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Navy Challenges and Opportunities with Low Global Warming Potential (GWP) Refrigerants

ABSTRACT

The Navy uses large quantities of hydrofluorocarbons (HFCs) as the refrigerant in its air conditioning (AC) plants. These plants range in cooling capacity from 125 to 1100 refrigeration tons (rTons) and circulate chilled water for various mission critical cooling applications including vital electronics, weapons systems and personnel. Many future high-powered electronic systems are being directly cooled using pumped two-phase cooling systems using these same HFCs refrigerants. Recent legislation, as well as international agreements, may affect the future availability and cost of these HFC's. In particular, the American Innovation and Manufacturing (AIM) Act (Public Law 116-260) calls for an 85% reduction of hydrofluorocarbons over the next 15 years. This paper summarizes challenges, opportunities and initial research efforts being pursued to identify low-GWP replacements suitable for use on Navy platforms.

BACKGROUND

Gases that trap heat in the atmosphere are known as greenhouse gases. These greenhouse gases have varying global warming potential (GWP). GWP is defined as the heat absorbed by the specific gas in the atmosphere as a multiple of the heat that would be absorbed by the same mass of carbon dioxide (CO_2) over a period of time, usually 100 years, unless specified otherwise.

An overview of greenhouse gas emissions in the United States in 2019 is shown in Figure 1. As shown, fluorinated gases have the smallest emissions but can have the most harmful impact on a mass basis, as these gases have long atmospheric lifetimes with GWP values thousands of times larger than carbon dioxide. Fluorinated gases have no known natural source and originate from human-related activities. The dominant source of emissions of fluorinated gas is HFCs leakage from vapor compression

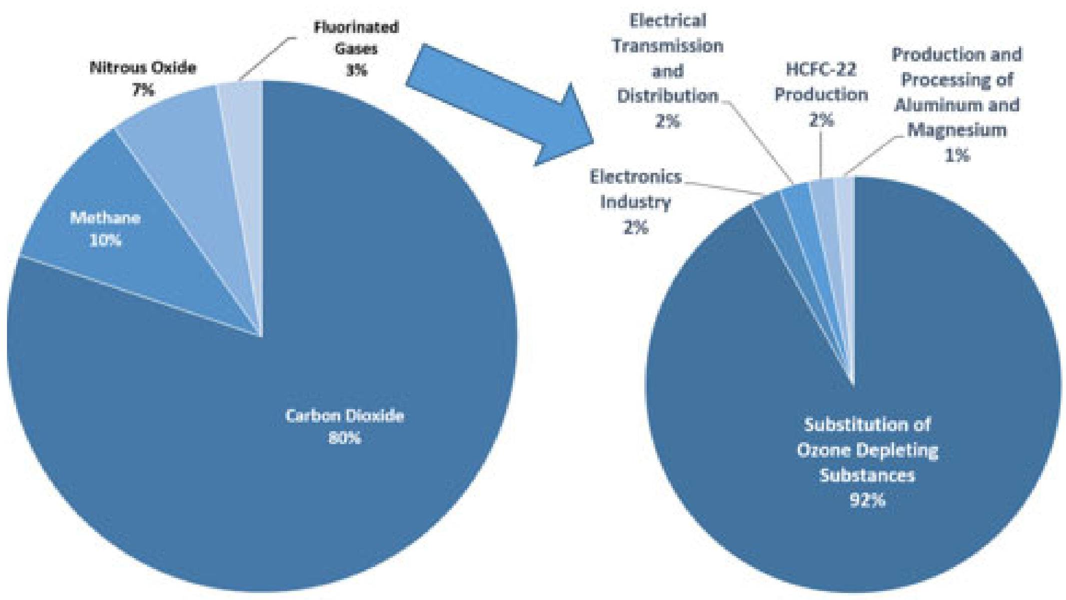

Figure 1 – Overview of Greenhouse Gas Emissions in United States in 2019 (EPA 2021)

cooling systems, such as air conditioning (AC), refrigeration systems and emerging pumped two-phase cooling systems. The AIM Act (enacted as section 103 in Division S, Innovation for the Environment, of the Consolidated Appropriations Act, 2021 (Public Law 116-260)) and implementing regulations in 40 CFR Subpart 84 (Phasedown of Hydrofluorocarbons) calls for an 85% reduction of HFCs over the next 15 years. As these regulations are enforced, the availability and price of these HFCs will result in operational challenges for the Fleet.

