**Naval Surface Warfare Center**
**Carderock Division**
West Bethesda, MD 20817-5700



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# Green Arctic Patrol Vessel


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**NSWCCD-CISD–2010/002** Green Arctic Patrol Vessel

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*In anticipation of more stringent environmental regulations, a Green Arctic Patrol Vessel (GAPV) concept was developed by a 2010 CISD summer intern project. The project focus was based on evolving the design developed by the APV project in 2009 to incorporate a range of 'green' technologies and design features with minimal changes to the structural concept. The aim was to reduce impact on the environment at the ship's systems level.*

*GAPV conceptual designs were developed for technologies available for the years 2015 and 2030. Green technologies were implemented throughout the ship in areas regarding power generation, alternative power sources, materials, coatings, waste treatment, ballast operations, and anti-icing techniques. Results include reduced emissions, reduced discharged material, and increased efficiency at the cost of increased weight and system complexity.*

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# ABSTRACT

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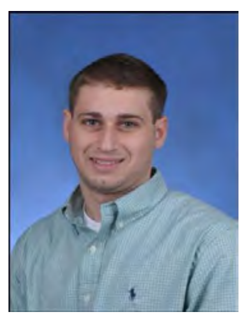

Kevin Meier

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# ACRONYMS

ABS – American Bureau of Shipping
APV – Arctic Patrol Vessel
BOP – Balance of Plant
BWT – Ballast Water Treatment
CISD – Center for Innovation in Ship Design
CMU – Compress Melting Unit
EHP – Effective Horsepower
GAPV – Green Arctic Patrol Vessel
Gensets – generator sets
GT – Gas Turbine
IMO – International Maritime Organization
IPS – Integrated Power System
MAGS – Micro-Auto Gasification System
MGT – Micro Gas Turbine
NSWCCD – Naval Surface Warfare Center Carderock Division
OBB – Odor Barrier Bags
PZT – Piezoelectric Transducer
PV – Photovoltaic
SHP – Shaft Horsepower
SOFC – Solid Oxide Fuel Cell
SWATH – Small Waterplane Area Twin Hull
SWS – Solid Waste Shredder
TEG – Thermoelectric Generator
THRP – Total Heat Recovery Plant
VOC – Volatile Organic Compounds
WETT – Wastewater Electrochemical Treatment Technology

# INTRODUCTION

A 2010 summer intern design team developed the Green Arctic Patrol Vessel (GAPV) design over the course of ten weeks at the Naval Surface Warfare Center Carderock Division (NSWCCD). The team included four summer interns and a full-time employee from the Center for Innovation in Ship Design (CISD). During the project, the interns worked under the Naval Research Enterprise Internship Program (NREIP) while overseen by full-time employees of CISD.

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| Sam Linder | University of Michigan | Naval Architecture |
| Kevin Meier | Florida Atlantic University | Ocean Engineering |

## Background

Navigation has become easier due to the receding ice in the Arctic Ocean and natural resources are becoming more accessible. As a result, countries bordering the Arctic have an increased interest in securing their respective territories. It is expected that an Arctic patrol vessel will be required to provide a dedicated independent capability to undertake patrol and support diplomatic initiatives with military capability.

A summer intern project conducted during the summer of 2009 at CISD resulted in the concept design of the Arctic Patrol Vessel (APV) shown in Figure 1. The principal characteristics are shown in Table 1.[1] The APV is a Small Waterplane Area Twin Hull (SWATH) ship outfitted for the following:

- Navigation in Arctic waters
- Long endurance patrol missions
- Detection and interdiction of foreign ships and submarines
- Transportation of personnel and cargo to remote Arctic ports and research facilities

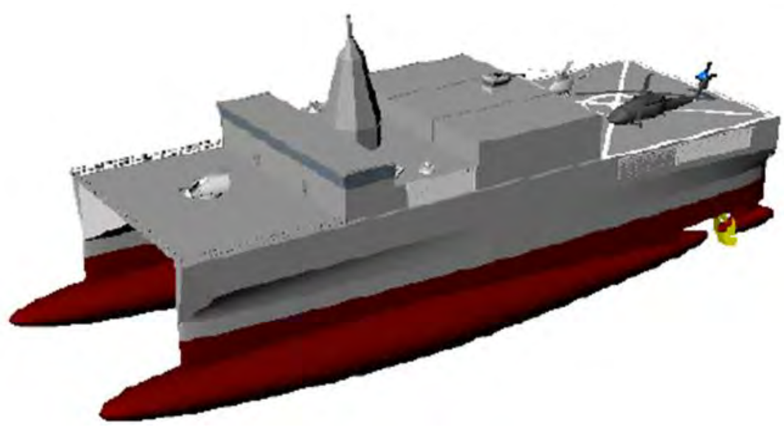

**Figure 1: 2009 APV Concept**

| | |
|---|---|
| Displacement - Lightship (LT) | 5,600 |
| Displacement - Full Load (LT) | 6,480 |
| Length Between Perpendiculars (ft) | 260 |
| Length Overall (ft) | 290 |
| Beam (ft) | 93 |
| Draft (ft) | 28 |
| Depth (ft) | 58 |
| Freeboard (ft) | 30 |
| Range at cruise speed of 12 knots (nm) | 7,000 |
| Trial speed (knots) | 20 |
| Machinery | Integrated Electric |
| Generators | 4 x 6.7 MW |
| Propulsion Output (hp) | 2 x 10,000 |

**Table 1: Principal characteristics of the APV**

The APV project did not focus on minimizing the impact of ship operations on the Arctic environment or defining systems for the vessel. As a result, this GAPV project was developed by CISD for the summer of 2010 to further define the specifics of the APV. The goal of the project was to incorporate "green" technologies into the original APV design that would improve overall efficiency and reduce environmental impacts.

## Requirements

The mission of the 2009 APV design was to navigate in Arctic waters, conduct long endurance patrol, detect and interdict foreign ships and submarines, and transport personnel or cargo to remote Arctic ports and research facilities. The APV project requirements and conclusions are summarized in **Table 2**.

| APV Project Requirements | APV Project Conclusions |
|---|---|
| • Operation temperature: -40 ºF<br>• Operational in sea state 6<br>• Survivable in sea state 8<br>• Range of 7,000 nm at 12 knots | • Integrated propulsion system<br>• SWATH hull<br>• Operational during July-November<br>• Trial speed of 20 knots<br>• Crew of 112 |

**Table 2: APV Project requirements and conclusions**

The GAPV, as a continuation of the APV project, needed to be capable of undertaking all of the missions outlined for the APV. The focus was on the systems within the design, rather than structural and hull form modifications. The systems that were defined had to work within the parameters of the APV.

The GAPV project focused on evolving the design developed by the APV project in 2009 by incorporating a range of "green" technologies and design features. The aims were to:

- Maximize efficiencies
- Minimize emissions and environmental impact
- Incorporate light-weight materials
- Limit discharge at sea by encouraging "reduce, re-use, and recycle"

- Incorporate modular designs to accommodate future technological advances
- Accommodate for more stringent environmental regulations in the future
- Provide both pollution control and pollution prevention equipment onboard

The GAPV design team defined two conceptual designs; one for the year 2015 and another for the 2030, in anticipation of maturing technologies and more stringent environmental regulations. Green technologies were researched that would improve efficiency and minimize the footprint left on the environment in the following areas:

- Propulsion & power plant
- Alternative power systems
- Coatings
- Materials
- Onboard waste management
- Anti-icing

The GAPV project performed initial integration of the systems into the ship for the 2015 design, but only estimated the impact from the systems for the 2030 design.

# GAPV POWER REQUIREMENTS & PROPULSION

## Power Requirements

The APV cruise speed of 12 knots requires 2.3 MW (3,100 SHP) as shown in Figure 2.[1] The trial speed was reduced from 20 knots to 17.5 knots in order to meet the design goals for the GAPV. The reduction in trial speed decreased the powering requirement by 14.9 MW (20,000 SHP). The GAPV will still be able to complete its mission with a trial speed of 17.5 knots requiring 7.45 MW (10,000 SHP) and will also benefit from an increased endurance. The operational profile called for 36 hrs of operation at trial speed. The change in speed from 20 to 17.5 knots would call for an additional 5 hours of operation at the reduced speed. The extension of the operational profile was deemed acceptable to the concept of operations when considering the tradeoff in power and fuel savings. The limited amount of time dedicated to the trial speed mission requirement justified the decision. The GAPV power plant will have sufficient margins to handle usage demands above and beyond the mission requirements.

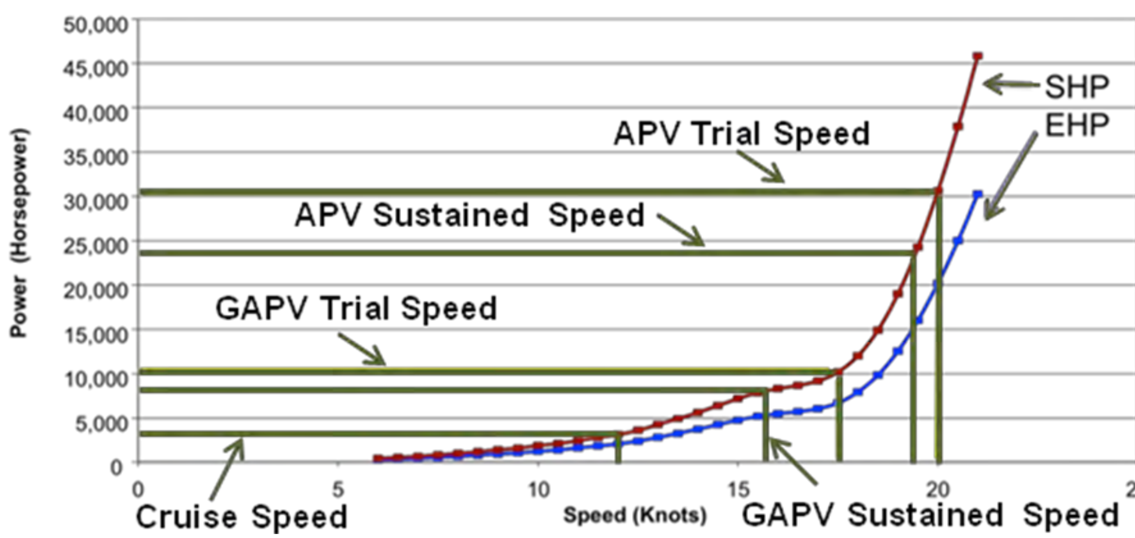


**Figure 2: Powering requirements**

## Base Loading

Base Loading was utilized to most effectively deal with the different power requirements of the GAPV. By sizing the system based on three distinct loading requirements, the system efficiency can be increased and energy wastes are reduced. The GAPV"s electrical load break down was as follows: Low, Cruising, and Peak Loads which can be seen in Table 3.

| Mode of Operation | Required Time at Load | Applications |
|---|---|---|
| Low | 15% | Low speed and low load |
| Cruise | 80% (7,000 nm) | 12 knot req. and hotel services |
| Peak | 5% | 17.5 knot req. and high load applications |

**Table 3: Load breakdown**

Other loads such as propulsion power, thermal anti-icing, and HVAC will all be accounted for as they fall into these base loads. For example, the peak load requirement will be responsible for the hotel services high load applications. In an effort to increase system efficiency, the GAPV"s loads were broken down and components sized specifically to optimize the drastic differences in power requirements.

# Integrated Power System

The APV Integrated Power System (IPS) design lacked detailed definition. The concept was expanded from the APV baseline in an effort to create an all-electric ship in conjunction with the electric drive from the Azipod propulsion units chosen in the APV design.[1] An IPS was chosen for both the 2015 and 2030 design.

## *Overview*

In the IPS, the prime movers will produce electricity to a common electric grid from which loads will be pulled. The electricity created by the generator sets will go to a high voltage line (either 3 phase AC or DC at 3.3 kV) with an electrical efficiency of 93%. Transformers, converters, and high/low pass filters will then condition the electricity to be directly supplied to where it is needed. For the 2015/2030 IPS layouts, see Appendix C.

### IPS Controls

The IPS controls are beyond the scope of this project. However, it is important to note that the optimization of different energy sources and loads that both produce and pull from the IPS common grid is an important area of development.

### Advantages

The advantages for using an IPS in an all-electric ship include reduced life cycle cost as well as reduced installed power. An IPS allows for a more modular design concept with the ability to easily incorporate newer technologies as they come to fruition. A crucial consideration for an IPS is the ability to locate machinery anywhere on the ship, which is extremely advantageous for the GAPV"s SWATH design as well as for survivability. An IPS creates a lower power generation requirement stemming from a reduced need for extraneous auxiliary systems by integrating multiple sources of power generation. With an IPS there are fewer rotating components, which translates to reduced noise pollution. The IPS increases the efficiency of the system by creating a commonality between the prime movers and loads (electricity), lowering the power requirement and decreasing fuel requirements.

### Disadvantages

The disadvantages of the IPS include the added weight from the increase in electrical components and excess heat if there is no recovery system for it.

## Electric Load

The APV hotel load estimate lacked detail. The hotel load was further evaluated using a similar vessel, the T-AGOS-23. The electric load was evaluated by creating a detailed list of the T-AGOS-23 hotel loads and then scaling the power requirements to the GAPV design. The total electrical load for the hotel services was estimated to be 1.85 MW. The reduction in propulsion power changed the total cruise and hotel load from 7.10 MW (APV design) to 4.15 MW. Peak and high load power was reduced from 25.50 MW (APV design) to 9.30 MW. For electrical load calculations, including service margins, see Appendix D.

