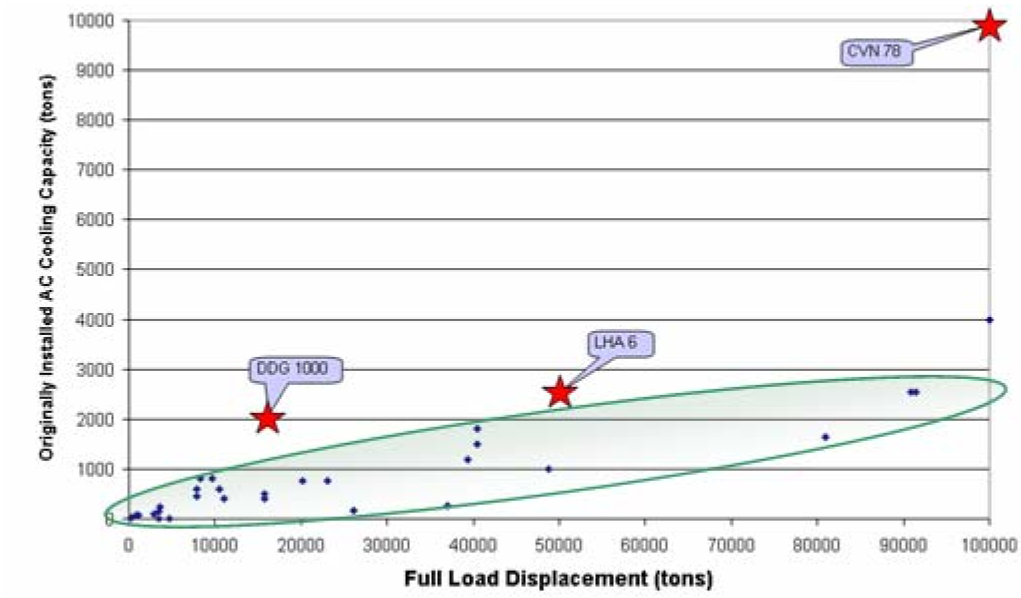

Figure 6 – Originally Installed AC Capacity per Ship's Full Load Displacement

This enormous projected increase in thermal loads has implications far beyond the obvious impact on ship system size, weight, power and cost due to the large number of additional AC plants that will be needed. Supporting ship systems including pumping, distribution piping, electrical power and the associated maintenance and operator efforts will be even more onerous.

Further, increased operations in the littoral are resulting in the upward revision of the traditional design weather and seawater temperatures which will have a major impact on the HVAC system load.

Finally, enhanced force protection doctrine is requiring additional CPS capability which causes an increase in thermal loads of Current Navy ships as well as Next Navy ships in the acquisition cycle.

Thus, there are ample opportunities and needs for advancements in the technology and the architecture of the HVAC system of future surface combatants. By adopting a new vision and shedding the paradigms of the past, a revolutionary new architecture can be defined which will improve the efficiency of the overall system, provide the flexibility to manage and allocate cooling to priority spaces/equipment, while maintaining crew comfort and minimizing the weight and volume of the HVAC system. It is conceivable that the new architecture can offset the expected gain in HVAC system weight and space that will result from the projected growth in thermal loads as new weapons and sensors are fielded in the future.

21st Century HVAC System Vision

The 21st Century HVAC System vision begins with a thoroughly automated system, fed by sensor data from every compartment, controlled by a digital control system. The system air flows will vary to meet the instantaneous demand of the compartment and if necessary to reduce those air flows in the event cooling is needed at a more vital location. Further, the air flow can be substantially reduced to unoccupied or under-occupied compartments. The premise guiding this vision is that flexible automation at the ship level will permit diversion of cooling to vital needs. That is, the designer need not account for all systems being on all the time – some future loads will be sporadic, not continuous. Non-vital needs will be served to ensure crew and equipment safety, not necessarily comfort when cooling is diverted. This philosophical shift will likely result in fewer AC plants than traditional design doctrine.

The HVAC Automation System will be integrated with a future ship-wide damage control and firefighting system to share sensor data to detect fires and other damage and to isolate those compartments from the remainder of the ship. The system will also be used to de-smoke damaged compartments. Integration with other ship systems and networks is also desirable. In commercial buildings, both security and lighting are controlled by a centralized building management system.

A second thrust for the 21st Century HVAC System is the development of a new catalog of advanced components – fans, cooling coils, ducting, filters, etc. Using advanced technology, the new components will be remarkably smaller and lighter and more efficient than those used today.

Finally, the current HVAC System requirements and paradigms will be challenged and modernized. Velocity limitations, flow requirements and distribution system traditions will be reviewed and new paradigms suitable for future combatants and the advanced technology components and systems generated. These design paradigm shifts will minimize the impact of future thermal load increases on ship distribution systems, but, may impact the size, weight and power requirements of the AC plants.

It should be noted that some European Navies are already fielding similar new systems in both existing ships and new construction ships to reduce manning and improve energy efficiency.

Objective

The objective of the effort reported herein is to develop a revolutionary new architecture for shipboard HVAC systems which will enable flexible thermal management at the ship level while providing a safe comfortable ship environment, rapid and redundant damage control capability, energy efficiency, reduced size and weight, and reduced manning.

Scope

This report documents an 18 month effort, conducted in two phases, to define the architecture and then quantify the advantages of a 21st Century HVAC System. In this limited effort, not all aspects of the HVAC system are addressed. For instance, the heating requirement is not addressed since the future challenge is clearly cooling.

Approach

The program approach consisted of five major distinct elements as follows:

- Identify and investigate modern HVAC system automation technology and assess the potential for application to naval combatants.
- Review current shipboard HVAC system design requirements and challenge the applicability of those requirements to future naval combatants.
- Assess the impact of revising current ship HVAC system design paradigms. Use Total Ship (the System of Systems) perspective.

- Identify modern commercial HVAC system component technology for application to naval combatants. Assess the impact of bundling a series of component advancements, since changes at the component level alone usually offers few advantages.
- Develop a simplified (macro-level) HVAC model capable of assessing the relative benefits of bundled system concepts. Apply the model to quantify the advantages of the 21st Century HVAC System technologies.

Since previous efforts in total ship thermal management concepts have concentrated on DDG 51 Class ships, the DDG 91 HVAC system design was selected as the benchmark for comparison. An extensive database of the thermal loads and components for that ship is available.

21st Century HVAC System Architecture

HVAC Automation

Commercial building automation is a mature technology. The American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE) have established standards and protocols for Building Automation and Control Networks (BACNET). Johnson Controls, Inc. assists in the management and operations of the Pentagon Building Operation Control Center (BOCC) and hosted a visit by Navy representatives. The BOCC is reportedly the largest building automation system in the world and was being modernized as part of the overall Pentagon modernization effort. As such, there was a mixture of state of the art technology and older technology in use and available for observation.

Graphics were furnished by Johnson Controls to illustrate their technology and the variety of methods available for display of the information gathered by the sensors and the control system status and actions underway. Figure 7 is an overall view of the Pentagon and the actual graphic used at the BOCC. From this view, a section (a "wedge" in the BOCC terminology) can be selected and further detailed views seen.

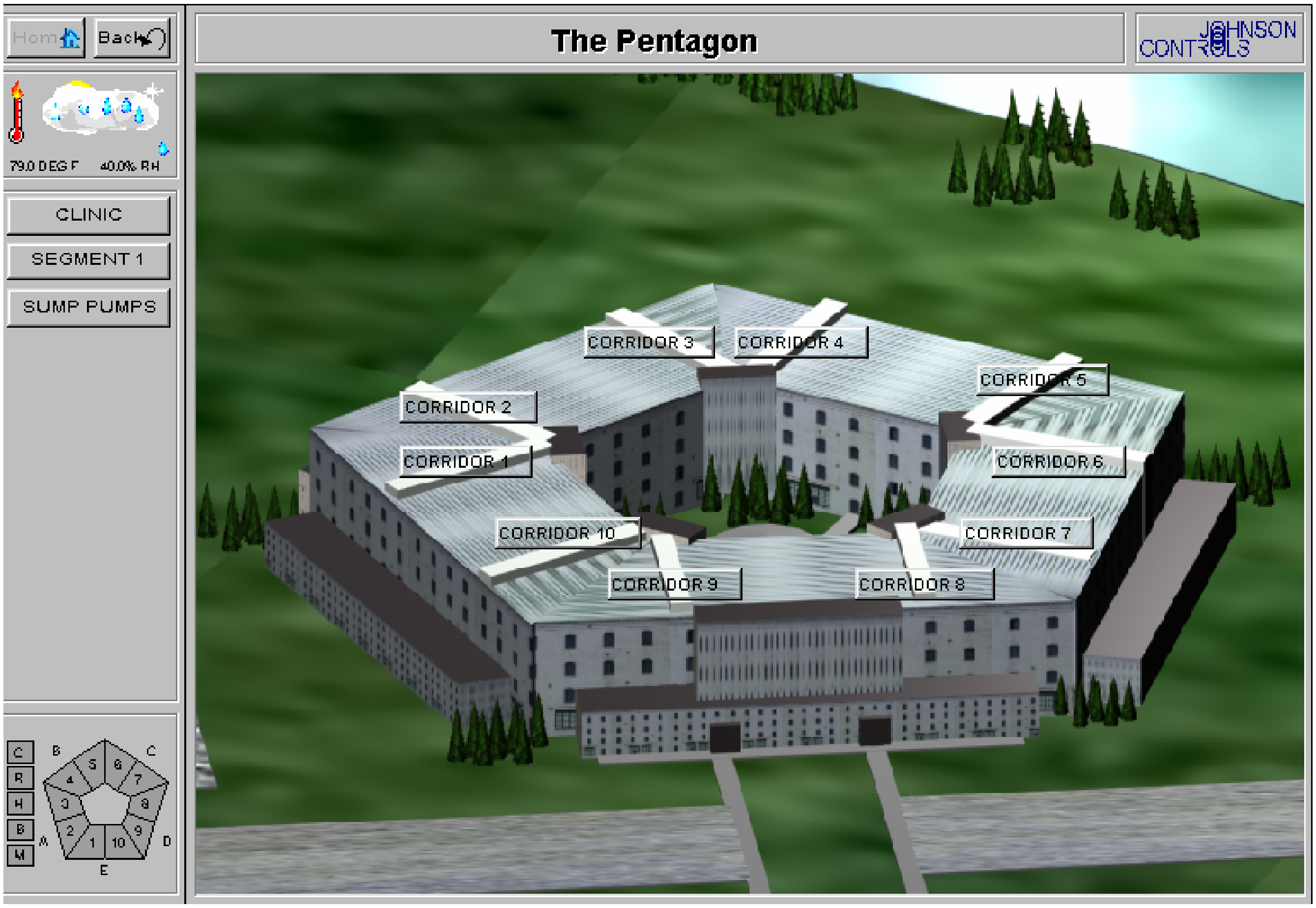

Figure 7 – Pentagon BOCC Graphic

A presentation from Johnson Controls Holding- Italy SrL, on their HVAC system automation efforts with the Italian Navy and other European Navies was reviewed. It is apparent that the Europeans are quite far advanced in bringing commercial building HVAC automation technology to their Navies. A "typical" layout of the control system is shown in Figure 8. A master supervisory system is at the top level, receiving information and issuing control decisions to the next lower level of workstations. These workstations receive information and issue control direction to local control units. The local controls may be for a fan, an AC plant, dampers, etc. The information gathered at the local control is passed up the network and is available at all of the workstations. Sensors (both compartment and equipment data) are connected to a local control unit. The workstations can autonomously control without repeated direction from the supervisory level, such as in a damage control scenario where communication between the systems may be impaired. The principal function of the supervisory system is display of the total ship status and to issue a major change in control strategy such as a decision to divert cooling to only vital needs or to seal off an area because of fire/smoke and to exhaust the smoke to the weather.

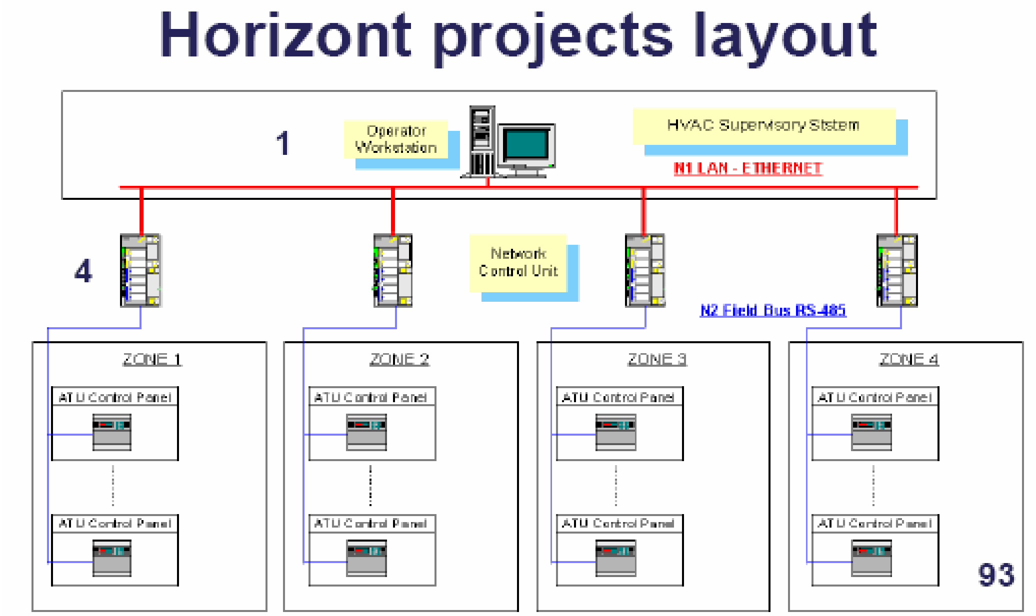

Figure 8 – European Navy HVAC Automation System Architecture

Johnson Controls shared the following slides (the slides are in Italian) illustrating the HVAC system automation used on the European Frigate Horizon, Figure 9.

Figure 9 – European Frigate

At the Total Ship level, Figure 10, a platform level or segment may be selected.

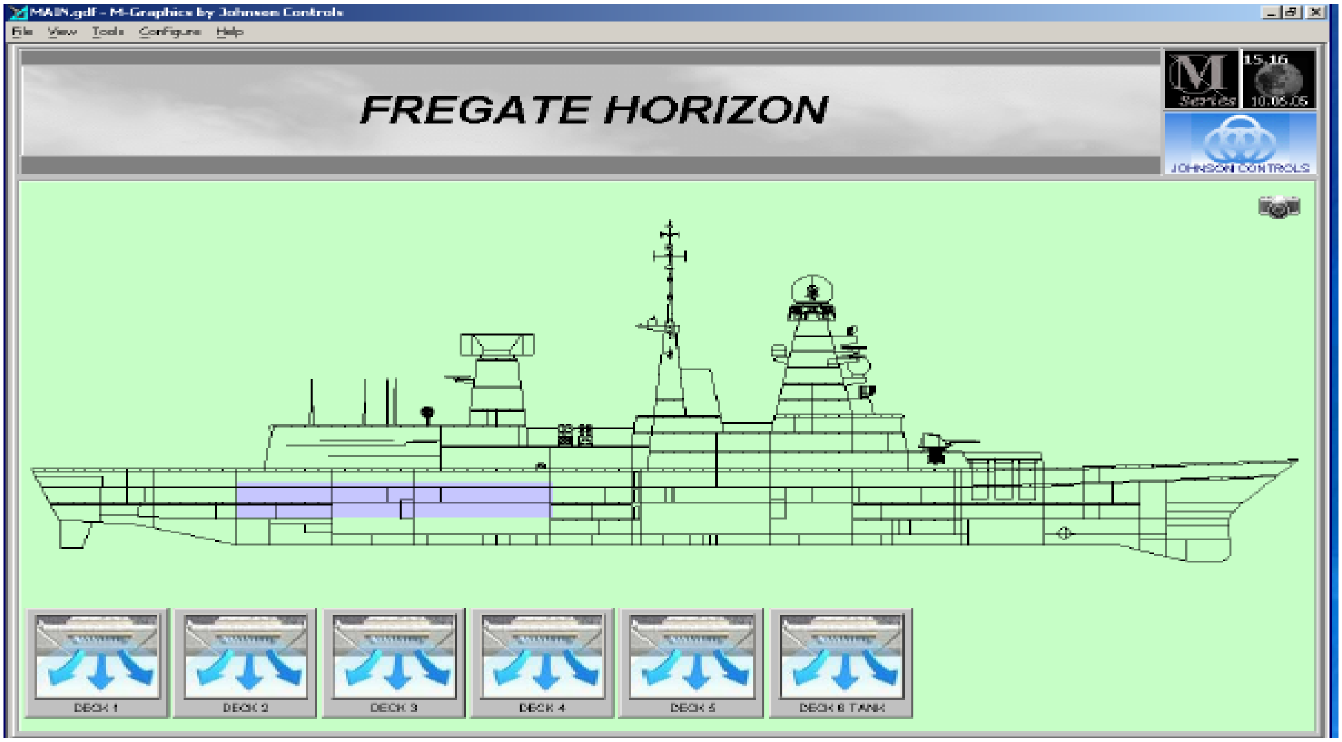

Figure 10 – Total Ship HVAC Automation View

Selecting a platform level view, Figure 11, then allows selection of a zone, Figure 12.

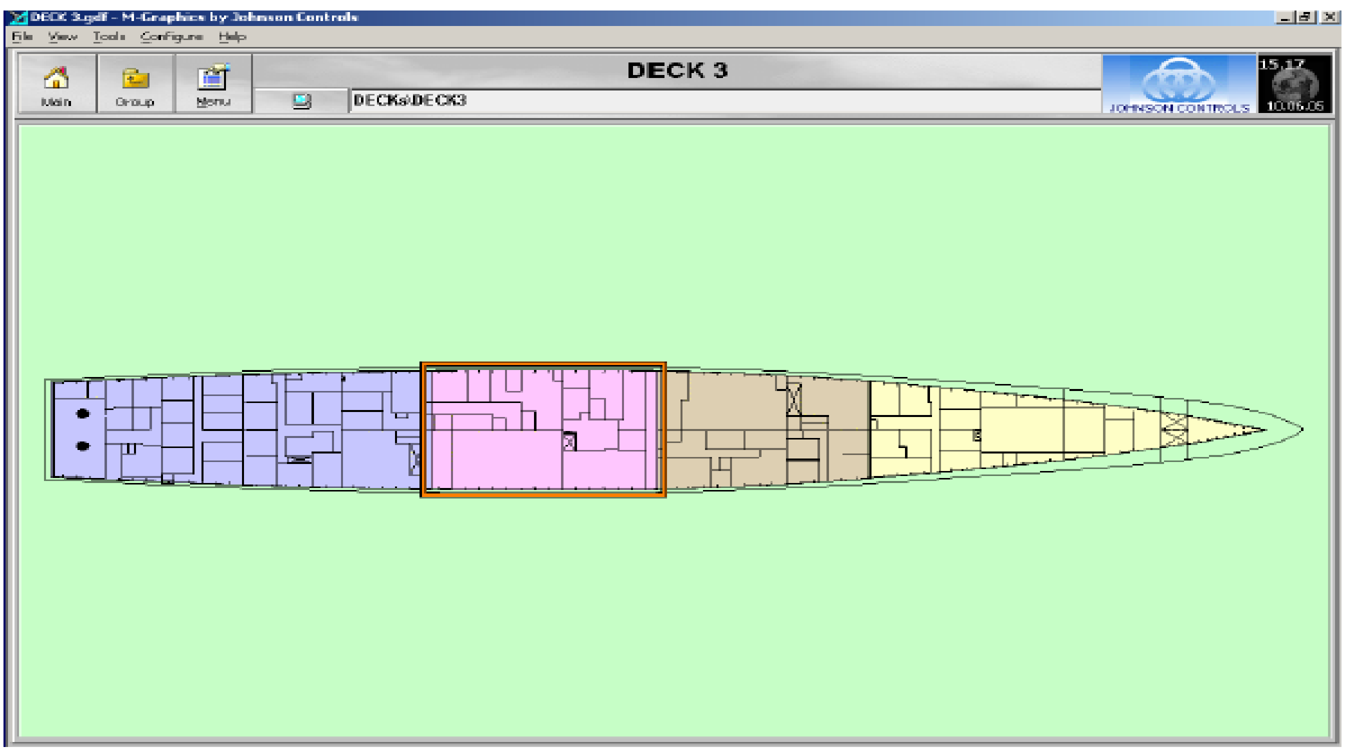

Figure 11 – Platform Level View

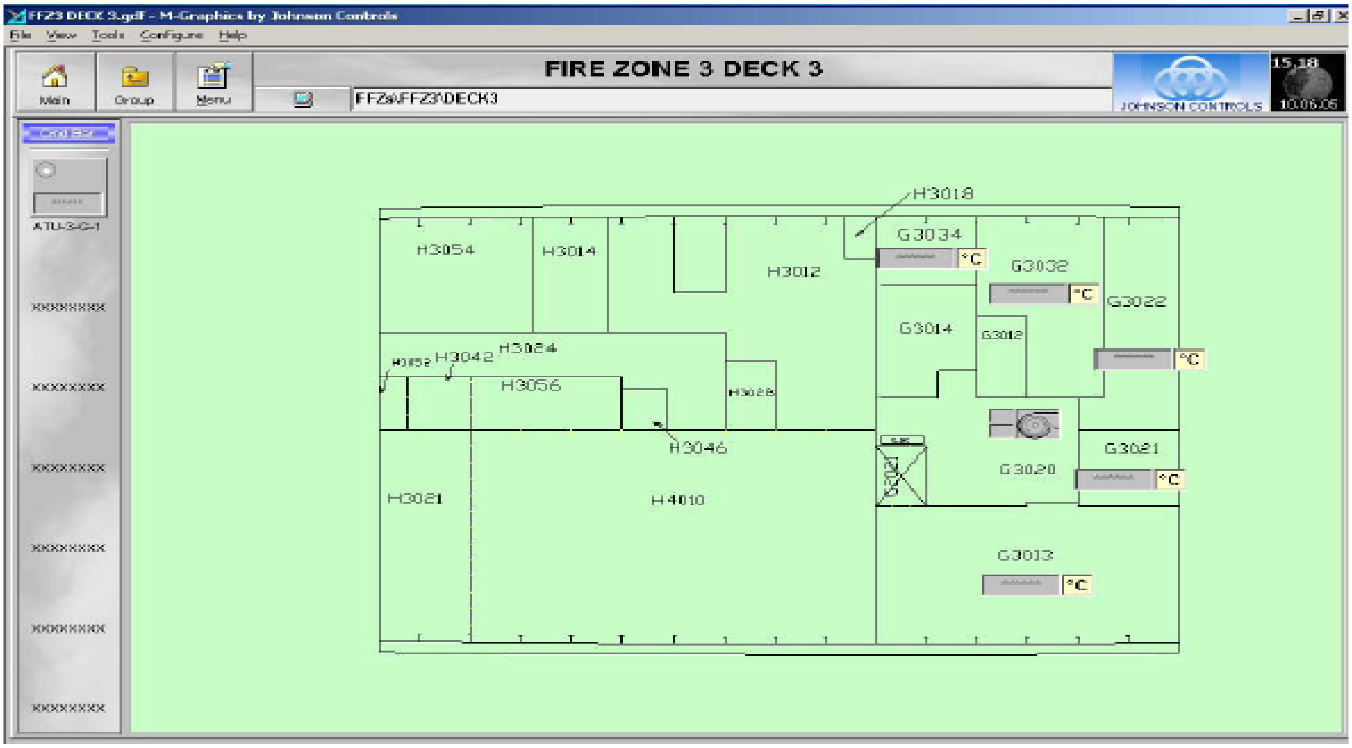

Figure 12 – Zone View

The zone distribution system can then be displayed as shown in Figure 13.

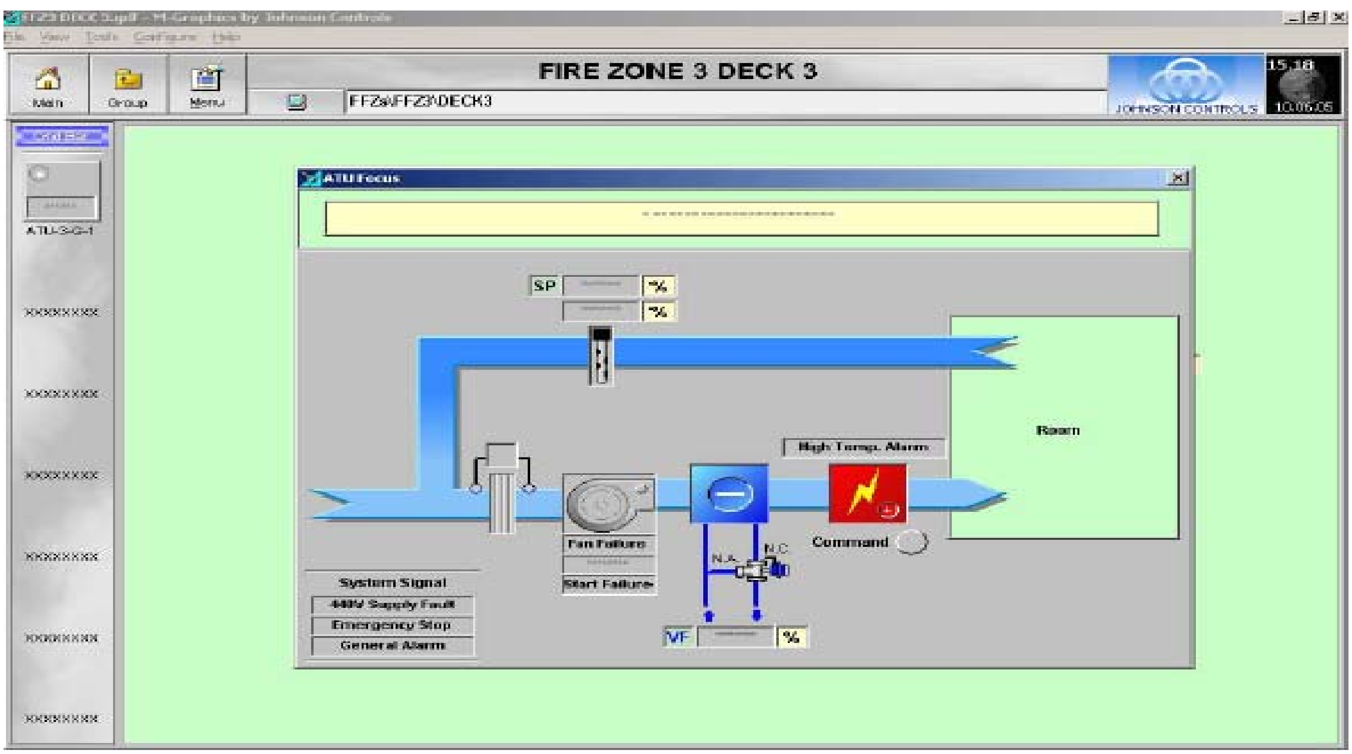

Figure 13 – Zone Distribution System

A complex zone distribution system is displayed in Figure14.

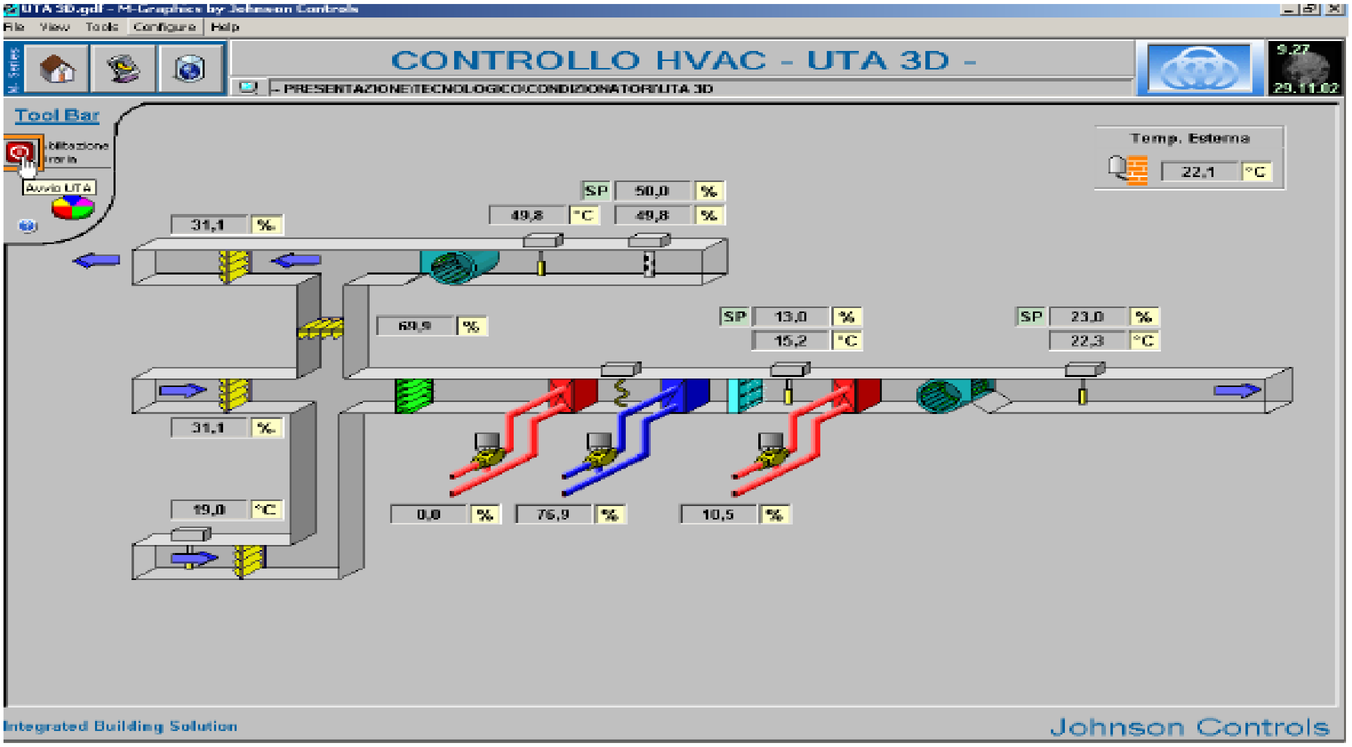

Figure 14 – Complex Zone Distribution System

Other portions of the distribution system can also be displayed as shown by Figure 15.