This paper is focused on AC plants used on US Navy Surface Ships, unless otherwise specified. A few key points are discussed below prior to identifying refrigerants used today.

Mission Critical Cooling Requirements

Naval surface ships AC plants utilize HFCs as the refrigerant to absorb the heat of the chilled water system and reject it to the sea. These plants have evolved and grown from small non-vital systems providing mostly habitability comfort cooling into large, robust and mission critical systems. Today, a failure of an AC plant is no longer just a matter of comfort; this condition could compromise vital command and control systems, sensors and weapon systems.

Shipboard design practices using highly reliable military-qualified AC plants provide high availability of cooling for mission critical systems. For instance, chillers are not centrally located but distributed throughout the ship to improve survivability. A spare AC plant is installed allowing cooling requirements to be met with any plant down for maintenance. Vital cooling requirements must be met with remaining AC plants when any space containing AC plants is lost due to flooding, fire or battle damage. Likewise, chilled water systems are vertically and horizontally segregated into multiple zones that support mission reliability and fight-through capability if one of the chilled water zones becomes degraded.

Military qualified AC plants are customized designs suitable for extended operation in salt-laden environments, sea states ranging from calm to hurricane conditions with temperature fluctuations ranging from arctic to tropic. Mission tempo, the inherent corrosion challenges of seawater, limited maintenance space, and thirty-plus year service life forces other design features of these units. Brazing and welding requires certification using approved processes and non-destructive verifications for compliance. During qualifications, these plants undergo stringent testing including shock, vibration, inclined operations (simulation of shipboard pitch and roll maximums), and electromagnetic interferences. AC plants are generally required to remain operational during these stringent tests, thus maximizing cooling availability when installed shipboard. To design, construct and qualify a new AC plant design typically takes many years. All of this 'military' customization while meeting strict noise requirements depends upon very specialized practices and expertise.

Refrigerant Boundary Integrity

Refrigerant leaks are quite common within AC and refrigeration systems. The Environmental Protection Agency (EPA) and Navy have established action levels associated with an equivalent of 10% - 30% refrigerant charge lost per year. Continuous improvement in design and maintenance practices helps minimize these leaks. The Air-Conditioning, Heating and Refrigeration Technology Institute (AHRTI)-Report No. 09006 Joining Techniques Assessment identified the major causes of joint leakage to be associated with compression fittings [Clodic 2014] which the Navy does not allow and brazed joints for which the Navy has far stricter requirements. It is important to note the following:

- All refrigerant systems are subject to increased leakage proportional to the operating pressure. The higher the operating pressure the greater the risk of leakage.
- All refrigerant systems using open-drive motor/compressors with motor shaft mechanical seals are subject to increased leakage.

However, Naval Surface Combatants are challenged in ways commercial industry is not. The main culprits of shipboard refrigerant leaks originate from the following:

- Vibration - Shipboard systems are exposed to various degrees of continuous external vibration from the ship's hull. Over time, this vibration can cause mechanical joints and connections to loosen or sustain damage.
- Load Variations - These systems are required to operate from artic to tropical conditions. This extreme range of operating conditions dictates that naval AC plants have a variety of controls to allow operation between 10% to 100% load. These additional controls have traditionally been accomplished with a variety of flow control devices and valves that add additional leak paths from shaft and valve stem seals.
- Thermal Cycling – All refrigerant systems are subject to thermal cycling at startup as the high-side heats ups and the low-side cools down. Navy systems could be exposed to further extremes as these units are generally installed in machinery rooms designed to maintain temperatures between 40 degrees Fahrenheit (°F) and 110°F. This cycling can stress poorly fabricated mechanical and brazed joints leading to leakage.
- Corrosion – The marine environment with its salt-laden high humidity air presents challenges for any ship. The shells of most AC plants are painted carbon steel, and the high humidity and low evaporator shell temperature combined with its insulation present the perfect environment to trap moisture and create conditions for corrosion.
- Operating Tempo – Naval combatants are often at-sea for extended operating periods, and the opportunity to perform maintenance and repair is often overcome by ship mission. Maintenance/repairs are more difficult to perform when at-sea; each action must be assessed to ensure it can be safely accomplished, required parts are available and it will not affect the ship's mission. Most maintenance/repairs are deferred to in-port periods, unless critical.
- Elastomers - Most mechanical joints use O-rings or flat gaskets to facilitate shipboard repairs; over time, these compounds are subject to compression set, and begin to leak as elastic properties are degraded.