## Propulsion

The APV design used two Azipods sized for 22.5 MW for propulsion. The GAPV features twin Azipod steerable propulsors from ABB Marine. The system gives the GAPV excellent maneuverability and improved fuel efficiency. Two VO 1600 Azipods provide the 7.45 MW needed at 17.5 knots. These pods are American Bureau of Shipping (ABS) classed and meet the International Maritime Organization (IMO) regulation for Icebreaker ICE-10 standards. Their unique design allows the pods to deflect, break, and take impact from ice flows that the GAPV will encounter during its operation.[1]

# 2015/2030 POWER PLANTS

The APV power plant consisted of four diesel generator sets (gensets) rated for 6.75 MW each. In Table 4 are the technologies the GAPV considered in its design, which led ultimately to a two stage design incorporating 2015 and 2030 technologies.[2]

| Type | Operating Temperature (°C) | Efficiency (%) |
|---|---|---|
| Diesel Engine | 1,550-1,580 | 18-42 |
| Gas Turbine (GT) | 1,170-1,200 | 36-40 |
| Micro Gas Turbine (MGT) | 830-940 | 23-28 |
| Solid Oxide Fuel Cell (SOFC) | 950-1,020 | 31-37 |
| SOFC w/ MGT (Bottoming cycle) | 950-1,010 | 54-59 |
| SOFC w/ CC (Topping cycle) | 1,080-1,120 | 64-72 |

**Table 4: Comparison of power plants for GAPV**

These technologies were assessed for their level of integration as well as their fit into the existing APV framework and will be explained throughout the report. In the 2015 design, the technology best suited for the APV was the diesel engine because of its efficiency and fuel ratings. However in an effort to incorporate more green technology, the GAPV added a Total Heat Recovery Plant (THRP) to recuperate the heat and energy loss from the diesel engine‟s exhaust.

By the 2030 time frame, a new power plant system will be available. Research has shown that, by 2030, fuel cell technology will be mature enough to use in ship designs. Fuel cells, although not as mature as the diesel engine, show the most potential in efficiency gains. Fuel cell technology is incorporated in the 2030 GAPV design. The gains in efficiency justified the change to the original APV design. Both systems are described in further detail below.

## 2015/2030 Total Heat Recovery Plant

The GAPV concepts include a THRP in both the 2015 and 2030 designs. The THRP is used to recover energy from the engine‟s exhaust. The recovered waste energy is then used to produce steam and electricity. The system is conservative in that the propulsion loads do not depend on the electricity generated from the THRP.

### *Overview*

A THRP consists of a dual pressure economizer, multi-stage dual pressure steam turbine, power turbine, alternator driven by both the steam turbine and power turbine, and a feed water pre-heating system.[3] The economizer and feed water pre-heating systems are part of the heat exchanger, located within the prime mover‟s exhaust stack. The high temperature exhaust is used to turn the water to steam. The steam is then used to drive a steam turbine which in turn generates electricity and assists the power turbine. The THRP system is currently being developed by Wartsila for large diesel engines. Experimental data has shown that the THRP can generate additional electricity equaling 11% of the installed power. The 3-Section Heat Exchanger consists of a superheater, steam generating bank, and an economizer that is located in the propulsion exhaust stack as seen in Figure 3. For a more detailed description see Appendix E.

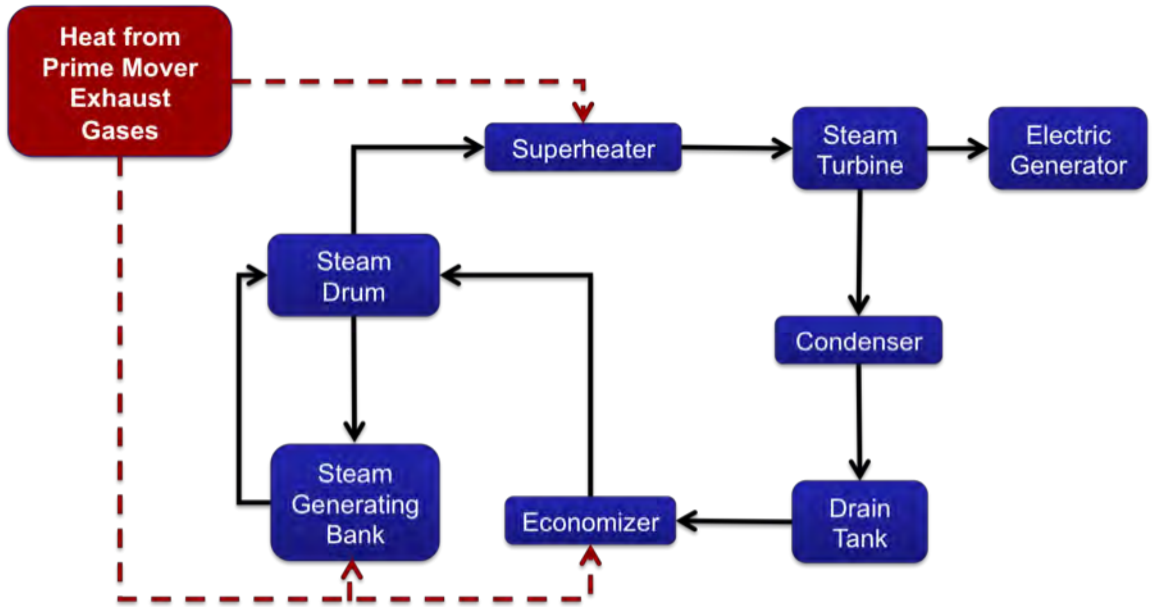


**Figure 3: Graphical representation of the Total Heat Recovery Plant (THRP)**

## 2015 Diesel/Micro Gas Turbine Power Plant

The reduction in trial speed decreased the overall installed powering requirement to 9.5 MW. This installed power is achievable with efficient medium speed (500 -1,000 rpm) diesel generator sets (gensets) with acceptable volume and weight characteristics. Use of Gas Turbine Alternator Sets (GTAS) was also considered, but discounted due to the poor Specific Fuel Consumption (SFC) characteristics of gas turbines at low loads and the limited level of improvement in installed weight and volume, especially when the additional mass of the extra fuel required is considered. Therefore, in the final selection, four diesel gensets were selected.

The micro gas turbine/power turbine (MGT) is incorporated as part of the THRP to recuperate waste heat energy to produce electricity. The efficiency of the system is then increased. By making use of the waste heat, the efficiency of the system has been shown to improve by 12%.[3]

### *Overview*

Four Wärtsilä 32 6L32 gensets were chosen for their ability to handle the load break down in an optimal way. Each genset is capable of producing 2,760 kW (720 rpm) with a 96% generator efficiency. The engines are assumed to operate at 80% of the maximum continuous rating to promote life. See Appendix F for additional information on the selected diesel genset.

## *Configuration*

The four gensets were chosen so that their use can be rotated during the low, cruise, and peak load modes of operation to extend the service life of each engine. One genset will produce 2.21 MW for the low load mode, two gensets will produce 4.42 MW for the cruise and hotel load, and with an additional 500 kW from the MGT, and all four gensets will produce 8.83 MW for the peak load condition and recover an additional 1 MW from the MGTs. The fuel endurance summaries in Appendix H show how much fuel is consumed. The THRP will also recover waste heat energy from the diesel exhaust gases. By using four gensets, the GAPV switchboard can be split between two diesel generators allowing for increased survivability and advantageous power distributions. See Appendix G for the 2015 system layout.

### Detailed Description of 2015 Power Plant

Two gensets will be located in each of the port and starboard machinery engine spaces. The exhaust gas stream will be directed to the MGT to generate electricity. The THRP will then recover waste heat from the turbine exhaust to generate steam and electricity.[3] There will be one MGT per every two gensets.

# 2030 Solid Oxide Fuel Cell for Primary Power Systems

Solid oxide fuel cells (SOFC) were used as a primary power source to incorporate additional green technology into the 2015 design. SOFC technology was considered because of its high system efficiency when used in combination with gas turbines, fuel flexibility, and reduced pollutants. Since combustion doesn"t take place, $NO_x$, $SO_x$ and particulates are not produced and the only byproducts of the system are carbon dioxide and water. SOFCs don"t have moving parts so they are quieter than internal combustion engines and require less maintenance. However, SOFCs operate at temperatures of 800 ˚C to 1,000 ˚C which causes some design challenges due to thermal expansion from material mismatches. Also, some relatively rare and expensive materials such as strontium, yttrium, zirconium and lanthanum are used in SOFC construction.

## *Fuel Cell Comparison*

Candidate fuel cell must run on commonly available fuels, generate power in the megawatt range, and reduce emissions beyond that of current internal combustion technology. Table 5 compares a range of fuel cell types that were considered for use in the design of the 2030 GAPV power systems.[2]

| Fuel Cell Type | Operating Temp. (˚C) | Efficiency | Advantages | Disadvantages | Applications |
|---|---|---|---|---|---|
| PEM | 85-105 | 40% | - Solid electrolytes reduce corrosion & simplifies the management of through life degradation<br>- Low temperature requires minimal cooling & results in quick start-up | - Requires expensive catalyst<br>- High sensitivity to fuel impurities | - Electric utility<br>- Portable power<br>- Transportation |
| Phosphoric Acid Fuel Cell (PAFC) | 160-220 | 40-45% | - Limited cogeneration of electricity & heat<br>- Impure $H_2$ as fuel | - Requires platinum catalyst (expensive)<br>- Low current & power<br>- Large size/weight ratio | - Electric utility<br>- Transportation |
| SOFC | 900-1,100 | 48-55% | - High temperature operation enables co/trigeneration resulting in very high efficiencies<br>- Fuel flexibility | - High temperature promotes corrosion & breakdown of cell components | - Electric utility |

**Table 5: Comparison of different fuel cells**

SOFCs were chosen to provide the primary load due to their ability to use various fuels, including reformed diesel fuel, provide power in the megawatt range, and a high temperature operation.

## *Fuel and Exhaust Cycle*

Diesel was chosen to fuel the system due to its availability, energy density, and its ease of handling. Although the SOFCs can tolerate a greater level of sulfur than other fuel cell types, it is still assumed that no sulfur will enter the fuel stream. Other fuels were considered such as hydrogen, acetylene, LNG and methanol, but were ruled out due to storage/volume considerations and hydrogen to carbon ratios. The term diesel is used to describe a variety of hydrocarbon based fuels. For the purposes of estimating the required amount of fuel needed to complete the mission, diesel fuel with a chemical formula of $C_{16}H_{34}$ and a density of 890 kg/m$^3$ was used in the calculations. The basic fuel cycle reaction is listed in the equation below. Figure 4 shows how a SOFC will work with diesel as the fuel.

$$C_{16}H_{34} + 24.5\ O_2 \rightarrow 16\ CO_2 + 17\ H_2O \qquad \text{(Eq. 1)}$$

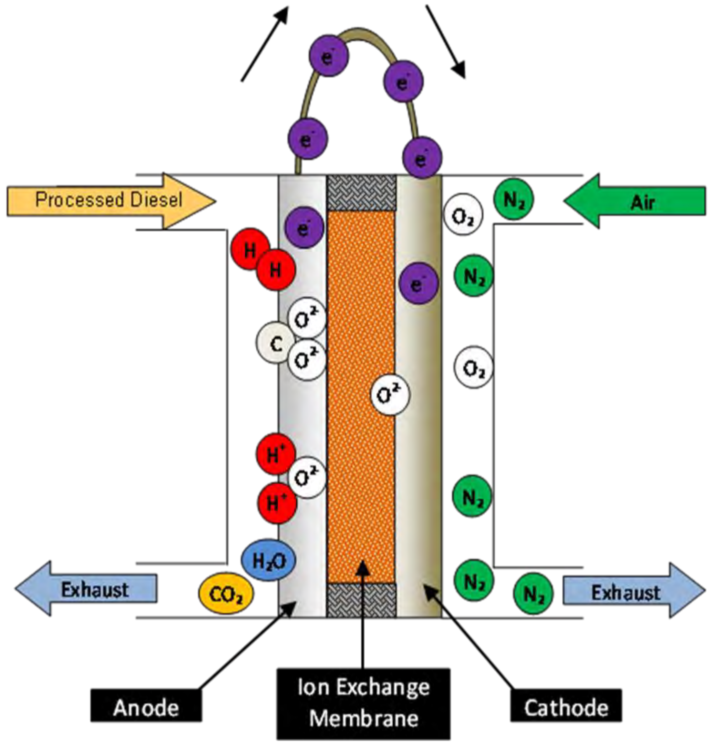


**Figure 4: Diesel fueled SOFC**

By knowing the chemical reaction through the cell, power requirements and system operating time, an estimate of the required amount of fuel and oxidizer can be made. Similarly the exhaust constituents can be calculated. The fuel cycle calculation is included in Appendix I as well as the assumptions and results.

# 2030 Solid Oxide Fuel Cell/Gas Turbine Hybrid System

A Solid Oxide Fuel Cell/Gas Turbine (SOFC/GT) hybrid system was chosen for the 2030 GAPV design because the technology has shown the most potential for gains in efficiency and for the environment. The hybrid system attained the world record in fuel-to-electricity conversion efficiency during its first trial.[4] The high temperature fuel cell"s low thermodynamic losses in combination with a thermal engine"s ability to operate at temperatures close to 950 °C allow for the two to act as complimentary devices.[5] The inefficiencies of the fuel cell create heat for the turbine cycle, linking the pair in a symbiotic relationship with a low environmental impact. The SOFC can "never be considered simply as fuel cells, but they must always be thought of an integral part of a complete fuel processing and heat generating system" [5], because of their ability to reform fuel, provide heat, and drive engines. It is at the system level where the SOFC/GT hybrid has the most energy efficiency gains. Early models and test have shown system efficiencies of $60^{+}$%. Predictions for future performance range from 70% to as high as 80%, especially if combined with other heat recovery systems creating a co/trigeneration system.

## *Overview*

The propulsion plant for the 2030 GAPV will watch power generation component capabilities to key load requirements. The SOFC/GT hybrid system will be responsible for handling the cruise, low speed, base load, and hotel loads. The separate GT will be used for high speed propulsion and rapidly varying loads. The separate GT also provides redundancy and rapid start up capability to composite for the slow start up time for the SOFC. This enables the system to be extremely versatile in all types of loading conditions.

### Assumptions

It is also assumed that very low sulfur fuel will be available world-wide after 2020 and on-board desulphurization will not be necessary. This assumption simplifies the fuel processing requirements and justifies the reduced SOFC volume.[6] This assumption enables the SOFC technology to be incorporated within the 2030 design by reducing system weight and complexity.

## *Configuration*

### Topping Cycle and Bottoming Cycle Configurations

A SOFC and GT can be incorporated in a number of ways. Two such configurations are the Topping and Bottoming cycles. Both installations are derivatives of the basic gas turbine cycle know as the Brayton cycle depicted in Figure 5.