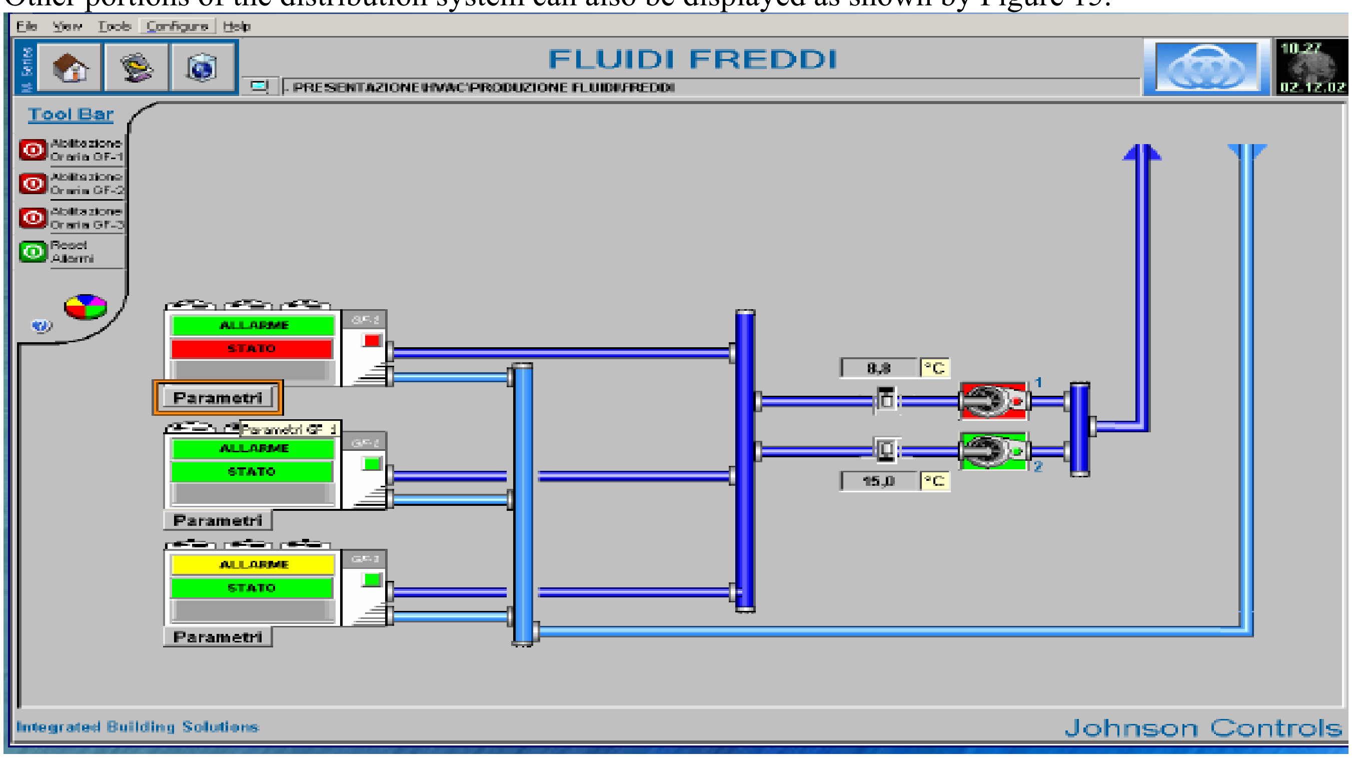

Figure 15 – Zone Distribution System Details

In the discussions with York Navy Systems of Johnson Controls, the benefits foreseen by the Europeans in adopting this technology were given as reduced manning and reduced energy consumption. Since the application is relatively new, validated savings have not, as yet, been documented. The ability to divert cooling to vital needs, as envisioned by the 21st Century HVAC System architecture, is not a feature of the Horizon system. As a frigate, the ship does not have the large thermal loads envisioned for US Navy future surface combatants.

Based on the literature review and the discussions with the manufacturers, it is clear that the adoption of commercial building automation architecture is feasible and desirable. The technology exists, the ability to produce easily understood software exists, the ability to process large amounts of sensor data and provide precise control under a large number of control strategies exists. The ability of the particular hardware items to withstand the shipboard environment (temperature, humidity, salt laden atmosphere, motion and shock/vibration) will need to be developed and demonstrated. The Europeans have reportedly shock tested some elements of the system, but the translation of the shock data to terms and values used by the US Navy is not clear and clarifications are being sought.

Variable Air Volume (VAV) / Demand Controlled Ventilation

VAV systems are used universally in commercial buildings. The power savings and the increased comfort are the principal benefits. VAV systems modulate airflow based on need while ensuring minimum personnel requirement are satisfied. VAV is essential to the 21st Century HVAC System concept. Commercially, VAV is usually achieved by varying diffuser positions and fan speed. Although bypass dampers are occasionally used and pre-rotation vanes (similar to those that control the capacity of centrifugal compressor AC plants) are sometimes used. Fan speed is varied usually using a Pulse Width Modulation (PWM) variable speed drive, although some applications use variable pitch pulley belt drives. Variable speed PWM drives have been proposed for naval ship application for the past 30 years. The high cost, size, weight and poor Electromagnetic Interference (EMI) performance of traditional PWM drives have prevented application. The development of a cost effective, lightweight, small and low EMI emission variable speed drive is the principal roadblock to deployment of this key element of the 21st Century HVAC System.

In addition to varying air flow into spaces based on cooling load, in newer commercial applications the flow is further restricted based on occupancy. Carbon Dioxide (CO_2) sensors are used as a measure of occupancy; fewer personnel will produce less CO_2. In the 21st Century HVAC System, this concept could provide further benefits since personnel are currently accounted for in the cooling load analysis roughly three times – on duty, in berthing and while eating or relaxing.

HVAC Automation System Integration with Other Shipboard Networks

The integration of an HVAC automation system with other ship automation systems also appears feasible and low risk. For instance, future ships will likely have a robust suite of sensors providing data for automated condition assessment (and perhaps prognostication). The data can be shared over a network and serve as the inputs for the HVAC automation system.

Integration with damage control and firefighting systems, once those systems are automated, also appears to be feasible and low risk. Currently, all compartments receive a damage control classification and the HVAC system design requirements address the classification via zones and systems serving those zones are connected to the appropriate vital/non-vital power sources. While there is linkage, there is no integration. New ship designs are integrating some firefighting capabilities with the HVAC system –

- LPD 17 has a “Smoke Ejection System” using the HVAC system
- DDG 1000 has a planned “Smoke Removal System” using the HVAC system

Earlier experimental work on these system designs has been reported[1].

In addition, new ships are being built with a heat detector in every compartment which could be used by the HVAC system as input for temperature control in that compartment. Alternatively, the temperature sensor for the compartment HVAC system could function as the fire detection element.

A Personnel Identification Tag is being developed by the Damage Control Community to assist in locating personnel in an emergency. This system requires a wireless network for best functionality. In the HVAC automation scheme, personnel location would be used to determine space occupancy and thus cooling and replenishment air needs.

The existing linkage in current ship designs between the HVAC system and the damage control/firefighting systems could readily be integrated, seamlessly, similar to the way it is currently done in commercial buildings.

Document Review / Requirements Challenge

Major ship HVAC specific design documents, as shown in Appendix A, were reviewed to produce the following general conclusions –

- The legacy HVAC system design is based on two conditions – weather air (used for replenishment) of 90°F dry bulb and 81°F wet bulb for the cooling design and 10°F dry bulb for the heating design (from Section 070 of the General Specifications). Some of the current ship designs, such as LCS and DDG 1000 are based on commercial Society of Naval Architects and Marine Engineers (SNAME) criteria (95°F dry bulb, 82°F wet bulb) or tropical conditions (105°F dry bulb, 87°F wet bulb). The selection of components is based on these temperatures. Consideration of other conditions is relatively limited. These conditions determine the replenishment air load that is a significant portion of the overall cooling load.
- Air flow to compartments is based on the rate of change for the compartment (a 15 minute rate of change means the entire compartment volume is changed every 15 minutes). The rate of change is dependent on the type of activity in the compartment, manning for the compartment and equipment type/function/criticality of the compartment. Once established at the design condition, the air flow is fixed and does not vary in response to actual thermal load or manning or equipment status. Air flows are balanced during construction by using orifices in the ductwork. There are no procedures or hardware to vary the air flow into a compartment.
- The component requirements are quite detailed for interface and selection purposes. Thus, components are standardized resulting in limited choices and manufacturers.
- The design paradigms that will limit future choices and thus require re-consideration are –

    - 4500 ft/min (round) duct velocity – review of this limitation is critical in order to reduce duct sizes, as envisioned by the 21st Century HVAC System, and the components that are often in the ductwork (fans, cooling coils, heaters). The limitation is believed to be based on a combination of acceptable friction loss and acceptable noise generation. Advanced technology fans, designed from the beginning to produce larger pressure differentials, could support the additional friction loss. Alternatively, smooth “frictionless” ducting, featuring hard surface coatings, could reduce the additional frictional loss. While higher duct velocities have traditionally resulted in higher noise generation, the relationship is not necessarily absolute. The smooth ducting could also be “quiet” ducting. In addition, methods to treat the ductwork with either sound absorbing materials and/or in the distribution flow path design exist.

- 500-600 ft/min (limit depends on coil size) cooling coil face velocity – in order to reduce cooling coil sizes, the existing face velocity limitation must be reconsidered. The limitation is based on preventing cooling coil condensation re-entrainment in the coil leaving air. At least one manufacturer offers a surface coating for the coil fins to promote rapid drainage of the condensate from the coil surface. Incorporation of separation devices either immediately downstream of the coil or in the coil surface could prevent moisture carryover. These additional items in the flow path will necessarily increase the frictional loss. But, as with the duct velocity increase discussed above, this could be accommodated with higher pressure differential fans.

- 3.6 gal/min per ton of cooling chilled water flow through the cooling coils is used in the cooling coil specifications and by default the chilled water flow through the AC plants. The genesis of this particular paradigm is unknown, presumably it was representative of the state of the art when established. Commercial buildings are using 1.5 – 2.0 gal/min per ton of cooling today. The Seawolf HVAC system design used 2.16 gal/min per ton of cooling. Reducing the chilled water flow rate (by 50%) has an enormous impact on the chilled water distribution system – the size and weight of pumps, piping and valves can be substantially reduced. The cooling coil leaving chilled water temperature will be higher, for the same cooling load. Lower chilled water flow rates offers the opportunity to further reduce the size of the cooling coil, provided the increased coil face velocity discussed above can be accommodated and the heat transfer coefficient on the air side can be increased by other techniques (such as more fins/ lower fin spacing or entirely different surfaces).

- 44°F chilled water leaving temperature is specified for the AC plants. The HVAC design uses 45°F as the cooling coil supply temperature. The one degree delta is an allowance for heating of the water as it travels through the distribution system to the coil, but the piping and components are well insulated. This supply temperature specification probably represented the lowest achievable temperature without risking freezing using the AC plant heat transfer technology when it was established. The AC plant evaporating temperature on many of the older design AC plants was 33-35°F, occasionally up to 37-38°F. Today’s modern design naval AC plants, with state of the art evaporator heat transfer surfaces, have evaporating temperatures of 40°F and above. Lowering the chilled water supply temperature to 42°F or 40°F is certainly possible. This reduction would provide more cooling capacity for a given coil size, implying that smaller and lighter weight cooling coils could be developed, subject again to overcoming the coil face velocity limitations discussed above. Combined (bundled) with the lower flow rate per ton of cooling discussed immediately above, there is opportunity to dramatically reduce the cooling coil sizes and reduce the weight of the cooling coils.

Advanced HVAC Component Technology

Commercial HVAC component technology was reviewed to identify existing state-of-the art designs that could potentially be applied to naval combatants. Fan, cooling coil and ducting technologies were examined.

The Navy currently uses three families of fans – vaneaxial, centrifugal and tubeaxial. The naval tubeaxial applications are quite limited and were not further explored. The Navy standard centrifugal fans are primarily used in exhaust systems. Futhermore, centrifugal fans, not part of the standard family, are used in Fan Coil Units (FCU) and Fan Coil Assemblies (FCA). These units designed to cool a compartment where the cooling coil, fan, filter, heater and controls are packaged into an assembly, usually mounted in the overhead. These units are low horsepower and were not examined in any significant detail. The focus of the fan exploration was vaneaxial fans.

Navy Standard Vaneaxial Fans

The Navy standard vaneaxial fan design is shown in Figure 16. There are 23 vaneaxial fan sizes each for a specific flow rate and pressure difference.

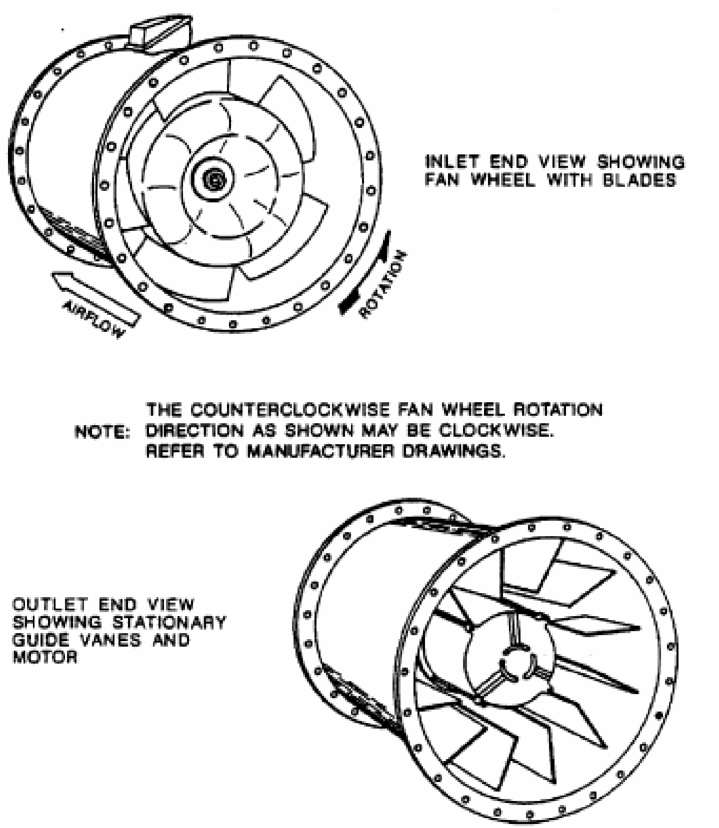

Figure 16 – Navy Standard Vaneaxial Fan

The fans are direct driven by synchronous (constant speed) motors. The family of fans was designed in the 1940s and the technology has not been refreshed in the intervening 60 years. At one time there were two competitive manufacturers – Buffalo Forge and Joy – but the industry has consolidated and realigned several times. Today, New Philadelphia Fan is the primary manufacturer, producing the Joy fan design. In the 1980s, the advent of CPS created a need for higher pressure fans to overcome the pressure drop of the CPS filters and provide sufficient static pressure to create the design zone pressure of 2 inches of water (relative to the weather). The design point pressure for the CPS fans is 14 inches of water. The first generation CPS fans, shown by Figure 17, were simply slightly modified versions of the standard vaneaxial fans – a family of 5 sizes was designed.

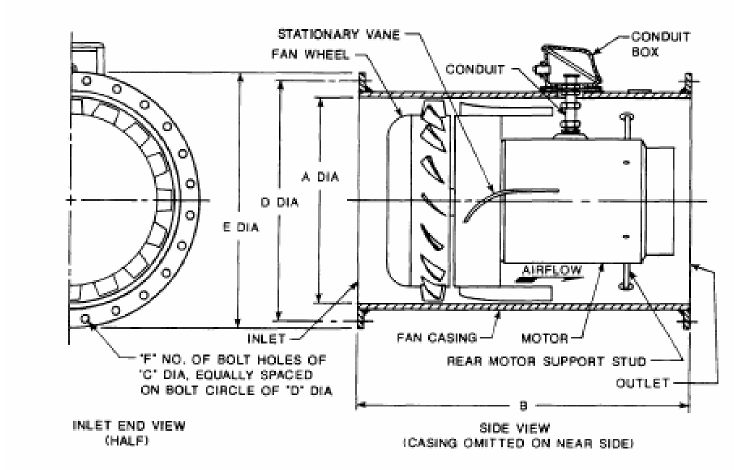

Figure 17 – CPS Fan Design

These early CPS fans were noisy and inefficient. As a result of those concerns, the Navy designed and built prototypes of a second generation CPS fan family using airfoil shaped blades and some quieting technology. The fans were significantly more efficient and remarkably quieter than the first generation CPS fans. The quiet CPS fans are finally being installed in new ship construction programs (LPD 17) and in the CPS backfit to some classes of Amphibious ships.

Advanced Fans

Commercial vaneaxial fan technology was examined. Detailed performance and efficiency data, in particular, were difficult to obtain. However, one manufacturer publishes extensive data on their fans[2]. These fans are state-of-the-art featuring airfoil blade technology and incorporate a variety of quieting features. Analysis of the commercial fan performance data reveals efficiencies on the order of 75%. It is believed that the standard Navy fan efficiencies are far lower, that data has also been difficult to obtain, and the limited data that was obtained indicated the efficiencies were in the 40–50% range, in some cases, and, nonsensically, above 100% in other cases. The commercial fans are belt driven, not direct driven as the Navy fans.

The CVN 21 program funded a study of the application of permanent magnet motors to ventilation fans[3]. The study emphasized reducing the motor size, incorporating variable speed operation to reduce the number of sizes in the family, and testing of several motors to determine EMI performance. The basic fan aerodynamic design was not addressed.

It is clear that, as a minimum, a new family of Navy fans can be designed which will be far quieter and far more efficient than that used today. Discussions with Navy fan experts indicate that fan efficiency improvements of 20-25% can be realized. Further, designing the fans to produce higher pressure differentials to enable smaller duct sizes and smaller cooling coils is also feasible. Incorporation of permanent magnet motors and variable speed is also feasible. Permanent magnet motor technology is ideally suited for variable speed operation and provides the opportunity to minimize the number of fan sizes by selecting the appropriate full performance speed. The cost effectiveness of these improvements at the component level is unknown but likely poor. However, bundled with the total ship concept of reduced HVAC system size and total ship HVAC system automation will likely produce a positive cost delta.

In a more advanced concept, the adoption of a permanent magnet motor offers the opportunity to no longer be limited by synchronous speeds (3600 rev/min). Instead, a motor that rotates at 10,000 rev/min or higher, coupled with advanced aerodynamic blade designs could result in dramatically smaller fans – reductions of fan size and weight on the order of 75% may be possible. Bearing technology such as magnetic bearings or foil bearing technology as used in high speed gas turbine engines may be necessary.

Many of the advanced technology features of the advanced fan discussed above have application to other shipboard advanced machinery systems - variable speed drives, permanent magnet high speed motors and magnetic bearings. Transition of this technology to the ship in these other applications has been limited by the high upfront development costs. The 21st Century HVAC System could serve as the vehicle for developing and deploying these technologies. The quantities required will be attractive to manufacturers and the hp range is moderate (5-25hp).

Similar technology to the high-speed, permanent magnet motor and magnetic bearing technology envisioned here has been demonstrated and is commercially available in state-of-the art oil-free centrifugal compressor AC plants manufactured by Turbocor[4]. These units have a 140-160 hp permanent magnet motor that rotate at speeds of 40,000 rev/min and higher with magnetic bearings supporting the motor rotor. This is done cost effectively – the compressor for that unit can be purchased for about $25K, implying the motor and bearing combination is probably on the order of $10K. The suitability of this design approach for the naval environment (shock, vibration, EMI) has not been demonstrated but will likely require substantial investment. Closer examination of the design of the Turbocor unit will be useful if the option to design a high speed fan family is pursued.

Advanced Cooling Coils

A Navy standard duct cooling coil is shown in Figure 18. Chilled water flows through the tubes, in a serpentine arrangement. Air flow is over a series of fins that are attached to the tubes.

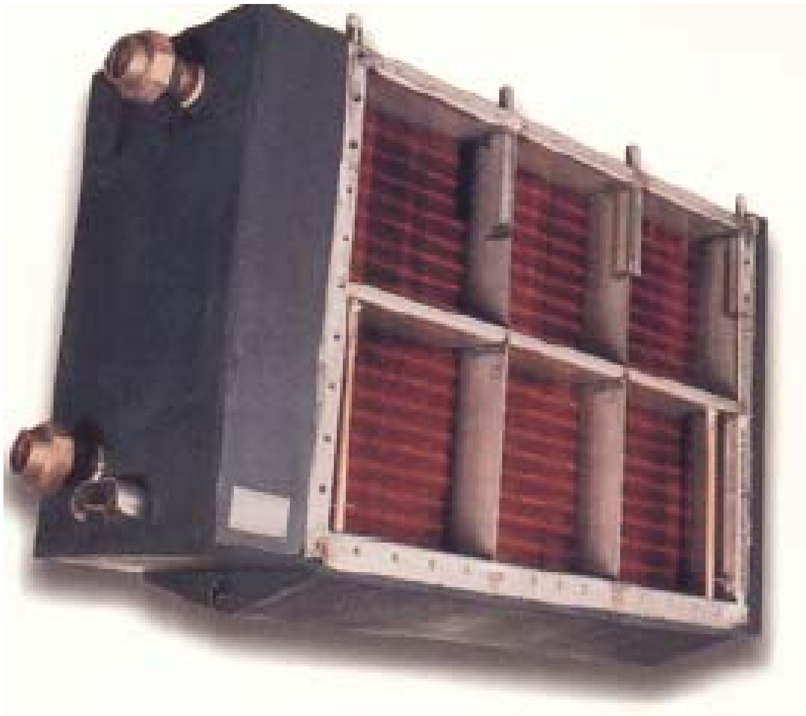

Figure 18 – Navy Standard Cooling Coil

The current coil design is the "60 series", an improved performance series (lower weight in same space envelope and at same heat transfer rate) developed in the late 1980s and early 1990s to replace the "50 series". The 50 series coils have flat fins, are 8 rows deep (1.5 to 2 serpentines), use 7 fins/inch and the fins are 0.016-iches thick. The 60 series coils have wavy fins, are 6 rows deep (1 to 1.5 serpentines), use 8 fins/inch and the fins are 0.010-inches thick. Essentially the difference between the two designs is the change from 8 rows depth to 6 rows depth which accounts for the 25% weight reduction. The increased air side pressure drop caused by the wavy fin is offset by the fewer rows of tubes. Although the "60 series" was developed and qualified over 15 years ago, the entire DDG 51 Class is/will be constructed with 50 series coils; the CVN 77 is being constructed with 40 series coils (the 1960s version of the coils). The LPD 17 Class is the first class being constructed with 60 series coils.

There are an almost endless variety of coil surfaces and geometries available. Each combination can produce a particular benefit, usually with a particular penalty. Defining the optimal coil configuration for the 21st Century HVAC System requires definition of the relevant priority of size, weight, water side pressure drop, air side pressure drop, reliability and cost. For instance, minimal size usually also provides minimal weight, but the increased velocities on the air side and perhaps on the water side will result in increased air and perhaps water side pressure drop due to either the velocity increase or the surface geometry selected. While these might have been fatal flaws using the existing catalog of fan designs, the development of efficient modern design fans discussed earlier should lessen the impact and permit consideration of those options.

Each coil manufacturer offers a variety of enhanced heat transfer surfaces. The Navy thermal management team met with DRS/Marlo Coil (the primary manufacturer of Navy cooling coils) in March 2006 to discuss advanced coil concepts, design paradigms and alternate coil configurations. A flattened tube coil design and a coil manufactured from graphite foam were discussed as potential advanced concept designs that would offer significant weight savings and better heat transfer.

A variety (York, Carrier, Marlo and Heatcraft) of commercially available software was acquired to investigate the effects of air flow rate (face velocity), chilled water flow rate and temperature, fin configuration and spacing, coil depth/ size/ serpentine arrangement/circuiting and, as available, alternate fin surface geometries. The software programs were furnished as individual executable files without the source code or useful help/tutorial information. In most cases, the choices were limited and many configurations of interest could not be analyzed. The York and Carrier programs were targeted almost exclusively to existing coil selections rather than allowing exploration of more radical design choices. The Heatcraft and Marlo softwareprograms allowed more choices but were also inflexible when examining more radical concepts. For baseline purposes, the Marlo software was used to analyze the Navy standard 50 series and 60 series coils. The software results did not compare well with the published tabulated “data” for the performance of the 50 series coils. The difference in heat transfer rates was significant. For the 60 series coils, the Marlo software and published coil performance data were in relatively good agreement. The performance of the Navy standard coils (as listed in the Navy specification) is shown in Table 1 below followed by that predicted by the Marlo software (Marlometrics), Table 2.

Table 1– Published 60 Series Coil Performance

60 Series Cooling Coil Performance at 80°F DB and 67°F WB entering air, 3.6 gpm/ton chilled water at 45°F						
Coil Size	***Airflow ft3/min***	***Velocity (ft/min)***	***Leaving air DB (°F)***	***Leaving air WB (°F)***	***Capacity (X 10^{-3} BTU/hr)***	***Capacity (tons)***
61	280	491	58.6	56.8	9.02	0.75
62	450	500	56.9	55.3	16.47	1.37
63	670	496	55.3	53.8	27.26	2.27
64	975	488	55.2	53.7	39.97	3.33
65	1450	485	53.1	52.5	63.44	5.29
66	2500	500	52.7	52.1	112.2	9.35
67	3800	507	51.1	50.8	183.6	15.30
68	5000	500	51.1	50.9	240.7	20.06
From MIL-PRF-2939G, 20 July 2001						
60 Series Coils have wavy fins, 6 rows deep,						
8 fins/inch, 0.010 thick fins, 1.5 serpentines						

Table 2– Calculated Performance of 60 Series Cooling Coils Using Marlometrics Software

Marlometrics Results										
Coil Size	Leaving air DB (°F)	Specification Leaving air DB (°F)	Leaving air WB (°F)	Specification Leaving air WB (°F)	Capacity ($X 10^{-3}$ BTU/hr)	Capacity (tons)	Water Pressure Drop (ft H20)	Water side drop from Chart (ft H20)	Air Side Pressure Drop ("H20)	Pressure Drop (Wet) from Chart ("H20)
61	56.50	58.60	56.10	56.80	9618.00	0.80	0.15	0.30	0.76	0.60
62	55.20	56.90	54.70	55.30	17233.00	1.44	0.32	0.90	0.96	0.70
63	53.10	55.30	52.60	53.80	29334.00	2.44	0.83	2.20	0.98	0.70
64	52.70	55.20	52.20	53.70	43654.00	3.64	1.34	2.40	1.08	0.70
65	51.70	53.10	51.30	52.50	68627.00	5.72	2.11	2.40	0.96	0.80
66	51.20	52.70	50.80	52.10	121315.00	10.11	3.82	4.00	1.03	0.80
67	51.10	51.10	50.60	50.80	185904.00	15.49	4.29	4.00	1.07	0.80
68	53.10	51.10	52.20	50.90	224497.00	18.71	6.62	3.50	1.06	0.95

The Heatcraft software was also in relatively good agreement with the published data for the 60 series coils.

The Marlo and Heatcraft software were used for a limited investigation of coil paradigm shifts. The size 65 cooling coil was used to examine the effects of varying water temperature, air flow, water flow, tube diameter, fin spacing, fin type, number of serpentines, fin thickness, and fin material. Most of the variations produced positive results (more heat transfer with same coil face size), as expected. A sampling of the results is shown in Table 3.