Shipboard detection of actual leaks is often difficult as leakage rates differ under different operational conditions. Although machinery spaces are monitored for refrigerant leakage, large air exchanges make detections of small leaks difficult. Leakage rates exceeding a few pounds per day can go unnoticed. Additionally, as with most other refrigeration systems, joints are often lagged with insulation making identification of the exact source of the leakage difficult. Aside from when a large leak causes an alarm from the refrigerant space monitor, only careful leak testing of the refrigerant system can detect small leaks. When larger quantities of refrigerant are lost, the effects can be observed by analyzing operating logs or careful observation of the refrigerant level within the evaporator's sight glass when the plant is secured.

What is often not appreciated is the inherent time necessary to perform repairs within the refrigerant boundary. Before a repair can be made, the refrigerant must first be removed. It may only take 30-minutes to remove the liquid, but it can take another 2-4 hours to remove the vapor to 15-inch Hg vacuum (EPA requirement). Following repairs, integrity of the refrigerant boundary is verified using a positive pressure test followed by evacuation to a vacuum of 500 microns. If additional leaks are identified, these tests could be performed several times until the system is able to pass all requirements. For a ship at-sea, small leaks are by necessity deferred to in-port periods.

Newer Design Features

A number of design features have been adopted within naval refrigerant systems to help reduce our carbon footprint by reducing refrigerant leakage/contamination and reducing energy usage. Below are a few of these items.

- Standard Navy AC plants use thicker walls in the 70/30 copper-nickel condensing tubes than used in commercial marine units. The latest chillers use life-time, seal-welded titanium condensers to support even tighter ship packaging by essentially eliminating tube pull-space. Contamination of the refrigerant boundary with seawater has been virtually eliminated.
- Standard Navy AC plants use thicker walls in the 90/10 copper-nickel or copper evaporating tubes than used in commercial marine units. The latest chillers use life-time, seal-welded evaporators. Contamination of the refrigerant boundary with chilled water has been virtually eliminated.
- Instrumentation improvements monitoring three parameters (flow, pressure & temperature) have helped eliminate the risk of freezing and rupture of evaporating tubes.
- Many AC plants provided today are equipped with hermetic motors, thus eliminating the potential of a shaft seal leak. Shaft seals are a common failure item and require the refrigerant to be removed prior to replacement. Hermetic motors are more expensive but improve the availability and reliability of these units. Shaft seal leakage has been the most significant contributor in defining the mean time between failure rates for applicable systems. [Frank 2004]
- The High Efficiency Super Capacity (HESC) AC plant uses an oil-free compressor design that eliminates the oil lubrication system. This dramatically simplifies the chiller; eliminating the difficult marriage of refrigerant and oil; eliminating 80 percent of the valves and fittings that are sources of refrigerant leakage (maintenance & global warming); oil and filter changes (maintenance & hazardous waste disposal); and on-board oil stowage (space & fire hazard).
- The HESC AC plant uses variable speed operation, thereby promoting optimum energy efficiency at all operating conditions while reducing the starting in-rush current by at least 75 percent. This reduces energy usage, improves reliability and reduces stress to the ship's electrical distribution system. Additionally, the lower starting current provides increased flexibility during emergency and casualty conditions when shipboard electrical power may be limited. The HESC is expected to require less energy than fixed-speed designs, especially at partial load and lower seawater temperature conditions, noting that a ships' greatest electrical demand is during the winter.
- Various sized (0.75 and 1.5 rTons) modular refrigeration units (MRUs) have been qualified for use. Unlike AC plants, MRUs use many commercial off-the-shelf components like hermetic scroll compressors, flat plate heat exchangers, fans, etc. These components are packaged within a self-contained unit to meet military requirements. MRUs are installed in multiples for cooling ships stores

freeze/chill rooms using forced circulation across an evaporator. The refrigerant charge has been reduced by about 80% and leakage has been reduced by an estimated 90% when compared with previous reciprocating compressor designs.