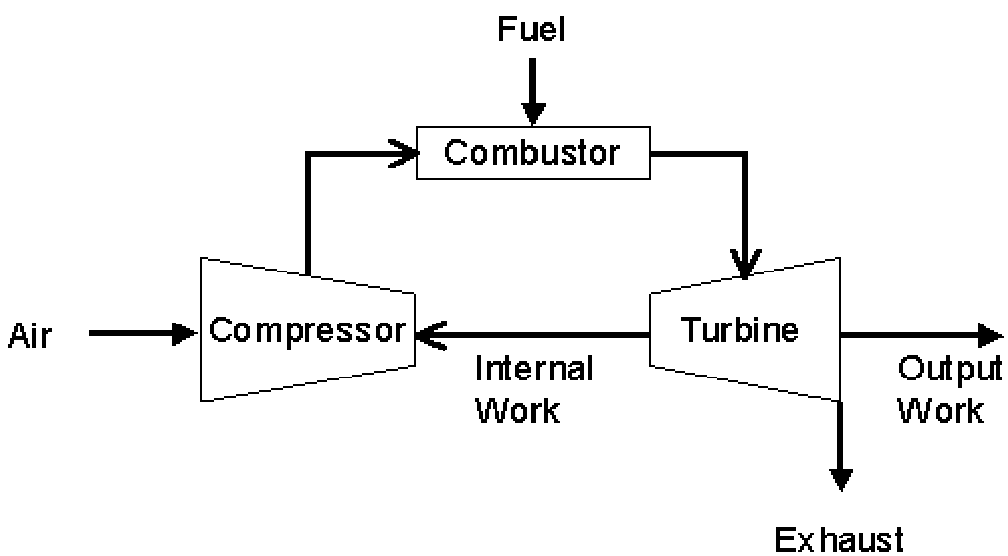


**Figure 5: Brayton cycle**

The Topping cycle replaces the combustor with the SOFC where it mitigates the inefficiencies of burning fuel in a combustor by replacing it with an electrochemical reaction that occurs within the fuel cell. In addition to the electricity that the turbine-generator produces the fuel cell itself is producing electricity. The waste heat energy from the SOFC is recaptured by the turbine to complete the cycle. The process is illustrated in Figure 6, which shows the SOFC integrated within a gas turbine cycle.[7] For further details see Appendix J.

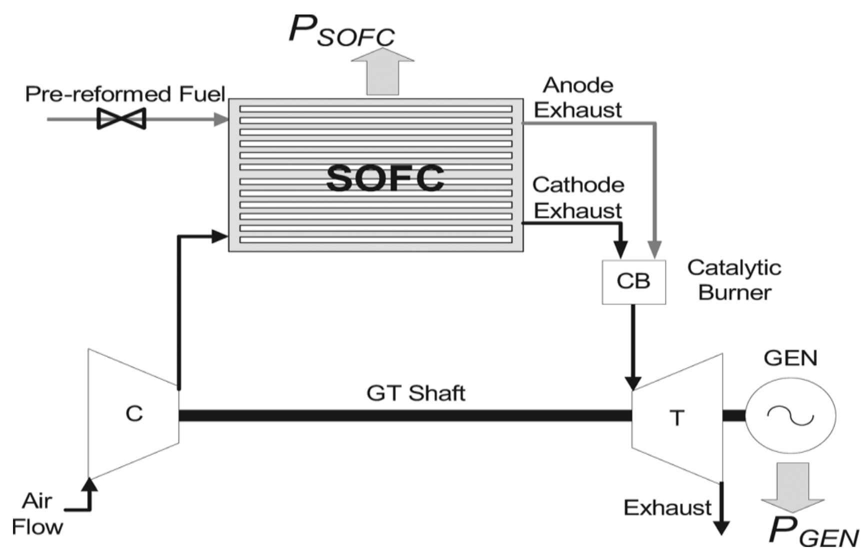


**Figure 6: Topping cycle: SOFC integrated with gas turbine**

Another derivative of the Brayton cycle that can be used with an SOFC is the Bottoming cycle. Within the Bottoming cycle, heat is extracted from the SOFC at the exhaust point where it is then run through a Brayton cycle. This high temperature heat, roughly 950 °C, increases the exhaust gas pressure which is then used by the gas turbine/Brayton cycle. A heat exchanger is used to run the Brayton cycle in which the exhaust heat from the SOFC generates steam and electricity in a similar manner to the THRP. This is another example of making use of the waste heat to create additional electricity to decrease fuel consumption and emissions.[8]

Both cycles have their merits. However, the balance of plant (BOP) consideration is among the top priorities when understanding a SOFC/GT hybrid system. The hybrid components including the compressor, fuel cell, afterburner, turbine, and heat exchanger must be sized and optimized together to make the coupling of the SOFC and GT achievable. For these reasons the GAPV chose a combined design to incorporate the advantages of both cycles.

## *Combined Design*

The proposed system for the 2030 design will use both the Topping and Bottoming cycles. However, the gas turbines incorporated into the hybrid design are not off-the-shelf technology and cannot be simply inserted into the process. The gas turbine is a finely tuned instrument and cannot be simply pulled apart and reassembled to include a SOFC as the combustion chamber. Detailed research and calculations must be undertaken with BOP considerations to design the optimal combination of the SOFC within a gas turbine cycle. This gas turbine must be created in conjunction with the hybrid system for its specific application.

In the first portion of this hybrid system, the Topping cycle will replace the combustion chamber in the gas turbine cycle with the SOFC. See Appendix K for further detailed description.

This system is self-contained. The SOFC exhaust is used to heat the air and fuel required as well as drive the compressors that provide both the pressurized fuel and air to the system. The system utilizes the high temperature, high pressure exhaust from the fuel cell within the Brayton cycle to increase efficiency by using the waste energy of the fuel cell to generate electricity.[8] However, the system needs to be started by an outside source. Therefore, there is a separate gas turbine incorporated into the system.

To add responsiveness into the system, a separate gas turbine, as well as batteries, are included to provide quick start up and peak load capability. This enables the system to handle loading spikes and enables the SOFC to increase its efficiency by starting the system so it can then operate as a self contained system.

The separate gas turbine generator will be sized for the additional trial speed propulsion load as well as the power requirements for SOFC activation. Electrical power generated by the gas turbine generator will be linked into the IPS.

### Power Generation and Weight Calculations

The power generation and weight estimates require further effort to reflect power, the weight, and space requirements of the GAPV. Weight and volume estimations, as well as power recovery, can be used to scale the system to its necessary size and weight. Although the system efficiency increases, the weight and complexity of the system increases as well. Further research and gains in technology development are needed before the system can be implemented.

## Efficiency Gains (2015 vs. 2030)

The possible gains for using a THRP was based on a study that incorporated a THRP with a low speed diesel system.[3] Figure 7 shows the possible improvements the 2015 design has made on a diesel system, when exhaust air is utilized to increase system efficiency, reduce installed power, and decrease fuel consumption.[3] The THRP also has been shown to reduce emissions.[3]

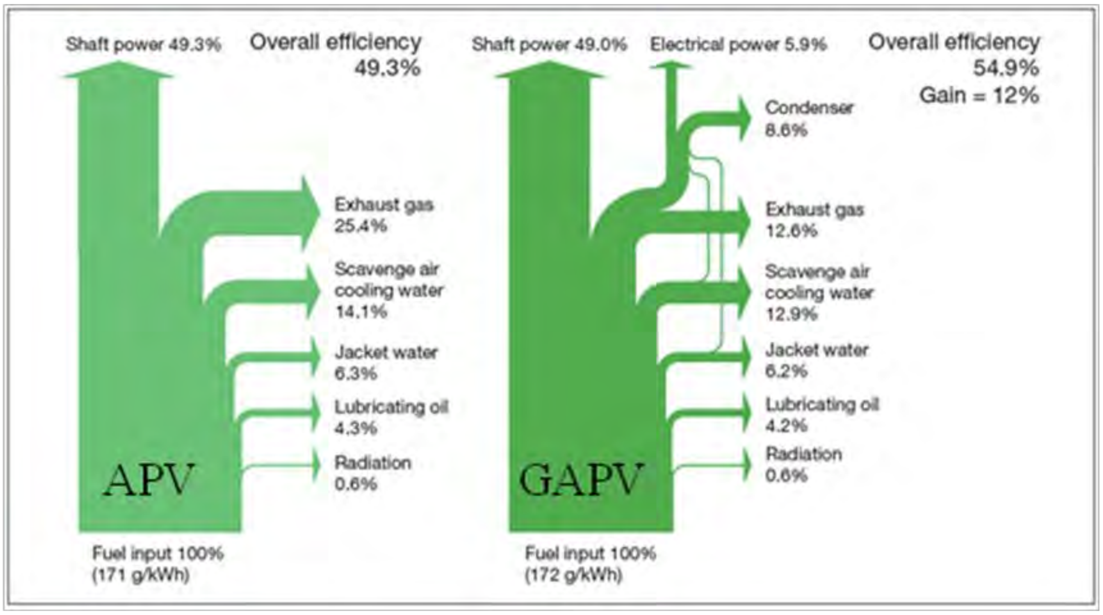


**Figure 7: Comparison of two designs: without a THRP (left) and with a THRP (right)**

Predictions have shown that the SOFC/GT hybrid system technology can range from 70% to 80% system efficiency. Results from initial tests of the system have demonstrated proven efficiencies of 60%.[4] This additional efficiency will reduce fuel consumption and emissions when the technology matures leading to an optimal system design for ships.

# ALTERNATIVE POWER SOURCES

There are several alternative sources of power available to the GAPV: wind, solar radiation, thermoelectrics, and piezoelectrics. The additional power generated by these sources will lower the amount of installed power for the system.

## Wind

The average wind speed in the Arctic during the summer is 10-15 mph.[9] Wind power options, such as the Fuller Wind Turbine[10] were explored. However, wind power options were not incorporated into the GAPV designs due to their low power density, ice problems, and requirement for topside space.

## Solar

**Figure 8** shows the annual solar radiation received by a given area for a given time around the world.[11] The amount of solar radiation during the summer in the Arctic region is 146 W/m$^2$. The total amount of possible power provided by the sun during the months of operation is 163 kW (calculated using the deck space of GAPV).

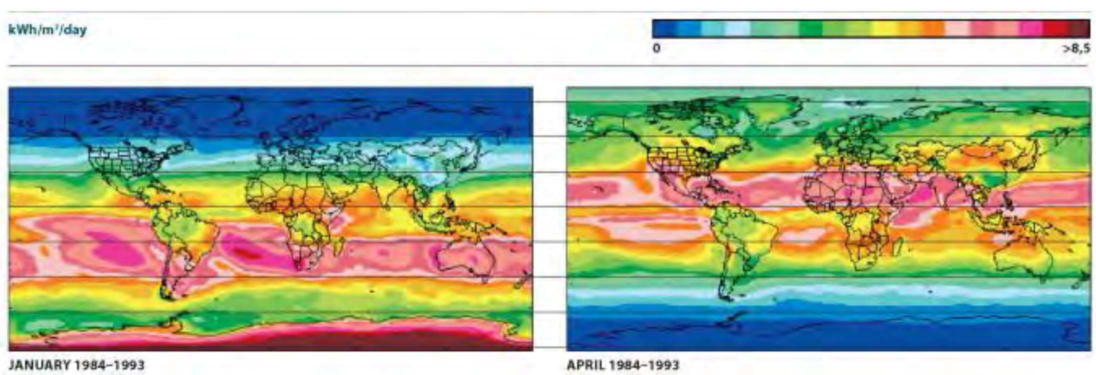


**Figure 8: Annual amounts of solar radiation around the world**

Three systems explored to convert solar radiation into useable power were solar cells/photovoltaics (PVs), solar heating, and a hybrid lighting system. A PV converts the solar radiation into electrical power, solar heating uses the solar radiation to heat water, and the hybrid lighting system utilizes solar radiation for onboard lighting.

A potential disadvantage of PVs and solar heating is the interference of icing. In addition, it would not be reasonable to implement PVs into either of the designs due to the low power to weight ratio. Only the hybrid lighting system was incorporated into the GAPV designs. Additional information on PVs and solar heating can be found in Appendix L and M respectively.

### *Hybrid Lighting System*

The hybrid lighting system works by channeling light through fiber optics fitted throughout the ship. The system uses the sun not to create energy, but rather redirects natural light into the vessel. Solar Direct, LLC has developed a 13.7 m (45 ft) long fiber optic bundle that is comprised of 127 optical fibers. Every two fibers emit the same amount of light as a 50 W light bulb.[12] There is a 1.2 m (48 in) diameter parabolic dish that collects solar rays and focuses them into a single beam that is then channeled into the fiber optics. **Figure 9** shows an illustration of the system.[12]

**Figure 9: Hybrid lighting system**

The hotel load for lighting was calculated to be 279 kW by scaling the lighting load for the T-AGOS-23. By using this system, electrical power for lighting can be reduced by 60% decreasing the hotel load by an average of 168 kW.[13] This system allows the artificial lights to be used in conjunction with the solar radiation to emit light into the fiber optics. Therefore on days without sun the lighting will not be affected. This hybrid lighting system will be implemented into both designs.

# Thermoelectric Generators (TEGs)

A thermoelectric generator (TEG) is an alternative power source that uses a temperature difference/gradient to generate electrical current. **Figure 10** depicts the general concept of a TEG.[14]

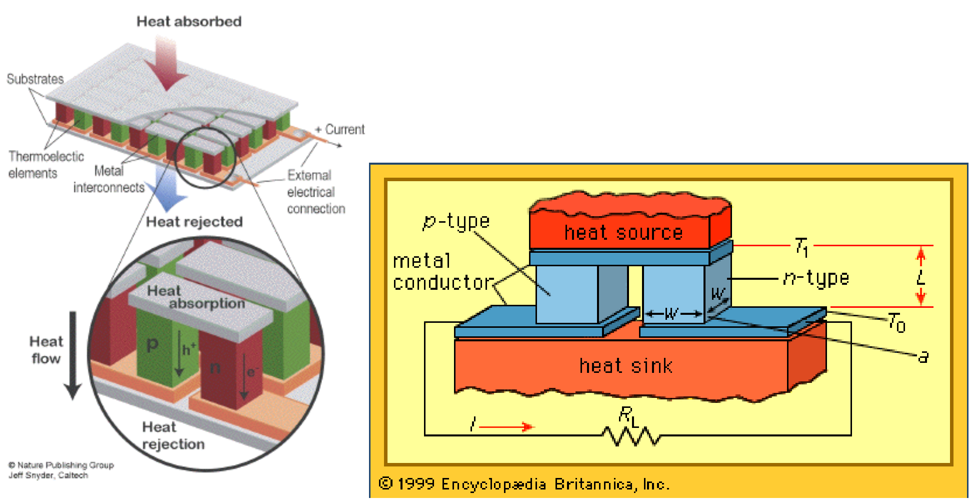


**Figure 10: Description of a TEG**

A 1 kW TEG is in development by Hi-Z Technology, Inc. for truck engines[15] (see Appendix N for pictures). Extrapolating data from that engine for a load of 2.3 MW (3,100 HP) from **Figure 11**, the TEG would produce 10 kW.[15] Since TEG technology is still in early development it will not be ready for the 2015 design. Therefore, it will only be included in the 2030 concept.