Table 3 – Coil Paradigm Shift Results

Designation	Coil Size	Airflow ft3/min	Chilled Water Inlet Temperature (°F)	Leaving air DB (°F)	Leaving air WB (°F)	Capacity (X 10-3 BTU/hr)	Tube Diameter (in)	Tube Wall (in)	Tube Material	Fin Type	Fin Thickness (in)	Fins per inch	Fin Material	Rows Deep	Serpentines	Water Flow (gpm)
Navy Standard, from Specification	65	1450	45	53.1	52.5	63.4	0.625	0.025	Copper	Wavy	0.01	8	Copper	6	1.5	19
Marlometrics	65	1450	45	51.7	51.3	68.6	0.625	0.025	Copper	Wavy	0.01	8	Copper	6	1.5	19
Heatcraft	65	1450	45	53.3	52.3	64.7	0.625	0.022	Copper	New Ripple (E-F)	0.0095	8	Copper	6	1.5	19
Heatcraft	65	1450	45	51.9	51.3	68.3	0.625	0.022	Copper	High F (C)	0.0095	8	Copper	6	1.5	19
	Vary Chilled Water Inlet Temperature															
Marlometrics	65	1450	45	51.7	51.3	68.6	0.625	0.025	Copper	Wavy	0.01	8	Copper	6	1.5	19
Marlometrics	65	1450	44	51	50.5	71.3	0.625	0.025	Copper	Wavy	0.01	8	Copper	6	1.5	19
Marlometrics	65	1450	43	50.2	49.8	74.0	0.625	0.025	Copper	Wavy	0.01	8	Copper	6	1.5	19
Marlometrics	65	1450	42	49.5	49	76.7	0.625	0.025	Copper	Wavy	0.01	8	Copper	6	1.5	19
Marlometrics	65	1450	41	48.7	48.3	79.3	0.625	0.025	Copper	Wavy	0.01	8	Copper	6	1.5	19
Marlometrics	65	1450	40	48	47.6	81.9	0.625	0.025	Copper	Wavy	0.01	8	Copper	6	1.5	19
	Vary Serpentines/Rows															
Marlometrics	65	1450	45	51.7	51.3	68.6	0.625	0.025	Copper	Wavy	0.01	8	Copper	6	1.5	19
Marlometrics	65	1450	45	52.9	52.2	65.0	0.625	0.025	Copper	Wavy	0.01	8	Copper	5	1.25	19
Marlometrics	65	1450	45	54.6	53.4	60.3	0.625	0.025	Copper	Wavy	0.01	8	Copper	4	1	19
Marlometrics	65	1450	45	57.1	55.1	53.9	0.625	0.025	Copper	Wavy	0.01	8	Copper	3	0.75	19
Marlometrics	65	1450	45	61.2	57.7	43.1	0.625	0.025	Copper	Wavy	0.01	8	Copper	2	1	19
	Vary Chilled Water Flow															
Marlometrics	65	1450	45	51.7	51.3	68.6	0.625	0.025	Copper	Wavy	0.01	8	Copper	6	1.5	19
Marlometrics	65	1450	45	52.7	52.2	64.9	0.625	0.025	Copper	Wavy	0.01	8	Copper	6	1.5	15
Marlometrics	65	1450	45	54.8	54.3	57.0	0.625	0.025	Copper	Wavy	0.01	8	Copper	6	1.5	10
Marlometrics	65	1450	45	58.7	58.2	40.8	0.625	0.025	Copper	Wavy	0.01	8	Copper	6	1.5	5
	Vary Air Flow															
Marlometrics	65	1450	45	51.7	51.3	68.6	0.625	0.025	Copper	Wavy	0.01	8	Copper	6	1.5	19
Marlometrics	65	2000	45	54.2	53.6	82.5	0.625	0.025	Copper	Wavy	0.01	8	Copper	6	1.5	19
Marlometrics	65	2500	45	55.9	55.2	92.1	0.625	0.025	Copper	Wavy	0.01	8	Copper	6	1.5	19
Marlometrics	65	3000	45	57.3	56.5	99.8	0.625	0.025	Copper	Wavy	0.01	8	Copper	6	1.5	19
	Vary Fin Count															
Marlometrics	65	1450	45	51.7	51.3	68.6	0.625	0.025	Copper	Wavy	0.01	8	Copper	6	1.5	19
Marlometrics	65	1450	45	50.7	50.4	71.7	0.625	0.025	Copper	Wavy	0.01	10	Copper	6	1.5	19
Marlometrics	65	1450	45	50	49.8	74.0	0.625	0.025	Copper	Wavy	0.01	12	Copper	6	1.5	19
Marlometrics	65	1450	45	49.5	49.3	75.7	0.625	0.025	Copper	Wavy	0.01	14	Copper	6	1.5	19
	Vary Fin Thickness															
Marlometrics	65	1450	45	51.7	51.3	68.6	0.625	0.025	Copper	Wavy	0.01	8	Copper	6	1.5	19
Marlometrics	65	1450	45	52.1	51.7	67.0	0.625	0.025	Copper	Wavy	0.007	8	Copper	6	1.5	19
	Vary Fin Material															
Marlometrics	65	1450	45	51.7	51.3	68.6	0.625	0.025	Copper	Wavy	0.01	8	Copper	6	1.5	19
Marlometrics	65	1450	45	52.4	52	65.9	0.625	0.025	Copper	Wavy	0.01	8	Aluminum	6	1.5	19
	Vary Tube Diameter (Fin Thickness Variation Required In Some Cases)															
Marlometrics	65	1450	45	51.7	51.3	68.6	0.625	0.025	Copper	Wavy	0.01	8	Copper	6	1.5	19
Heatcraft	65	1450	45	53.3	52.3	64.7	0.625	0.025	Copper	New Ripple (E-F)	0.0095	8	Copper	6	1.5	19
Heatcraft	65	1450	45	51.9	51.3	68.3	0.625	0.025	Copper	High F (C)	0.0095	8	Copper	6	1.5	19
Heatcraft	65	1450	45	53.7	52.6	63.4	0.5	0.022	Copper	High F (C)	0.0095	8	Copper	6	1.5	19
Heatcraft	65	1450	45	52.3	51.5	67.5	0.375	0.025	Copper	High F (C)	0.0075	8	Copper	6	1.5	19
Heatcraft	65	1450	45	52.4	51.6	67.1	0.375	0.016	Copper	High F (C)	0.0075	8	Copper	6	1.5	19
Heatcraft	65	1450	45	52.6	51.9	66.3	0.375	0.016	Copper	High F (C)	0.006	8	Copper	6	1.5	19
	Vary Fin Design															
Marlometrics	65	1450	45	51.7	51.3	68.6	0.625	0.025	Copper	Wavy	0.01	8	Copper	6	1.5	19
Heatcraft	65	1450	45	53.3	52.3	64.7	0.625	0.025	Copper	New Ripple (E-F)	0.0095	8	Copper	6	1.5	19
Heatcraft	65	1450	45	51.9	51.3	68.3	0.625	0.025	Copper	High F (C)	0.0095	8	Copper	6	1.5	19
Heatcraft	65	1450	45	58	55	54.3	0.375	0.016	Copper	Flat	0.0075	8	Copper	6	1.5	19
Heatcraft	65	1450	45	54.1	52.8	62.8	0.375	0.016	Copper	New Ripple (E-F)	0.0075	8	Copper	6	1.5	19
Heatcraft	65	1450	45	52.4	51.6	67.1	0.375	0.016	Copper	High F (C)	0.0075	8	Copper	6	1.5	19
Heatcraft	65	1450	45	50.3	50.2	72.4	0.375	0.016	Copper	Lanced	0.0075	10	Aluminum	6	1.5	19
	Combined Variations															
Marlometrics	65	1450	40	60.1	59.2	36.5	0.625	0.025	Copper	Wavy	0.01	14	Copper	4	1	5

The following general conclusions on the feasibility of developing advanced cooling coil designs, revising design paradigms and pursuing the development of advanced concept coil designs are offered –

- A detailed examination of advanced cooling coil designs and coil design paradigms is recommended. Reductions of 50% in cooling coil size and weight are expected.
- Commercially available software is unsuited for the extensive coil parameter and design paradigm shifting effort envisioned. Without the source code, it is unclear whether the analysis is being performed using a physics based approach or an extrapolation/interpolation based approach. Generation of a flexible, user friendly coil analysis software program is recommended. The Navy developed a Fortran coil analysis software in the 1980s that has recently been resurrected and may provide a suitable starting platform for that analysis. Eventually, experimental verification of the software will be necessary.
- Innovative methods to overcome the moisture carryover issues that will occur with the increased face velocity (smaller coil size) are required.
- Modern water side enhancement technology and much higher water velocities should also be considered. The water side pressure drop through the existing coil family is low, on the order of 0.5 – 3 lbf/in^2; pressure drops of 10-15 lbf/in^2 should be considered.
- Lower chilled water inlet temperature provides significant benefits, but will impact the AC plant design and power consumption. However, the bundled effect of lower chilled water temperature, lower chilled water flow rates and lower cooling coil size and weight will probably provide substantial overall benefits at the total ship level.
- The investigation of coatings to enhance condensate drainage and reduce pressure drop should be pursued.
- Radically different cooling coil configurations (Navy coils are flat plate - fin generic design) are of interest and may be desirable – flattened (oval) tube[5], graphite foam and micro-channel. It is recommended that these concepts be pursued.

Smooth, Low Friction and Frictionless Duct

Two potential smooth duct technologies were identified. One is a polymer coated duct used in the chemical processing industry with very low surface roughness. The other is a glass coating technology that could be applied to ducts. As yet, that coating has not been applied to ducts.

It is recommended that samples of both materials be acquired and tested to determine the frictional loss. The test setup and execution should be relatively straightforward and inexpensive.

Success in reducing duct frictional losses may permit raising the current 4500 ft/min duct velocity limit to 10,000 ft/min (or more). Even if raising the velocity causes an increased frictional loss with the advanced ducting, the advanced, efficient fans will produce higher ΔP, perhaps at the same relative power consumption.

In addition, the smooth ducts may prove to be less likely to collect dirt and other debris than the current steel or aluminum ducting thus requiring less frequent cleaning and the coatings may provide additional corrosion resistance.

Advanced Filtration

Cleaning of shipboard HVAC systems is a major fleet burden and has been cited as one of the top cumbersome work practices in the fleet. The 21st Century HVAC system with higher velocity duct flows and coil flows and smooth ducting will require a higher level of cleanliness. As a start, all of the air flowing through the ducting should be filtered beginning at the return air grill in the compartment. The Navy standard filters are more aptly categorized as "strainers", the filtration efficiency is extremely poor. A family of disposable filters was developed in the late 1990s and early 2000s which were more efficient[6]. However, filtration efficiency is directly related to pressure drop and the choices for replacement disposable filters was limited by available pressure drop. In a fresh start design such as the 21st Century HVAC System, additional pressure drop can be accommodated and much more efficient filters specified.

Simplified HVAC System Model Concept

The purpose of the simplified, macro- level HVAC system model(s) is to quantify the relative differences between the current HVAC system design and the 21st Century HVAC system design(s) in weight, space and power for both the HVAC system and the chilled water distribution system. The DDG 51 Class and DDG 91, in particular, were selected as the baseline for the models. Detailed HVAC system calculations, drawings and a detailed weight report were available for that ship. In addition, a thermal loads database, created in an earlier thermal management effort, was also available. As work began, it became clear that several models, each addressing a sub-system/system level, would be the best approach for this effort. Three models were developed – a compartment level model, a system level model and a total ship model.

The compartment model is the beginning for any HVAC calculation; the source cooling loads are identified, quantified, and summed; the required compartment air flow and replenishment air flow are determined. The requirements for a series of individual compartments, served by the same ventilation or recirculation system, can be easily summed to provide the input for the ventilation or recirculation system model.

The system level model selects the components for the HVAC System – fan(s), cooling coil(s), chilled water requirement and ducting based on the required cooling load and air flow rates. This model allows assessment of the advanced component benefits (fans, cooling coils, ducting) and the design paradigm shifts (lower chilled water temperature, lower chilled water flow rate, higher duct velocity). The approach will be to select a few HVAC sub-systems for DDG 91: a recirculation system with a high electronic cooling load, a recirculation system with a highly variable population, a complex recirculation system with a low equipment load, a simple supply system, a complex supply system and a simple exhaust system. Analysis of all the DDG 91 sub-systems would require a large effort.

The total ship HVAC model sums the results of all HVAC systems to provide the total ship HVAC load. Then, this HVAC load is added to the non-HVAC chilled water loads to provide the total ship chilled water load. This load determines the number of AC plants required to meet the load, based on Navy policy and the AC plant capacity selected as an input. This model allows assessment of the 21st Century HVAC System design at the total ship level.

Compartment Level HVAC Model

The HVAC System Compartment level model identifies the cooling loads in each compartment and calculates the total cooling load for that compartment, the required compartment air flow rate and the required replenishment air flow rate. There are five basic load sources – transmission from adjoining compartments (or the weather as applicable), lighting, equipment within the compartment, personnel (both latent and sensible), piping (rarely encountered on gas turbine powered ships, a carryover from the steam powered ship era) and occasionally a sixth source where some or all of the equipment load is directly returned to the HVAC system without first being directed into the compartment. The equipment loads are scaled by a "use factor" from 0-1. Most combat equipment is assigned use factors near or at 1, most other equipment is assigned use factors of 0.5 and below to reflect the expected time the equipment will be on and dissipating heat. Many of the combat loads also incorporate a growth factor for future increases.

In the very simplified version developed in this effort, some of the results are actually inputs. For instance – the transmission load is calculated based on the temperature in each adjoining (top, sides and bottom) compartment, the adjoining areas and the transmission path (insulated and degree of insulation). This is a tedious calculation and requires full definition of each compartment, something not defined during ship concept design studies. The personnel load is based on the number of people assigned to that compartment and the level of activity – essentially whether the activity is stressful, such as at work or exercising, or at rest, such recreation or berthing.

In a similar manner the replenishment air flow is based on the number of people assigned to that compartment and their level of activity.

Ordinarily, the compartment rate of change is an input and the compartment flow rate is based on the rate of change and the compartment volume. (A 1500 ft^3 compartment with a 15 minute rate of change requires a compartment flow rate of 1500/15 = 100 ft^3/min). However, in most of the compartments analyzed in this effort, the rate of change was more often than typical, driven by the cooling load, which in turn was driven by the equipment loads.

A sample of a compartment model result is shown in Table 4 below. Shown are the results for two adjoining compartments served by a single recirculation system with the sum of the compartment loads shown in the last column. The critical results which are used in the next higher level model are highlighted.
A growth factor has been applied to the equipment load. Note the rapid rate of change, usually indicative of a large equipment load in a relatively small compartment.

Table 4 – Sample HVAC Compartment Model Results

Inputs			
Compartment Name	Combat Information Center - Main Deck	Combat Information Center - Projection Area	Combined
Compartment Number	1-126-0-C	1-126-0-C	1-126-0-C
Weather Air Dry Bulb Temperature (°F)	90	90	90
Weather Air Wet Bulb Temperature (°F)	81	81	81
Compartment Air Dry Bulb Temperature (°F)	80	80	80
Compartment Air Wet Bulb Temperature (°F)	68	68	68
Compartment Volume (ft^3)	17424.43	758	18182.43
System Damage Control Classification	W	W	W
Compartment Rate of Change (min)	3.3	4.6	3.3
Number of Personnel	26	0	0

Inputs			
Compartment Name	Combat Information Center - Main Deck	Combat Information Center - Projection Area	Combined
Equipment Loads (BTU/hr)	83400	3381	86781
Results			
Transmission Load (BTU/hr)	6845	0	6845
Equipment Load (BTU/hr)	95910	3888.15	99798.15
Lighting (BTU/hr)	9396	188	9584
Personnel Sensible Load (BTU/hr)	6240	0	6240
Total Sensible Load (BTU/hr)	118391	4076.15	122467.2
Personnel Latent Load (BTU/hr)	9360	0	9360
Total Load (BTU/hr)	127751	4076.15	131827.2
Required Replenishment Air Flow Rate (ft^3/min)	260	0	260
Required Compartment Flow Rate (ft^3/min)	5280	165	5445
Room Slope	0.93	1.00	0.93

Advanced Component and Technology Projections/Goals

A pre-requisite to the development of an HVAC system model is the establishment of the component characteristics - performance, size, weight and power requirements (if any) - of the advanced technology components that will be implemented as enablers of the 21st Century HVAC system. Since these components do not exist, the characteristics were projected based on the anticipated technology benefits. Advanced fans, cooling coils, and ducting components are discussed and some of the appropriate design paradigm changes are embedded within these advanced designs.

A spiral development process is envisioned where low to moderate risk technology can be applied as a 21st Century Flight 1 system and which can be available (designed, developed and demonstrated/qualified) within 5-7 years for implementation into new ship designs. For Flight1 technologies, the benefits are expected to be modest.

The 21st Century Flight 2 spiral development will address moderate to high risk technologies and will require 10-12 years to fully demonstrate before implementation into new ship designs. There is of course the risk that the development will be unsuccessful. The performance characteristics for this technology set should be viewed as goals. However, if successful, the benefits are expected to be significant.

The 21st Century Flight 3 spiral development will address high risk technologies, require on the order of 20 years to develop and demonstrate before implementation into new ship designs. The performance characteristics for this technology set should be viewed as “aggressive” goals. If successful, the benefits should be revolutionary.

In each area described below, the technology is described as either legacy (current Navy and some ships still in the construction phase, e.g., DDG 51), today (ships in the construction phase – LPD 17), or 21st

Century Flight 1, 2 or 3. No attempt was made to "game" the performance characteristics/goals. The goals were established prior to final model construction and before any results were available. Later, in the results, it is clear that better definition of the goals for each design and the range of application is necessary prior to development of any of the components.

Fans

There are five fan types/categories used on Navy ships – vaneaxial, high-pressure/CPS vaneaxial, centrifugal, FCA and FCUfan coil unit. The latter two types employ centrifugal fans, but are not part of the centrifugal fan family. The FCA and the FCU are packaged systems incorporating a cooling coil and other components/controls and are widely used in recirculation systems. The weight and volume of these packaged systems is included in the fan subset.

The performance characteristics of the Navy's legacy fan family, sorted by type and then organized by descending flow rate, is shown in Table 5.

Table 5 – Navy Legacy Fan Family Performance Characteristics

Legacy						
	Designation	Flow (ft^3/min)	Head (inches H_2O)	Power (hp)	Weight (lbm)	Volume (ft^3)
Navy Standard Vaneaxial Fans	A 30	25000	4.2	25.0	1850	46.3
	A 25	22000	3.95	25.0	1750	42.7
	A 28	18750	6.4	25.0	1500	29.5
	A 20	18000	4.85	20.0	1300	22.9
	A 16	13200	4.75	15.0	1100	16.8
	A 17	12300	6.2	17.5	1200	22.4
	A 12	10250	5	10.0	850	14.7
	A 11	8700	5.5	12.5	900	17.8
	A 10	8500	4.2	7.5	750	12.5
	A 8	7300	3.3	6.0	600	10.9
	A 6	6300	3.65	5.0	530	8.5
	A 7	5200	7	7.5	450	5.5
	A 4	4300	3.5	4.0	425	6.6
	A 5	4200	3.75	4.0	450	7.3
	A 3 1/2	3750	3.5	3.0	425	5.8
	A 4 1/2	3220	7	5.0	320	4.0
	A 3	3200	3.4	3.0	375	6.0
	A 2 1/2	2600	3.4	2.0	250	2.6
	A 2	2000	3.4	1.5	180	2.8
	A 1 1/2	1500	3	1.3	160	1.8
	A 1	1030	2.65	1.0	125	1.4
	A 1/2	660	2.5	0.3	80	0.8
	A 1/4	250	2.5	0.2	65	0.7
CPS Fans	AN 105	5400	14	20.0	640	7.1
	AN 104	3600	14	15.0	620	6.7
	AN 103	2400	14	15.0	620	6.5

Legacy						
	Designation	Flow (ft^3/min)	Head (inches H_2O)	Power (hp)	Weight (lbm)	Volume (ft^3)
	AN 102	1800	14	10.0	600	6.3
	AN 101	1200	14	10.0	580	5.5
Navy Standard Centrifugal	CC 10	6350	5	10.0	1260	102.8
	CC 6	4500	4	5.0	1110	78.5
	CC 8	4050	5.2	7½	1210	101.0
	CC 5	2750	5.3	5.0	955	33.5
	CC 4	2300	5.25	4.0	610	32.7
	CC 3	1760	4.25	3.0	560	27.5
	CC 2	1090	3.06	1½	310	16.4
	CC 1 1/2	980	2.58	1.0	215	13.4
	CC 1	760	2.5	1.0	190	9.1
	CC 1/2	400	2.5	3/4	170	7.9
	CC 1/4	180	1.74	¼	100	3.0
Fan Coil Assemblies	FCA 25	3800	2	7.5	1836	89.9
	FCA 24	2550	2	5.0	1590	81.9
	FCA 23	1800	2	5.0	1472	66.7
	FCA 22	1260	2	3.0	1289	53.5
	FCA 21	760	2	1.5	1203	53.5
Fan Coil Units	FCU 8	1650	1	0.8	780	26.1
	FCU 7	1100	1	0.8	660	21.9
	FCU 6	950	1	0.8	500	20.0
	FCU 5	690	0.25	0.5	500	18.5
	FCU 4	530	0.25	0.5	420	15.2
	FCU 3	350	0.25	0.5	350	11.4
	FCU 2	240	0	0.3	285	7.2
	FCU 1	145	0	0.3	275	7.2

Today's fan family is identical to the legacy family, except that the CPS fans are a second generation, quieter and more efficient than the original designs used in the legacy family. To differentiate between the two, the legacy CPS fans are designated in this report as "AN" and today's CPS fans as "AQ". In actual use, the CPS fans are designated "A".

The 21st Century Flight 1 fan family will use advanced aerodynamic fan blades (similar to the second generation CPS fans) and will be quieter and more efficient than the legacy or today family. The fans will be driven at variable speed using PWM motor controllers. The motors will be conventional 3600 rev/min, high-efficiency, shipboard qualified, induction motors.

A fan efficiency of 80% was used across the board for all fan designs in this family. The efficiencies of the legacy and today fans are not clearly known.

Instead of 23 different vaneaxial fans, it is projected that only six basic vaneaxial fan designs will be used in the Flight 1 family. The full load fan speed (less than 3600 rev/min) will be established to meet the design flow rate requirement when that requirement falls between fan sizes.

Similarly, only one basic CPS fan size is projected with lower flow requirements met by speed reduction.

The centrifugal subset for this family will also use improved blade shapes and thus higher efficiencies. No attempt was made to analyze in any further depth the potential performance of the centrifugal subset, the FCA subset or the FCU subset. No significant weight or size benefits are anticipated for this family but improvements in power consumption is clear.

The components in the Flight 1 fan family incorporate an "X" designation into the basic numbering scheme used for the legacy and today's fan families.

The projected performance of the 21st Century fan family is shown in Table 6. Note that the same vaneaxial fan designation is shown multiple times at various flow rates to match the flow rates used in the legacy and today family. Also note that there are weight and size differences shown for the FCAs and the FCUs – these result from the cooling coil technology advancements that will be used in the Flight 1 family and are discussed later in the cooling coil section.

Table 6 – 21st Century Flight 1 Fan Performance Characteristics

21st Century Flight 1						
	Designation	Flow (ft^3/min)	Head (inches H_2O)	Power (hp)	Weight (lbm)	Volume (ft^3)
Vaneaxial Fans	AX 32	32000	10	62.9	1850	46.0
	AX 32	25000	8	39.3	1850	46.0
	AX 32	20000	6	23.6	1850	46.0
	AX 16	16000	10	31.5	1300	23.0
	AX 16	14000	8	22.0	1300	23.0
	AX 16	12000	7	16.5	1300	23.0
	AX 16	10000	6	11.8	1300	23.0
	AX 16	9000	5	8.8	1300	23.0
	AX 8	8000	8	12.6	750	12.0
	AX 8	7500	7	10.3	750	12.0
	AX 8	7000	6	8.3	750	12.0
	AX 8	6500	5	6.4	750	12.0
	AX 8	6000	5	5.9	750	12.0
	AX 8	5000	5	4.9	750	12.0
	AX 4	4000	6	4.7	425	6.0
	AX 4	3500	6	4.1	425	6.0
	AX 4	3000	5	2.9	425	6.0
	AX 4	2500	4	2.0	425	6.0
	AX 2	2000	5	2.0	180	3.0
	AX 2	1500	4	1.2	180	3.0
	AX 1	1000	5	1.0	125	1.5
	AX 1	500	4	0.4	125	1.5
	AX 1	250	3	0.1	125	1.5

21st Century Flight 1						
	Designation	Flow (ft^3/min)	Head (inches H_2O)	Power (hp)	Weight (lbm)	Volume (ft^3)
CPS Fans	AX 105	5000	14	13.8	640	7.1
	AX 105	4000	14	11.0	640	7.1
	AX 105	3000	12	7.1	640	7.1
	AX 105	2000	10	3.9	640	7.1
	AX 105	1000	8	1.6	640	7.1
Centrifugal Fans	CCX 10	6350	5	6.2	1260	102.8
	CCX 6	4500	4	3.5	1110	78.5
	CCX 8	4050	5.2	4.1	1210	101.0
	CCX 5	2750	5.3	2.9	955	33.5
	CCX 4	2300	5.25	2.4	610	32.7
	CCX 3	1760	4.25	1.5	560	27.5
	CCX 2	1090	3.06	0.7	310	16.4
	CCX 1½	980	2.58	0.5	215	13.4
	CCX 1	760	2.5	0.4	190	9.1
	CCX ½	400	2.5	0.2	170	7.9
	CCX ¼	180	1.74	0.1	100	3.0
Fan Coil Assemblies	FCAX 25	3800	2	1.5	1200	60.0
	FCAX 24	2550	2	1.0	1000	55.0
	FCAX 23	1800	2	0.7	1000	40.0
	FCAX 22	1260	2	0.5	900	35.0
	FCAX 21	760	2	0.3	900	35.0
Fan Coil Units	FCUX 8	1650	1	0.3	700	25.0
	FCUX 7	1100	1	0.2	600	20.0
	FCUX 6	950	1	0.2	400	18.0
	FCUX 5	690	0.25	0.0	400	15.0
	FCUX 4	530	0.25	0.0	350	12.0
	FCUX 3	350	0.25	0.0	300	10.0
	FCUX 2	240	0	0.0	200	6.0
	FCUX 1	145	0	0.0	200	6.0

The Flight 2 fan family incorporates permanent magnet motor technology into the Flight 1 fan designs. A 30-45% weight reduction and a 35% size reduction are projected. The Flight 2 family incorporates "XX" into the basic fan numbering scheme. The Flight 2 performance goals are shown in Table 7.

Table 7 – 21st Century Flight 2 Fan Performance Characteristics

21st Century Flight 2						
	Designation	Flow (ft^3/min)	Head (inches H_2O)	Power (hp)	Weight (lbm)	Volume (ft^3)
Vaneaxial Fans	AXX 32	32000	10	62.9	1100	30.0
	AXX 32	25000	8	39.3	1100	30.0

21st Century Flight 2						
	Designation	Flow (ft^3/min)	Head (inches H_2O)	Power (hp)	Weight (lbm)	Volume (ft^3)
	AXX 32	20000	6	23.6	1100	30.0
	AXX 16	16000	10	31.5	800	15.0
	AXX 16	14000	8	22.0	800	15.0
	AXX 16	12000	7	16.5	800	15.0
	AXX 16	10000	6	11.8	800	15.0
	AXX 16	9000	5	8.8	800	15.0
	AXX 8	8000	8	12.6	450	8.0
	AXX 8	7500	7	10.3	450	8.0
	AXX 8	7000	6	8.3	450	8.0
	AXX 8	6500	5	6.4	450	8.0
	AXX 8	6000	5	5.9	450	8.0
	AXX 8	5000	5	4.9	450	8.0
	AXX 4	4000	6	4.7	300	4.0
	AXX 4	3500	6	4.1	300	4.0
	AXX 4	3000	5	2.9	300	4.0
	AXX 4	2500	4	2.0	300	4.0
	AXX 2	2000	5	2.0	100	2.0
	AXX 2	1500	4	1.2	100	2.0
	AXX 1	1000	5	1.0	70	1.0
	AXX 1	500	4	0.4	70	1.0
	AXX 1	250	3	0.1	70	1.0
CPS Fans	AXX 105	5000	14	13.8	400	4.0
	AXX 105	4000	14	11.0	400	4.0
	AXX 105	3000	12	7.1	400	4.0
	AXX 105	2000	10	3.9	400	4.0
	AXX 105	1000	8	1.6	400	4.0
Centrifugal Fans	CCXX 10	6350	5	6.2	800	70.0
	CCXX 6	4500	4	3.5	700	60.0
	CCXX 8	4050	5.2	4.1	800	70.0
	CCXX 5	2750	5.3	2.9	700	20.0
	CCXX 4	2300	5.25	2.4	400	20.0
	CCXX 3	1760	4.25	1.5	450	18.0
	CCXX 2	1090	3.06	0.7	200	11.0
	CCXX 1½	980	2.58	0.5	150	10.0
	CCXX 1	760	2.5	0.4	120	7.0
	CCXX ½	400	2.5	0.2	100	5.0
	CCXX ¼	180	1.74	0.1	70	2.0
Fan Coil Assemblies	FCAXX 25	3800	2	1.5	1200	60.0
	FCAXX 24	2550	2	1.0	1100	50.0
	FCAXX 23	1800	2	0.7	1000	40.0
	FCAXX 22	1260	2	0.5	800	35.0
	FCAXX 21	760	2	0.3	800	35.0
	FCUXX 8	1650	1	0.3	600	18.0

21st Century Flight 2						
	Designation	Flow (ft^3/min)	Head (inches H_2O)	Power (hp)	Weight (lbm)	Volume (ft^3)
	FCUXX 7	1100	1	0.2	400	14.0
Fan Coil Units	FCUXX 6	950	1	0.2	350	14.0
	FCUXX 5	690	0.25	0.0	350	13.0
	FCUXX 4	530	0.25	0.0	300	10.0
	FCUXX 3	350	0.25	0.0	250	8.0
	FCUXX 2	240	0	0.0	200	5.0
	FCUXX 1	145	0	0.0	180	5.0

The Flight 3 fan family incorporates high speed permanent magnet motors and further fan blade design improvements. The fan diameters will be reduced, substantially, at the higher speeds. Speeds on the order of 10,000 rev/min are anticipated. This will result in a minimum 50% weight and size reduction. The Flight 3 family incorporates the designation "XXX" into the basic fan numbering scheme. The goals for the performance of the Flight 3 fan family are shown in Table 8. The goals are quite aggressive.