Life Cycle Climate Performance

Life Cycle Climate Performance (LCCP) is an evaluation method to evaluate the global warming impact from manufacturing to disposal. This method analyzes direct emission of refrigerants to the atmosphere through its service life from leaks, servicing and disposal; it includes indirect emissions from CO_2 that are emitted by generating the electrical power to drive the AC plant over its lifetime. This becomes complex as Navy ships are generally powered by shore power supplied from the electrical grid when in-port and reliant on shipboard power plants at sea. LCCP also includes embodied emissions to capture the global warming effects of manufacturing, transport, installation and disposal of this equipment. The lower the LCCP is, the better it is for the environment.

It is obviously desirable that any lower GWP refrigerant replacement have energy efficiency comparable to that of the HFCs currently in use. If not, the benefits from direct emissions will be offset by indirect emission. When underway, all ships except for nuclear-powered aircraft carriers and submarines generate electricity using gas turbine or diesel generators, which are typically operating with efficiencies between 20 and 40 percent. One extra kilowatt of electrical power each hour over a six-month underway period has an equivalent increase in its carbon footprint of approximately 7,400 pounds. This is equivalent to a HFC-134a (GWP 1430) leak of 5.2 pounds during the same period. It is important to understand this trade off when analyzing the true benefits of low GWP replacement candidates.

Lastly, it is important that LCCP be accomplished at the total ship level for Next Navy ships. Naval AC plants sometimes trade space for performance. Space is typically a premium on a Navy ship with equipment tightly packed within. AC plants can be made smaller by reducing heat transfer surfaces in the evaporator and condenser. However, this system would likely require more compressor power. But this action could allow the ship to have a smaller hull and thereby use less propulsion power. In this case, more fuel would likely be saved as propulsion needs are an order of magnitude greater than the power differences between the two AC plant configurations.

REFRIGERANTS USED TODAY

The Navy implemented a strategy to utilize non-ozone depleting substances (ODS) as refrigerants in the mid-1990s [Toms 2002]. The HFCs used in today's AC plants are a direct result of that program known as the Chlorofluorocarbons (CFCs) Elimination Program. Further details are summarized below.

HFC-134a was selected as the refrigerant of choice for all future fleet ship construction in both air conditioning and refrigeration systems on surface ships and submarines. This refrigerant has been installed on most ships commissioned after 2001.

Legacy reciprocating compressor air conditioning and refrigeration systems using refrigerant CFC-12 were retrofitted to utilize ozone-friendly refrigerant HFC-134a. Many of these ships are being converted to MRUs, which can reduce refrigerant leakage by 90%.

CFC-114 centrifugal compressor AC Plants used in surface ship applications were retrofitted to utilize refrigerant HFC-236fa (GWP-9810). The Navy currently uses Refrigerant HFC-236fa in over three hundred and twenty AC plants aboard aircraft carriers, destroyers, cruisers and amphibious class ships. These plants are currently over twenty years old and their population continues to shrink as these ships are decommissioned.

Legacy self-contained compact refrigerant systems have transitioned to ozone-friendly alternatives through natural attrition as these systems have shorter service lives. Preferred refrigerants for self-contained and modular refrigeration equipment include HFC-134a, HFC-404A, HFC-407A, HFC-410A, HFC-422b and HFC-507. These units are easily replaced shipboard similar to a household refrigerator and not addressed in this paper.

Historically, there have been difficulties maintaining Navy's systems operating in vacuum. Two examples include CFC-11 in centrifugal AC plants applications and lithium bromide in absorption applications. These systems were very difficult to maintain as air and moisture would enter the refrigerant boundary that operated with portions of the system in a vacuum.