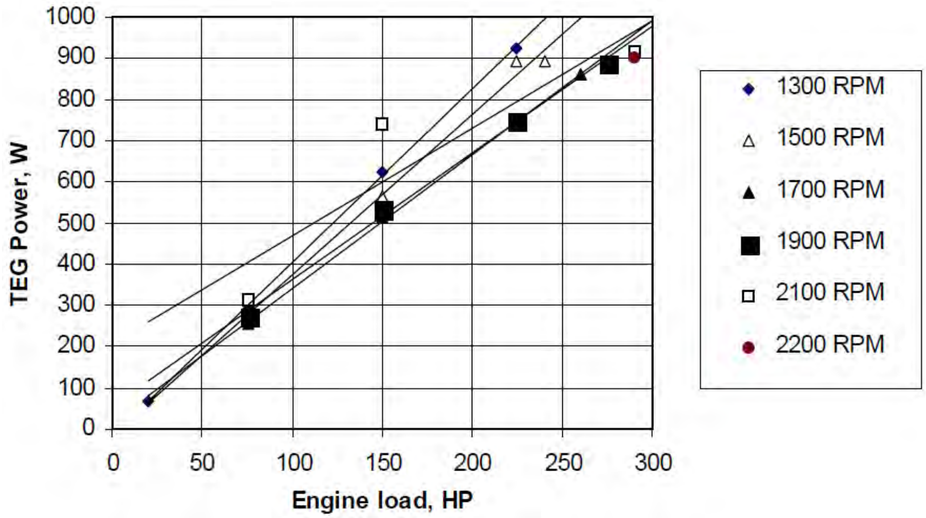


**Figure 11: TEG power relative to engine load for diesel truck**

A more recent and efficient type of thermoelectric in development is the pyroelectric. However, they aren‟t currently developed enough for either of the designs. Additional research is warranted because of its practicality in design.

## Piezoelectric Transducers (PZTs)

A Piezoelectric Transducer (PZT) creates an electric potential through applied mechanical strain. This is an evolving technology so there is minimal information on the output of power related to the amount of stress applied. However, currently PZTs are being used on dance floors in London and sidewalks in New York City to collect energy from the mechanical strain applied.[16]

Currently most of the power being captured by a PZT is on the micro scale. They weren‟t implemented in the GAPV designs because of the burden of weight. It is recommended to investigate PZTs in the future because of their unique way to recapture energy from strain, which would be a good fit for use in naval applications.

# COATINGS

Coatings are incorporated to reduce the environmental impacts from the ship while also reducing the ship impacts of icing and noise. The exploration of coatings is based on commercially available products along with research being done at NSWCCD‟s coatings laboratory. Coatings will be placed below the waterline on the hull, topside portions of the vessel exposed to the environment, the inner lining of the ballast tanks, the propeller, machinery areas, and non-skid coatings on deck spaces. Their purpose and locations are formulated in Table 6. See Appendix O for additional information on their placement.

| | | | | | |
|---|---|---|---|---|---|
| **Purpose** | Ice phobic | Anti-fouling | Non-skid | Non-skid | Anti-fouling |
| **Location** | Topside | Underwater hull | Flight deck | Walkways | Propeller |

**Table 6: Coating placements for the GAPV**

All recommended coatings have full functionality in a cold climate, are solvent free, contain low levels of Volatile Organic Compounds (VOCs), and have strong adhesion qualities to the applicable materials. To prevent noise pollution in the operating environment and the habitable areas of the GAPV, noise dampening coatings will be used on machinery spaces.[17]

## Topside Coatings

Managing topside icing is a fundamental challenge of the GAPV since topside icing can add a substantial amount of weight to the vessel requiring more propulsion power and subsequently decreasing the fuel efficiency of the vessel. In addition to reducing fuel efficiency, which goes against the prescribed aims of the GAPV design, topside icing can be a direct threat to the safety of the ship and crew. All of the GAPV‟s superstructure exposed to the environment, where no crew traffic will occur, are coated with an ice phobic (eco-friendly) coating to help manage topside icing.[18]

In addition to ice phobic coatings, non-skid coatings are used on portions of the deck where there is crew traffic. These areas include pathways to exterior weapon systems, radar mast, flight deck, mooring line handing locations, as well as Rigid Hull Inflatable Boat (RHIB) and lifeboat access areas.

## Underwater Coatings

Anti-fouling coatings are used below the waterline of the vessel to prevent the adhesion of marine life to the hull. The anti-fouling coating used is non-toxic, has low VOCs, and poses no harm to marine life. Fouling prevention is a concern of the GAPV mission since transporting exotic species into the fragile environment of the Arctic could be severely detrimental to the Arctic ecosystem.[19] Reducing fouling on the GAPV‟s hull also decreases the ship‟s resistance therefore improving fuel efficiency. Propeller coatings are also used to improve propeller performance by increasing wear resistance, reducing friction by preventing fouling, and cavitation erosion on the propeller blades.[20] An anti-fouling coating made specifically for ballast tanks is used to further reduce the possibility of transporting foreign marine life into fragile ecosystems.[21]

# MATERIALS

Materials used in the GAPV designs were chosen based on their light weight and environmentally responsible characteristics. Weight reduction satisfies the common theme of improving fuel efficiency and will help balance the increase in the GAPV"s system weight. Composites and recycled steel are recommended for shipboard use. Recycled steel will satisfy the cradle-to-grave green life cycle of the GAPV. High strength steel will be used on the ice belt of the GAPV"s SWATH. All materials recommended comply with the mission requirements of being nontoxic, light weight, having an environmentally sound through-life cycle, and requiring minimal maintenance.

## Composites

Composite materials for naval application on military ships have undergone a slow progression that is dependent on several factors such as manufacturing challenges, ballistic impact capabilities, and mission dependability. The US Navy will integrate a composite deckhouse with a steel hull on board the ZUMWALT Class destroyer (DDG 1000). Foreign Navies, particularly the Norwegian Navy, have developed small composite ships.[22] Composites provide benefits such as reduced radar signature to improve stealth capabilities, reduction in weight, improved tensile strength, and through-life durability in comparison to traditional steel.[22]

The superstructure of the GAPV will be constructed out of a composite material similar to the DDG 1000. A sandwich composite structure which consists of two layers of composite laminates with a balsa wood or syntactic foam center will be used to construct the superstructure of the GAPV.[23]

### *Composite Variations Onboard*

Similar to the composite material designed for use on the DDG 1000, three different types of composites will be used as seen in **Table 7**. A unidirectional weave of composite laminate will be used in locations which require a high tensional load in one direction including the flight deck, roof of the hangar, and bridge. Other composite weaves include a combination of a non-crimp and plain-weave weave that will provide high tensile strength in portions of the ship that require load control from a range of directions.[23]

In addition to varying the weave characteristics, different densities and types of materials will be sandwiched between the two composite laminates. **Table 7** is a breakdown of the type and location of the composites used in the GAPV designs.[23]

| Piece | Type | Weight/Area ($lb/ft^2$) | Total Weight (lb) |
|---|---|---|---|
| Flight Deck | Unidirectional/Syntactic Foam | 33.3 | 278,500 |
| Hangar Sides | Noncrimp + Plain-weave/Balsa Wood (15) | 15.3 | 24,800 |
| Forward Deck | Noncrimp + Plain-weave/Balsa Wood (20) | 20.3 | 113,200 |

**Table 7: Composite types for GAPV**

# ONBOARD WASTE MANAGEMENT

A variety of wastes will be created onboard the GAPV. Solid waste includes plastics, glass, metal, food waste, paper, and cardboard products. Liquid waste includes blackwater (sewage), greywater (showers, sinks, galley water), and bilgewater (oily water). Typically, solid waste is disposed overboard or kept aboard until it can be offloaded at port.[24] For the 2015 design, a waste management plan that processed and then stored the waste before offloading at port was developed. For the 2030 design, inorganic waste will be processed for holding while organic waste is destroyed onboard.

Each of these waste streams requires a specific waste treatment system to eliminate the need to discharge at sea. A table of all the technologies used concerning waste management is seen below in **Table 8**. Onboard incineration of solid waste streams was not considered due to the air emissions from the process possibly violating future air emission regulations.

| Year | Technology | Waste Stream Treated | Brief Description | Naval Application |
|---|---|---|---|---|
| 2015 | Solid Waste Shredder (SWS) | Glass/Metal | Shreds the glass and metal with a volume reduction of 3 to 1 | Used on Navy ships |
| 2015 | Small Pulper | Food, Paper, and Cardboard | Pulps food and paper/cardboard products with seawater for storage | Used on Navy ships |
| 2015 | Oily Water Separator | Oily Liquid | Separates the water from oil contaminants with a four-stage emulsion-breaking separator | Used on Navy ships |
| 2015 | Greywater/ Blackwater Treatment | Non-oily Liquid | Physical filtration, membrane bioreactor, and UV advanced oxidation treatment of water | Tested for use on Navy ships |
| 2015 & 2030 | Compact Melting Unit (CMU) | Plastics | Reduces volume of plastics from 30 to 1 and melts into large discs for easy storage/transfer | Used on Navy ships |
| 2030 | Micro Auto Gasification System (MAGS) | Solid Waste | Decomposes organic material and sterilizes inorganic material for recycling | Needs to be tested for Naval use |
| 2030 | Wastewater Electro-chemical Treatment Technology (WETT) | Liquid Waste (Oily and Non-oily) | Intakes all liquid waste for physical separation and electrochemical processing before it outputs non-potable water for re-use | Needs to be tested for Naval use |

**Table 8: GAPV Solid and liquid waste management technologies**

## Solid Waste Technologies

The GAPV isn‟t required to replenish at sea. As a consequence, the expected onboard solid waste generation is lower than other ships in comparison.[25] This allows the GAPV to avoid additional waste related to packaging. **Table 9** summarizes the expected amounts of shipboard generated solid waste for the GAPV in both 2015 and 2030.[25]

| Solid Waste Type | lbs/person/day | lbs/day (crew of 112) |
|---|---|---|
| Glass/Metal | 0.27 | 30.2 |
| Food | 1.20 | 134 |
| Paper/Cardboard | 0.82 | 91.8 |
| Plastics | 0.21 | 23.5 |
| Total | 2.50 | 280 |

**Table 9: GAPV Expected solid waste generation**

## *Glass/Metal*

In the 2015 design, glass and metal are processed with a Solid Waste Shredder (SWS). The SWS is simple, reliable, and already used on US Navy ships. It uses cutters that rotate to shred the metal and glass down to a third of its original volume.[26] The end result consists of shredded material that can be bagged for storage in Odor Barrier Bags (OBB) already in use by the Navy. The system will not need to run until there is a need to process the waste. Operation requires only one crew member to operate with minimum skill training.[26]

In the 2030 design, glass and metal are fed into a Micro Auto Gasification System (MAGS) after shredding. The MAGS unit sanitizes the metal and glass so that they are ready for recycling. The recyclable material is held until it can be offloaded at port. The GAPV team predicted MAGS technology will be suitable for naval applications in 2030, although it has not yet been tested for Navy waste.

## *Food & Paper/Cardboard*

A small pulper is used in the 2015 design to process food, paper, and cardboard. One small pulper combined with a solid-liquid extractor processes both food and paper/cardboard products. The two waste streams are pulped at different times and are pumped into separate holding tanks. The small pulper processes 200 lbs/hr of food waste and 100 lbs/hr of paper/cardboard. The small pulper does not need to be run continuously and does not require additional crew members to operate or maintain.[26]

The MAGS unit is also utilized to process food, paper and cardboard waste in addition to glass and metal for the 2030 design. However, the organic waste is destroyed in the process and the need to store pulped food, paper, and cardboard products after treatment is eliminated. The end result is a small amount of land-fill safe ash. The system uses some of the gases produced from treatment of waste as fuel and needs only a small amount of fuel to begin the process.

## *Plastics*

Since plastics are under a zero discharge policy, a Compress Melting Units (CMU) were integrated into both the 2015 and 2030 designs. The CMU takes in all plastics and melts them together with a volume reduction ratio of 30:1 into a plastic disc that can be placed into an OBB for storage. Presently, the plastic disc is not accepted for recycling, but is expected to be recycled as capabilities and facilities emerge.[26]

# Liquid Waste Technologies

A liquid waste generation rate of 48 gallons/person/day of non-oily waste water (greywater and blackwater) was used for the GAPV. This rate is appropriate for the Vacuum Collecting, Holding and Transfer system (VCHT) in both concepts.

## *Non-Oily Liquid Waste*

The Navalis Orion black and gray wastewater system was chosen for the 2015 design. Greywater and blackwater are treated together through the use of solid filtration, a membrane bioreactor, and UV advanced oxidation. It is a reliable and simple automated system that requires minimal manning and maintenance; one person to operate and two people to maintain the membrane bioreactor when necessary. The technology has already been tested for naval application. The treated effluent passes any current or expected regulations for discharge but it is suitable for non-potable reuse onboard.[27]

Wastewater Electrochemical Treatment Technology (WETT) was chosen to be implemented in the 2030 design. It is a complete waste water system that handles greywater and blackwater through physical filtration and electrochemical processes. The outputted effluent consists of potable water for possible reuse and a small amount of sludge to be held. Though it has not been tested for naval applications it is expected to be suitable for the 2030 design.