Table 8 – 21st Century Flight 3 Fan Performance Characteristics

21st Century Flight 3						
	Designation	Flow (ft^3/min)	Head (inches H_2O)	Power (hp)	Weight (lbm)	Volume (ft^3)
Vaneaxial Fans	AXXX 32	32000	10	62.9	800	15.0
	AXXX 32	25000	8	39.3	800	15.0
	AXXX 32	20000	6	23.6	800	15.0
	AXXX 16	16000	10	31.5	600	7.0
	AXXX 16	14000	8	22.0	600	7.0
	AXXX 16	12000	7	16.5	600	7.0
	AXXX 16	10000	6	11.8	600	7.0
	AXXX 16	9000	5	8.8	600	7.0
	AXXX 8	8000	8	12.6	300	4.0
	AXXX 8	7500	7	10.3	300	4.0
	AXXX 8	7000	6	8.3	300	4.0
	AXXX 8	6500	5	6.4	300	4.0
	AXXX 8	6000	5	5.9	300	4.0
	AXXX 8	5000	5	4.9	300	4.0
	AXXX 4	4000	6	4.7	150	2.0
	AXXX 4	3500	6	4.1	150	2.0
	AXXX 4	3000	5	2.9	150	2.0
	AXXX 4	2500	4	2.0	150	2.0
	AXXX 2	2000	5	2.0	70	1.0
	AXXX 2	1500	4	1.2	70	1.0
	AXXX 1	1000	5	1.0	40	0.5
	AXXX 1	500	4	0.4	40	0.5
	AXXX 1	250	3	0.1	40	0.5
CPS Fans	AXXX 105	5000	14	13.8	250	3.0
	AXXX 105	4000	14	11.0	250	3.0
	AXXX 105	3000	12	7.1	250	3.0

21st Century Flight 3						
	Designation	Flow (ft^3/min)	Head (inches H_2O)	Power (hp)	Weight (lbm)	Volume (ft^3)
	AXXX 105	2000	10	3.9	250	3.0
	AXXX 105	1000	8	1.6	250	3.0
Centrifugal Fans	CCXXX 10	6350	5	6.2	400	35
	CCXXX 6	4500	4	3.5	350	30
	CC 8	4050	5.2	4.1	400	35
	CCXXX 5	2750	5.3	2.9	350	10
	CCXXX 4	2300	5.25	2.4	200	10
	CCXXX 3	1760	4.25	1.5	225	9
	CCXXX 2	1090	3.06	0.7	100	5.5
	CCXXX 1½	980	2.58	0.5	75	5
	CCXXX 1	760	2.5	0.4	60	3.5
	CCXXX ½	400	2.5	0.2	50	2.5
	CCXXX ¼	180	1.74	0.1	35	1
Fan Coil Assemblies	FCAXXX 25	3800	2	1.5	600	30
	FCAXXX 24	2550	2	1.0	550	25
	FCAXXX 23	1800	2	0.7	500	20
	FCAXXX 22	1260	2	0.5	400	20
	FCAXXX 21	760	2	0.3	400	20
Fan Coil Units	FCUXXX 8	1650	1	0.3	300	9.0
	FCUXXX 7	1100	1	0.2	200	7.0
	FCUXXX 6	950	1	0.2	175	7.0
	FCUXXX 5	690	0.25	0.0	175	6.5
	FCUXXX 4	530	0.25	0.0	150	5.0
	FCUXXX 3	350	0.25	0.0	125	4.0
	FCUXXX 2	240	0	0.0	100	2.5
	FCUXXX 1	145	0	0.0	90	2.5

Cooling Coils

There are three cooling coil types/categories used on Navy ships – duct mounted cooling coil, and as described in the fan section, FCA and FCU.

The performance characteristics of the Navy's legacy cooling coil family, sorted by type and then organized by descending cooling rate, is shown in Table 9. Note that the weight and volume of the FCAs and the FCUs are included under the fan weight and volume.

Table 9 – Performance Characteristics of Legacy Cooling Coils

	Legacy					
Duct Cooling Coils	Designation	Capacity (BTU/hr)	Air Flow (ft^3/min)	Weight (lbm)	Volume (ft^3)	Face Area (ft^2)
	58	206494	5000	1310	23.7	10.3
	57	163077	3800	1040	18.8	7.8
	56	107763	2500	666	12.9	5.0
	55	50405	1450	434	8.8	3.0
	54	41994	975	295	6.6	2.0
	53	27672	670	248	5.0	1.3
	52	18248	450	200	3.9	0.9
	51	11835	280	156	3.1	0.6
Fan Coil Assemblies	FCA 25	133686	3800	Weight and Volume of Fan Coil Assemblies and Fan Coil Units included in Fan Sub-Set		6.2
	FCA 24	87714	2550			4.2
	FCA 23	63586	1800			3.7
	FCA 22	45214	1260			2.5
	FCA 21	25771	760			1.5
Fan Coil Units	FCU 8	72920	1650			4.5
	FCU 7	45560	1100			2.8
	FCU 6	39910	950			2.6
	FCU 5	30500	690			2.2
	FCU 4	22890	530			1.8
	FCU 3	15280	350			1.3
	FCU 2	9690	240			0.7
	FCU 1	5850	145			0.5

The today cooling coil family is shown in Table 10. The 60 series cooling coils were developed in the late 1980s and employ six rows of tubes and "wavy" fins versus eight rows and flat fins used in the 50 series. The original goal was to produce lighter weight and smaller coils with the same nominal cooling capacity. In the end, the smaller size goal was abandoned in order to produce fit and form equivalence with the 50 series. The 60 series coils are 25% lighter than the 50 series coils. The fan coil assemblies and the fan coil units are identical to the legacy family.

Table 10 – Performance Characteristics of Today Cooling Coils

Today						
	Designation	Capacity (BTU/hr)	Air Flow (ft^3/min)	Weight (lbm)	Volume (ft^3)	Face Area (ft^2)
Duct Cooling Coils	68	240700	5000	894	23.7	10.3
	67	183600	3800	815	18.8	7.8
	66	112200	2500	435	12.9	5.0
	65	63440	1450	305	8.8	3.0
	64	39970	975	231	6.6	2.0
	63	27260	670	182	5.0	1.3
	62	16470	450	129	3.9	0.9

Today						
	Designation	Capacity (BTU/hr)	Air Flow (ft^3/min)	Weight (lbm)	Volume (ft^3)	Face Area (ft^2)
	61	9020	280	114	3.1	0.6
Fan Coil Assemblies	FCA 25	133686	3800	Weight and Volume of Fan Coil Assemblies and Fan Coil Units included in Fan Sub-Set		6.2
	FCA 24	87714	2550			4.2
	FCA 23	63586	1800			3.7
	FCA 22	45214	1260			2.5
	FCA 21	25771	760			1.5
Fan Coil Units	FCU 8	72920	1650			4.5
	FCU 7	45560	1100			2.8
	FCU 6	39910	950			2.6
	FCU 5	30500	690			2.2
	FCU 4	22890	530			1.8
	FCU 3	15280	350			1.3
	FCU 2	9690	240			0.7
	FCU 1	5850	145			0.5

The projected performance of the 21st Century cooling coil family is shown in Table 11. The coils will use 2.0 gal/min/ton of cooling (instead of the 3.6 gal/min/ton used with the legacy and today series) with a chilled water supply of 40°F (instead of 45°F) to compensate for the lower flow. This change is expected to have a major, positive impact on the chilled water distribution piping. In addition, it is expected that fewer chilled water tubes will be required in the coil, four rows of tubes instead of six. That, and realizing the size changes that were available for the 60 series coils, should result in a weight reduction on the order of 25% and a volume reduction on the order of 50%. The 21st Century duct cooling coils are designated in this report as the 70 series and with an "X" to indicate the developmental status. The fan coil assemblies and fan coil units are numbered as described in the fan section.

Table 11 – Performance Characteristics of 21st Century Flight 1 Cooling Coils

21st Century Flight 1						
	Designation	Capacity (BTU/hr)	Air Flow (ft^3/min)	Weight (lbm)	Volume (ft^3)	Face Area (ft^2)
Duct Cooling Coils	78X	360000	5000	670.5	11.8	10.3
	77X	240000	3800	611.3	9.4	7.8
	76X	150000	2500	326.3	6.4	5.0
	75X	84000	1450	228.8	4.4	3.0
	74X	52000	975	173.3	3.3	2.0
	73X	36000	670	136.5	2.5	1.3
	72X	20000	450	96.8	2.0	0.9
	71X	12000	280	85.5	1.5	0.6
Fan Coil Assemblies	FCAX 25	140000	3800			6.2
	FCAX 24	90000	2550			4.2
	FCAX 23	65000	1800			3.7

21st Century Flight 1						
	Designation	Capacity (BTU/hr)	Air Flow (ft³/min)	Weight (lbm)	Volume (ft³)	Face Area (ft²)
	FCAX 22	50000	1260	Coil Unit Weight and Volume of Fan Coil Assemblies and Fans included in Fan Sub-Set		2.5
	FCAX 21	30000	760			1.5
Fan Coil Units	FCUX 8	75000	1650			4.5
	FCUX 7	50000	1100			2.8
	FCUX 6	45000	950			2.6
	FCUX 5	35000	690			2.2
	FCUX 4	25000	530			1.8
	FCUX 3	20000	350			1.3
	FCUX 2	12000	240			0.7
	FCUX 1	7000	145			0.5

The 21st Century Flight 2 cooling coils will be based on the Flight 1 designs and will be designed to use twice the face velocity (up to 1000 ft/min, instead of 500 ft/min) of the Legacy/Today/Flight 1 coils. This is a moderate to high risk effort. The major concerns are moisture entrainment in the coil leaving air and larger air side pressure drops through the coil. Incorporation of a passive moisture separation design/device at the outlet of the coil, rapid drainage coatings for the coil surface and unique fin surfaces are possible solutions. The higher pressure drop can be accommodated with the advanced Flight 2 fan designs. Doubling the face velocity will halve the coil face area and thus halve the size and weight of the coil. The performance goals for the Flight 2 cooling coils are shown in Table 12. These coils are designated in this report as the 80 series and with an “X”.

Table 12 – Performance Characteristics of 21st Century Flight 2 Cooling Coils

21st Century Flight 2						
	Designation	Capacity (BTU/hr)	Air Flow (ft³/min)	Weight (lbm)	Volume (ft³)	Face Area (ft²)
Duct Cooling Coils	88X	500000	10000	335.3	5.9	10.3
	87X	300000	8000	305.6	4.7	7.8
	86X	240000	5000	163.1	3.2	5.0
	85X	120000	3000	114.4	2.2	3.0
	84X	80000	2000	86.6	1.7	2.0
	83X	50000	1500	68.3	1.3	1.3
	82X	32000	1000	48.4	1.0	0.9
	81X	18000	500	42.8	0.8	0.6
Fan Coil Assemblies	FCAXX 25	140000	3800	Weight and Volume of Fan Coil Assemblies and Fan Coil Units included in Fan Sub-Set		3.1
	FCAXX 24	90000	2550			2.1
	FCAXX 23	65000	1800			1.8
	FCAXX 22	50000	1260			1.2
	FCAXX 21	30000	760			0.8
Fan Coil Units	FCUXX 8	75000	1650			2.2
	FCUXX 7	50000	1100			1.4

21st Century Flight 2						
	Designation	Capacity (BTU/hr)	Air Flow (ft^3/min)	Weight (lbm)	Volume (ft^3)	Face Area (ft^2)
	FCUXX 6	45000	950			1.3
	FCUXX 5	35000	690			1.1
	FCUXX 4	25000	530			0.9
	FCUXX 3	20000	350			0.7
	FCUXX 2	12000	240			0.4
	FCUXX 1	7000	145			0.3

The 21st Century Flight 3 cooling coil family will build on the successes of the Flight 1 and 2 families and employ radically different heat exchanger concepts and heat transfer surfaces. Flattened tube, micro-channel, graphite foam and unique fin designs/materials are some of the concepts to be explored. The performance goals are shown in Table 13. These coils are designated in this report as the 90 series with an "X" designation. This is a high risk/high payoff effort.

Table 13 – Performance Characteristics of 21st Century Flight 3 Cooling Coils

21st Century Flight 3						
	Designation	Capacity (BTU/hr)	Air Flow (ft^3/min)	Weight (lbm)	Volume (ft^3)	Face Area (ft^2)
Duct Cooling Coils	98X	500000	10000	167.6	3.0	10.3
	97X	300000	8000	152.8	2.3	7.8
	96X	240000	5000	81.6	1.6	5.0
	95X	120000	3000	57.2	1.1	3.0
	94X	80000	2000	43.3	0.8	2.0
	93X	50000	1500	34.1	0.6	1.3
	92X	32000	1000	24.2	0.5	0.9
	91X	18000	500	21.4	0.4	0.6
Fan Coil Assemblies	FCAXXX 25	140000	3800	Weight and Volume of Fan Coil Assemblies and Fan Coil Units included in Fan Sub-Set		3.1
	FCAXXX 24	90000	2550			2.1
	FCAXXX 23	65000	1800			1.8
	FCAXXX 22	50000	1260			1.2
	FCAXXX 21	30000	760			0.8
Fan Coil Units	FCUXXX 8	75000	1650			2.2
	FCUXXX 7	50000	1100			1.4
	FCUXXX 6	45000	950			1.3
	FCUXXX 5	35000	690			1.1
	FCUXXX 4	25000	530			0.9
	FCUXXX 3	20000	350			0.7
	FCUXXX 2	12000	240			0.4
	FCUXXX 1	7000	145			0.3

Paradigm Changes

The paradigm changes for the chilled water system and cooling coils are shown in Table 14.

Table 14 – Cooling Coil and Chilled Water System Paradigm Changes

Technology	Flow per ton of Cooling (gal/min/ton	Chilled Water Inlet Temperature (°F)	Air Side Friction Factor (dimensionless)	Face Velocity Limit (ft/min)
Legacy	3.6	45	0.0765	500
Today	3.6	45	0.0765	500
21st Century Flight 1	2	40	0.0383	500
21st Century Flight 2	2	40	0.0383	1000
21st Century Flight 3	2	40	0.0191	1000

Ducts

The Navy uses two styles of ductwork – rectangular/square or round, made from either galvanized steel or aluminum. There are also transitions, such as to slow down the flow to a cooling coil, and plenums. Generally, the ductwork is flanged. Water tight ductwork is used below the damage control deck. The routing can be quite complex and often tortuous. Duct velocities are limited to 3600 ft/min for rectangular ducts and 4500 ft/min for round ducts. In order to simplify the concept and to allow consistent quantification, only round ducting is considered in this report.

Table 15 shows the primary characteristics of interest for the ducting in use, either in legacy or today applications, and projections for those characteristics in the 21st Century Flights 1-3 family of components. The difference is in the smoothness (roughness) of the ducts, future ducts will be progressively smoother as coatings are developed and applied. The increased smoothness permits higher velocity limits, for the same or somewhat higher pressure drop, which in turn permits smaller duct sizes for comparable air flow rates.

Table 15 – Performance Characteristics of Ducting

Technology	Velocity Limit (ft/min)	Roughness (ft)
Legacy	4500	0.0003
Today	4500	0.0003
21st Century Flight 1	9000	0.0001
21st Century Flight 2	9000	0.00005
21st Century Flight 3	12000	0.000025

In addition, some maintenance benefits, such as less likely to accumulate dirt and debris and superior corrosion resistance may be realized.

HVAC System Model

Structure

The HVAC System Model consists of four basic sections – inputs, psychrometrics, component selection, and system results. There are 3 versions of the system model – recirculation, supply and exhaust with the latter two essentially identical.

A sample of the input section is shown in Table 16. The inputs can be linked to a compartment model, if the system serves only a single compartment, or, if multiple compartments are served by the system, to a summary spreadsheet where all the compartments parameters are summed. The inputs begin with the system identification and identification of the compartment(s). Next, compartment and weather air temperatures (both wet bulb and dry bulb) are specified. The specific compartment total loads, required flow rates, both to the compartment and replenishment air, are then entered. The system equivalent duct and chilled water pipe lengths are then entered. Determination of these for an actual system is complex, for a notational system, a reasonable estimate can be entered and comparisons can be made based on the technology selected. The technology level is selected from a menu – legacy, today, 21st Century Flight 1, 2, or 3. The type of system is also selected from a menu – vaneaxial fan and duct cooling coil, CPS fan and duct cooling coil, centrifugal fan and duct cooling coil, FCA or FCU. Finally, the number of fans and cooling coils for the system specified. The critical parameters are highlighted.

Table 16 – System Model Input Sample

Inputs	
System	RS2-105-2 (44)
Compartment Name	Crew Living Space No. 1
Compartment Number	2-78-01-L
Weather Air Dry Bulb Temperature (°F)	90
Weather Air Wet Bulb Temperature (°F)	81
Compartment Air Dry Bulb Temperature (°F)	80
Compartment Air Wet Bulb Temperature (°F)	68
System Damage Control Classification	Z
Total Sensible Load (BTU/hr)	40680
Personnel Latent Load (BTU/hr)	15660
Total Compartment Load (BTU/hr)	56340
Required Replenishment Air Flow Rate (ft^3/min)	435
Required Compartment Flow Rate (ft^3/min)	1811
Duct Equivalent Length (ft)	72
Chilled Water Piping Equivalent Length (ft)	50
Select Technology	Legacy
Select System Type	FCA
Number of Fans	1
Number of Cooling Coils	1

An EXCEL function was written to calculate the psychrometric properties of air, using ASHRAE Fundamentals equations and techniques. In the psychrometric section of the model, this is applied to calculate all relevant state points as shown by the sample below in Table 17.

The highlighted values are the critical results. The replenishment cooling load is based on the replenishment air flow rate and the enthalpy difference between the replenishment air and the compartment air. The total cooling load is the sum of the compartment load (both sensible and latent), the replenishment load and the fan load which is based on the fan selected in the results section.

Table 17 – System Model Psychrometrics Sample

Psychrometrics	
Compartment Air	
Air Dry Bulb Temperature (°F)	80
Air Wet Bulb Temperature (°F)	68
Humidity (%)	54.8
Density (lbm/ft^3)	0.072
Enthalpy (BTU/lbm)	32.31
Replenishment Air	
Air Dry Bulb Temperature (°F)	90
Air Wet Bulb Temperature (°F)	81
Humidity (%)	68.7
Density (lbm/ft^3)	0.070
Enthalpy (BTU/lbm)	44.66
Replenishment Air Cooling Load (BTU/hr)	22584
Mixed Air Entering Coil	
Air Dry Bulb Temperature (°F)	82.4
Air Wet Bulb Temperature (°F)	71.4
Humidity (%)	59.3
Density (lbm/ft^3)	0.072
Enthalpy (BTU/lbm)	35.16
Total Coil Cooling Load (BTU/hr)	93228
Cooling Coil Air Outlet	
Air Dry Bulb Temperature (°F)	55.8
Air Wet Bulb Temperature (°F)	55.0
Humidity (%)	95
Density (lbm/ft^3)	0.076
Enthalpy (BTU/lbm)	23.21
Fan Air Outlet	
Air Dry Bulb Temperature (°F)	63.1
Air Wet Bulb Temperature (°F)	55.0
Humidity (%)	60.5
Density (lbm/ft^3)	0.075
Enthalpy (BTU/lbm)	24.94
Fan Load (BTU/hr)	14304

A sample of the results section is shown in Table 18. Using the required compartment flow rate, the technology selected and the system type, the fan is selected. The performance characteristics for that particular fan are then copied to the results. Similarly, the cooling coil is selected based on the total cooling load, technology selected and system type and the performance parameters copied to the results. Note that the coil face velocity is computed and compared to the limit for the technology selected. The chilled water flow rate is determined based on the cooling load and technology selected. Next the duct size is determined based on the system flow rate and velocity limitation (from the technology selected), the weight and volume calculated based on the equivalent length and the pressure drop calculated. Finally, the chilled water piping size is determined based on the chilled water flow rate , the weight and volume of the piping determined based on the piping equivalent length and a pressure drop calculated.

Table 18 – System Model Results Sample

Results	
Fan Selection	FCA 24
Weight (lbm)	1590
Volume (ft^3)	81.9
Power (hp)	5.0
Fan Load (BTU/hr)	14304
Flow Rate (ft^3/min)	2550
Pressure Available (inches H_2O)	2
Cooling Coil Selection	FCA 25
Weight (lbm)	Included with Fan
Volume (ft^3)	Included with Fan
Chilled Water Inlet Temperature (°F)	45
Chilled Water Flow per Ton of Cooling (gal/min/ton)	3.6
Water Flow (gal/min)	28.0
Face Area (ft^2)	6.2
Face Velocity (ft/min)	292.1
Face Velocity Limit (ft/min)	500
Coil Performance	Acceptable
Air Side Friction Factor (dimensionless)	0.077
Air Pressure Drop (inches H_2O)	0.45
Ducting Size	
Velocity Limit (ft/min)	4500
Minimum Diameter (in)	9
Diameter (in)	10
Weight (lbm)	684.0
Volume (ft^3)	39.3
Duct Velocity (ft/min)	3320
Reynolds Number (dimensionless)	282234
Roughness (ft)	0.0003
Friction Factor (dimensionless)	0.017
Pressure Drop (inches H_2O)	1.0
Chilled Water Piping	
Diameter (in)	1.25
Weight (lbm)	70
Volume (ft^3)	0.8
Velocity (ft/sec)	5.0
Reynolds Number (dimensionless)	43582
Darcy Friction Factor (dimensionless)	0.02
Pressure Drop (lbf/in^2)	0.1

A sample of the system results section is shown in Table 19. The total weight, volume and power are summed for the fan, cooling coil, ducting and chilled water piping and the total air side pressure drop. The air side pressure drop is compared to the fan capability and a determination made if the fan is acceptable on that basis. The weight and volume differences compared to the legacy technology are computed and displayed – ordinarily the technology comparison is made by selecting each technology in adjoining columns.

Table 19 – System Model System Results Sample

System Characteristics	
Weight (lbm)	2343.6
Volume (ft^3)	121.9
Power (hp)	5.0
Total Air Frictional Loss (in H_2O)	1.49
Fan Performance	Acceptable
Weight Differences (% reduction from Legacy)	
Fan Coil Assembly	0.0
Duct	0.0
Chilled Water Piping	0.0
Total	0.0
Volume Differences (% reduction from Legacy)	
Fan Coil Assembly	0.0
Duct	0.0
Chilled Water Piping	0.0
Total	0.0

The supply and exhaust system models follow the same general procedure, however there is no cooling coil selected and the psychrometric section is less complex.

Results

The complete model results for the three recirculation systems, the two supply systems and the one exhaust system are contained in Appendix B. The system results section summary is shown below for each system.

The first system analyzed was RS2-105-2 (44), a non-vital space serving a crew berthing space and employing a fan coil assembly. The results are shown below in Table 20.

Table 20 – System Characteristics for Recirculation System RS2-105-2 (44)

System Characteristics	Legacy	Today	21st Century Flight 1	21st Century Flight 2	21st Century Flight 3
Weight (lbm)	2343.6	2343.6	1586.2	1686.2	999.4
Volume (ft^3)	121.9	121.9	80.4	75.4	39.4
Power (hp)	5.0	5.0	1.0	1.0	1.0
Total Air Frictional	1.49	1.49	3.26	4.04	11.39

System Characteristics	Legacy	Today	21st Century Flight 1	21st Century Flight 2	21st Century Flight 3
Loss (in H_2O)					
Fan Performance	Acceptable	Acceptable	Unacceptable, select bigger fan or higher speed	Unacceptable, select bigger fan or higher speed	Unacceptable, select bigger fan or higher speed
Weight Differences (% reduction from Legacy)					
Fan Coil Assembly	0.0	0.0	-37.1	-30.8	-65.4
Duct	0.0	0.0	-20.0	-20.0	-40.0
Chilled Water Piping	0.0	0.0	-44.4	-44.4	-44.4
Total	0.0	0.0	-32.3	-28.1	-57.4
Volume Differences (% reduction from Legacy)					
Fan Coil Assembly	0.0	0.0	-32.8	-39.0	-69.5
Duct	0.0	0.0	-36.0	-36.0	-64.0
Chilled Water Piping	0.0	0.0	-60.0	-60.0	-60.0
Total	0.0	0.0	-34.0	-38.1	-67.7

As shown in Figure 19, the weight and volume reductions for the 21st Century HVAC system components at the component and system level are dramatic – from 20-60%. In particular, the adoption of low chilled water flow and temperature cooling coils can provide a 40-60% reduction in the chilled water distribution system.

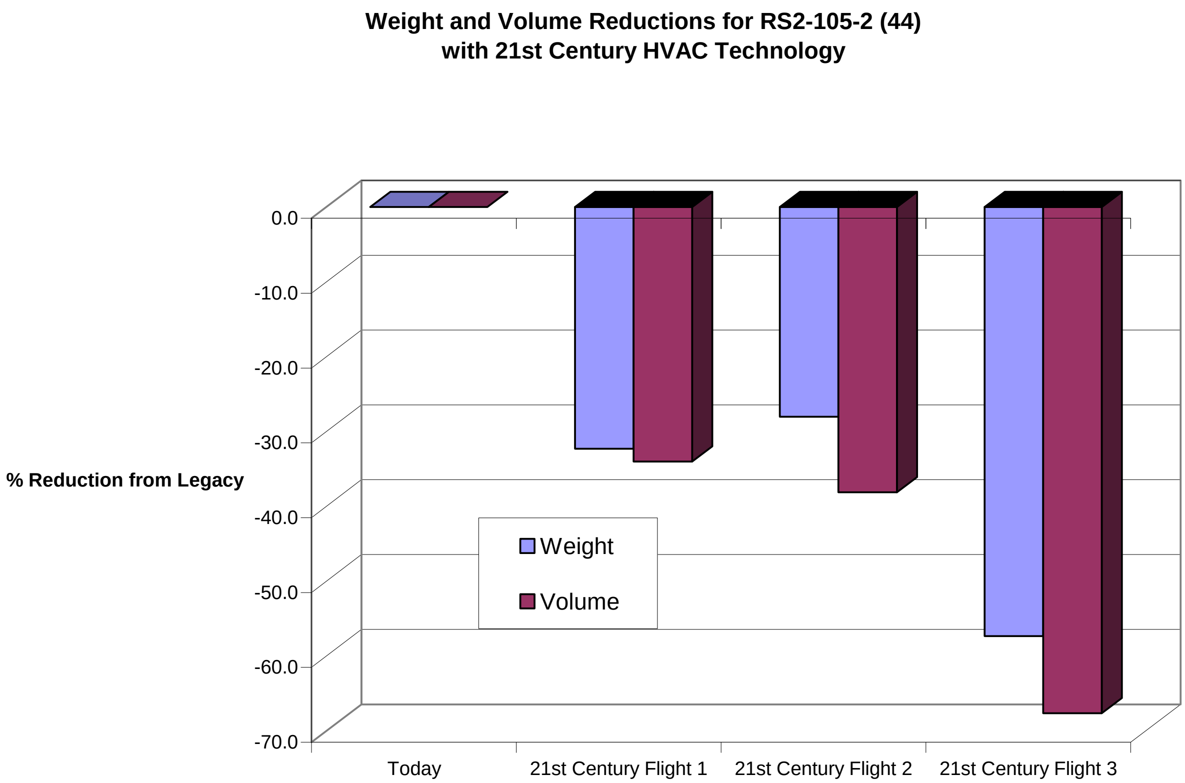

Figure 19 – Weight and Volume Reductions for RS2-105-2 (44) with 21st Century HVAC Technology

While the reductions are based on the aggressive performance goals for the components and the dramatic shifts in design philosophy/paradigms, selection of more modest goals or design philosophy changes will result in lower reductions, the basic premise that advanced components can produce significant savings is clear.