CHARACTERISTICS OF AN IDEAL REFRIGERANT

The ideal replacement refrigerant must meet various key parameters. First, the refrigerant must have a safe toxicity profile, be non-flammable, non-explosive and have acceptable decomposition products. Additionally, the refrigerant must be environmentally compatible meeting ozone depletion potential (ODP) and global warming potential (GWP) restrictions. Pure fluids or azeotropes blends (such as R-513A) are preferred as the composition of refrigerant mixtures could change over time from leaks and affect performance. Refrigerant physical parameters such as boiling point, critical temperature, evaporating pressure and condensing pressure must be considered. The refrigerant flowrate, cycle efficiency, material compatibility, and thermodynamic properties are all factors, which must be evaluated. Research is being conducted to help identify viable replacement candidates [McLinden 2017]. It is important that the refrigerant be available and affordable; ideally having multiple domestic production facilities while not being restricted by current and anticipated future regulations. Several of these alternatives may be increasing atmospheric degradation products such as trifluoroacetic acid (TFA) [Behringer 2021; Holland 2021]. It is uncertain whether these findings will further restrict refrigerant candidates.

Safety

Many of the lowest GWP refrigerants are more flammable. The American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) Standard 34 provides a method to classify the safety aspect of different refrigerants. The first capital letter (A or B) classifies toxicity. "A" being less toxic and "B" being more toxic. Next is a number from 1 to 3 designating flammability; "1" being non-flammable, "2" being flammable and "3" being extremely flammable. Subclass 2L was added, which designates flammable refrigerant that burn slowly (≤ 3.9 inches per second). Ideally, refrigerants with a designation of "A1" are preferred.

Testing has shown that the flammability of many of these lower GWP alternatives increases with temperature and humidity. Navy machinery spaces are typically not air-conditioned but are cooled by ventilation with outside ambient air in which the dew point could exceed 86°F. Machinery rooms are generally designed to maintain the normal space temperature below 110°F during summer conditions, but casualty conditions could elevate the temperature to as high as 150°F. This worst-case scenario for refrigerant flammability must be assessed.

Compatibility of the refrigerant with elastomers, seals, plastics, hermetic motor materials, and the lubricating oil will all need to be evaluated for suitability.

Performance

Obviously, it is desirable that the performance of any lower GWP refrigerant candidate meets or exceeds performance of the HFCs currently in use. This includes lower specific power (kilowatt per rTon) over the entire operational range while still meeting design capacity at desired conditions. Thermodynamic properties for centrifugal compressor applications prefer maximum boiling coefficients, maximum condensing coefficients, maximum speed of sound value of the suction gas, minimum mass flow and minimum isentropic enthalpy differences among the high and low pressure side of the cycle.

It is important to ensure the entire operational range is optimized for the chosen compressor. Detailed analysis requires proprietary compressor maps from the Original Equipment Manufacturer (OEM) that are often unavailable. Compressor maps are experimentally generated in dedicated compressor test facilities and represent a significant investment. Normalizing the data into dimensionless groups is important as it allows one to analyze compressor performance at a given speed, with any similar fluid at any flow and head (pressure difference) coefficients. Concentric contours defining the compressor isentropic efficiency islands at different flow and head coefficients are typically shown between the surge and choke lines. System lines are often plotted on this map to illustrate the expected operating regime at various seawater temperatures and cooling capacities.

Without access to this information, modeling of the AC performance within its operating regime becomes very difficult. The main sources of inefficiencies originate from the compressor/motor assembly. Control actuators, like pre-rotational vanes (PRVs), variable geometry diffuser (VGD), hot gas bypass (HGB), variable orifices (VOs) and condenser water control valves (CWCVs) all add further complexity as the integration of these many controls are necessary for optimum performance.

LOW GWP ALTERNATIVES FOR BACK-FIT APPLICATIONS

There are challenges to back-fit low GWP alternatives into the Fleet. Naval AC plants are located deep in the ship with very tight packaging and intended to last the life of the ship. Maintenance routes are designed by the ship's planning yard so large components, like a compressor, can be removed from the ship and replaced. However, this is not an easy process, as it typically requires disassembly and reassembly of other systems along the route. Replacement of an entire AC plant or condensing unit would require expensive hull cuts in a dry dock availability as well as disassembly and reassembly of other systems.

The Navy is beginning to investigate back-fit options for its HFC-134a and HFC-236fa AC plants. Obviously, it is desirable that the performance of a candidate refrigerant in an actual AC plant meet or exceed the performance of the original refrigerant.