## *Oily Liquid Waste*

Bilgewater, gathered from leaks and condensation, consists of contaminants such as oil, grease, lubricants, and other oily waste. To treat oily wastewater for the 2015 design, the Wärtsilä Senitec M-series oily water treatment system was chosen. It consists of four stages: dissolved air flotation and oil skimming, emulsion breaking, sludge skimming, and activated carbon filtration. It has a guaranteed limit of 5 ppm with actual case studies demonstrating <1 ppm. (These limits are dependent upon the sea state and ship motion due to the mixing of oil and water in the tank.) Study results show the oily water treatment system reduces sludge and discharged material for a 9,000 DWT RO-RO vessel as seen in Table 10.[28]

| | Actual values | Other market equipment | Wärtsilä Senitec M1000 + SolidPac |
|---|---|---|---|
| **Sludge** | 360 ton/year | Reduction: 0% | Reduction: 40% |
| **Bilge** | 1,260 ton/year | Reduction: 45% | Reduction: 92% |
| **Total to discharge ashore** | 1,620 ton/year | 1,053 ton/year | 316 ton/year |
| **Discharge fee** | EUR 112/ton | EUR 117,936/year | EUR 35,482/year |
| **NET SAVING** | | | EUR 82,454/year |
| Value from actual study case (RO-RO vessel, 9000 DWT, fuel consumption = 10,000 ton/year) | | | |

**Table 10: Oily water treatment system results for a 9,000 DWT RO-RO vessel**

For the 2030 design, the same WETT unit that is utilized for non-oily liquid water is used for oily wastewater.

## Ballast Water Management

More stringent standards for varying types of organisms in ballast water discharge are in development by the IMO. Ships require an approved Ballast Water Treatment (BWT) or Ballast Water Exchange (BWE). Ballast water exchange flushes the ballast tanks in open water, which jeopardizes stability. Hence, a ballast water treatment system was chosen for both 2015 and 2030 designs. An anti-fouling coating for ballast tanks was also incorporated to further reduce the possibility of transporting foreign marine life into a fragile ecosystem.

A PureBallast treatment system was chosen for both the 2015 and 2030 designs. It is a BWT system that uses advanced oxidation technology to treat the water during ballast and de-ballast operations. The water is run through a physical filtration process and then UV radiation process to rid the water of organisms. Test results showing the effectiveness of the system are shown in Table 11.[29] This particular process already meets current regulations and is expected to meet future regulations as the technology improves.[30]

| Type of Organism | Unit | Initial | Control (day 0) | Control (day 5) | Treated (day 0) | Treated (day 5) | IMO req. |
|---|---|---|---|---|---|---|---|
| > 50 μm | Ind/$m^3$ | 468,000 | 517,000 | 725,000 | 0.0 | 6.6 | 10 |
| ≥ 10-50 μm | Ind/ml | 500 | 2,300 | 480 | 0.2 | 0.2 | 10 |
| E-coli bacteria | Cfu/100 ml | $3.4x10^6$ | $3.2x10^6$ | 5,300 | 0.3 | 10.0 | 250 |

**Table 11: Pilot test results of PureBallast technology**

# ANTI-ICING

The build-up of ice and snow on a vessel has a direct impact on its stability. The increase in weight leads to a loss of stability, a decrease in reserve buoyancy, and an increase of loads on the decks and superstructures.[9] The effect of topside icing on the vertical center of the GAPV are shown in Appendix Q.

Current methods for anti-icing used by the US Navy and in industry include brute force, high-pressure water spray, and ice-phobic coatings. A number of new anti-icing tactics were investigated including a redesign of the superstructure with cambered surfaces, use of environmentally benign anti-icing fluids, a composite structure with electric strip heaters, and heating external surfaces from internal compartments.

There are environmentally benign fluids that can be used to help remove ice from the surfaces of ships.[31] Additional research is required before this technology can be assessed.

One way to prevent ice from accumulating is by placing electric strip heaters into the topside surfaces of the design. Electric strip heaters were not implemented in either of the designs because of the high power requirements.[32]

## Ice-Phobic Coatings

Ice-phobic coatings were used on surfaces that will be affected by water spray and will be placed on most surfaces above the waterline. The surfaces colored blue in Appendix O are the surfaces that will be coated.

## Flight Deck Anti-Icing

One area of the GAPV that will not have the ice-phobic coating is the flight deck because anti-skid coating is already used there.

The flight deck portion of the GAPV was analyzed using heat transfer equations for both the conduction and convection on the surface, assuming convection over a flat plate. The amount of radiation absorbed by the flight deck was neglected due to the complexity of calculation required. However, any radiation that would occur would only benefit the design.

The internal compartments of the GAPV will be set at least to 20 °C (68 °F), according to ABS requirements for vessels operating in cold climates.[33] The amount of heat required to keep the external surfaces from freezing was found to be 664 W/m$^2$. This amount is higher than the ABS requirement of 300 W/m$^2$ for heated surfaces for anti-icing.[33]

This method is only feasible if the internal compartments are kept at 30.00 °C (86.00 °F) as shown in Table 12. This high temperature would be uncomfortable for the crew inside. Therefore, future research is needed to make the internal compartments below the flight deck not accommodations for the crew. The equations used in the analysis are provided in Appendix P. **Table 12** is a breakdown of the temperatures in each layer from the figure in Appendix P.

| Location | Temperature (°C) |
|---|---|
| Outside | - 40.00 |
| Surface Outside | 2.00 |
| Outside Middle | 2.14 |
| Surface Inside | 2.15 |
| Plate Inside | 22.00 |
| Inside | 30.00 |

**Table 12: Breakdown of temperatures for flight deck**

# SYSTEMS INTEGRATION IMPACT

The systems defined for both GAPV designs were chosen for their ability to complement each other. The reduction of trial speed led to decreased power requirements. The machinery options chosen contributed to decreased emissions, weights, and sizes of systems. The decrease in weight and space requirements for power allowed waste management systems to be added and reduced the waste discharged at sea. The integration of lighter-weight materials reduced weight resulting in less fuel consumption.

For the 2015 design, general arrangements, updated from the original 2009 APV design as well as a weights and trim analysis can be found in Appendix Q. The APV weight calculations, electric loads, and system specifics were inaccurate, so a comparison of the 2015 design ship integration to the APV would not be appropriate.

For the 2030 design, there were limitations in the estimations of weights due to necessary technological advances for them to be achievable. Consequently, development of an integrated design was not possible.

# CONCLUSIONS

This project was focused on defining green technologies for the Green Arctic Patrol Vessel (GAPV), rather than modifying the previously defined structures. The green technologies implemented cover power generation, alternative power sources, materials, coatings, waste treatments, ballast operations, and anti-icing techniques. The main changes from the initial APV design are highlighted in Table 13.

| | 2009 APV | 2015 GAPV | 2030 GAPV |
|---|---|---|---|
| **Waste Management** | Not addressed | Onboard processing & storage | Onboard destruction & storage |
| **Materials** | Steel | Steel/composites | Steel/composites |
| **Power** | Diesel gensets | Diesel/MGT & THRP | SOFC/GT & THRP |
| **Alternative Energies** | Not addressed | Solar lighting | Solar lighting & TEG |
| **Ballast** | Not treated | Advanced oxidation | Advanced oxidation |

**Table 13: Summary of changes from initial APV design**

To improve upon the APV diesel power plant system, a Total Heat Recover System (THRP) is included in both the 2015 and 2030 GAPV designs. The THRP will recover heat and an additional 12% of energy in the engine‟s exhaust. The recovered waste energy is then used to produce steam and electricity.

There are four diesel gensets and two micro gas turbines (MGT) for the 2015 GAPV design. Compared to the APV design, the addition of the MGT will increase the efficiency of the system. The total amount of power the MGTs will provide is approximately 1 MW.

The 2030 GAPV design will incorporate a Solid Oxide Fuel Cell/Gas Turbine (SOFC/GT) hybrid system. The SOFC/GT hybrid system was chosen for its high system efficiencies and its low environmental impact. This technology is predicted to have 70% to 80% system efficiency. Results from tests on prototypes have already proven efficiencies of 60%.[4] This additional efficiency will reduce fuel consumption and emissions leading to an optimal design for ships.

There are several alternative sources of power available to the GAPV: wind, solar radiation, thermoelectrics, and piezoelectrics. However, the only systems incorporated will be a thermoelectric generator (TEG) for the 2030 design and a hybrid lighting system for both the 2015 and 2030 designs. The additional power obtained will lower the electrical hotel loads for the GAPV by 10 kW and 168 kW for the TEG and hybrid lighting system, respectively.

Coatings will be used on the GAPV to reduce the environmental impact while also reducing the ship impacts of icing and noise. The exploration of coatings was based on commercially available products along with research being done at NSWCCD‟s coatings laboratory. Coatings will be placed below the waterline of the hull, on topside portions of the vessel exposed to the environment, on the inner lining of the ballast tanks, on the propeller, and in machinery areas. Non-skid coatings are used on deck spaces.

The GAPV design incorporates composites and recycled steel for structures. Steel is used for the hull with high strength steel on the ice belt of the GAPV. Composites are used for the superstructure. All materials comply with the requirements of nontoxic, having an environmentally sound through-life cycle, being light weight, and requiring minimal maintenance.

The 2015 waste management plan will reduce the amount of material brought onboard, separate and process the resulting waste, and store the processed waste until portside recycling is available. The 2030 waste management plan will incorporate advanced systems such as a waste water electro-chemical treatment system, and a micro-auto gasification system. These technologies allow for reusable potable water requiring minimal excess waste storage onboard. Both of the waste management systems will eliminate the need to discharge at sea and encourage “reduce, re-use and recycle”, therefore accommodating for more stringent environmental regulations in the future.

Ballast Water Treatment (BWT) is incorporated into the GAPV designs. It uses advanced oxidation technology to treat the water during ballasting and de-ballasting operations. The system utilizes physical filtration and UV radiation to rid the water of the majority of organisms. An anti-fouling coating for ballast tanks was also incorporated to further reduce the possibility of transporting foreign marine life into a fragile ecosystem. Implementing the BWT will provide both pollution control and pollution prevention and will minimize the environmental impact.

A “greener” APV was achieved by improving fuel efficiency, advancing waste management processes, incorporating alternative energy sources, and minimizing the GAPV‟s impact in the area of operation.

## Future Recommendations and Work

The 2030 technologies require further research into their predicted capabilities, power, sizes, and weights to enable system integration into the vessel. Further refinement of the original APV design to assure accuracy of design calculations including weights, stability, trim, and fuel consumption is also recommended.

Investigation of additional technologies is also recommended including:

- Optimization of the hull
- Emerging battery technologies
- Development of contoured surfaces for anti-icing
- Application of friction stir welding
- Emerging ballast water treatments/systems

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# APPENDICES

## Appendix A – Requirements

### *Introduction*

1. The combined impact of shrinking sea ice in the Arctic Ocean and the growing desire by Northern Hemisphere nations to exploit the natural resources available within it is likely to result in renewed interest in marine operations in the far north.
2. Many political analysts expect the Arctic Ocean and its economic resources to become a significant potential source of international tensions and even conflict.
3. In this environment, both the USN and USCG have recently published strategies relating to Arctic Ocean operations and their expected future infrastructure and equipment needs to support them. It is likely, therefore, that a significant amount of effort will be required in the future to patrol the region and to protect U.S. interests.
4. It is expected that an Arctic Patrol Vessel may be required to provide a dedicated independent capability to undertake patrol and support diplomatic initiatives with military capability. As a result of this need an initial concept Arctic Patrol Vessel was developed during a CISD summer project in 2009.
5. This year‟s project focus is on evolving the design developed in 2009 to incorporate a range of „green" technologies and design features with the aim of reducing the impact of the design on the environment. A secondary aim is reducing the vessels overall through-life costs.
6. The emphasis on „greening" the design is based on several factors, which include:
    a. In an effort to reduce environmental impact and the U.S. dependency on foreign oil the U.S. Secretary of the Navy has called for having half the fleets energy demand met through the use of alternative fuels and technologies by the year 2020.
    b. As a direct impact of operating a vessel within the Arctic ecosystem, it is highly desirable for the vessel to have as little an impact on the environment as possible.
    c. A green ship earns political kudos and the potential to support novel American technologies and companies.
    d. Reducing demand for fuel is likely to have significant benefits in terms of endurance, required supportability, and hence infrastructure cost reduction in operations far from major bases (e.g. reducing transport cost for fuel delivered to Arctic bases).
    e. The Arctic is likely to be subject to a greater level of environmental restrictions than other marine operating areas in the future – hence an arctic patrol vessel should be at the forefront of environmentally friendly technological development.

## *Aim*

7. The project should aim to integrate green technologies and design features aboard the Arctic Patrol Vessel concept to minimize the vessel‟s impact on the environment through its life – this should be achieved at a systems level.
8. As a secondary aim technologies incorporated should aim to reduce the vessel‟s overall through life cost.
9. The project should aim to identify technical issues and requirements associated with that design that require further investigation and development.
10. The technologies used should be shown to be feasible with Navy or commercial backing within the coming decades.

## *Ship Design Requirements*

11. The vessel shall be capable of undertaking all of the missions outlined for the Arctic Patrol Vessel in the APV report from 2009.
12. The following technologies are likely to be investigated (this list should not be considered exhaustive):
    a. Power systems - Future electrical power systems, motors, generation options, and alternative fuels.
    b. Novel propulsor and hull design features to maximize efficiency;
    c. Advanced materials & coatings for reduced build cost, lighter structure, reduced maintenance, and/or reduced environmental impact through life (sustainability).
    d. A range of auxiliary systems – improved ballast water management; noise reduction systems; use of sustainable lubricants; improved thermal management; improved anti-icing systems; reduced electrical consumption; reduced water use; improved emission reduction or capture systems etc.

## *Constraints*

13. The report and design shall be unclassified.
14. The vessel shall be designed to meet the implied design requirements of the original Arctic Patrol Vessel design and also to meet the classification and safety regulations relating to a vessel with an appropriate Arctic operating regime.
15. The focus of the project is on the systems and materials within the design, rather than major modification to the original design concept – major changes to the previous project‟s basic design concept should be avoided.

## *Approach*

16. The team should research Green ship concepts and review previous studies.
17. The team will review requirements and then brainstorm potential ideas.
18. Suitable ideas shall be assessed for architectural, environmental, ship interface, and performance impacts as well as technical feasibility.
19. The competing ideas shall be reduced to a preferred concept using a decision making process.

20. A complete ship synthesis shall be undertaken. A balanced ship design shall result with performance analyses and a general arrangement developed. A stability assessment shall be made which includes the effects of topside icing.
21. The implications of any new technology or operational issues shall be noted. Recommendations for follow on work shall be developed.

### *Deliverables*

22. During the first 2 weeks the team will produce a team project plan of actions, assignments and milestones to be presented to CISD leadership for approval. During the project this plan shall be maintained.
23. The team will develop and give informal intermediate presentations and a final project presentation.
24. The resulting ship design shall be detailed including a single sheet summary of characteristics, estimated performance, a comprehensive SWBS weight breakdown, a hull form body plan and a full general arrangement drawing.
25. The project will be documented in a CISD Technical Report. The final report and presentation shall be suitable for unclassified public release.
26. The team will be encouraged to produce a technical paper from the final report that is suitable for publishing at professional society conference.