The comments (unacceptable, select bigger fan or higher speed) in Table 20 regarding the fan performance are based on the particular estimated head for the fan selected. Further efforts to better define the needed performance characteristics across the range are necessary as a next step before proceeding to develop that fan family. Similarly, the fan weight for the 21st Century Flight 2 fan is based on the selection of a particular fan applied across a range of flows and better definition of specific flow range for each fan size will be necessary. It is further believed that the characteristics (weight, volume and power) are obtainable to meet the estimated system head at the desired flow rate.

The next system analyzed was RS01-159-1 (13), a vital system serving the Combat Information Center and Projection Area and thus with a large equipment load. The system uses duct mounted cooling coils and a vaneaxial fan.

The results are shown in Table 21.

Table 21 – System Characteristics for Recirculation System RS01-159-1 (13)

System Characteristics	Legacy	Today	21st Century Flight 1	21st Century Flight 2	21st Century Flight 3
Weight (lbm)	5094.3	4632.3	3849.6	3223.3	2530.2
Volume (ft^3)	315.9	315.9	183.8	173.3	118.1
Power (hp)	5.0	5.0	8.3	8.3	8.3
Total Air Frictional Loss (in H_2O)	3.49	3.49	8.99	8.58	19.13
Fan Performance	Acceptable	Acceptable	Unacceptable, select bigger fan or higher speed	Unacceptable, select bigger fan or higher speed	Unacceptable, select bigger fan or higher speed
Weight Differences (% reduction from Legacy)					
Fan	0.0	0.0	41.5	-15.1	-43.4
Cooling Coil	0.0	-34.7	-51.0	-75.5	-87.8
Duct	0.0	0.0	-25.0	-25.0	-37.5
Chilled Water Piping	0.0	0.0	-44.4	-44.4	-44.4
Total	0.0	-9.1	-24.4	-36.7	-50.3
Volume Differences (% reduction from Legacy)					
Fan	0.0	0.0	41.2	-5.9	-52.9
Cooling Coil	0.0	0.0	-50.0	-75.0	-87.5
Duct	0.0	0.0	-43.8	-43.8	-60.9
Chilled Water Piping	0.0	0.0	-23.7	-23.7	-23.7
Total	0.0	0.0	-41.8	-45.1	-62.6

As with the previous recirculation system, the weight and volume reductions are dramatic as shown in Figure 20. The earlier comments regarding the fan comments and fan weight also apply for this system.

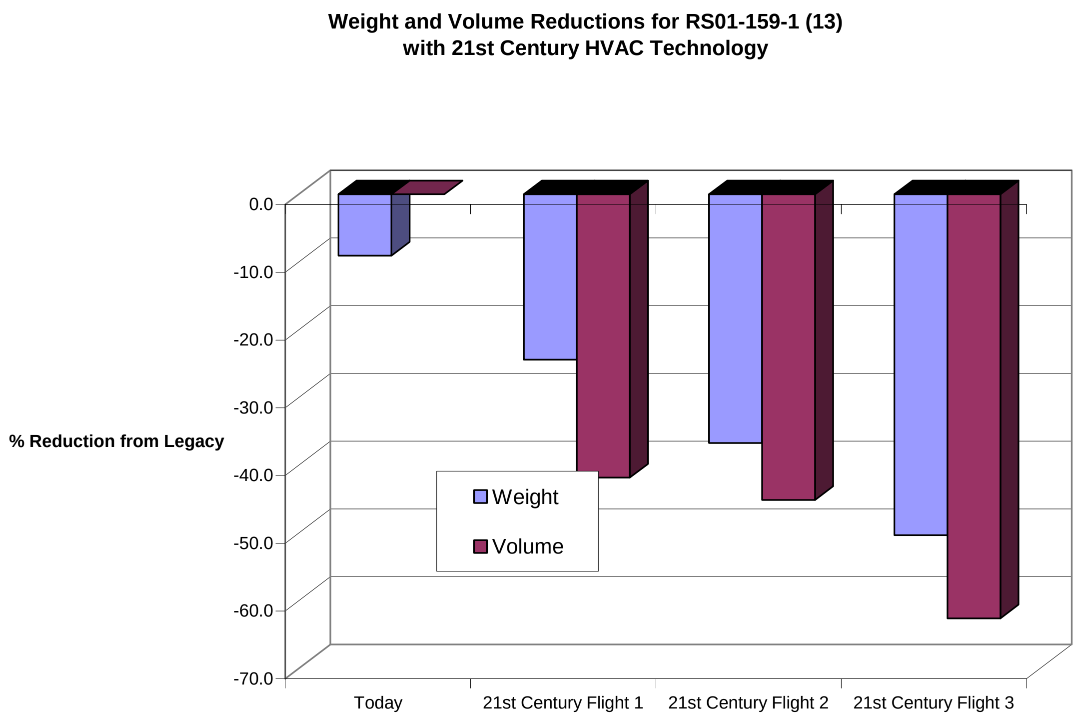

Figure 20 – Weight and Volume Reductions for RS01-159-1 (13) with 21st Century HVAC Technology

The last recirculation system analyzed was RS1-67-2 (21), a vital system serving a large number of compartments and employing a duct mounted cooling coil and a vaneaxial fan. The results are shown below in Table 22.

Table 22 – System Characteristics for Recirculation System RS1-67-2 (21)

System Characteristics	Legacy	Today	21st Century Flight 1	21st Century Flight 2	21st Century Flight 3
Weight (lbm)	1499.4	1268.4	1216.8	928.7	600.2
Volume (ft^3)	44.3	44.3	30.8	25.6	14.2
Power (hp)	2.0	2.0	2.0	2.0	2.0
Total Air Frictional Loss (in H_2O)	1.73	1.73	2.95	2.82	9.82
Fan Performance	Acceptable	Acceptable	Acceptable	Acceptable	Unacceptable, select bigger fan or higher speed
Weight Differences (% reduction from Legacy)					
Fan	0.0	0.0	70.0	20.0	-40.0
Cooling Coil	0.0	-34.7	-51.0	-75.5	-87.8
Duct	0.0	0.0	-20.0	-20.0	-40.0
Chilled Water Piping	0.0	0.0	-44.4	-44.4	-44.4
Total	0.0	-15.4	-18.8	-38.1	-60.0

System Characteristics	Legacy	Today	21st Century Flight 1	21st Century Flight 2	21st Century Flight 3
Volume Differences (% reduction from Legacy)					
Fan	0.0	0.0	128.9	52.6	-23.7
Cooling Coil	0.0	0.0	-50.0	-75.0	-87.5
Duct	0.0	0.0	-36.0	-36.0	-64.0
Chilled Water Piping	0.0	0.0	-36.2	-36.2	-36.2
Total	0.0	0.0	-30.3	-42.1	-67.9

Again, the weight and volume reductions are dramatic as shown in Figure 21.

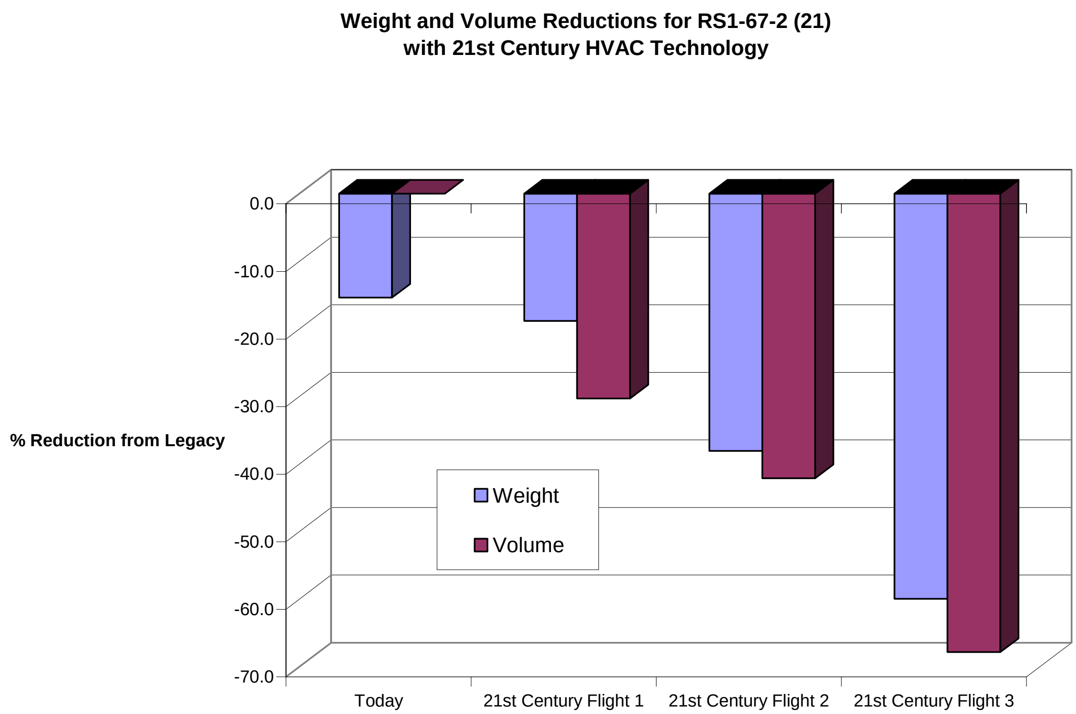

Figure 21 – Weight and Volume Reductions for RS1-67-2 (21) with 21st Century HVAC Technology

The weight and volume reductions for each recirculation system are all similar even though the systems serve quite different functional ship areas and the recirculation system type and loads differ, substantially. This leads to the conclusion that similar reductions in weight and space for all recirculation systems could be achieved.

The first supply system analyzed was SS-01-150-3 (97), which provides ventilation air to Auxiliary Machinery Room 1 employing two vaneaxial fans. The results are shown in Table 23.

Table 23 – System Characteristics for Supply System SS-01-150-3 (97)

System Characteristics	Legacy	Today	21st Century Flight 1	21st Century Flight 2	21st Century Flight 3
Weight (lbm)	6097.5	6097.5	5280.0	4680.0	3907.5
Volume (ft^3)	288.2	288.2	170.6	162.6	120.2
Power (hp)	15.0	15.0	12.8	12.8	12.8

Total Frictional Loss (in H_2O)	0.75	0.75	3.32	3.15	5.88
Fan Performance	Acceptable	Acceptable	Acceptable	Acceptable	Unacceptable, select bigger fan or higher speed
Weight Differences (% reduction from Legacy)					
Fan	0.0	0.0	66.7	0.0	-33.3
Duct	0.0	0.0	-27.3	-27.3	-36.4
Total	0.0	0.0	-13.4	-23.2	-35.9
Volume Differences (% reduction from Legacy)					
Fan	0.0	0.0	117.0	44.7	-27.7
Duct	0.0	0.0	-47.1	-47.1	-59.5
Total	0.0	0.0	-40.8	-43.6	-58.3

As shown, the weight and volume reductions are again significant although not as dramatic as with the recirculation systems, Figure 22. As before, the particular fan selected for the 21st Century Flight 1 application has a broad flow range and better refinement of the flow ranges and sizes will be necessary to ensure optimum application.

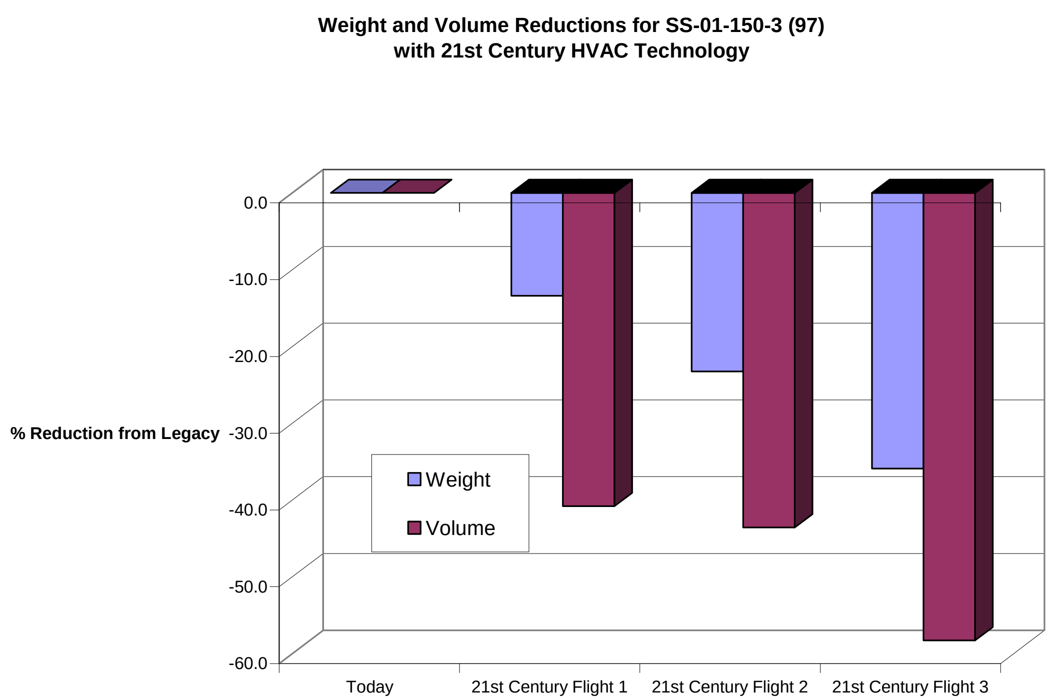

Figure 22 – Weight and Volume Reductions for SS01-150-3 (97) with 21st Century HVAC Technology

The second supply system selected for analysis was SS01-136-1 (82), a CPS system supplying ventilation air and replenishment air to a large number of recirculation systems and compartments, employing two CPS fans. The results of that analysis are shown in Table 24.

Table 24 – System Characteristics for Supply System SS01-136-1 (82)

System Characteristics	Legacy	Today	21st Century Flight 1	21st Century Flight 2	21st Century Flight 3
Weight (lbm)	10555.0	10555.0	8525.0	8045.0	6710.0
Volume (ft^3)	419.8	419.8	260.1	253.9	186.6
Power (hp)	30.0	30.0	22.0	22.0	22.0
Total Frictional Loss (in H_2O)	2.25	2.25	7.04	6.70	13.83
Fan Performance	Acceptable	Acceptable	Acceptable	Acceptable	Acceptable
Weight Differences (% reduction from Legacy)					
Fan	0.0	0.0	3.2	-35.5	-59.7
Duct	0.0	0.0	-22.2	-22.2	-33.3
Total	0.0	0.0	-19.2	-23.8	-36.4
Volume Differences (% reduction from Legacy)					
Fan	0.0	0.0	6.1	-40.2	-55.2
Duct	0.0	0.0	-39.5	-39.5	-55.6
Total	0.0	0.0	-38.1	-39.5	-55.5

As shown in Figure 23, the weight and volume reductions are dramatic, similar to the recirculation system results.

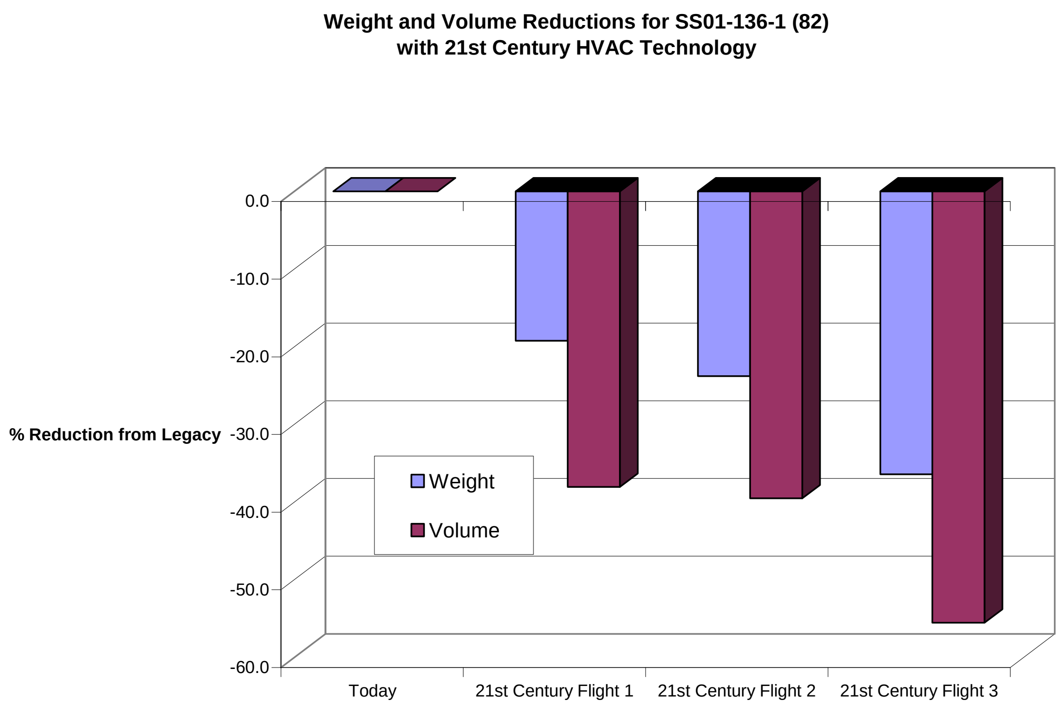

Figure 23 – Weight and Volume Reductions for SS01-136-1 (82) with 21st Century HVAC

The only exhaust system analyzed was ES-01-146-3 (8A) serving Auxiliary Machinery Room 1 employing two vaneaxial fans. The results are shown in Table 25.

Table 25 – System Characteristics for Exhaust System ES-01-146-3 (8A)

System Characteristics	Legacy	Today	21st Century Flight 1	21st Century Flight 2	21st Century Flight 3
Weight (lbm)	5515.0	5515.0	4740.0	4140.0	3435.0
Volume (ft^3)	254.6	254.6	149.7	141.7	104.2
Power (hp)	10.0	10.0	16.5	16.5	16.5
Total Frictional Loss (in H_2O)	0.83	0.83	3.65	3.47	6.46
Fan Performance	Acceptable	Acceptable	Acceptable	Acceptable	Unacceptable, select bigger fan or higher speed
Weight Differences (% reduction from Legacy)					
Fan	0.0	0.0	41.5	-15.1	-43.4
Duct	0.0	0.0	-27.3	-27.3	-36.4
Total	0.0	0.0	-14.1	-24.9	-37.7
Volume Differences (% reduction from Legacy)					
Fan	0.0	0.0	41.2	-5.9	-52.9
Duct	0.0	0.0	-47.1	-47.1	-59.5
Total	0.0	0.0	-41.2	-44.4	-59.1

As shown in Figure 24, the weight and volume reductions are substantial, similar to the supply system and recirculation system results.

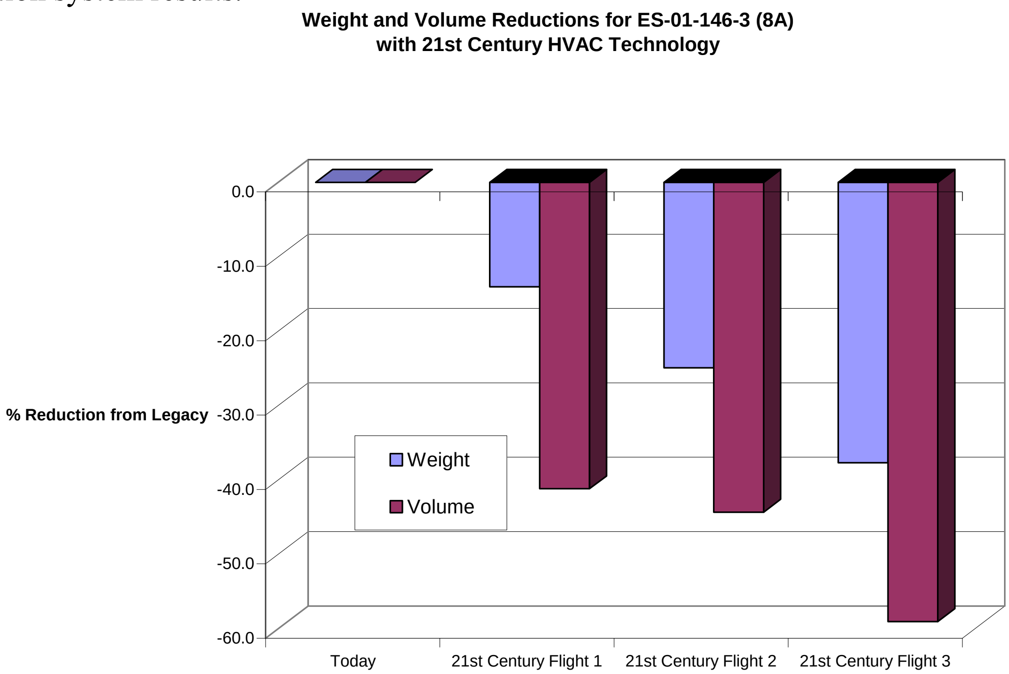

Figure 24 – Weight and Volume Reductions for ES01-146-3 (8A) with 21st Century HVAC

As a general conclusion, the 21st Century HVAC system components and design philosophy/paradigm shifts will produce significant weight and volume reductions across the ship regardless of system type, functional areas served, loads, or system function - recirculation, supply or exhaust. On DDG 91, the total weight of the HVAC System is approximately 350,000 lbm (obtained from the DDG 91 detailed weight report). It is apparent that weight reductions of 30-60% are significant and worth pursuing. Further, the chilled water system weight is approximately 150,000 lbm. Chilled water system weight reductions of 40-50%, by use of low chilled water temperature/low chilled water flow rates cooling coils, are also significant and worth pursuing.

HVAC Total Ship Model

In order to assess the benefits of certain aspects of the 21st Century HVAC System, a simplified model of the total ship HVAC system was developed. In this model, the non-HVAC chilled water loads are listed and added to the HVAC chilled water loads to provide the total ship chilled water load and to define the quantity of AC plants necessary to support that load, using standard Navy policy regarding the number of AC plants. At the total ship level, the benefits of automation and VAV as reflected in total ship fan power become apparent. The impact of potential paradigm shifts as larger combat related cooling loads are added can also be assessed.

A sample of the Total Ship HVAC Model results is shown in Table 26. The model process begins with the inputs – identification of the ship/design concept, the particular condition being examined, the capacity of the AC plants, the weather air and compartment air conditions and the number of personnel. Significant inputs and results are highlighted. Next, the non-HVAC related chilled water loads are entered and summed. Inputs for a new category, for the 21st Century HVAC system concept, similar to the non-HVAC chilled water loads follows and will be detailed later in this report. Next, the HVAC system loads are entered for the vital (combat) and non-vital systems. These are the ship totals, created by summing all of the individual compartment level elements for the ship or estimates if a concept ship is being modeled. The total fan power, again summed from each recirculation, supply and exhaust system follows. The vital cooling load is determined by adding the vital HVAC system load and the non-HVAC chilled water load and the number of AC plants required (based on the input AC plant capacity) to meet that load determined. The non-vital HVAC system cooling load is then added to determine the cruise load and the number of AC plants required to meet the cruise load determined. The power required to meet the cooling load is calculated based on 0.85 kw/ton of cooling, a representative value for production of 44°F chilled water and rejection to seawater at 97°F, to be discussed later in this report. A kw/ton of 0.79-0.80 is more appropriate for the DDG 51 Class ships where the rejection to seawater design temperature is 88°F. The AC plant power is then added to the fan power and the intermediate sink system power,if used, to produce the total cooling system power. Finally, the psychrometric properties are detailed.

Table 26 – Total Ship HVAC Model

Ship >>>>>>	**DDG 91 Design**
Condition >>>>>>>	**Summing from Compartment Spreadsheets**
Inputs -	

AC Plant Size (tons)	200
Weather Air Dry Bulb Temperature (°F)	90
Weather Air Wet Bulb Temperature (°F)	81
Cooled Compartment Dry Bulb Temperature (°F)	80
Cooled Compartment Wet Bulb Temperature (°F)	68
Number of Personnel	323
Non-HVAC Chilled Water Loads (tons)	
Rast	2
SQS-53 - via intermediate demineralized FW loop	18.5
C&D - via intermediate demineralized FW loop	48.9
SLQ-32 - via intermediate demineralized FW loop	2.6
LP Air Condenser Filter	6.6
AC Plant TPE	6.4
AC Plant Lube Oil Cooler	31.8
Reefer TPE	2.8
CEC Environmental Unit	6.4
CEC Data Terminal	1.56
SPY Antenna	30.3
Total Non-HVAC Chilled Water Loads (tons)	157.8
21st Century Intermediate Water Sink Loads (tons)	
Former intermediate demineralized FW loop loads	0.0
CEC Environmental Unit	0.0
CEC Data Terminal	0.0
Former HVAC Equipment Loads	0.0
New Loads	0.0
Total Intermediate Water Sink Loads (tons)	0.0
Intermediate Sink Power (kw)	0.0
HVAC Loads	
Vital - (W) + W	
Replenishment Air Flow (ft^3/min)	10600
Compartment Air Flow (ft^3/min)	100895
Fan Power (hp)	176.1
Transmission Load (tons)	39.6
Lighting Load (tons	15.7
Personnel Load (tons)	12.2
Personnel Latent Load (tons)	17.1
Equipment Load (tons)	134.3
Equipment Direct Return Load (tons)	19.4
Replenishment Air Load (tons)	45.9
Fan Load (tons)	41.5
Piping Load (tons)	0
Total (tons)	325.7

Non-Vital - (Z) + Z	
Replenishment Air Flow (ft3/min)	5240
Compartment Air Flow (ft3/min)	41825
Fan Power (hp)	73.5
Transmission Load (tons)	1.4
Lighting Load (tons)	13.4
Personnel Load (tons)	4.4
Personnel Latent Load (tons)	5.9
Equipment Load (tons)	107.9
Equipment Direct Return Load (tons)	0
Replenishment Air Load (tons)	22.7
Fan Load (tons)	17.3
Piping Load (tons)	24.8
Total (tons)	197.9
Fans	
Recirculation Fan Power (hp)	249.6
Supply System Fan Power (hp)	181.7
Exhaust System Fan Power (hp)	87.5
Total Fan Power (hp)	518.8
Total Fan Power (kw)	430.0
Total Vital Chilled Water Load (tons)	483.5
Required Number of AC Plants for Combat Load	3
Total Cruise Chilled Water Load (tons)	681.4
Required Number of AC Plants for Cruise Load	5
AC Plant Power (kw)	579.2
Total Cooling System Power (kw)	1009.2
Psychrometrics	
Compartment Air	
Air Dry Bulb Temperature (°F)	80
Air Wet Bulb Temperature (°F)	68
Humidity (%)	54.8
Density (lbm/ft^3)	0.072
Enthalpy (BTU/lbm)	32.31
Vital Replenishment Air	
Air Dry Bulb Temperature (°F)	90
Air Wet Bulb Temperature (°F)	81
Humidity (%)	68.7
Density (lbm/ft^3)	0.070

Enthalpy (BTU/lbm)	44.66
Replenishment Air Cooling Load (BTU/hr)	550330
Non-Vital Replenishment Air	
Air Dry Bulb Temperature (°F)	90
Air Wet Bulb Temperature (°F)	81
Humidity (%)	68.7
Density (lbm/ft^3)	0.070
Enthalpy (BTU/lbm)	44.66
Replenishment Air Cooling Load (BTU/hr)	272050

In a fully functional (not the simple macro level model shown herein) Total Ship HVAC System model, all of the individual supply, recirculation and exhaust systems would be linked and summed to provide the inputs.

In the discussion that follows, for brevity, only the relevant portions of the model results will be shown. Each of the following sections addresses an element of the 21st Century HVAC System at the total ship level. Not all of the benefits are readily quantifiable.

Automation

In the 21st Century HVAC System, the HVAC system will be managed and controlled at the total ship level. When General Quarters is sounded, the ship can be reconfigured, quickly, at the press of a button or touch of a screen or via entering a command. The non-vital HVAC systems can be shed and all available cooling directed to vital compartments and needs. If damage occurs, the involved HVAC systems can be disabled and/or reconfigured. Levels of criticality can be established so that the most vital needs can be served in the event of damage. Selected systems can be underserved to maintain life but not necessarily comfort while that cooling is diverted to a more vital function. Some of the new weapon systems will be sporadic, requiring cooling for only brief periods, and diversion of cooling from less vital areas to serve those needs may be an acceptable approach – essentially the installed cooling capacity can be based on the combat system needs alone instead of the combat and non-vital needs.