Refrigerant HFC-134a Alternatives

Since HFC-134a is a commonly used commercial refrigerant, the Navy is able to leverage work already accomplished by industry and academia. Many HFC-134a replacement candidates, with lower GWPs, have been identified [Domanski 2018]. Manufacturers and researchers are working to find solutions that minimize negative impacts on safety, first cost, and energy efficiency, among other considerations.

A simplified model was used to assess many lower GWP HFC-134a alternatives assuming a nominal 200 rTons of cooling. The calculations assumed a common saturated evaporator temperature of 40°F and a common saturated condensing temperature of 110°F in an ideal cycle, in which the compressor and motor were assumed to be 100% efficient. These results are shown in Table 1.

Table 1 – Comparison of HFC-134a Alternatives

Characteristics	HFC-134a	R513A	R450A	R1234ZEE	R1234YF
ODS Potential	0	0	0	0	0
GWP Potential	1430	629	601	6	1
Safety Classification	A1	A1	A1	A2L	A2L
Evaporator Pressure (psia) T_{sat} of 40°F	49.7	54.8	44.1	36.9	53.1
Condensing Pressure (psia) T_{sat} of 110°F	161.1	169.4	142.9	121.6	160.6
Differential Pressure (psid)	111.3	114.5	98.8	84.7	107.5
Isentropic Enthalpy of Compression (BTU/lb)	10.5	9.2	10.1	9.6	8.5
Mass Flow (lbs/min)	665.3	788.8	707.3	729.9	874.3
Volumetric Flow (ft^3/min)	633.9	632.9	737.4	855.8	687.2
Speed of Sound (ft/s)	481.5	458.0	466.2	456.2	442.9
Ideal Compressor Power (kW)	122.8	127.4	125.4	123.6	130.0

Results show several promising candidates from a thermodynamic viewpoint. All Navy HFC-134a AC plants are hydro tested during production to 400 pounds per square inch gauge, which appears suitable for these alternatives. This analysis indicates these alternatives will require slightly higher power. Higher fidelity modeling is necessary to better understand power usage and overall cooling capacity when operating with these alternatives. For instance, boiling coefficients, condensing coefficients, suction losses, discharge losses and compression efficiency will differ among these refrigerants. All of these differences will have impacts to performance that must be assessed to ensure the Navy is positively affecting the environment.

A preliminary hazard analysis (PHA) is currently being conducted, which addresses several of these low GWP alternatives. This will document and assess the risks associated with each alternative refrigerant. This will include pressure vessel safety, toxicity, flammability, material compatibility, ignitions sources and how these all relate to various leak/rupture events. The PHA is intended to advise and guide the Navy in a process that can be used to approve low-GWP refrigerants for shipboard use.

The National Institute of Standards and Technology (NIST) conducted a study under the Strategic Environmental Research and Development Program (SERDP) to investigate low-GWP alternative refrigerant blends for HFC-134a. As most pure fluids are at least mildly flammable, this project investigated formulating non-flammable ternary refrigerant blends that could satisfy the requirements of military systems [Domanski 2018].

There are a number of different capacity AC plants using HFC-134a in the Navy. Nominal capacity of these plants range from 200 to 1100 rTons when supplying 42 to 44°F chilled water with actual capacities varying with seawater temperatures ranging from 85 to 97°F.

Refrigerant HFC-236fa Alternatives

The Navy is the main user of HFC-236fa as a refrigerant. As such, there has been less research on potential replacements. Ships with HFC-236fa AC plants are almost entirely over twenty years old and their population continues to shrink as these ships are decommissioned.

The same simplified HFC-134a model was used to assess many lower GWP HFC-236fa alternatives assuming a nominal 200 rTons of cooling capacity using the previous assumptions for saturation conditions. CFC-114 was added for comparison as when the Navy converted from CFC-114 to HFC-236fa, a compressor change was required. Specific results are provided in Table 2.