# Appendix B – Additional References – Not Cited

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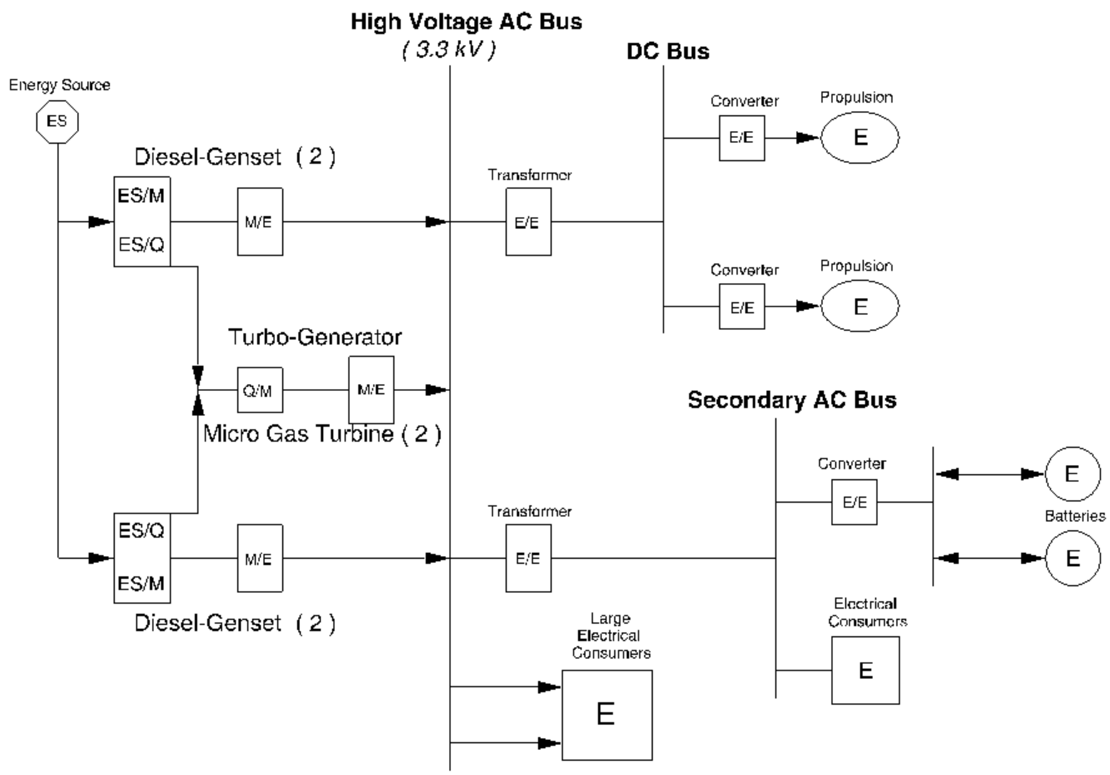
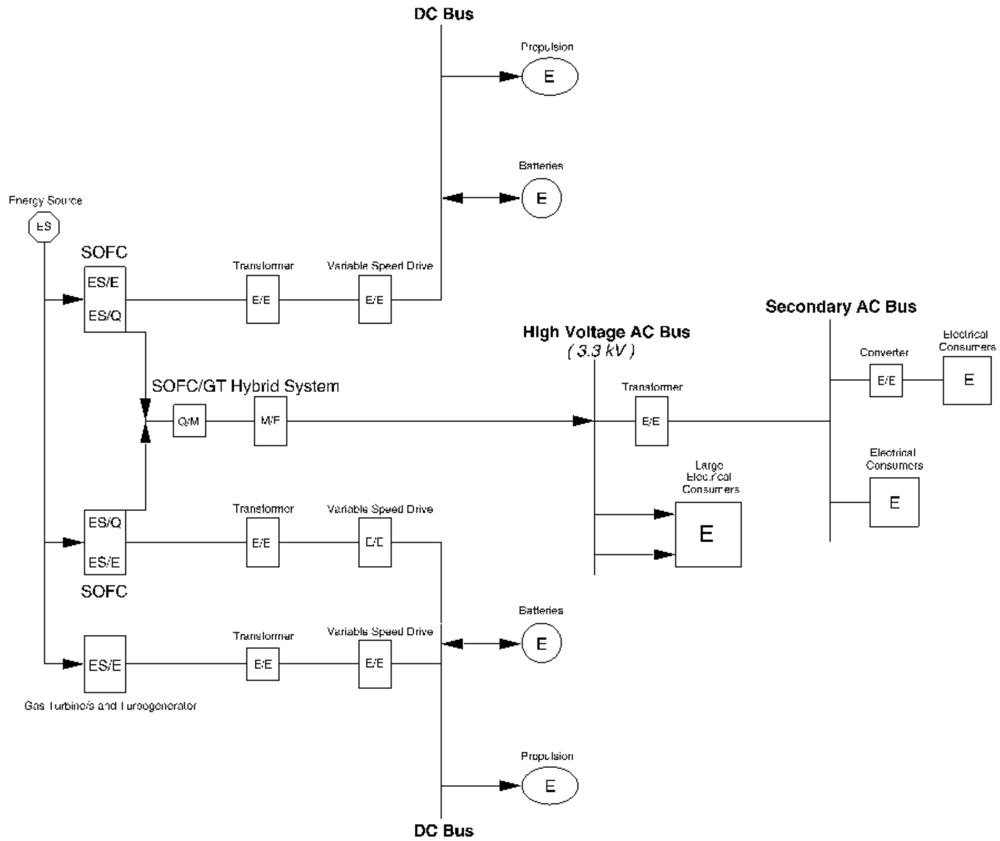
# Appendix C – Integrated Power System Layout (2015/2030)




**2015 Integrated Power System (IPS) layout**




**2030 Integrated Power System (IPS) layout**

# Appendix D – Electric Load Summary

| SWBS Group | 12 knots (kW) | 17.5 knots (kW) | Scaling Factor |
|---|---|---|---|
| 200 – Propulsion Plant | 2,300 | 7,450 | N/A |
| 300 – Electric Plant | 91 | 91 | N/A |
| 400 – Command & Surveillance | 60 | 60 | Constant |
| 500 – Auxiliary Systems | 264 | 265 | Displacement Ratio |
| 510 – HVAC | 1,021 | 1,021 | Low Temperature & Volume Ratio |
| 600 – Outfit & Furnishing | 150 | 150 | Crew Number Ratio |
| 700 – Mission | 24 | 24 | N/A |
| | | | |
| Non-Propulsion w/ 20% Margin | 2,013 | 2,013 | |
| Installment of Hybrid Lighting System | -167 | -167 | |
| | | | |
| Hotel Load | 1,845 | 1,845 | |
| 24 Hour Average Load | 1,208 | 1,209 | |
| | | | |
| Hotel Load & Propulsion | 4,145 | 9,295 | |

**Electric loads for SWBS Groups**

| | T-AGOS-23 | GAPV |
|---|---|---|
| **Crew** | 45 | 112 |
| **Displacement (LT)** | 5,370 | 6,090 |
| **Volume ($ft^3$)** | 625,000 | 686,380 |

**Factors used for elecric load calculations**

The hotel loads were scaled from the electric loads of the T-AGOS-23 and using the factors shown in the above table. The SWBS 400 electric load was held constant, while the SWBS 500 and 600 were scaled by a displacement ratio and a crew number ratio respectively. The SWBS 510 electric load was scaled by a combination of a volumetric ratio and a low temperature factor for operating in the Arctic.

# Appendix E – Breakdown of Total Heat Recovery Plant

The Turbogenerator includes a dual pressure steam turbine, a generator, and a power turbine. The steam turbine/generator uses the steam generated by the 3-Section Heat Exchanger to produce electricity. A power turbine works in conjunction with the steam turbine by supplying additional shaft energy to the generator. The power turbine also provides the power to run the fuel and air compressors, which ready the necessary fuel and air requirements for the respective prime mover. The exhaust from the power turbine is then used in a 3-Section Heat Exchanger, which is located in the propulsion exhaust stack.[34]

## *Steam Drum*

Water is separated from steam within the steam drum. A circulating pump operates with suction from the bottom of the drum and pumps the saturated steam mixture into the Steam Generating Bank. In the steam drum water absorbs heat from a portion of the exhaust gas and is converted into a saturated steam/water mixture.

## *Steam Generating Bank*

The generating bank produces the dry saturated steam, which is then used by the superheater. Water is separated from the steam/water mixture and then is re-circulated back into the steam drum.

## *Superheater*

Within the superheater the saturated steam acquires more heat from the exhaust gases and reaches a superheated state. The superheated steam exits to the steam turbine. There is a dump and bypass line so that excess steam can be automatically discharged from the superheater to the condenser preventing over pressurization.

## *Steam Turbine/Electric Generator*

The superheated steam then drives a steam turbine, which in turn drives an electric generator. Exhaust steam is then run into a condenser. The flow rate of the exhaust steam is regulated by an automated throttle valve to maintain constant generator speed and electrical frequency.

### *Condenser*

The condenser takes the exhaust steam from the steam turbine as well as the dump valve (to prevent over pressurization of the steam system during low load operation) and outputs water to a feed pump. The latent heat from the condenser is absorbed by seawater (de-icing) pumped through the condenser‟s tubes. The feed pump then sends water to the economizer.

### *Economizer*

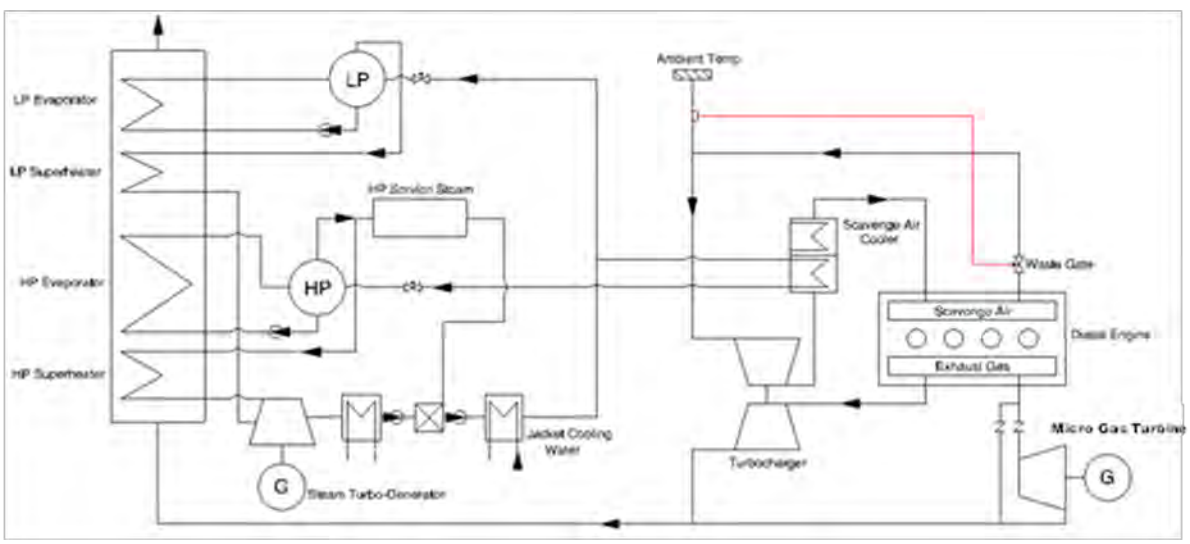
Water is preheated in the economizer and is returned to the steam drum. A valve regulates the pump flow rate to maintain a constant water level in the steam drum.

## Appendix F – Diesel Genset Selected for 2015

| Engine Model | Weight (kg) | Fuel Rate (kg/hr) | Amount of Power for # of Engines w/ Losses (kW) | | | Amount of Power for MGT for # of Engines w/ Losses (kW) | | Total Power at Cruise (kW) | Total Power at Peak (kW) |
|---|---|---|---|---|---|---|---|---|---|
| | | | 1 | 2 | 4 | 2 | 4 | | |
| Wärtsilä 32 6L32 | 228 | 384 | 2,208 | 4,416 | 8,832 | 500 | 1,010 | 4,916 | 9,842 |

**Deiesel genset information**

## Appendix G – 2015 Power Generation Schematic




**2015 System layout**

# Appendix H – 2015 GAPV Fuel Endurance Calculations

| Load Type | Hours | Number of Diesel Gensets |
|---|---|---|
| 7,000 nm @ 12 knots | 583.33 | 2 |
| 437.5 nm @ 17.5 knots | 36.50 | 4 |
| Base Load: Maneuvering and low loads | 100.00 | 1 |

| Flow Rate for each Diesel Genset | | |
|---|---|---|
| MCR: Wärtsilä Diesel Gensets 32 6L32 | 2,760 | kW |
| 80% MCR | 2,208 | kW |
| Fuel Flow Rate at SFC: 174 g/kW*hr (Diesels) | 384 | kg/hr |

| Fuel for 7,000 nm @ 12 knots | | |
|---|---|---|
| Fuel Load | 448,220 | kg |
| Fuel Volume | 519 | $m^3$ |

| Fuel for 437.5 nm @17.5 knots | | |
|---|---|---|
| Fuel Load | 56,090 | kg |
| Fuel Volume | 65 | $m^3$ |

| Fuel for Base Load | | |
|---|---|---|
| Fuel Load | 38,420 | kg |
| Fuel Volume | 45 | $m^3$ |

| Total Fuel Amounts | | |
|---|---|---|
| Total Fuel Load (w/ 10% margin added) | 603,040 | kg |
| Total Fuel Volume | 629 | $m^3$ |

**Fuel endurance calculations**

The above calculations used a density of 863 kg/$m^3$ for the fuel.

# Appendix I – Fuel Cell and Emissions Calculations

The operating time is derived by dividing the vessels range by its cruising speed and the power is the wattage needed to drive the propulsion and hotel loads. The cell voltage is an assumed voltage within a range similar to existing systems and could be as high as 0.99 V, but a more conservative estimate of 0.8 V is used for calculations. The system current is calculated from the power divided by the voltage. The total fuel and air requirements are derived from these operating requirements.