Generation of a case to quantify the automation benefits is difficult without more detailed characteristics of future weapon/sensor systems cooling and operational requirements – "normal" and maximum cooling load, expected usage and cycle. However, the flexibility of the arrangement and the ability to provide cooling where and when needed clearly provides tangible if un-quantifiable benefits.

Variable Air Volume (VAV)

In the legacy and in the current (today) design approach, the cooling system design is based on a static, almost worst case, condition. This is necessary to ensure that adequate cooling is provided regardless of the actual compartment cooling load. This is necessary because the current/legacy system is a constant volume air distribution system - the air flow rates are determined during design, set during construction, and are fixed during operation. In the 21st Century HVAC System, a "VAV" distribution system will be used - the compartment air flow will vary directly in response to the cooling load. Instead of a simple thermostat closing a solenoid valve feeding the chilled water cooling coil when the compartment temperature is satisfied (legacy/current approach), the air flow into the compartment will be reduced (via variable speed fans and dampers) as the set point temperature is approached. The airflow will increase as the compartment actual temperature and set point diverge. This approach compensates for all of the variable cooling loads within the compartment – personnel, transmission, lighting and most significantly equipment. In addition, the variable fan speed will result in lower fan power which is also a cooling load.

Creating a condition to adequately determine the benefits of the VAV system at the total ship level becomes difficult - the results will be based solely on the variability of assumed loads and will therefore be quite arguable. However, it is clear that a dynamic system able to respond to the variable cooling loads, as in the VAV approach, is preferable to a static system unable to respond to variable load changes.

Although capturing the full benefits of the VAV system at the total ship level is difficult, the benefits can be determined for some elements of the total cooling load.

For instance, in the static analysis, personnel are accounted for multiple times – at work, at rest/recreation/dining and in berthing. In the actual dynamic operation of the system, there is no means to determine where the personnel are, either directly with a personnel locator tag system or based on the cooling load they produce. In the VAV system, the personnel load can be met wherever they may be. As shown in Table 27, although there are 323 personnel on a DDG 51 Class ship, the personnel cooling load accounts for 833 personnel (by summing all of the individual compartment numbers). For the comparison, all of the personnel, in the actual case, are listed under the vital load category and the personnel loads for that case were based on the working load per person. The comparison shows that there is an additional 25 tons of cooling required to meet the static design requirement.

Table 27 – Total Ship HVAC Model – Effect of Personnel

Ship >>>>>>	**DDG 91 Design**	**DDG 91 Design**
Condition >>>>>>>	**Number of personnel from compartment summing**	**Number of personnel - actual**
Number of Personnel	833	323
HVAC Loads		
Vital - (W) + W		
Personnel Load (tons)	16.7	6.5
Personnel Latent Load (tons)	25.0	9.7
Total (tons)	338.0	312.5
Non-Vital - (Z) + Z		
Personnel Load (tons)	0.0	0.0
Personnel Latent Load (tons)	0.0	0.0
Total (tons)	187.5	187.5
Total Vital Chilled Water Load (tons)	495.9	470.4
Total Cruise Chilled Water Load (tons)	683.4	657.9

In a similar manner, replenishment air flows are also based on the static personnel count. In addition, at the supply system level, minimum flow rates are necessary (because of the inability to adequately control the flows and ensure the correct amount is being supplied), e.g., a compartment may require only 20 ft^3/min of replenishment air but will receive 50 ft^3/min. As shown in Table 28, the oversupply of replenishment air is on the order of 10%, because of the minimum flow requirement, and approximately 3X the required flow rate for the number of personnel actually on the ship. The replenishment flow per person was based on the at work requirement. The effect on the total ship cooling load is about 45 tons. In order to realize this benefit of the VAV system, location of the personnel is necessary. The damage control system personnel identification tag, under development, could fulfill this need. Alternatively, measuring the CO_2 content in each compartment would provide a direct indication of the number of personnel and the replenishment air requirement. The CO_2 sensing element could be incorporated into the compartment dry bulb and wet bulb temperature sensing device.

Table 28 – Total Ship HVAC Model – Effect of Replenishment Air Flow

Ship >>>>>>	**DDG 91 Design**	**DDG 91 Design**	**DDG 91 Design**
Condition >>>>>>>	**Replenishment Air Flow Based on Sum of Compartment Replenishment Air Requirements**	**Replenishment Air Flow based on Sum of Supply System Flows**	**Replenishment Air Flow Based on Number of Personnel**
Inputs -			
Number of Personnel	323	323	323
HVAC Loads			
Vital - (W) + W			
Replenishment Air Flow (ft^3/min)	10600	17485	6460
Compartment Air Flow (ft^3/min)	100895	100895	100895
Total (tons)	325.7	355.4	294.6
Non-Vital - (Z) + Z			
Replenishment Air Flow (ft3/min)	5240	0	0
Compartment Air Flow (ft3/min)	41825	41825	41825
Total (tons)	197.9	175.2	164.9
Total Vital Chilled Water Load (tons)	483.5	513.3	452.4
Required Number of AC Plants for Combat Load	3	3	3
Total Cruise Chilled Water Load (tons)	681.4	688.5	617.3
Required Number of AC Plants for Cruise Load	5	5	5
AC Plant Power (kw)	579.2	585.2	524.7
Total Cooling System Power	1009.2	1015.2	954.7

(kw)			

The primary quantifiable benefit of the VAV concept is reduced fan power consumption at off design conditions. In Table 29, the model results for a "DDG 91" ship using the 21st Century HVAC System technology, specifically the advanced efficient fan designs and the low chilled water flow and temperature cooling coils, is compared to the DDG 91 at the design condition and at a more moderate condition. Note the substantially lower fan power at the comparable design condition and the lower fan power at the off design condition. The total power consumption reflects a higher AC plant specific power consumption, 0.91 kw/ton which was calculated based on a 40°F chilled water supply temperature.

Table 29 – Total Ship HVAC Model – Effect of VAV at Off Design Conditions

Ship >>>>>>	DDG 91 Design	DDG 91 Using 21st Century Technology	DDG 91 Using 21st Century Technology
Condition >>>>>>>	Replenishment Air Flow based on number of personnel and using actual number of personnel	VAV Fans, Advanced Cooling Coils, Design Condition Weather	VAV Fans, Advanced Cooling Coils, 80F Weather
Inputs -			
Weather Air Dry Bulb Temperature (°F)	90	90	80
Weather Air Wet Bulb Temperature (°F)	81	81	71
Cooled Compartment Dry Bulb Temperature (°F)	80	80	80
Cooled Compartment Wet Bulb Temperature (°F)	68	68	68
Number of Personnel	323	323	323
HVAC Loads			
Vital - (W) + W			
Replenishment Air Flow (ft^3/min)	6460	6460	6460
Compartment Air Flow (ft^3/min)	100895	100895	77712
Fan Power (hp)	176.1	132.1	60.4
Transmission Load (tons)	39.6	39.6	13.2
Replenishment Air Load (tons)	27.9	27.9	5.9
Fan Load (tons)	41.5	31.1	14.2
Total (tons)	294.6	284.2	218.9
Non-Vital - (Z) + Z			
Replenishment Air Flow (ft3/min)	0	0	0
Compartment Air Flow (ft3/min)	41825	41825	41825
Fan Power (hp)	73.5	55.1	55.1
Transmission Load (tons)	1.4	1.4	1.4

Ship >>>>>>	DDG 91 Design	DDG 91 Using 21st Century Technology	DDG 91 Using 21st Century Technology
Condition >>>>>>>	Replenishment Air Flow based on number of personnel and using actual number of personnel	VAV Fans, Advanced Cooling Coils, Design Condition Weather	VAV Fans, Advanced Cooling Coils, 80F Weather
Replenishment Air Load (tons)	0.0	0.0	0.0
Fan Load (tons)	17.3	13.0	13.0
Total (tons)	164.9	160.5	160.5
Fans			
Recirculation Fan Power (hp)	249.6	187.2	115.5
Supply System Fan Power (hp)	181.7	136.3	84.0
Exhaust System Fan Power (hp)	87.5	66	40
Total Fan Power (hp)	518.8	389.1	240.0
Total Fan Power (kw)	430.0	322.5	198.9
Total Vital Chilled Water Load (tons)	452.4	442.1	376.8
Required Number of AC Plants for Combat Load	3	3	2
Total Cruise Chilled Water Load (tons)	617.3	602.6	537.3
Required Number of AC Plants for Cruise Load	5	5	4
AC Plant Power (kw)	524.7	548.4	488.9
Total Cooling System Power (kw)	954.7	870.9	687.9

Intermediate Temperature Heat Sink

The chilled water load can be divided into two categories – equipment and hotel. The equipment load is the sum of the non-HVAC chilled water loads and the HVAC equipment load. The hotel load is the sum of the individual HVAC loads (personnel, lighting, transmission, piping, fan load and replenishment air load) less the equipment load. This distribution is shown in Figure 25. The chilled water load is clearly dominated by the equipment cooling requirement.

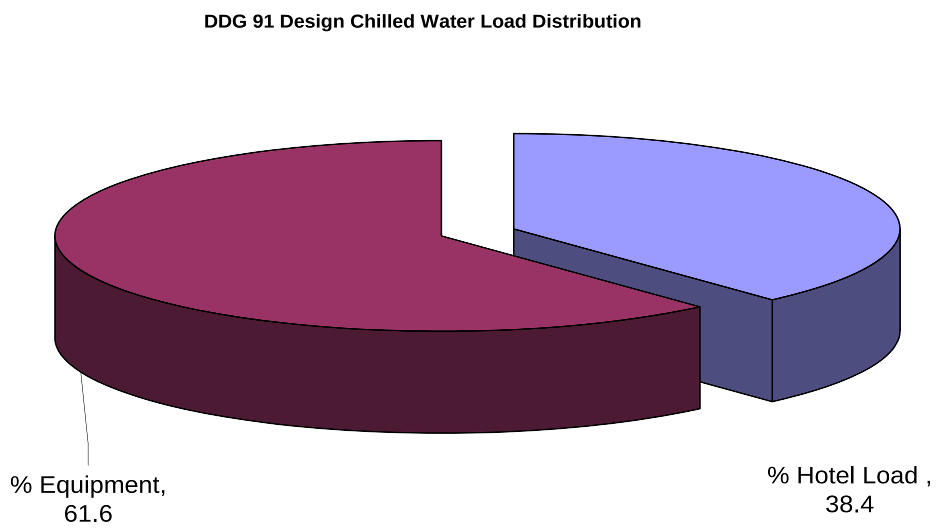

Figure 25 – DDG 91 Chilled Water Load Distribution

Equipment cooling using 40-44°F water is not absolutely necessary; it is used as a matter of convenience. Further, cooling equipment using the HVAC system is inefficient – chilled water cools air to 50-55°F which mixes with compartment air at 80°F before entering the equipment. So, the equipment is being cooled by essentially 80°F air.

On a Future Surface Combatant, the addition of a portion of the future projected thermal load increase (a notational additional 500-tons directly to the chilled water system and 500-tons to the HVAC System), and using the 21st Century HVAC System Technology, results in a dramatic impact to the Total Ship HVAC System as shown in Table 30. DDG 91 loads were used as the baseline. Important entries and results are highlighted.

Table 30 – Effect of Additional 1000-ton Thermal Load on Future Combatant

Ship >>>>>>	DDG 91 Using 21st Century Technology	Future Combatant Using 21st Century Technology
Condition >>>>>>>	VAV Fans, Advanced Cooling Coils	VAV Fans, Advanced Cooling Coils, Large New Loads
Inputs -		
AC Plant Size (tons)	200	200
Weather Air Dry Bulb Temperature (°F)	90	90
Weather Air Wet Bulb Temperature (°F)	81	81
Cooled Compartment Dry Bulb Temperature (°F)	80	80
Cooled Compartment Wet Bulb Temperature (°F)	68	68
Number of Personnel	323	100

Ship >>>>>>	DDG 91 Using 21st Century Technology	Future Combatant Using 21st Century Technology
Non-HVAC Chilled Water Loads (tons)		
Rast	2	2
SQS-53 - via intermediate demineralized FW loop	18.5	18.5
C&D - via intermediate demineralized FW loop	48.9	48.9
SLQ-32 - via intermediate demineralized FW loop	2.6	2.6
LP Air Condenser Filter	6.6	6.6
AC Plant TPE	6.4	6.4
AC Plant Lube Oil Cooler	31.8	31.8
Reefer TPE	2.8	2.8
CEC Environmental Unit	6.4	6.4
CEC Data Terminal	1.56	1.56
SPY Antenna	30.3	30.3
New Load		500.0
Total Non-HVAC Chilled Water Loads (tons)	157.8	657.8
HVAC Loads		
Vital - (W) + W		
Replenishment Air Flow (ft^3/min)	6460	2000
Compartment Air Flow (ft^3/min)	100895	288078
Fan Power (hp)	132.1	377.1
Transmission Load (tons)	39.6	39.6
Lighting Load (tons	15.7	15.7
Personnel Load (tons)	6.5	2.0
Personnel Latent Load (tons)	9.7	3.0
Equipment Load (tons)	134.3	634.3
Equipment Direct Return Load (tons)	19.4	19.4
Replenishment Air Load (tons)	27.9	8.7
Fan Load (tons)	31.1	88.9
Piping Load (tons)	0	0
Total (tons)	284.2	811.6
Non-Vital - (Z) + Z		
Replenishment Air Flow (ft3/min)	0	0
Compartment Air Flow (ft3/min)	41825	41825
Fan Power (hp)	55.1	55.1
Transmission Load (tons)	1.4	1.4
Lighting Load (tons)	13.4	13.4
Personnel Load (tons)	0.0	0.0
Personnel Latent Load (tons)	0.0	0.0
Equipment Load (tons)	107.9	107.9
Equipment Direct Return Load (tons)	0	0
Replenishment Air Load (tons)	0.0	0.0
Fan Load (tons)	13.0	13.0

Ship >>>>>>	DDG 91 Using 21st Century Technology	Future Combatant Using 21st Century Technology
Piping Load (tons)	24.8	24.8
Total (tons)	160.5	160.5
Fans		
Recirculation Fan Power (hp)	187.2	432.2
Supply System Fan Power (hp)	136.3	136.3
Exhaust System Fan Power (hp)	66	66
Total Fan Power (hp)	389.1	634.1
Total Fan Power (kw)	322.5	525.6
Total Vital Chilled Water Load (tons)	442.1	1469.4
Required Number of AC Plants for Combat Load	3	8
Total Cruise Chilled Water Load (tons)	602.6	1629.9
Required Number of AC Plants for Cruise Load	5	10
AC Plant Power (kw)	548.4	1483.2
Total Cooling System Power (kw)	870.9	2008.9

As shown, an additional 5 AC Plants are required; the total cooling system power required increases by 150%. A portion of the power increase is caused by the additional fan power needed to move significantly more air through the compartments where the additional equipment HVAC loads are located. The equipment load fraction has increased to 87% as shown by Figure 26.

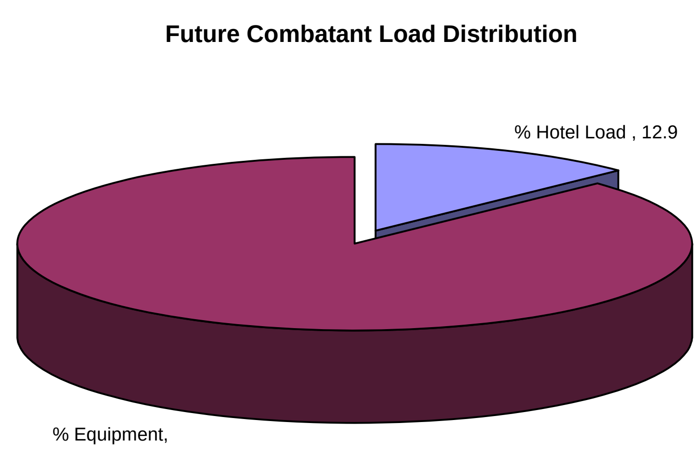

Figure 26 – Load Distribution for Future Surface Combatant with Large Additional Thermal Load

HVAC equipment cooling is accomplished by drawing compartment air at 80°F through the equipment and exhausting the heated air back into the compartment, or in some cases exhausting the heated air directly into the return ductwork. Incorporation of an intermediate sink temperature loop, at a notational 65°F, for cooling the HVAC equipment loads and the non-HVAC chilled water loads is an alternative thermal management strategy which provides significant benefits. The intermediate sink fluid would be circulated directly through the equipment using either conventional cold plate designs or a cooling coil and closed system recirculation fan within the equipment. The intermediate loop would be cooled by dedicated intermediate sink cooling systems, essentially identical to the AC plants, except the cooling water outlet temperature would be 65°F instead of 40-45°F. This will dramatically lower the power consumption of these units from the 0.85-0.91 kw/ton of an AC plant to only 0.55 kw/ton for the intermediate sink plant. Further, directly cooling the HVAC equipment with the intermediate loop will substantially reduce the recirculation fan power requirement. A schematic of this concept is shown in Figure 27.

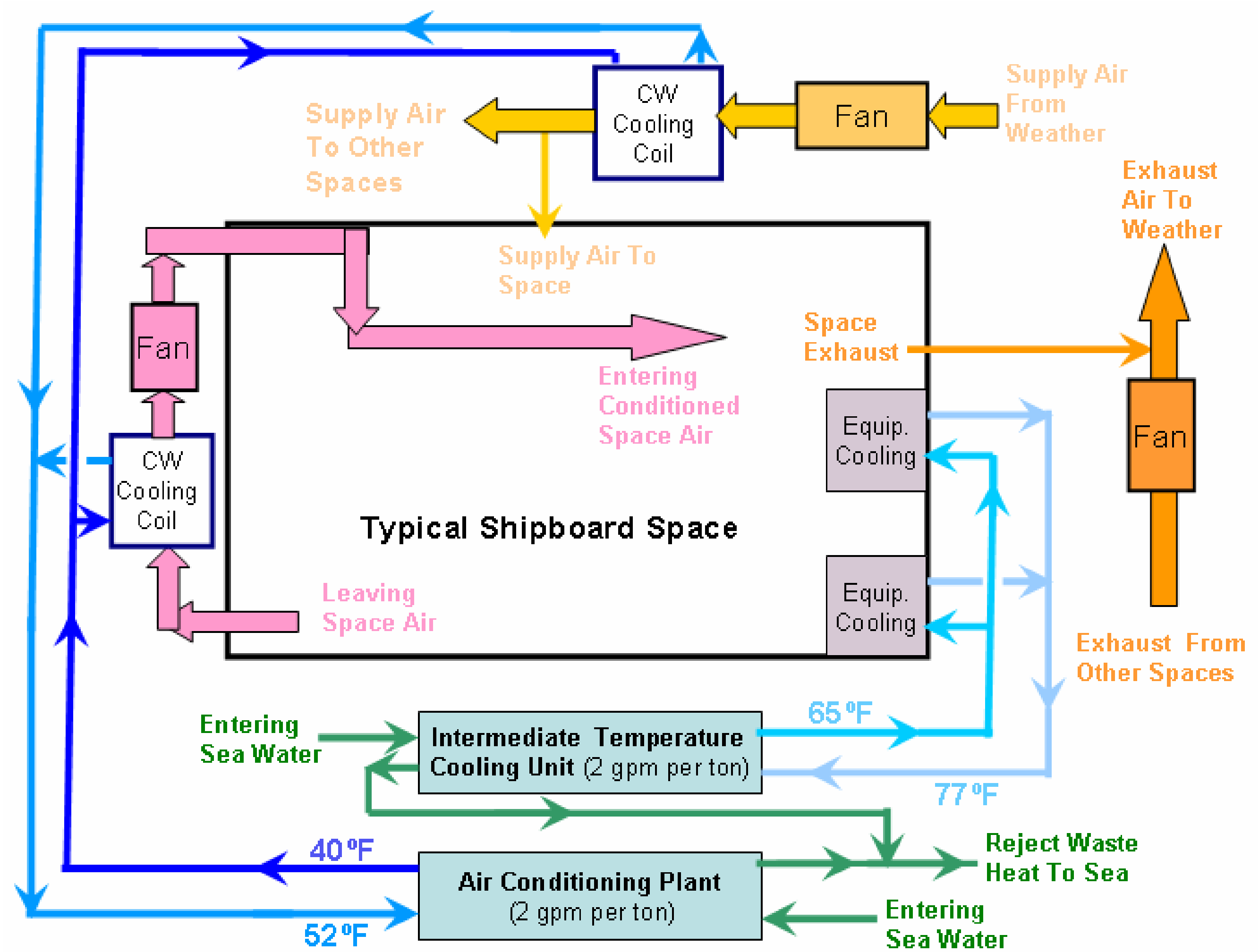

Figure 27 - Intermediate Water Heat Sink Concept Schematic

Table 31 shows the impact of an intermediate temperature loop on the cooling system power and number of AC plants for a Future Surface Combatant using DDG 91 technology and methods, using the 21st Century technology and methods, and using the Intermediate Heat Sink Concept.

Table 31 – Impact of Intermediate Heat Sink on Total Ship Cooling System for Future Surface Combatant with Large Thermal Load Increase

Ship >>>>>>	Future Combatant Using DDG 91 Technology	Future Combatant Using 21st Century Technology	Future Combatant Using 21st Century Technology
Condition >>>>>>>	Constant Speed, Low Efficiency Fans, Legacy Cooling Coils, Large New Loads No Intermediate Heat Sink System	VAV Fans, Advanced Cooling Coils, Large New Loads, No Intermediate Heat Sink System	VAV Fans, Advanced Cooling Coils, Large New Loads, with Intermediate Heat Sink System
Inputs -			
AC Plant Size (tons)	200	200	200
Weather Air Dry Bulb Temperature (°F)	90	90	90
Weather Air Wet Bulb Temperature (°F)	81	81	81
Cooled Compartment Dry Bulb Temperature (°F)	80	80	80
Cooled Compartment Wet Bulb Temperature (°F)	68	68	68
Number of Personnel	600	100	100
Non-HVAC Chilled Water Loads (tons)			
Rast	2	2	2
SQS-53 - via intermediate demineralized FW loop	18.5	18.5	0.0
C&D - via intermediate demineralized FW loop	48.9	48.9	0.0
SLQ-32 - via intermediate demineralized FW loop	2.6	2.6	0.0
LP Air Condenser Filter	6.6	6.6	6.6
AC Plant TPE	6.4	6.4	6.4
AC Plant Lube Oil Cooler	31.8	31.8	31.8
Reefer TPE	2.8	2.8	2.8
CEC Environmental Unit	6.4	6.4	0.0
CEC Data Terminal	1.56	1.56	0
SPY Antenna	30.3	30.3	0.0
New Load	500.0	500.0	
Total Non-HVAC Chilled Water Loads (tons)	657.8	657.8	49.6
21st Century Intermediate Water Sink Loads (tons)			

Ship >>>>>>	Future Combatant Using DDG 91 Technology	Future Combatant Using 21st Century Technology	Future Combatant Using 21st Century Technology
Condition >>>>>>>	Constant Speed, Low Efficiency Fans, Legacy Cooling Coils, Large New Loads No Intermediate Heat Sink System	VAV Fans, Advanced Cooling Coils, Large New Loads, No Intermediate Heat Sink System	VAV Fans, Advanced Cooling Coils, Large New Loads, with Intermediate Heat Sink System
Former intermediate demineralized FW loop loads	0.0	0.0	60.0
CEC Environmental Unit	0.0	0.0	6.4
CEC Data Terminal	0.0	0.0	1.6
Spy Antenna	0.0		500.0
Former HVAC Equipment Loads		0.0	149.7
New Loads	0.0	0.0	500.0
Total Intermediate Water Sink Loads (tons)	0.0	0.0	1217.7
Intermediate Sink Power (kw)	0.0	0.0	669.7
HVAC Loads			
Vital - (W) + W			
Replenishment Air Flow (ft^3/min)	10600	2000	2000
Compartment Air Flow (ft^3/min)	326257	288078	39621
Fan Power (hp)	569.5	377.1	51.9
Transmission Load (tons)	39.6	39.6	39.6
Lighting Load (tons	15.7	15.7	15.7
Personnel Load (tons)	12.0	2.0	2.0
Personnel Latent Load (tons)	18.0	3.0	3.0
Equipment Load (tons)	634.3	634.3	0.0
Equipment Direct Return Load (tons)	19.4	19.4	0.0
Replenishment Air Load (tons)	45.9	8.7	8.7
Fan Load (tons)	134.3	88.9	12.2
Piping Load (tons)	0	0	0
Total (tons)	919.1	811.6	81.2
Non-Vital - (Z) + Z			
Replenishment Air Flow (ft3/min)	5240	0	0
Compartment Air	41825	41825	41825

Ship >>>>>>	Future Combatant Using DDG 91 Technology	Future Combatant Using 21st Century Technology	Future Combatant Using 21st Century Technology
Condition >>>>>>>	Constant Speed, Low Efficiency Fans, Legacy Cooling Coils, Large New Loads No Intermediate Heat Sink System	VAV Fans, Advanced Cooling Coils, Large New Loads, No Intermediate Heat Sink System	VAV Fans, Advanced Cooling Coils, Large New Loads, with Intermediate Heat Sink System
Flow (ft3/min)			
Fan Power (hp)	73.5	55.1	55.1
Transmission Load (tons)	1.4	1.4	1.4
Lighting Load (tons)	13.4	13.4	13.4
Personnel Load (tons)	0.0	0.0	0.0
Personnel Latent Load (tons)	0.0	0.0	0.0
Equipment Load (tons)	107.9	107.9	107.9
Equipment Direct Return Load (tons)	0	0	0
Replenishment Air Load (tons)	22.7	0.0	0.0
Fan Load (tons)	17.3	13.0	13.0
Piping Load (tons)	24.8	24.8	24.8
Total (tons)	187.5	160.5	160.5
Fans			
Recirculation Fan Power (hp)	643.0	432.2	107.0
Supply System Fan Power (hp)	181.7	136.3	136.3
Exhaust System Fan Power (hp)	87.5	66	66
Total Fan Power (hp)	912.1	634.1	308.9
Total Fan Power (kw)	756.1	525.6	256.0
Total Vital Chilled Water Load (tons)	1576.9	1469.4	130.8
Required Number of AC Plants for Combat Load	8	8	1
Total Cruise Chilled Water Load (tons)	1764.5	1629.9	291.4
Required Number of AC Plants for Cruise Load	10	10	3
AC Plant Power (kw)	1499.8	1483.2	265.1
Total Cooling System Power (kw)	2255.9	2008.9	1190.9

Note the far fewer number of AC plants required, although a comparable number of intermediate sink plants will be necessary. Significantly, far less power, about 50%, will be required at the total ship level with the intermediate sink plant concept. For a ship at sea for 2000 hours per year and at a power cost of $0.44/kw-hr, the intermediate sink system would provide $937,000 per year per ship in power generation savings.

The intermediate heat sink system and the AC plant can be integrated into a common system with two evaporators, a common condenser and a two-stage compressor. Each evaporator would cool one fluid stream, the chilled water evaporator vapor would enter the first stage of the compressor, the intermediate sink evaporator vapor would enter the second stage of the compressor (along with the flash gas from a 2-stage economizer).

Adoption of an intermediate heat sink concept enables consideration of additional synergistic thermal management strategies. A de-centralized cooling system using small capacity cooling systems located throughout the ship as needed, perhaps on the order of 50 systems, a few-tons in capacity, could be employed for compartment cooling, since the hotel load is relatively modest. This would allow elimination of the chilled water system (cooling coils, piping and associated AC plants). Further, these small cooling units could use the intermediate sink system for heat rejection, lowering the power required for these small cooling systems from a nominal 1 kw/ton to 0.5 kw/ton and lower. Depending on arrangements, much of the recirculation ductwork could be eliminated. As in home systems, these small cooling units could be used as heat pumps to provide heating as necessary, thus eliminating many of the space heaters and reheaters. Development of the components, discussed earlier, would continue to be applicable to the supply and exhaust systems. A schematic of this advanced concept is shown in Figure 28.