Table 2 – Comparison of HFC-236fa Alternatives

Characteristics	HFC-236FA	R1233ZDE	R1336MZZZ	R1336MZZE	CFC-114
ODS Potential	0	0	0	0	1
GWP Potential	9810	1	2	18	10000
Safety Classification	A1	A1	A1	A1	A1
Evaporator Pressure (psia) T_{sat} of 40°F	18.7	8.5	4.4	12.8	15.2
Condensing Pressure (psia) T_{sat} of 110°F	69.9	34.7	20.8	51.2	54.0
Differential Pressure (psid)	51.2	26.3	16.4	38.4	38.8
Isentropic Enthalpy of Compression (BTU/lb)	8.2	10.9	9.4	8.1	7.2
Mass Flow (lbs/min)	859.4	603.1	714.5	870.3	958.2
Volumetric Flow (ft^3/min)	1532.1	2845.6	5148.6	2130.4	1901.5
Speed of Sound (ft/s)	399.7	444.9	394.6	387.0	382.1
Ideal Compressor Power (kW)	123.5	115.1	117.9	123.4	120.6

Results show a compressor replacement would be required to obtain comparable performance with listed alternatives. All Navy HFC-236fa

AC plants were hydro tested to 105 pounds per square inch gauge, which appears suitable for these alternatives. There is a concern with the higher volumetric flow requirements of alternatives as liquid droplets entrained in the vapor entering the compressor will likely limit obtainable capacity, likely less than current design values. Furthermore, all of these potential alternatives would have portions of the system operating in a vacuum that will need to adapt to an aging condensing unit. This is a concern, as prior experience with CFC-11 showed that air and moisture entering these units resulted in an increase in equipment failures, maintenance and repair. Furthermore, hermetic motors are currently not used in these AC plants but may need to be adopted for any system operating in a vacuum to help reduce the likelihood of air and moisture entering the system and improve reliability. Flammability (at high dew points and temperatures), toxicity and material compatibility are compounding issues as they are for HFC-134a low-GWP alternatives.

Retrofitting these systems with a new compressor/motor assembly and low-GWP refrigerant presents challenges. It would probably take four to seven years to approve the refrigerant, develop/qualify the equipment and finalize the logistical documentation to support shipboard installations. Shipboard installations would probably start slowly so lesson-learned could be applied to later installations, thereby reducing installation time and costs. Longer availabilities would likely be required to accomplish the anticipated work package; this would limit opportunity to perform the alteration.

The conversion kit hardware would likely not be available until nearly 2030. Likewise, it may not be cost effective to convert a ship with a remaining service life of five years or less. Any conversion efforts would then focus on ships whose service lives extend well beyond 2030, such as CVN 71-75, LHDs and DDG 64-82. These ships use AC plants with nominal capacity ratings of 200, 300 and 363 cooling rTons when supplying 44°F chilled water with 88°F seawater.

FORWARD FIT OPTIONS

The Navy must identify the refrigerant of choice for future platforms that can be approved for shipboard use. The ability of the refrigerant to adapt to the Navy's latest AC plants is desirable, as this would promote a quicker and cheaper transition into the Next Navy.

Future development of AC plants can be customized for the actual refrigerant and design conditions. Many of the requirements specified earlier will likely still be required. There are areas in which further improvements could be adapted. A few targets could include reducing operating refrigerant charges, enhancing long-term mechanical joint integrity, reducing weight/space/power requirements, compact/effective economizers for two-stage applications, reducing fouling in seawater cooled condenser, and adopting instrumentation to better identify refrigerant loss and other operating inefficiencies in real time.

NEXT STEPS

The AIM Act mandates that EPA allocate the full quantity of HFC production and consumption allowances for mission-critical military end uses (MCMEU), which includes Navy shipboard chillers. However, it also mandates that the EPA review the availability of substitutes not less frequently than once every five years. In addition, the EPA regulations implementing the AIM Act (40 CFR Subpart 84) require that Department of Defense (DoD) provide, as part of their annual HFC allowance, allocation request for MCMEU, a description of plans to transition to HFCs or HFC blends with a lower exchange value (exchange value is equivalent to GWP) or alternatives to HFCs, including not-in-kind substitutes. Furthermore, EPA granted petitions under the technology transition subsection of the AIM Act on 14 October 2021, which call for a 2024 ban on the use of refrigerants with a GWP greater than 750 in new stationary chillers. EPA has already made the determination that suitable substitutes are available in these commercial chillers. Similarly, several States including California, Washington, and Virginia have passed regulations banning the use of HFC-134a and other refrigerants with GWP greater than 750 in new stationary chillers effective 1 January 2024.