The fuel requirement does not take utilization factors into account and could require an additional 20% (over the calculated amount of fuel). Similarly, the air requirements may be up to five times larger to accommodate cooling of the fuel cell stack. Unused fuel that passes through the fuel cells will be combusted in the gas turbine. However, the turbines will also require their own fuel source beyond what is scavenged from the fuel cell exhaust.

| **SOFC Operating Requirements** | |
|---|---|
| Operating Time (hr) | 583 |
| Power (kW) | 4,000 |
| Cell Voltage (V) | 0.8 |
| Current (A) | 5,000,000 |

| **SOFC Fuel Requirements** | |
|---|---|
| Mass of Diesel (kg) | 724,760 |
| Mass Flow Rate (kg/hr) | 1,242 |
| Volume of Diesel ($m^3$) | 814 |
| Volume Flow Rate ($m^3$/hr) | 1.4 |

| **SOFC Air Requirements** | |
|---|---|
| Mass of Air (kg) | 10,027,840 |
| Mass Flow Rate (kg/hr) | 17,190 |
| Volume of Air ($m^3$) | 8,356,530 |
| Volume Flow Rate ($m^3$/hr) | 14,330 |

| **SOFC Emissions** | |
|---|---|
| Mass of $CO_2$ (kg) | 2,253,740 |
| Mass Flow Rate of $CO_2$ (kg/hr) | 3,860 |
| Mass of $H_2O$ (kg) | 2,734,670 |
| Mass Flow Rate of $H_2O$ (kg/hr) | 4,690 |

**SOFC Requirements and emissions**

The below calculations were developed in order to find the total fuel and air required to meet a mission endurance of 7,000 nm at 12 knots. Emissions produced are assumed to be solely carbon dioxide and water, which have also been calculated for. The assumed diesel formula is $C_{16}H_{34}$ and oxygen is pulled directly from the surrounding atmosphere.

### *Step 1: Define system power requirements*

Power required: 4 MW
Fuel cell voltage: 0.8 V (Assume between 0.7 V and 0.99 V)
Fuel cell current: P/V = I, 4 MW/0.8 V = 5,000,000 A
Operating time: Distance/Speed = Time, 7,000 nm/12 kn = 583.33

### *Step 2: Define fuel, oxidizer, emission characteristics and reaction*

Reaction – $C_{16}H_{34} + 24.5\ O_2 \rightarrow 16\ CO_2 + 17\ H_2O$

| Element | H | C | O |
|---|---|---|---|
| AMU or g/mol | 1.0079 | 12.011 | 15.99 |

| Reactant → Product | $C_{16}H_{34}$ | $O_2$ | → | $CO_2$ | $H_2O$ |
|---|---|---|---|---|---|
| Moles | 1 | 24.5 | | 16 | 17 |
| AMU or g/mol | 226.44 | 31.98 | | 43.99 | 18.01 |
| Density (kg/m3) @ STP | $890_l$ | $1.43_g$ | | $1.98_g$ | $1000_l$ |

[The "Fuel Cell Handbook 7th edition", pg 9-1 & 9-2 details the calculation for the mass flow rate of $H_2$ to generate 1 ampere of current in a fuel cell which is summarized in the calculations below.][35]

*$H_2$ mole flow rate*:
(1 mol $H_2$/ 2 mol $e^-$)*(1 mol $e^-$/96,487 coulombs)*(1 coulomb/A*s)*(3,600 s/hr) =
**0.018655 mol $H_2$/A*hr**
*$H_2$ mass flow rate*:
(0.018655 mol $H_2$/A*hr)*(2.0158 g* $H_2$/mol $H_2$) = **0.037605 g* $H_2$/A*hr)**

### *Step 3: Calculate the required $H_2$*

*$H_2$ molar density* = 2*(1.0079 g H/ mol) = **2.0158 g $H_2$/ mol**
*Mass $H_2$* = (0.018655 mol $H_2$/A*hr)*(583.33 hr)*(5*$10^6$ A)*(2.0158 g/mol* $H_2$)*(1 kg/1,000 g) = **109,680.52 kg**
*Mass flow rate $H_2$* = 109,680.52 kg/ 583.33 hr = **188.02 kg/hr**

### *Step 4: Calculate total diesel fuel ($C_{16}H_{34}$) for mission*

*From Step 2; $C_{16}H_{34}$ + 24.5 $O_2$ → 16 $CO_2$ + 17 $H_2O$ also ρ = 890 kg/$m^3$*
*Note: 1 kg $H_2$ = 1 kg H and 1 mol $H_2$ = 2 mol H*
Moles of $C_{16}H_{34}$ = (109,680.52 kg H)*(1000 g/kg)*(1 mol H/1.0079 g)*(1 mol $C_{16}H_{34}$/34 mol H) = **3,200,612 mol $C_{16}$ $H_{34}$**

Mass $C_{16}H_{34}$ = (3,200,612 mol $C_{16}H_{34}$)*(226.44 g/mol $C_{16}H_{34}$)*(1 kg/1,000 g) = **724,761.47 kg**
Mass flow $C_{16}H_{34}$ = 724,761.47 kg/583.33 hr = **1,242.45 kg/hr**
Volume $C_{16}H_{34}$ = 724,761.47 kg/(890 kg/$m^3$) = **814.34 $m^3$**
Volume flow rate $C_{16}H_{34}$ = 814.34 $m^3$/ 583.33 hr = **1.4 $m^3$/hr**

### *Step 5: Calculate total Air for system*

*Note; 1 kg $O_2$ = 1 kg O and 24.5 mol $O_2$ = 49 mol O*
*Air is 79% N2 and 21% O2 by volume and ρ = 1.2 kg/$m^3$ @ STP*
Moles O = (49 mol O/ mol $C_{16}H_{34}$)*(3,200,612 mol $C_{16}H_{34}$) = **156,830,024.5 mol O**
Mass O = (156,830,024.5 mol O)*(15.99 g/mol O)*(1 kg/1,000 g) = **2,507,712.09 kg**
Volume $O_2$ = 2,507,712.09 kg/ (1.43 kg/$m^3$) = **1,754,872.00 $m^3$**
Volume Air = 1,754,872.00 $m^3$/0.21 = **8,356,533.35 $m^3$**
Volume flow rate Air = 8,356,533.35 $m^3$/ 583.33 hr = **14,325.49 $m^3$/hr**

### *Step 6: Calculate Emissions*

*Water*
Mol $H_2O$ = (17 mol $H_2O$/mol $C_{16}H_{34}$)* 3,200,612 mol $C_{16}H_{34}$ = **54,410,416.67 mol $H_2O$**
Mass $H_2O$ = (54,410,416.67 mol $H_2O$)*(18.01 g/mol)*(1 kg/1,000 g) = **979,703.08 kg $H_2O$**
Mass flow rate $H_2O$ = 979,703.08 kg $H_2O$/ 583.33 hr = **1,679.49 kg/hr**

*Carbon dioxide*
Mol $CO_2$ = (16 mol $CO_2$/mol $C_{16}H_{34}$)* 3,200,612 mol $C_{16}H_{34}$ = **51,209,803.92 mol $CO_2$**
Mass $CO_2$ = (51,209,803.92 mol $CO_2$)*(43.99 g/mol)*(1 kg/1,000 g) = **2,252,770.48 kg $CO_2$**
Mass flow rate $CO_2$ = (2,252,770.48 kg $CO_2$)/583.33 hr = **3,861.89 kg $CO_2$/hr**

# Appendix J – How the Topping Cycle Works

A fuel compressor feeds fuel to the anode side of the fuel cell, while an air compressor supplies air to the cathode side. The exhaust from the anode (excess fuel and water) is then used in the fuel heater to heat incoming fuel, while the exhaust from the cathode (excess oxygen, nitrogen, and non-oxygen species) is channeled to the air heater to heat the incoming air. Both exhaust streams are utilized in the catalytic burner to further increase the temperature of the exhaust gases. The high temperature leads to a high pressure exhaust flow expansion, which is used to power the turbine, "thereby providing a mechanism to recuperate the exhaust energy".[7] The turbine produces work that is used to drive a generator as well as a fuel and air compressor. The exhaust gases are then sent to the THRP for further energy recuperation. By replacing the combustion process with a more efficient electrochemical one the gas turbine cycle can be improved, creating additional electricity by making use of the waste heat.

# Appendix K – Detailed Description of SOFC/GT Hybrid System

- SOFC: Reformed diesel can be used to run the SOFC because of its high temperature properties. The SOFC produces exhaust from both the anode and cathode (anode exhaust: excess fuel and water, cathode exhaust: excess oxygen, nitrogen, and non-oxygen species). These exhausts are then used to heat the incoming fuel and air (cooling air must be heated to 700 °C).[34]
- Fuel/Air heaters: The heaters using the exhaust streams to heat the fuel and air going into the fuel cell serve an important purpose. The fuel cell requires the heated air, around 700 °C, in order to operate. The air is used within the electrochemical process and also serves in an effort to cool the fuel stack itself. The diesel fuel, used by the fuel cell, requires heat in order to break it down into smaller components so that it can be used by the fuel cell. After leaving the heaters the two exhaust steams are sent to the catalytic burner.[34]
- Catalytic Burner: In the catalytic burner the unutilized fuel from the fuel cell is burned off, adding increased energy to the high temperature and high pressure exhaust gases. This added energy increases the exhaust gases temperature to around 1,000 °C. The utilization of the fuel cell was previously determined from Dr. Sun"s report to be 85%, leaving extra fuel for the catalytic burner.[6] Too high of a utilization rate can result in local starvation within the fuel cell stack, which would produce decreased voltages and can kill the fuel cell. Too low of a utilization rate will also decrease the efficiency of the fuel cell. The exhaust from the afterburner is then channeled into the turbine.
- Turbine: The high temperature and high pressure exhaust gas then powers the turbine, which in turn drives an air compressor, fuel compressor and generator.

# Appendix L – Photovoltaics (PVs)

Solar cells or photovoltaics (PVs) convert solar radiation into direct current (DC) electrical power. However, alternating current (AC) electrical power is achievable if the power is supplied to a battery and then followed by an Inverter.[36]

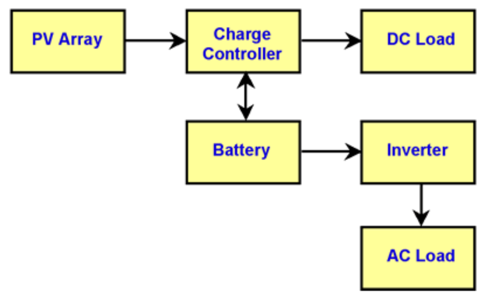
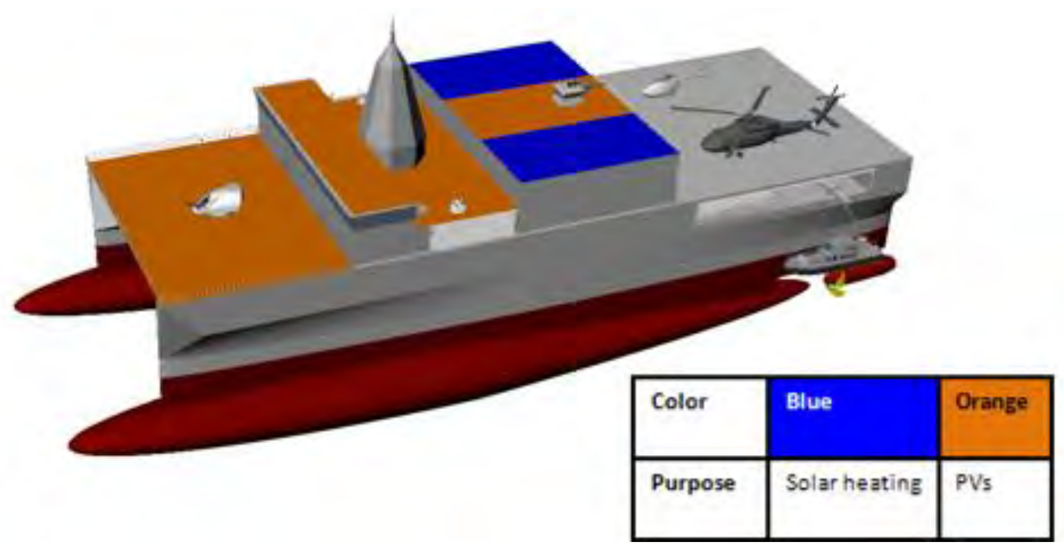



**Diagram of stand-alone PV system with batter storage powering DC and AC loads**

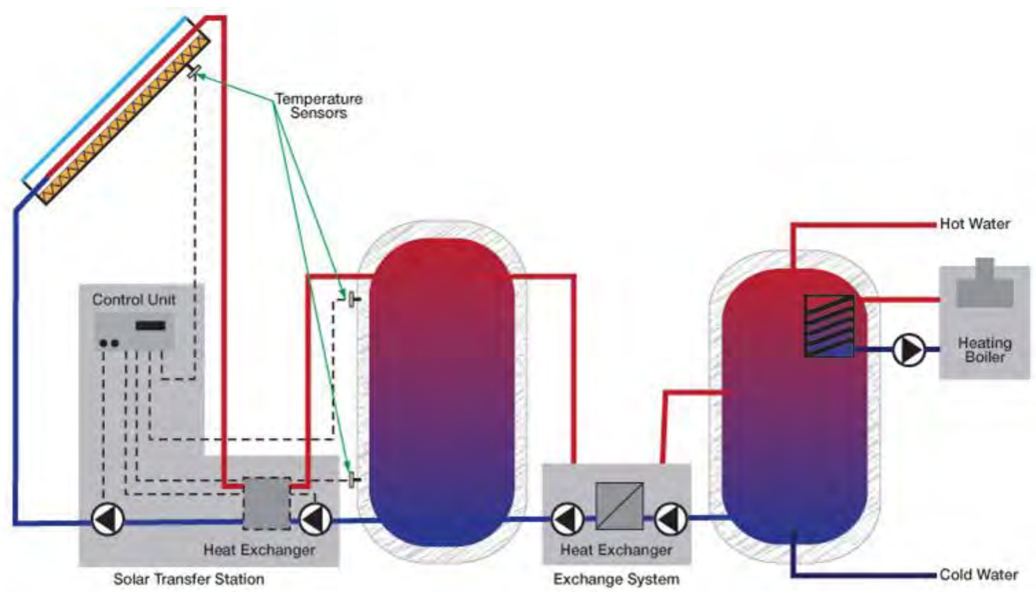
If the GAPV surfaces, that are colored in orange in the below figure, incorporate PVs, the total area would be 1,131 $m^2$. The amount of power generated by the PVs for the 2015 design would be then 34 kW, and for 2030 would be 70 kW. This amount of energy is much smaller than the potential amount of power the sun is providing for the whole vessel, 327 kW. The reason for this is that only half of the topside area is covered with PVs and only a percent of the power from the sun is converted due to the efficiencies of the PVs. These values were obtained by multiplying the amount of power the sun provides for the GAPV by the efficiencies of PVs for 2015 (21%) and 2030 (42.8%).