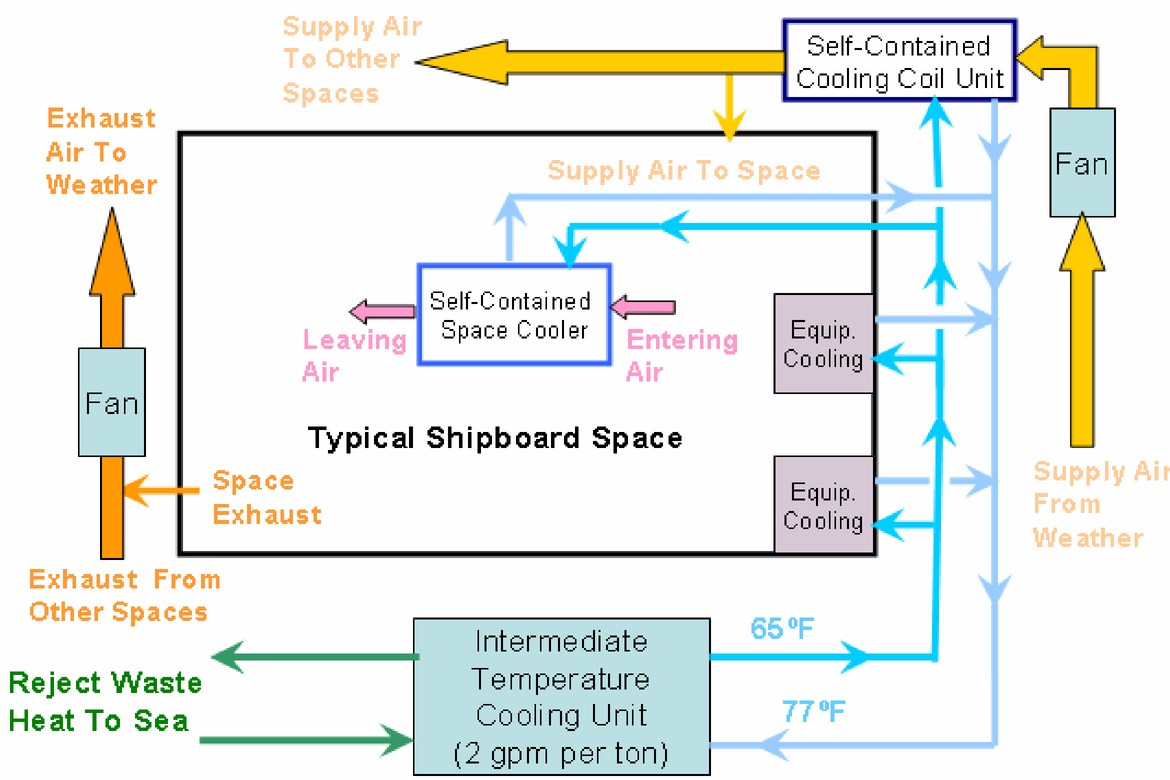

Figure 28 – Advanced Intermediate Sink Water System Concept Schematic

The application of these small cooling systems could, in the longer term, utilize advanced cooling concepts[7] that have struggled with large temperature differentials and large capacities.

Deployment Strategy

The 21st Century HVAC System, in general, is a complete, bundled concept. Piecemeal implementation of certain items/technologies will likely produce a poor return on investment. Grouping of a bundle of technologies may produce a positive return on investment. The total system is targeted at the next Future Surface Combatant Design. It will be too late for DDG 1000. Application of the technology to CG(X) and a future DDG(X) is possible for some elements. A spiral development process targeting component level goals could be utilized to field some portions for CG(X) while eventually taking advantage of the synergies of the total package for follow on surface ship combatant designs as illustrated by Figure 29, a roadmap to the 21stCentury HVAC System.

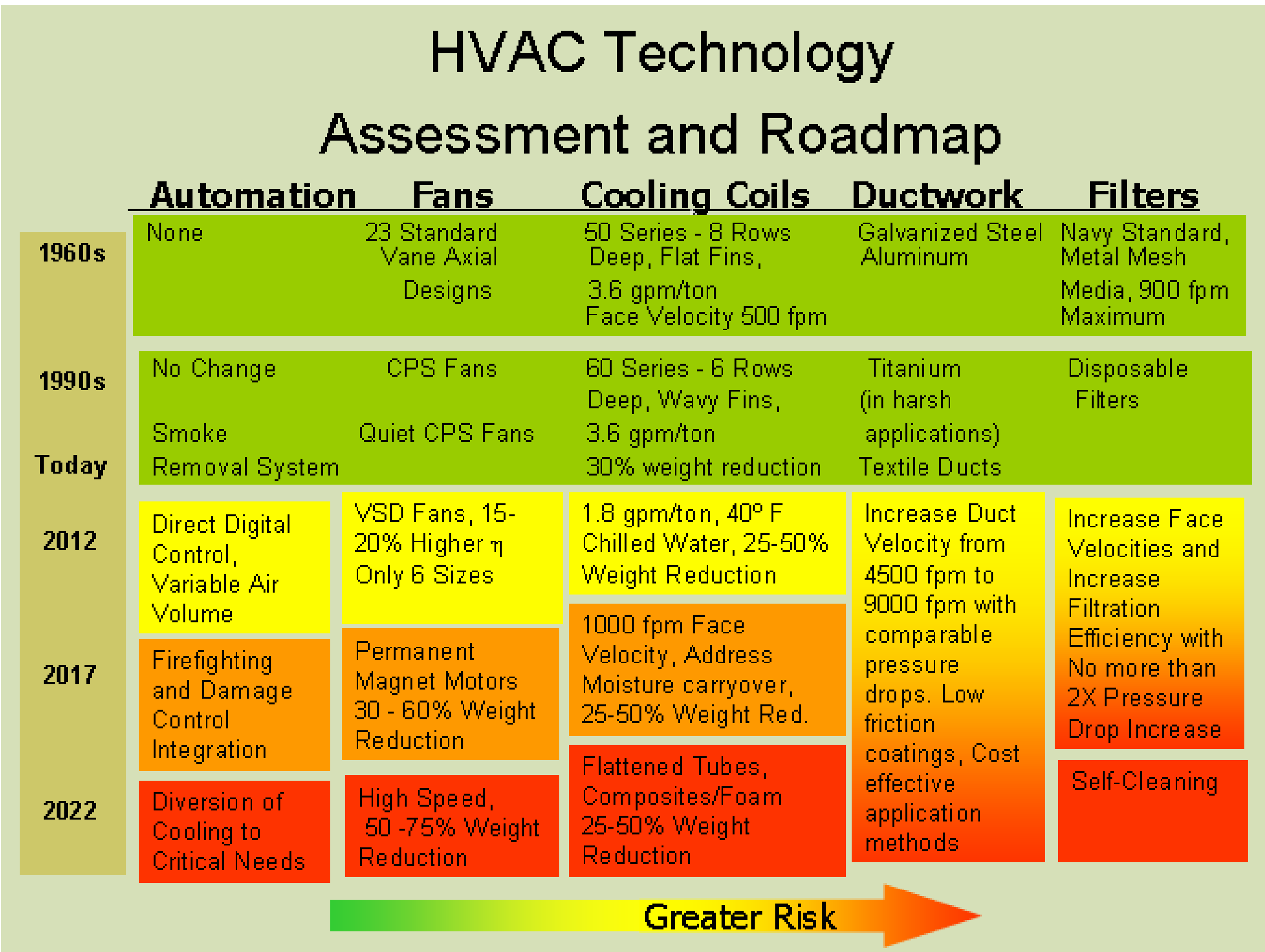

Figure 29 – 21st Century HVAC System Development Roadmap

Conclusions/Recommendations

Current ship HVAC design methods, paradigms and components are outdated and poorly suited for the warships of tomorrow where advanced technology weapon and sensor systems will challenge the available space, weight, power and cost parameters.

Innovative technology can be applied to develop a new series of HVAC components and design paradigms which can reduce the weight, space and power requirements by 30-60%. Automation can be used at the Total Ship Level to provide a flexible thermal management system capable of directing cooling to the most critical combat system needs and to divert cooling as necessary in the event of damage.

An intermediate heat sink system to cool equipment loads, as an alternative to direct chilled water cooling, can provide substantial power reductions.

It is recommended that development of the 21st Century HVAC System be initiated.

- Flight 1 components and technologies should be pursued.
- The automation/VAV software development should begin by writing the code based on Next Navy designs. This will provide a platform for developing Navy unique algorithms suitable for US Navy damage control, firefighting and HVAC system operational doctrine. A virtual test bed could be established to demonstrate and prove the concept. Then, if incorporated on a Navy After Next Surface Combatant, the needed changes should only be related to the ship configuration, not the basic concept.

- The HVAC System Model should be utilized to model the HVAC systems of a stabilized Next Navy design. This effort would permit further verification of the model and also serve as a validation of the Next Navy Ship's HVAC design. Further, the component design ranges for the Flight 1, 2 and 3 fans and cooling coils could be established using this platform.

- The simplified Total Ship HVAC Model should be further refined to enable more menu driven choices and increased flexibility and then applied to the Next Navy design.

- The intermediate heat sink concept should be further explored and definitized using Next Navy design as a baseline.

- A functional, flexible realistic cooling coil model should be developed and demonstrated. This would permit design of the advanced cooling coils recommended for the 21st Century HVAC System.

- A land based facility should be established to develop, prove and demonstrate the 21st Century HVAC System technologies. In this facility the advanced components could be integrated into a representative portion of a ship and the bundled benefits determined and demonstrated. A companion version of today's HVAC technology could also be constructed for direct comparison.

Technology Challenges/Gaps

The specific technology gaps and technical challenges are grouped and summarized below. While some elements of these technologies are in use commercially, in general, the designs are not suitable for the unique Navy environment – shock, vibration, EMI, corrosion, mobile platform subject to large motions, limited access, no at sea maintenance or repair capability requiring very high reliability.

- The first and most important technology gap is a shipboard quality VSD. This is essential for the 21st Century automation and VAV technology. There have been only limited shipboard applications of this technology thus far and reports on the development status are somewhat confusing. Commercial units are usually large, heavy, untested for shock and vibration, emit unacceptable EMI and expensive. Pursuit of the Turbocor VSD concept[4] may be an introductory path to a successful development.
- The development of shipboard quality permanent magnet motors, initially at 3600 rev/min and later at 10,000 or higher rev/min, is the next most significant technical challenge. Again there are only a few limited proposed shipboard applications for these motors. There are also only limited commercial applications. Again, pursuit of the Turbocor[3] approach may be warranted.
- The design and development of a family of efficient, variable speed driven fans is a technology challenge. Commercial fans are unsuited for the naval environment. Using the quiet CPS fans as a basis for these designs is recommended.
- The development of low chilled water temperature/low chilled water flow rate cooling coils is a technical challenge. Again, commercial cooling coils are unsuited for the naval environment.
- The development of high face velocity cooling coils is a substantial challenge. The potential and likelihood for moisture carryover and increased air pressure drop are the major anticipated difficulties. Unique fin designs and coatings may be the solution.
- The development of compact, non-traditional cooling coil designs, such as flattened tube or graphite foam construction, is a substantial technical challenge. These concepts are in the early stages of commercial development.
- The development of smooth, low friction ductwork, coated with polymers or silicates, is a technical challenge. The potential for increased noise at higher duct velocities will also require attention.

References

1. "Automated Control of Shipboard Ventilation Systems: Phase 2 Part A Test Results", BRADLEY J. HAVLOVICK, JOHN T. YADON, *Havlovick Engineering Services, Inc. Idaho Falls, ID;* JOHN P. FARLEY, FREDERICK W. WILLIAMS *Navy Technology Center for Safety and Survivabiliy,Chemistry Division* May 31, 2002, Report Number NRL/MR/6180--02-8624.

2. http://www.trane.com/webcache/ah/fans%20(fan)/product/fan-ds-2_08012000.pdf

3. "Proof of Concept Evaluation of the Permanent Magnet Motors for Vaneaxial Vent Fans for CVN 21", Prepared by The McConnell Technology and Training Center, 1930 Bishop Lane, Suite 1011, Louisville, KY 40218-1929, December 22, 2004.

4. "Experimental Investigation of an Advanced Oil-Free Centrifugal Compressor Air Conditioning Plant", Matthew V. Frank and Kevin C. King, NSWCCD-98-TR–2005/20 September 2005, Machinery Research Department Technical Report, Limited Distribution.

5. "An Assessment of the State of the Art, and Potential Design Improvements, for Flat-Tube Heat Exchangers in Air Conditioning and Refrigeration Applications – Phase I, Final Report", ARTI-21CR/20020-01, September 2001, A.M. Jacobi, Y. Park, D. Tafti, X. Zhang, University of Illinois Urbana-Champaign, Department of Mechanical and Industrial Engineering, 1206 West Green Street, Urbana, IL 610801, Prepared for the AIR-CONDITIONING AND REFRIGERATION TECHNOLOGY INSTITUTE, Suite 425, 4301 N. Fairfax Drive, Arlington, Virginia 22203

6. "Selection of Disposable Air Filters for Shipboard Heating, Ventilating and Air Conditioning Systems", August 18, 2003, Carderock Division, Naval Surface Warfare Center, Philadelphia, PA (Code 9213), William Sorg, PE

7. "An Evaluation of Thermoelectric Air Conditioning Technology and Future Applications", Thomas W. Bein, DTRS-PAS-89/29 of October 1989, David Taylor Research Center

Appendix A – Document Review List

The following top level general specification sections were reviewed –

- NAVSEA S9AAO-AA-SPN-010, GENERAL SPECIFICATIONS FOR SHIPS OF THE UNITED STATES NAVY
    - SECTION 512, HEATING, VENTILATION, AND AIR CONDITIONING (HVAC), 1994 Edition
    - SECTION 070, GENERAL REQUIREMENTS FOR DESIGN AND CONSTRUCTION, 1995 Edition
    - SECTION 202,MACHINERY CENTRALIZED CONTROL SYSTEM
    - SECTION 252, MACHINERY CONTROL STATIONS
    - SECTION 331, GENERAL REQUIREMENTS FOR LIGHTING SYSTEMS DISTRIBUTION AND CONTROL
    - SECTION 664, DAMAGE CONTROL SPACES
- S9AA0-AB-GOS-010, 1996 Edition, GENERAL SPECIFICATIONS FOR OVERHAUL OF SURFACE SHIPS (GSO), SECTION 512, HEATING, VENTILATION AND AIR CONDITIONING (HVAC)
- ADDENDUM 2, HEATING, VENTILATION AND AIR CONDITIONING DESIGN CRITERIA MANUAL, LPD 19 and Follow, 23 AUGUST 2000

The following relevant detailed component specifications were reviewed –

- MIL-PRF-2939G, 20 July 2001, COOLING COILS, AIR, DUCT TYPE AND GRAVITY TYPE,NAVAL SHIPBOARD ENVIRONMENTAL CONTROL SYSTEMS
- MIL-C-2939F, 31 December 1990, 60 Series Cooling Coils
- MIL-C-2939E, 21 March 1984, 50 Series Cooling Coils
- MIL-PRF-18953C(SH) 14 February 2005, SUPERSEDING MIL-F-18953B(SH), FANS, VANEAXIAL AND TUBEAXIAL, VENTILATION AND AIR CONDITIONING, NAVAL SHIPBOARD
- MIL-F-18953B, 22 October 1990, FANS, VANEAXIAL AND TUBEAXIAL, VENTILATION AND AIR CONDITIONING, NAVAL SHIPBOARD
- MIL-A-19865C, 20 March 1990, AIR CONDITIONER, MECHANICALLY REFRIGERATED
- MIL-PRF-23798D(SH), 13 December 2004, SUPERSEDING MIL-A-23798C(SH), 6 March 1995, AIR CONDITIONER, FAN-COIL ASSEMBLY
- MIL-C-24746(SH), AMENDMENT 1, 8 November 1996, COOLERS, UNIT FORCED AIR FOR SHIP’S REFRIGERATED STORES]
- MIL-C-24746(SH), 31 December 1990,COOLERS, UNIT FORCED AIR FOR SHIP'S REFRIGERATED STORES
- MIL-PRF-24755A, 31 May 2001, SUPERSEDING MIL-F-24755(SH) FANS, VANEAXIAL, HIGH PRESSURE, NAVAL SHIPBOARD
- MIL-F-24755, 27 December 1990MIL-PRF-24775A(SH), 31 January 2005, SUPERSEDING MIL-A-24775(SH), AIR CONDITIONING FAN COIL UNITS, HORIZONTAL AND VERTICAL TYPES, NAVAL SHIPBOARD
- MIL-PRF-32107, 27 June 2002, HOSE, AIR DUCT, GENERAL SPECIFICATION FOR

- MIL-M-17060F(SH), 25 May 1995, MOTORS, 60-HERTZ, ALTERNATING CURRENT, INTEGRAL-HORSEPOWER, SHIPBOARD USE

Reviewed the following equipment guides and NSTM sections -

- S9512-BS-MMA-010, EQUIPMENT MANUAL, HEATING, VENTILATING AND AIR CONDITIONING, 31 JAN 1991
- S9086-RQ-STM-010, NAVAL SHIPS' TECHNICAL MANUAL, CHAPTER 510, HEATING, VENTILATING, AND AIR CONDITIONING SYSTEMS FOR SURFACE SHIPS, 1 APR 2005
- S9086-RS-STM-010/CH-512R2, NAVAL SHIPS' TECHNICAL MANUAL, CHAPTER 512, FANS, 1 SEP 1999
- S9086-RW-STM-010/CH-516R4, NAVAL SHIPS' TECHNICAL MANUAL, CHAPTER 516, REFRIGERATION SYSTEMS, 10 DEC 1997
- S9DDG-CS-SIB-070/DDG 83, SHIP INFORMATION BOOK, DDG 83 USS HOWARD, HEATING, VENTILATION AND AIR CONDITIONING SYSTEMS (HVAC), 30 JUL 2002
- S9248-AB-DSP-010, TECHNICAL MANUAL, TEXTILE DUCTING DESIGN GUIDE, 27 JUL 2001
- S9248-AC-MMO-010, TECHNICAL MANUAL, SHIPBOARD GUIDE FOR TEXTILE DUCTING, 30 MAR 2003
- 0938-LP-018-0010, HEATING, VENTILATION AND AIR CONDITIONING DESIGN CRITERIA MANUAL FOR SURFACE SHIPS OF THE UNITED STATES NAVY, 29 March 1991
- NAVSEA T9500-AA-PRO-130, NAVSEA DESIGN PRACTICES AND CRITERIA MANUAL FOR AIR CONDITIONING, VENTILATION, AND HEATING OF SURFACE SHIPS, CHAPTER 510, May 1998

Reviewed the following relevant design data sheets –

- Design Data Sheets, DDS 512-1 and DDS 512-2, determining the sizes of ventilation ducts and the pressure losses of ventilation fittings
- Design Data Sheet DDS 511-2, guidance in selection of heat transfer coefficients

Reviewed the following relevant drawings –

- NAVSEA Drawing 6983501, Textile Duct Mounting Standard Drawing, 11/2002
- NAVSEA Drawing 6983502, Textile Duct Installation Standard Drawing, 11/2002

Reviewed the following reports –

- Surface Ship Thermal Management Survey – Part 1, CARDIVNSWC-TR-92-03-21 July 2003, R. Steck
- Capital Investment for Labor Machinery Space Ventilation Program Final Report, NSWCCD-TR–62-02-05, September 2002, Norm Clayton and John Miller
- Evaluation of Advanced Techniques to Increase the Heat Transfer Performance of Navy Chilled Water Cooling Coils, PAS-86-31, April 1987, Charles M. Hogg and Thomas W. Bein

- Shock and Vibration Qualification of Three Advanced Chilled Water Cooling Coils, DTRC-TM-27-89-2, January 1989, Charles M. Hogg and Thomas W. Bein
- Selection of Disposable Air Filters for Shipboard Heating, Ventilating and Air Conditioning Systems, August 18, 2003, Carderock Division, Naval Surface Warfare Center, Philadelphia, PA (Code 9213), William Sorg, PE

Appendix B – System Model Results

Table 32 – System Model Results for Recirculation System RS2-105-2 (44)

Inputs					
System	RS2-105-2 (44)	RS2-105-2 (44)	RS2-105-2 (44)	RS2-105-2 (44)	RS2-105-2 (44)
Compartment Name	Crew Living Space No. 1	Crew Living Space No. 1	Crew Living Space No. 1	Crew Living Space No. 1	Crew Living Space No. 1
Compartment Number	2-78-01-L	2-78-01-L	2-78-01-L	2-78-01-L	2-78-01-L
Weather Air Dry Bulb Temperature (°F)	90	90	90	90	90
Weather Air Wet Bulb Temperature (°F)	81	81	81	81	81
Compartment Air Dry Bulb Temperature (°F)	80	80	80	80	80
Compartment Air Wet Bulb Temperature (°F)	68	68	68	68	68
System Damage Control Classification	Z	Z	Z	Z	Z
Total Sensible Load (BTU/hr)	40680	40680	40680	40680	40680
Personnel Latent Load (BTU/hr)	15660	15660	15660	15660	15660
Total Compartment Load (BTU/hr)	56340	56340	56340	56340	56340
Required Replenishment Air Flow Rate (ft^3/min)	435	435	435	435	435
Required Compartment Flow Rate (ft^3/min)	1811	1811	1811	1811	1811
Duct Equivalent Length (ft)	72	72	72	72	72
Chilled Water Piping Equivalent Length (ft)	50	50	50	50	50
Select Technology	Legacy	Today	21st Century Flight 1	21st Century Flight 2	21st Century Flight 3
Select System Type	FCA	FCA	FCA	FCA	FCA
Number of Fans	1	1	1	1	1
Number of Cooling Coils	1	1	1	1	1
Psychrometrics					
Compartment Air					
Air Dry Bulb Temperature (°F)	80	80	80	80	80
Air Wet Bulb Temperature (°F)	68	68	68	68	68
Humidity (%)	54.8	54.8	54.8	54.8	54.8
Density (lbm/ft^3)	0.072	0.072	0.072	0.072	0.072
Enthalpy (BTU/lbm)	32.31	32.31	32.31	32.31	32.31
Replenishment Air					
Air Dry Bulb Temperature (°F)	90	90	90	90	90
Air Wet Bulb Temperature (°F)	81	81	81	81	81

Humidity (%)	68.7	68.7	68.7	68.7	68.7
Density (lbm/ft^3)	0.070	0.070	0.070	0.070	0.070
Enthalpy (BTU/lbm)	44.66	44.66	44.66	44.66	44.66
Replenishment Air Cooling Load (BTU/hr)	22584	22584	22584	22584	22584
Mixed Air Entering Coil					
Air Dry Bulb Temperature (°F)	82.4	82.4	82.4	82.4	82.4
Air Wet Bulb Temperature (°F)	71.4	71.4	71.4	71.4	71.4
Humidity (%)	59.3	59.3	59.3	59.3	59.3
Density (lbm/ft^3)	0.072	0.072	0.072	0.072	0.072
Enthalpy (BTU/lbm)	35.16	35.16	35.16	35.16	35.16
Total Coil Cooling Load (BTU/hr)	93228	93228	81794	81794	81794
Cooling Coil Air Outlet					
Air Dry Bulb Temperature (°F)	55.8	55.8	58.2	58.2	58.2
Air Wet Bulb Temperature (°F)	55.0	55.0	57.3	57.3	57.3
Humidity (%)	95	95	95	95	95
Density (lbm/ft^3)	0.076	0.076	0.076	0.076	0.076
Enthalpy (BTU/lbm)	23.21	23.21	24.68	24.68	24.68
Fan Air Outlet					
Air Dry Bulb Temperature (°F)	63.1	63.1	59.7	59.7	59.7
Air Wet Bulb Temperature (°F)	55.0	55.0	57.3	57.3	57.3
Humidity (%)	60.5	60.5	87.6	87.6	87.6
Density (lbm/ft^3)	0.075	0.075	0.075	0.075	0.075
Enthalpy (BTU/lbm)	24.94	24.94	25.02	25.02	25.02
Fan Load (BTU/hr)	14304	14304	2869	2869	2869
Results					
Fan Selection	FCA 24	FCA 24	FCAX 24	FCAXX 24	FCAXXX 24
Weight (lbm)	1590	1590	1000	1100	550
Volume (ft^3)	81.9	81.9	55.0	50.0	25.0
Power (hp)	5.0	5.0	1.0	1.0	1.0
Fan Load (BTU/hr)	14304	14304	2869	2869	2869
Flow Rate (ft^3/min)	2550	2550	2550	2550	2550
Pressure Available (inches H_2O)	2	2	2	2	2
Cooling Coil Selection	FCA 25	FCA 25	FCAX 24	FCAXX 24	FCAXXX 24
Weight (lbm)	0	0	0	0	0
Volume (ft^3)	0.0	0.0	0.0	0.0	0.0
Chilled Water Inlet Temperature (°F)	45	45	40	40	40
Chilled Water Flow per Ton of Cooling (gal/min/ton)	3.6	3.6	2	2	2
Water Flow (gal/min)	28.0	28.0	13.6	13.6	13.6

Face Area (ft^2)	6.2	6.2	4.2	2.1	2.1
Face Velocity (ft/min)	292.1	292.1	431.2	862.4	862.4
Face Velocity Limit (ft/min)	500	500	500	1000	1000
Coil Performance	Acceptable	Acceptable	Acceptable	Acceptable	Acceptable
Air Side Friction Factor (dimensionless)	0.077	0.077	0.038	0.038	0.019
Air Pressure Drop (inches H_2O)	0.45	0.45	0.43	1.34	0.67
Ducting Size					
Velocity Limit (ft/min)	4500	4500	9000	9000	12000
Minimum Diameter (in)	9	9	7	7	6
Diameter (in)	10	10	8	8	6
Weight (lbm)	684.0	684.0	547.2	547.2	410.4
Volume (ft^3)	39.3	39.3	25.1	25.1	14.1
Duct Velocity (ft/min)	3320	3320	5188	5188	9223
Reynolds Number (dimensionless)	282234	282234	352793	352793	470391
Roughness (ft)	0.0003	0.0003	0.0001	0.00005	0.000025
Friction Factor (dimensionless)	0.017	0.017	0.016	0.015	0.014
Pressure Drop (inches H_2O)	1.0	1.0	2.8	2.7	10.7
Chilled Water Piping					
Diameter (in)	1.25	1.25	0.75	0.75	0.75
Weight (lbm)	70	70	39	39	39
Volume (ft^3)	0.8	0.8	0.3	0.3	0.3
Velocity (ft/sec)	5.0	5.0	6.6	6.6	6.6
Reynolds Number (dimensionless)	43582	43582	35004	35004	35004
Darcy Friction Factor (dimensionless)	0.02	0.02	0.02	0.02	0.02
Pressure Drop (lbf/in^2)	0.1	0.1	0.4	0.4	0.4
System Characteristics					
Weight (lbm)	2343.6	2343.6	1586.2	1686.2	999.4
Volume (ft^3)	121.9	121.9	80.4	75.4	39.4
Power (hp)	5.0	5.0	1.0	1.0	1.0
Total Air Frictional Loss (in H_2O)	1.49	1.49	3.26	4.04	11.39
Fan Performance	Acceptable	Acceptable	Unacceptable, select bigger fan or higher speed	Unacceptable, select bigger fan or higher speed	Unacceptable, select bigger fan or higher speed
Weight Differences (% reduction from Legacy)					
Fan Coil Assembly	0.0	0.0	-37.1	-30.8	-65.4
Duct	0.0	0.0	-20.0	-20.0	-40.0
Chilled Water Piping	0.0	0.0	-44.4	-44.4	-44.4
Total	0.0	0.0	-32.3	-28.1	-57.4

Volume Differences (% reduction from Legacy)					
Fan Coil Assembly	0.0	0.0	-32.8	-39.0	-69.5
Duct	0.0	0.0	-36.0	-36.0	-64.0
Chilled Water Piping	0.0	0.0	-60.0	-60.0	-60.0
Total	0.0	0.0	-34.0	-38.1	-67.7

Table 33 – System Model Results for Recirculation System RS-01-159-1 (13)

Inputs					
System	RS-01-159-1 (13)	RS-01-159-1 (13)	RS-01-159-1 (13)	RS-01-159-1 (13)	RS-01-159-1 (13)
Compartment Name	Combat Information Center and Projection Area	Combat Information Center and Projection Area	Combat Information Center and Projection Area	Combat Information Center and Projection Area	Combat Information Center and Projection Area
Compartment Number	1-126-0-C	1-126-0-C	1-126-0-C	1-126-0-C	1-126-0-C
Weather Air Dry Bulb Temperature (°F)	90	90	90	90	90
Weather Air Wet Bulb Temperature (°F)	81	81	81	81	81
Compartment Air Dry Bulb Temperature (°F)	80	80	80	80	80
Compartment Air Wet Bulb Temperature (°F)	68	68	68	68	68
System Damage Control Classification	W	W	W	W	W
Total Sensible Load (BTU/hr)	122467	122467	122467	122467	122467
Personnel Latent Load (BTU/hr)	9360	9360	9360	9360	9360
Total Compartment Load (BTU/hr)	131827	131827	131827	131827	131827
Required Replenishment Air Flow Rate (ft^3/min)	260	260	260	260	260
Required Compartment Flow Rate (ft^3/min)	5465	5465	5465	5465	5465
Duct Equivalent Length (ft)	200	200	200	200	200
Chilled Water Piping Equivalent Length (ft)	120	120	120	120	120
Select Technology	Legacy	Today	21st Century Flight 1	21st Century Flight 2	21st Century Flight 3
Select System Type	VA&DW	VA&DW	VA&DW	VA&DW	VA&DW
Number of Fans	1	1	1	1	1
Number of Cooling Coils	2	2	2	2	2
Psychrometrics					
Compartment Air					
Air Dry Bulb Temperature (°F)	80	80	80	80	80
Air Wet Bulb Temperature (°F)	68	68	68	68	68
Humidity (%)	54.8	54.8	54.8	54.8	54.8
Density (lbm/ft^3)	0.072	0.072	0.072	0.072	0.072
Enthalpy (BTU/lbm)	32.31	32.31	32.31	32.31	32.31
Replenishment Air					