The Office of Naval Research (ONR) has begun a program to research approaches to replace HFC currently used in Navy systems with low GWP replacements. This program will also evaluate alternative (non-refrigerant) chiller technologies for shipboard use. Initial efforts are focusing on pursuing approval to use promising low-GWP refrigerants shipboard. As issues and concerns are identified, solutions and/or mitigation strategies can be pursued. Also, fidelity of AC plant models are being expanded so the performance with low-GWP alternatives can be better analyzed. Initial focus will be directed towards R-513A (GWP of 629) as a potential direct replacement in HFC-134a (GWP of 1430) systems. Indirect effects from potential increase in energy usage may offset the benefit from the lower GWP value and this effect will be further analyzed.

The Navy's equivalent carbon footprint from direct refrigerant release from AC plants is projected to be reduced by almost 60% in the next fifteen years, as shown in Figure 2. This reduction originated from decommissioning of ships using high GWP refrigerant (HFC-236fa) while commissioning ships that use HFC-134a, which has a much lower GWP value. The percentage of Fleet AC plants with newer design features, which reduce the potential for refrigerant leakage, continues to grow. The ability to implement lower GWP alternatives within the Fleet's AC plants may accelerate and improve this projected reduction.

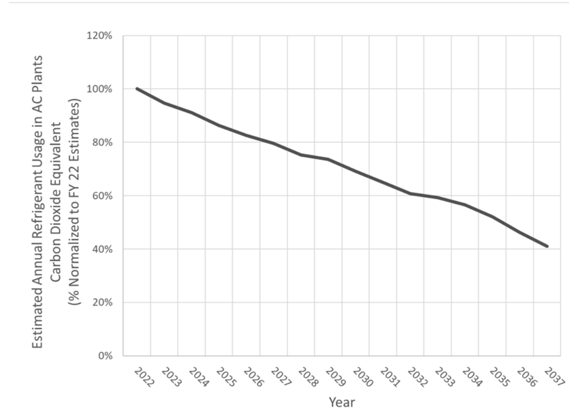

Figure 2 – Equivalent Carbon Footprint from Projected Refrigerant Loss

The ability to better maintain AC plants in the Fleet will also reduce the Navy's carbon footprint. A greater emphasis toward identifying and repairing refrigerant leaks is needed fleet wide. Understanding the source of leakage can help designers focus on improvements. Improved training and field support will likely help. An AC plant that is operated in a degraded condition (low charge, fouled condenser or improper controls) can cause as much as a 50% increase in power usage. Fully implementing annual 'grooming' by experienced field personnel could have wide ranging benefits from reducing refrigerant leakage to improved equipment availability and efficiency, thereby lowering the Navy's carbon-footprint.

The Navy has various programs targeting shipboard energy reductions. Two of these Naval Sea Systems Command (NAVSEA) programs are the Fleet Energy Research and Development Program (FERDP) and the Energy Resilience, Efficiency, Assurance, Conservation, Training and Security (Energy REACTS). These efforts will also help reduce the Navy's carbon footprint.

CONCLUSIONS

The HVAC industry is in the middle of another major refrigerant transition. However, unlike the orderly transition from ODS to HFCs, the transition to low-GWP refrigerants is far more complex due a wider variety of potential alternatives that require evaluation, including the assessment and mitigation of fire safety, while not being restricted by current and anticipated future regulations. Similar to commercial industry and other DoD agencies, the Navy is working to find solutions that minimize negative impacts on safety, first cost, and energy efficiency, among other considerations. Many unique requirements will likely require expertise from academia, industry and various government agencies to resolve. Many challenges, as well as opportunities, to improve these AC plants remain as the Navy pursues steps to transition to low-GWP alternatives.

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ACKNOWLEDGEMENTS

The authors wish to warmly thank the many members of NAVSEA, NSWCPD, Noblis MSD and CACI International who helped contribute to this paper, with special mention to Joshua Bowman, David New, Michael San Antonio, Shan Abeywickrama, P.E., Russel Bizaro, Jim Winward, Jason Aschenbach, Kevin Wiley and Alberto Tecce, Neil Antin and Pete Mullenhard.

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