Air Dry Bulb Temperature (°F)	90	90	90	90	90
Air Wet Bulb Temperature (°F)	81	81	81	81	81
Humidity (%)	68.7	68.7	68.7	68.7	68.7
Density (lbm/ft^3)	0.070	0.070	0.070	0.070	0.070
Enthalpy (BTU/lbm)	44.66	44.66	44.66	44.66	44.66
Replenishment Air Cooling Load (BTU/hr)	13499	13499	13499	13499	13499
Mixed Air Entering Coil					
Air Dry Bulb Temperature (°F)	80.5	80.5	80.5	80.5	80.5
Air Wet Bulb Temperature (°F)	68.6	68.6	68.6	68.6	68.6
Humidity (%)	55.6	55.6	55.6	55.6	55.6
Density (lbm/ft^3)	0.072	0.072	0.072	0.072	0.072
Enthalpy (BTU/lbm)	32.82	32.82	32.82	32.82	32.82
Total Coil Cooling Load (BTU/hr)	159630	159630	168956	168956	168956
Cooling Coil Air Outlet					
Air Dry Bulb Temperature (°F)	60.4	60.4	59.8	59.8	59.8
Air Wet Bulb Temperature (°F)	59.5	59.5	58.9	58.9	58.9
Humidity (%)	95	95	95	95	95
Density (lbm/ft^3)	0.075	0.075	0.075	0.075	0.075
Enthalpy (BTU/lbm)	26.08	26.08	25.69	25.69	25.69
Fan Air Outlet					
Air Dry Bulb Temperature (°F)	62.8	62.8	63.8	63.8	63.8
Air Wet Bulb Temperature (°F)	59.5	59.5	58.9	58.9	58.9
Humidity (%)	83.2	83.2	75.7	75.7	75.7
Density (lbm/ft^3)	0.075	0.075	0.075	0.075	0.075
Enthalpy (BTU/lbm)	26.66	26.66	26.65	26.65	26.65
Fan Load (BTU/hr)	14304	14304	23630	23630	23630
Results					
Fan Selection	A 6	A 6	AX 8	AXX 8	AXXX 8
Weight (lbm)	530	530	750	450	300
Volume (ft^3)	8.5	8.5	12.0	8.0	4.0
Power (hp)	5.0	5.0	8.3	8.3	8.3
Fan Load (BTU/hr)	14304	14304	23630	23630	23630
Flow Rate (ft^3/min)	6300	6300	7000	7000	7000
Pressure Available (inches H_2O)	3.65	3.65	6	6	6
Cooling Coil Selection	56	66	76X	86X	96X
Weight (lbm)	666	435	326.25	163.125	81.5625
Volume (ft^3)	12.9	12.9	6.4	3.2	1.6
Chilled Water Inlet Temperature (°F)	45	45	40	40	40

Chilled Water Flow per Ton of Cooling (gal/min/ton)	3.6	3.6	2	2	2
Water Flow (gal/min)	47.9	47.9	28.2	28.2	28.2
Face Area (ft^2)	5.0	5.0	5.0	5.0	5.0
Face Velocity (ft/min)	545.8	545.8	545.8	545.8	545.8
Face Velocity Limit (ft/min)	500	500	500	1000	1000
Coil Performance	Unacceptable - Select Larger Coil or Multiple Coils	Unacceptable - Select Larger Coil or Multiple Coils	Unacceptable - Select Larger Coil or Multiple Coils	Acceptable	Acceptable
Air Side Friction Factor (dimensionless)	0.077	0.077	0.038	0.038	0.019
Air Pressure Drop (inches H_2O)	1.26	1.26	0.63	0.63	0.31
Ducting Size					
Velocity Limit (ft/min)	4500	4500	9000	9000	12000
Minimum Diameter (in)	15	15	11	11	10
Diameter (in)	16	16	12	12	10
Weight (lbm)	3040.0	3040.0	2280.0	2280.0	1900.0
Volume (ft^3)	279.3	279.3	157.1	157.1	109.1
Duct Velocity (ft/min)	3914	3914	6958	6958	10020
Reynolds Number (dimensionless)	532306	532306	709742	709742	851690
Roughness (ft)	0.0003	0.0003	0.0001	0.0001	0.0000
Friction Factor (dimensionless)	0.016	0.016	0.014	0.013	0.013
Pressure Drop (inches H_2O)	2.2	2.2	8.4	7.9	18.8
Chilled Water Piping					
Diameter (in)	1.5	1.5	1.25	1.25	1.25
Weight (lbm)	192	192	167	167	167
Volume (ft^3)	2.4	2.4	1.8	1.8	1.8
Velocity (ft/sec)	6.3	6.3	5.0	5.0	5.0
Reynolds Number (dimensionless)	64424	64424	43879	43879	43879
Darcy Friction Factor (dimensionless)	0.02	0.02	0.02	0.02	0.02
Pressure Drop (lbf/in^2)	0.4	0.4	0.3	0.3	0.3
System Characteristics					
Weight (lbm)	5094.3	4632.3	3849.6	3223.3	2530.2
Volume (ft^3)	315.9	315.9	183.8	173.3	118.1
Power (hp)	5.0	5.0	8.3	8.3	8.3
Total Air Frictional Loss (in H_2O)	3.49	3.49	8.99	8.58	19.13
Fan Performance	Acceptable	Acceptable	Unacceptable, select bigger fan or higher speed	Unacceptable, select bigger fan or higher speed	Unacceptable, select bigger fan or higher speed
Weight Differences (%					

reduction from Legacy)					
Fan	0.0	0.0	41.5	-15.1	-43.4
Cooling Coil	0.0	-34.7	-51.0	-75.5	-87.8
Duct	0.0	0.0	-25.0	-25.0	-37.5
Chilled Water Piping	0.0	0.0	-44.4	-44.4	-44.4
Total	0.0	-9.1	-24.4	-36.7	-50.3
Volume Differences (% reduction from Legacy)					
Fan	0.0	0.0	41.2	-5.9	-52.9
Cooling Coil	0.0	0.0	-50.0	-75.0	-87.5
Duct	0.0	0.0	-43.8	-43.8	-60.9
Chilled Water Piping	0.0	0.0	-23.7	-23.7	-23.7
Total	0.0	0.0	-41.8	-45.1	-62.6

Table 34 – System Model Results for Recirculation System RS1-67-1 (21)

Inputs					
System	RS1-67-1 (21)	RS1-67-1 (21)	RS1-67-1 (21)	RS1-67-1 (21)	RS1-67-1 (21)
Compartment Name	Storeroom, Library, Passages, etc.	Storeroom, Library, Passages, etc.	Storeroom, Library, Passages, etc.	Storeroom, Library, Passages, etc.	Storeroom, Library, Passages, etc.
Compartment Number	0.5-42-2-A	0.5-42-2-A	0.5-42-2-A	0.5-42-2-A	0.5-42-2-A
Weather Air Dry Bulb Temperature (°F)	90	90	90	90	90
Weather Air Wet Bulb Temperature (°F)	81	81	81	81	81
Compartment Air Dry Bulb Temperature (°F)	80	80	80	80	80
Compartment Air Wet Bulb Temperature (°F)	68	68	68	68	68
System Damage Control Classification	W and Z	W and Z	W and Z	W and Z	W and Z
Total Sensible Load (BTU/hr)	54543	54543	54543	54543	54543
Personnel Latent Load (BTU/hr)	1440	1440	1440	1440	1440
Total Compartment Load (BTU/hr)	55983	55983	55983	55983	55983
Required Replenishment Air Flow Rate (ft^3/min)	40	40	40	40	40
Required Compartment Flow Rate (ft^3/min)	2061	2061	2061	2061	2061
Duct Equivalent Length (ft)	51	51	51	51	51
Chilled Water Piping Equivalent Length (ft)	100	100	100	100	100
Select Technology	Legacy	Today	21st Century Flight 1	21st Century Flight 2	21st Century Flight 3
Select System Type	VA&DW	VA&DW	VA&DW	VA&DW	VA&DW
Number of Fans	1	1	1	1	1
Number of Cooling Coils	1	1	1	1	1
Psychrometrics					
Compartment Air					
Air Dry Bulb Temperature (°F)	80	80	80	80	80
Air Wet Bulb Temperature (°F)	68	68	68	68	68
Humidity (%)	54.8	54.8	54.8	54.8	54.8
Density (lbm/ft^3)	0.072	0.072	0.072	0.072	0.072
Enthalpy (BTU/lbm)	32.31	32.31	32.31	32.31	32.31
Replenishment Air					
Air Dry Bulb Temperature (°F)	90	90	90	90	90

Air Wet Bulb Temperature (°F)	81	81	81	81	81
Humidity (%)	68.7	68.7	68.7	68.7	68.7
Density (lbm/ft^3)	0.070	0.070	0.070	0.070	0.070
Enthalpy (BTU/lbm)	44.66	44.66	44.66	44.66	44.66
Replenishment Air Cooling Load (BTU/hr)	2077	2077	2077	2077	2077
Mixed Air Entering Coil					
Air Dry Bulb Temperature (°F)	80.2	80.2	80.2	80.2	80.2
Air Wet Bulb Temperature (°F)	68.2	68.2	68.2	68.2	68.2
Humidity (%)	55.0	55.0	55.0	55.0	55.0
Density (lbm/ft^3)	0.072	0.072	0.072	0.072	0.072
Enthalpy (BTU/lbm)	32.49	32.49	32.49	32.49	32.49
Total Coil Cooling Load (BTU/hr)	63781	63781	63686	63686	63686
Cooling Coil Air Outlet					
Air Dry Bulb Temperature (°F)	59.3	59.3	59.3	59.3	59.3
Air Wet Bulb Temperature (°F)	58.4	58.4	58.4	58.4	58.4
Humidity (%)	95	95	95	95	95
Density (lbm/ft^3)	0.075	0.075	0.075	0.075	0.075
Enthalpy (BTU/lbm)	25.36	25.36	25.37	25.37	25.37
Fan Air Outlet					
Air Dry Bulb Temperature (°F)	61.9	61.9	61.8	61.8	61.8
Air Wet Bulb Temperature (°F)	58.4	58.4	58.4	58.4	58.4
Humidity (%)	82.2	82.2	82.4	82.4	82.4
Density (lbm/ft^3)	0.075	0.075	0.075	0.075	0.075
Enthalpy (BTU/lbm)	25.97	25.97	25.97	25.97	25.97
Fan Load (BTU/hr)	5722	5722	5626	5626	5626
Results					
Fan Selection	A 2 1/2	A 2 1/2	AX 4	AXX 4	AXXX 4
Weight (lbm)	250	250	425	300	150
Volume (ft^3)	2.6	2.6	6.0	4.0	2.0
Power (hp)	2.0	2.0	2.0	2.0	2.0
Fan Load (BTU/hr)	5722	5722	5626	5626	5626
Flow Rate (ft^3/min)	2600	2600	2500	2500	2500
Pressure Available (inches H_2O)	3.4	3.4	4	4	4
Cooling Coil Selection	56	66	76X	86X	96X
Weight (lbm)	666	435	326.25	163.125	81.5625
Volume (ft^3)	12.9	12.9	6.4	3.2	1.6
Chilled Water Inlet Temperature (°F)	45	45	40	40	40
Chilled Water Flow per Ton of Cooling (gal/min/ton)	3.6	3.6	2	2	2

Water Flow (gal/min)	19.1	19.1	10.6	10.6	10.6
Face Area (ft^2)	5.0	5.0	5.0	5.0	5.0
Face Velocity (ft/min)	411.7	411.7	411.7	411.7	411.7
Face Velocity Limit (ft/min)	500	500	500	1000	1000
Coil Performance	Acceptable	Acceptable	Acceptable	Acceptable	Acceptable
Air Side Friction Factor (dimensionless)	0.077	0.077	0.038	0.038	0.019
Air Pressure Drop (inches H_2O)	0.79	0.79	0.39	0.39	0.20
Ducting Size					
Velocity Limit (ft/min)	4500	4500	9000	9000	12000
Minimum Diameter (in)	10	10	7	7	6
Diameter (in)	10	10	8	8	6
Weight (lbm)	484.5	484.5	387.6	387.6	290.7
Volume (ft^3)	27.8	27.8	17.8	17.8	10.0
Duct Velocity (ft/min)	3779	3779	5904	5904	10497
Reynolds Number (dimensionless)	321202	321202	401502	401502	535337
Roughness (ft)	0.0003	0.0003	0.0001	0.0001	0.0000
Friction Factor (dimensionless)	0.017	0.017	0.015	0.015	0.014
Pressure Drop (inches H_2O)	0.9	0.9	2.6	2.4	9.6
Chilled Water Piping					
Diameter (in)	1	1	0.75	0.75	0.75
Weight (lbm)	99	99	78	78	78
Volume (ft^3)	0.9	0.9	0.6	0.6	0.6
Velocity (ft/sec)	5.6	5.6	5.1	5.1	5.1
Reynolds Number (dimensionless)	38145	38145	27255	27255	27255
Darcy Friction Factor (dimensionless)	0.02	0.02	0.02	0.02	0.02
Pressure Drop (lbf/in^2)	0.4	0.4	0.5	0.5	0.5
System Characteristics					
Weight (lbm)	1499.4	1268.4	1216.8	928.7	600.2
Volume (ft^3)	44.3	44.3	30.8	25.6	14.2
Power (hp)	2.0	2.0	2.0	2.0	2.0
Total Air Frictional Loss (in H_2O)	1.73	1.73	2.95	2.82	9.82
Fan Performance	Acceptable	Acceptable	Acceptable	Acceptable	Unacceptable , select bigger fan or higher speed
Weight Differences (% reduction from Legacy)					
Fan	0.0	0.0	70.0	20.0	-40.0
Cooling Coil	0.0	-34.7	-51.0	-75.5	-87.8
Duct	0.0	0.0	-20.0	-20.0	-40.0
Chilled Water Piping	0.0	0.0	-44.4	-44.4	-44.4
Total	0.0	-15.4	-18.8	-38.1	-60.0

Volume Differences (% reduction from Legacy)					
Fan	0.0	0.0	128.9	52.6	-23.7
Cooling Coil	0.0	0.0	-50.0	-75.0	-87.5
Duct	0.0	0.0	-36.0	-36.0	-64.0
Chilled Water Piping	0.0	0.0	-36.2	-36.2	-36.2
Total	0.0	0.0	-30.3	-42.1	-67.9

Table 35 – System Model Results for Supply System SS-01-150-3 (97)

Inputs					
System	SS-01-150-3 (97)	SS-01-150-3 (97)	SS-01-150-3 (97)	SS-01-150-3 (97)	SS-01-150-3 (97)
Compartment Name	AMR	AMR	AMR	AMR	AMR
Compartment Number	4-126-0-E	4-126-0-E	4-126-0-E	4-126-0-E	4-126-0-E
Weather Air Dry Bulb Temperature (°F)	90	90	90	90	90
Weather Air Wet Bulb Temperature (°F)	81	81	81	81	81
Compartment Air Dry Bulb Temperature (°F)	110	110	110	110	110
Compartment Air Wet Bulb Temperature (°F)	90	90	90	90	90
System Damage Control Classification	(W)	(W)	(W)	(W)	(W)
Total Sensible Load (BTU/hr)	150203	150203	150203	150203	150203
Personnel Latent Load (BTU/hr)	0	0	0	0	0
Total Compartment Load (BTU/hr)	150203	150203	150203	150203	150203
Required Replenishment Air Flow Rate (ft^3/min)	0	0	0	0	0
Required Compartment Flow Rate (ft^3/min)	10400	10400	10400	10400	10400
Duct Equivalent Length (ft)	105	105	105	105	105
Select Technology	Legacy	Today	21st Century Flight 1	21st Century Flight 2	21st Century Flight 3
Select System Type	VA	VA	VA	VA	VA
Number of Fans	2	2	2	2	2
Psychrometrics					
Compartment Air					
Air Dry Bulb Temperature (°F)	110	110	110	110	110
Air Wet Bulb Temperature (°F)	90	90	90	90	90
Humidity (%)	46.9	46.9	46.9	46.9	46.9
Density (lbm/ft^3)	0.067	0.067	0.067	0.067	0.067
Enthalpy (BTU/lbm)	55.63	55.63	55.63	55.63	55.63
Replenishment Air					
Air Dry Bulb Temperature (°F)	90	90	90	90	90
Air Wet Bulb Temperature (°F)	81	81	81	81	81
Humidity (%)	68.7	68.7	68.7	68.7	68.7
Density (lbm/ft^3)	0.070	0.070	0.070	0.070	0.070

Enthalpy (BTU/lbm)	44.66	44.66	44.66	44.66	44.66
Replenishment Air Cooling Load (BTU/hr)	0	0	0	0	0
Fan Air Outlet					
Air Dry Bulb Temperature (°F)	94.1	94.1	93.5	93.5	93.5
Air Wet Bulb Temperature (°F)	81.0	81.0	81.0	81.0	81.0
Humidity (%)	57.8	57.8	59.3	59.3	59.3
Density (lbm/ft^3)	0.070	0.070	0.070	0.070	0.070
Enthalpy (BTU/lbm)	45.64	45.64	45.50	45.50	45.50
Fan Load (BTU/hr)	42912	42912	36570	36570	36570
Results					
Fan Selection	A 7	A 7	AX 8	AXX 8	AXXX 8
Weight (lbm)	450	450	750	450	300
Volume (ft^3)	5.5	5.5	12.0	8.0	4.0
Power (hp)	7.5	7.5	6.4	6.4	6.4
Fan Load (BTU/hr)	21456	21456	18285	18285	18285
Flow Rate (ft^3/min)	5200	5200	6500	6500	6500
Pressure Available (inches H_2O)	7	7	5	5	5
Ducting Size					
Velocity Limit (ft/min)	4500	4500	9000	9000	12000
Minimum Diameter (in)	21	21	15	15	13
Diameter (in)	22	22	16	16	14
Weight (lbm)	5197.5	5197.5	3780.0	3780.0	3307.5
Volume (ft^3)	277.2	277.2	146.6	146.6	112.2
Duct Velocity (ft/min)	3940	3940	7448	7448	9729
Reynolds Number (dimensionless)	736720	736720	1012989	1012989	1157702
Roughness (ft)	0.0003	0.0003	0.0001	0.0001	0.0000
Friction Factor (dimensionless)	0.015	0.015	0.013	0.012	0.012
Pressure Drop (inches H_2O)	0.8	0.8	3.3	3.2	5.9
System Characteristics					
Weight (lbm)	6097.5	6097.5	5280.0	4680.0	3907.5
Volume (ft^3)	288.2	288.2	170.6	162.6	120.2
Power (hp)	15.0	15.0	12.8	12.8	12.8
Total Frictional Loss (in H_2O)	0.75	0.75	3.32	3.15	5.88
Fan Performance	Acceptable	Acceptable	Acceptable	Acceptable	Unacceptable, select bigger fan or higher speed
Weight Differences (% reduction from Legacy)					
Fan	0.0	0.0	66.7	0.0	-33.3

Duct	0.0	0.0	-27.3	-27.3	-36.4
Total	0.0	0.0	-13.4	-23.2	-35.9
Volume Differences (% reduction from Legacy)					
Fan	0.0	0.0	117.0	44.7	-27.7
Duct	0.0	0.0	-47.1	-47.1	-59.5
Total	0.0	0.0	-40.8	-43.6	-58.3

Table 36 – System Model Results for Supply System SS01-136-1 (82)

Inputs					
System	SS01-136-1 (82)	SS01-136-1 (82)	SS01-136-1 (82)	SS01-136-1 (82)	SS01-136-1 (82)
Compartment Name	Fan Room	Fan Room	Fan Room	Fan Room	Fan Room
Compartment Number	01-126-3-Q	01-126-3-Q	01-126-3-Q	01-126-3-Q	01-126-3-Q
Weather Air Dry Bulb Temperature (°F)	90	90	90	90	90
Weather Air Wet Bulb Temperature (°F)	81	81	81	81	81
Compartment Air Dry Bulb Temperature (°F)	80	80	80	80	80
Compartment Air Wet Bulb Temperature (°F)	68	68	68	68	68
System Damage Control Classification	W	W	W	W	W
Total Sensible Load (BTU/hr)	0	0	0	0	0
Personnel Latent Load (BTU/hr)	0	0	0	0	0
Total Compartment Load (BTU/hr)	0	0	0	0	0
Required Replenishment Air Flow Rate (ft^3/min)	0	0	0	0	0
Required Compartment Flow Rate (ft^3/min)	7200	7200	7200	7200	7200
Duct Equivalent Length (ft)	230	230	230	230	230
Select Technology	Legacy	Today	21st Century Flight 1	21st Century Flight 2	21st Century Flight 3
Select System Type	CPS	CPS	CPS	CPS	CPS
Number of Fans	2	2	2	2	2
Psychrometrics					
Compartment Air					
Air Dry Bulb Temperature (°F)	80	80	80	80	80
Air Wet Bulb Temperature (°F)	68	68	68	68	68
Humidity (%)	54.8	54.8	54.8	54.8	54.8
Density (lbm/ft^3)	0.072	0.072	0.072	0.072	0.072
Enthalpy (BTU/lbm)	32.31	32.31	32.31	32.31	32.31
Replenishment Air					
Air Dry Bulb Temperature (°F)	90	90	90	90	90
Air Wet Bulb Temperature (°F)	81	81	81	81	81
Humidity (%)	68.7	68.7	68.7	68.7	68.7
Density (lbm/ft^3)	0.070	0.070	0.070	0.070	0.070
Enthalpy (BTU/lbm)	44.66	44.66	44.66	44.66	44.66
Replenishment Air Cooling Load (BTU/hr)	0	0	0	0	0

Fan Air Outlet					
Air Dry Bulb Temperature (°F)	101.8	101.8	98.7	98.7	98.7
Air Wet Bulb Temperature (°F)	81.0	81.0	81.0	81.0	81.0
Humidity (%)	41.7	41.7	47.6	47.6	47.6
Density (lbm/ft^3)	0.069	0.069	0.069	0.069	0.069
Enthalpy (BTU/lbm)	47.50	47.50	46.74	46.74	46.74
Fan Load (BTU/hr)	85824	85824	63013	63013	63013
Results					
Fan Selection	AN 104	AQ 104	AX 105	AXX 105	AXXX 105
Weight (lbm)	620	620	640	400	250
Volume (ft^3)	6.7	6.7	7.1	4.0	3.0
Power (hp)	15.0	15.0	11.0	11.0	11.0
Fan Load (BTU/hr)	42912	42912	31506	31506	31506
Flow Rate (ft^3/min)	3600	3600	4000	4000	4000
Pressure Available (inches H_2O)	14	14	14	14	14
Ducting Size					
Velocity Limit (ft/min)	4500	4500	9000	9000	12000
Minimum Diameter (in)	18	18	13	13	11
Diameter (in)	18	18	14	14	12
Weight (lbm)	9315.0	9315.0	7245.0	7245.0	6210.0
Volume (ft^3)	406.4	406.4	245.9	245.9	180.6
Duct Velocity (ft/min)	4074	4074	6735	6735	9167
Reynolds Number (dimensionless)	623378	623378	801486	801486	935067
Roughness (ft)	0.0003	0.0003	0.0001	0.0001	0.0000
Friction Factor (dimensionless)	0.015	0.015	0.014	0.013	0.012
Pressure Drop (inches H_2O)	2.2	2.2	7.0	6.7	13.8
System Characteristics					
Weight (lbm)	10555.0	10555.0	8525.0	8045.0	6710.0
Volume (ft^3)	419.8	419.8	260.1	253.9	186.6
Power (hp)	30.0	30.0	22.0	22.0	22.0
Total Frictional Loss (in H_2O)	2.25	2.25	7.04	6.70	13.83
Fan Performance	Acceptable	Acceptable	Acceptable	Acceptable	Acceptable
Weight Differences (% reduction from Legacy)					
Fan	0.0	0.0	3.2	-35.5	-59.7
Duct	0.0	0.0	-22.2	-22.2	-33.3
Total	0.0	0.0	-19.2	-23.8	-36.4
Volume Differences (%					

reduction from Legacy)					
Fan	0.0	0.0	6.1	-40.2	-55.2
Duct	0.0	0.0	-39.5	-39.5	-55.6
Total	0.0	0.0	-38.1	-39.5	-55.5

Table 37 – System Model Results for Exhaust System ES01-146-3 (8A)

Inputs					
System	ES01-146-3 (8A)	ES01-146-3 (8A)	ES01-146-3 (8A)	ES01-146-3 (8A)	ES01-146-3 (8A)
Compartment Name	AMR	AMR	AMR	AMR	AMR
Compartment Number	4-126-0-E	4-126-0-E	4-126-0-E	4-126-0-E	4-126-0-E
Weather Air Dry Bulb Temperature (°F)	90	90	90	90	90
Weather Air Wet Bulb Temperature (°F)	81	81	81	81	81
Compartment Air Dry Bulb Temperature (°F)	110	110	110	110	110
Compartment Air Wet Bulb Temperature (°F)	90	90	90	90	90
System Damage Control Classification	(W)	(W)	(W)	(W)	(W)
Total Sensible Load (BTU/hr)	150203	150203	150203	150203	150203
Personnel Latent Load (BTU/hr)	0	0	0	0	0
Total Compartment Load (BTU/hr)	150203	150203	150203	150203	150203
Required Replenishment Air Flow Rate (ft^3/min)	0	0	0	0	0
Required Compartment Flow Rate (ft^3/min)	10820	10820	10820	10820	10820
Duct Equivalent Length (ft)	112	112	112	112	112
Select Technology	Legacy	Today	21st Century Flight 1	21st Century Flight 2	21st Century Flight 3
Select System Type	VA	VA	VA	VA	VA
Number of Fans	2	2	2	2	2
Psychrometrics					
Compartment Air					
Air Dry Bulb Temperature (°F)	110	110	110	110	110
Air Wet Bulb Temperature (°F)	90	90	90	90	90
Humidity (%)	46.9	46.9	46.9	46.9	46.9
Density (lbm/ft^3)	0.067	0.067	0.067	0.067	0.067
Enthalpy (BTU/lbm)	55.63	55.63	55.63	55.63	55.63
Fan Air Outlet					
Air Dry Bulb Temperature (°F)	110.0	110.0	110.0	110.0	110.0
Air Wet Bulb Temperature (°F)	90.0	90.0	90.0	90.0	90.0
Humidity (%)	46.9	46.9	46.9	46.9	46.9
Density (lbm/ft^3)	0.067	0.067	0.067	0.067	0.067
Enthalpy (BTU/lbm)	56.28	56.28	56.71	56.71	56.71

Fan Load (BTU/hr)	28608	28608	47260	47260	47260
Results					
Fan Selection	A 6	A 6	AX 8	AXX 8	AXXX 8
Weight (lbm)	530	530	750	450	300
Volume (ft^3)	8.5	8.5	12.0	8.0	4.0
Power (hp)	5.0	5.0	8.3	8.3	8.3
Fan Load (BTU/hr)	14304	14304	23630	23630	23630
Flow Rate (ft^3/min)	6300	6300	7000	7000	7000
Pressure Available (inches H_2O)	3.65	3.65	6	6	6
Ducting Size					
Velocity Limit (ft/min)	4500	4500	9000	9000	12000
Minimum Diameter (in)	21	21	15	15	13
Diameter (in)	22	22	16	16	14
Weight (lbm)	4455.0	4455.0	3240.0	3240.0	2835.0
Volume (ft^3)	237.6	237.6	125.7	125.7	96.2
Duct Velocity (ft/min)	4099	4099	7749	7749	10121
Reynolds Number (dimensionless)	766472	766472	1053899	1053899	1204456
Roughness (ft)	0.0003	0.0003	0.0001	0.0001	0.0000
Friction Factor (dimensionless)	0.015	0.015	0.013	0.012	0.012
Pressure Drop (inches H_2O)	0.8	0.8	3.7	3.5	6.5
System Characteristics					
Weight (lbm)	5515.0	5515.0	4740.0	4140.0	3435.0
Volume (ft^3)	254.6	254.6	149.7	141.7	104.2
Power (hp)	10.0	10.0	16.5	16.5	16.5
Total Frictional Loss (in H_2O)	0.83	0.83	3.65	3.47	6.46
Fan Performance	Acceptable	Acceptable	Acceptable	Acceptable	Unacceptable, select bigger fan or higher speed
Weight Differences (% reduction from Legacy)					
Fan	0.0	0.0	41.5	-15.1	-43.4
Duct	0.0	0.0	-27.3	-27.3	-36.4
Total	0.0	0.0	-14.1	-24.9	-37.7
Volume Differences (% reduction from Legacy)					
Fan	0.0	0.0	41.2	-5.9	-52.9
Duct	0.0	0.0	-47.1	-47.1	-59.5
Total	0.0	0.0	-41.2	-44.4	-59.1

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