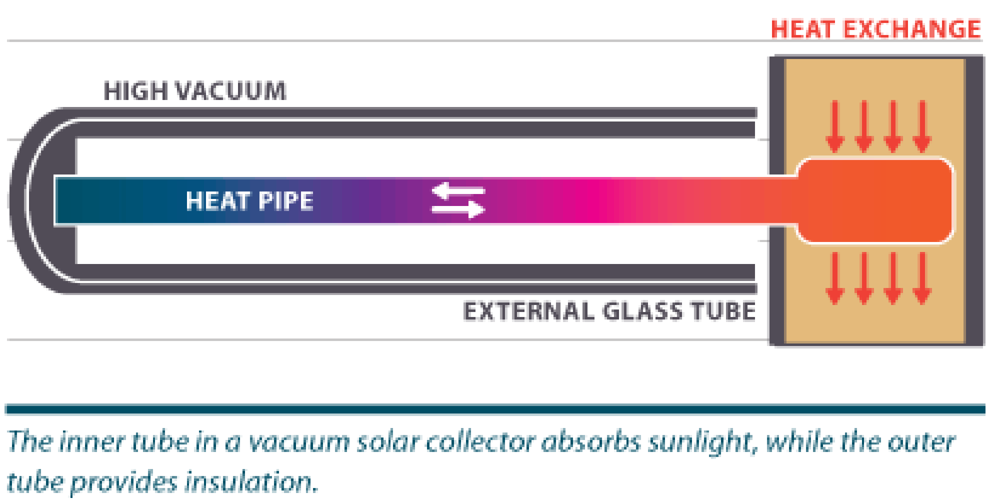

**Proposed location of PVs and solar heating tubes for GAPV**

# Appendix M – Solar Heating

Solar heating is used to convert solar radiation into power that heats water. The hotel load for water heating for the GAPV is 72 kW. The efficiency for solar heating is 50-75 %.[37] S-Solar AB has made a Zenit Vacuum Tube solar collector that is in use in the Nordic regions.[38] The total amount of topside area needed to capture 72 kW for the tubes is 216 $m^2$. The tubes will be placed on the roofs of the hangars; this is shown above in the figure with the color blue. The figures and table below provide a description of how solar heating works and the technical data for the tubes.[38]




**Configuration of a large-scale solar thermal system**

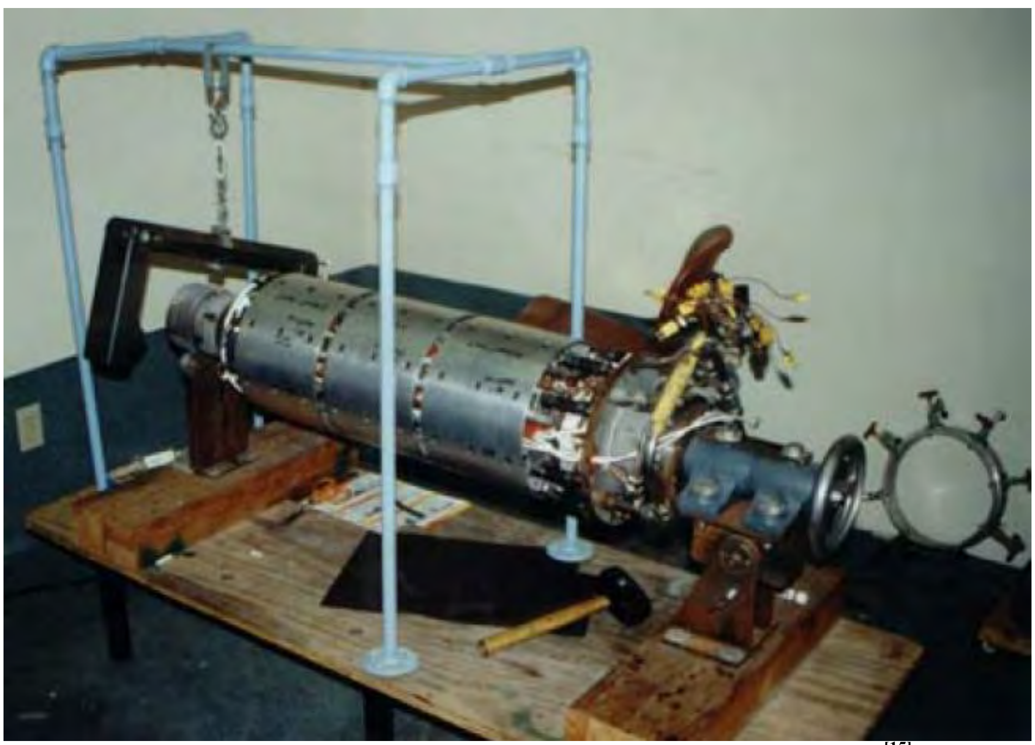



**Zenit vacuum tube solar collector**

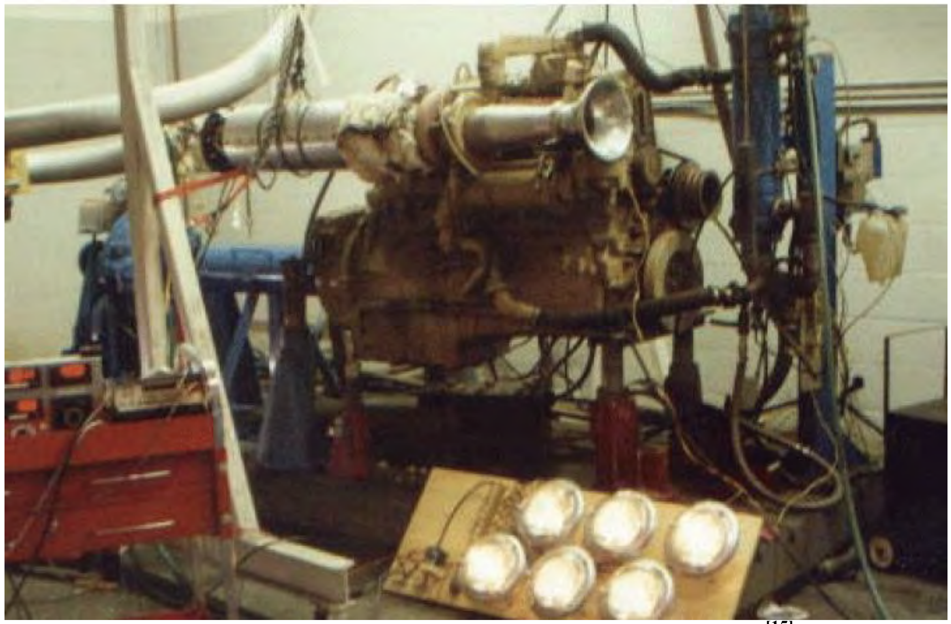
| | |
|---|---|
| Height | 140 mm |
| Length | 2,000 mm |
| Width | 2,040 mm |
| Weight | 75 kg |
| Number of pipes | 24 (+6 extra) |
| Max. output at 50°C surface temp. | 1.32 kW |
| Connection (dimensions, material) | Dia. 22 mm x 1 mm, soft copper pipe |
| Angle of inclination | 30°- 87° |
| Approval | SP, Solar Keymark 012 |
| Subsidy-entitlement designation | Zenit |

**Technical data for Zenit vacuum tube solar collector**

# Appendix N – Thermoelectric Generators (TEGs)

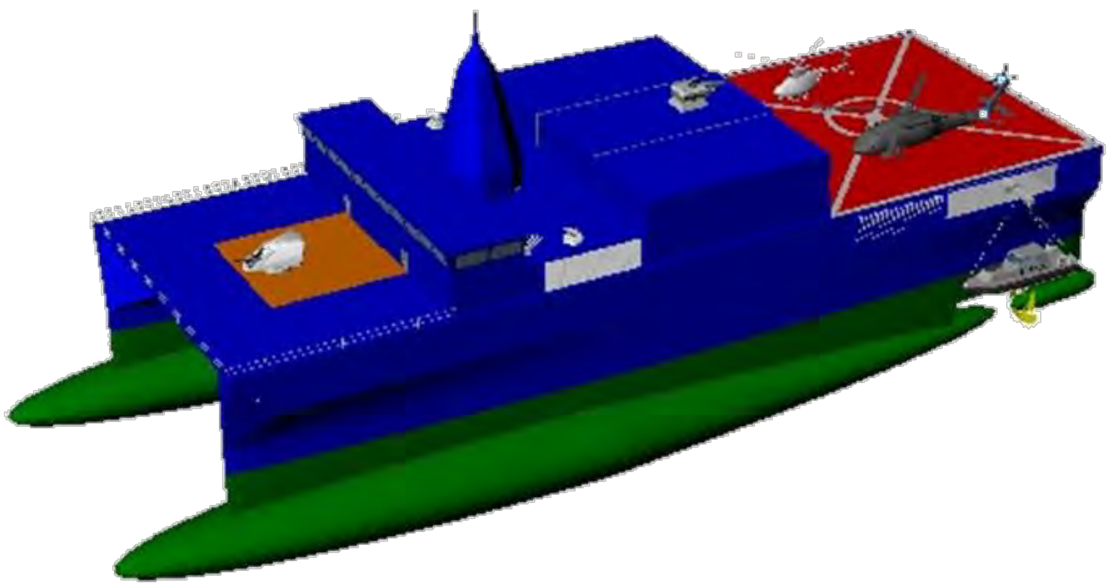


**1 kW TEG for class 8 heavy diesel trucks by Hi-Z Technology, Inc.[15]**



**1 kW TEG connected to the engine of the diesel truck[15]**

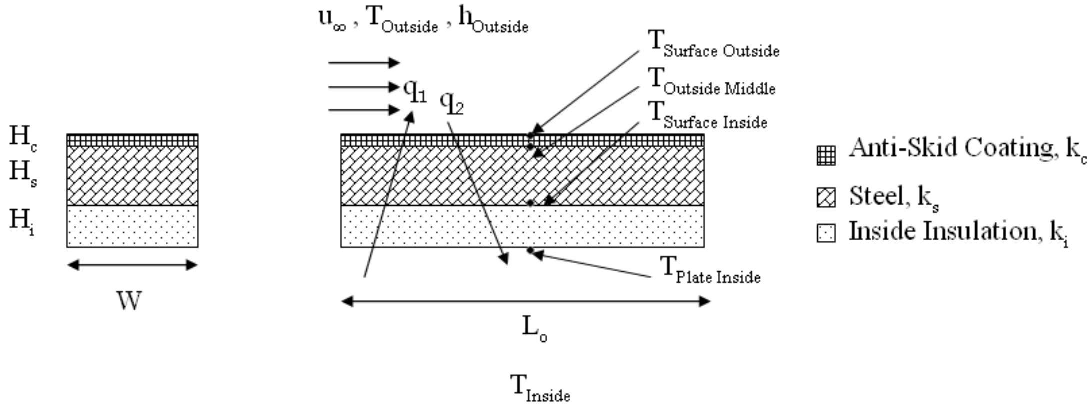
# Appendix O – Placement of Coatings on GAPV



| Color | Blue | Green | Red | Orange | Yellow |
|---|---|---|---|---|---|
| **Purpose** | Ice phobic | Anti-fouling | Non-skid | Non-skid | Anti-fouling |
| **Location** | Topside | Underwater hull | Flight deck | walkways | Propeller |

**Placement of different coatings on GAPV**

# Appendix P – Flight Deck Anti-Icing Calculations




**Cross-sectional view of the flight deck used for analysis**

***Step 1: Find the amount of power created from the convection caused by the wind***

Assumptions:

$u_\infty = 6.7056$ m/s (15 mph)

$T_{Outside} = -40°$ C = 233.15 K

$T_{Surface\ Outside} = 2°$ C = 275.15 K

$T_f = (T_{Outside} + T_{Surface\ Outside})/2 = -19°$ C = 254.15 K ≈ 250 K

$Re_L = u_\infty L_o/\nu = 1.17 \times 10^7$ , Turbulent

Assumed Isothermal Plate:

A = 871

$Nu_L = (0.037Re_L^{4/5} - A)Pr^{1/3} = 14,211$

$h_{Outside} = Nu_L*k_f/L_o = 15.846$ W/m$^2$ • K

$q_1 = h_{Outside}*A*(T_{Surface\ Outside} - T_{Outside})$ = **53,243 W**

$q_1$/A = **665 W/m$^2$**

***Step 2: Find the amount of power created from the convection caused by the quiescent air inside the vessel***

Assumptions:

$T_{Inside} = 20°$ C = 293.15 K

$T_{Plate\ Inside} = 22°$ C = 295.15 K

$T_f = (T_{Inside} + T_{Plate\ Inside})/2 = = 21°$ C = 294.15K ≈ 300 K

$L = A_s/P = W/[2(W + H)]$

$Ra_L = g\beta(T_{Plate\ Inside} - T_{Inside})L^3/(\nu\alpha) = 3.03 \times 10^5$ , therefore Laminar

$Nu_L = 0.68 + 0.670Ra_L^{1/4}/[1 + (0.492/Pr)^{9/16}]^{4/9} = 2.4111$

$h_{Inside} = Nu_L*k_f/L = 0.539$ W/m$^2$ • K

$A = W*L_o$

$q_2 = h_{Inside} * A * (T_{Plate\ Inside} - T_{Inside})$ = **86.24 W**
$q_2/A$ = **1.07 W/m$^2$**

***Step 3: Find the overall amount of heat transferred to outside***
$q_{Overall} = q_1 - q_2$ = **53,157 W**
$q_{Overall}/A$ = **664 W/m$^2$**

***Step 4: Find the thickness of insulation needed***
$q_{Overall} = (T_{Plate\ Inside} - T_{Surface\ Inside}) * k_i * A / t * L_o$
$t = (T_{Plate\ Inside} - T_{Surface\ Inside}) * k_i * Lo * A / q_{Overall}$ = **0.02 m**

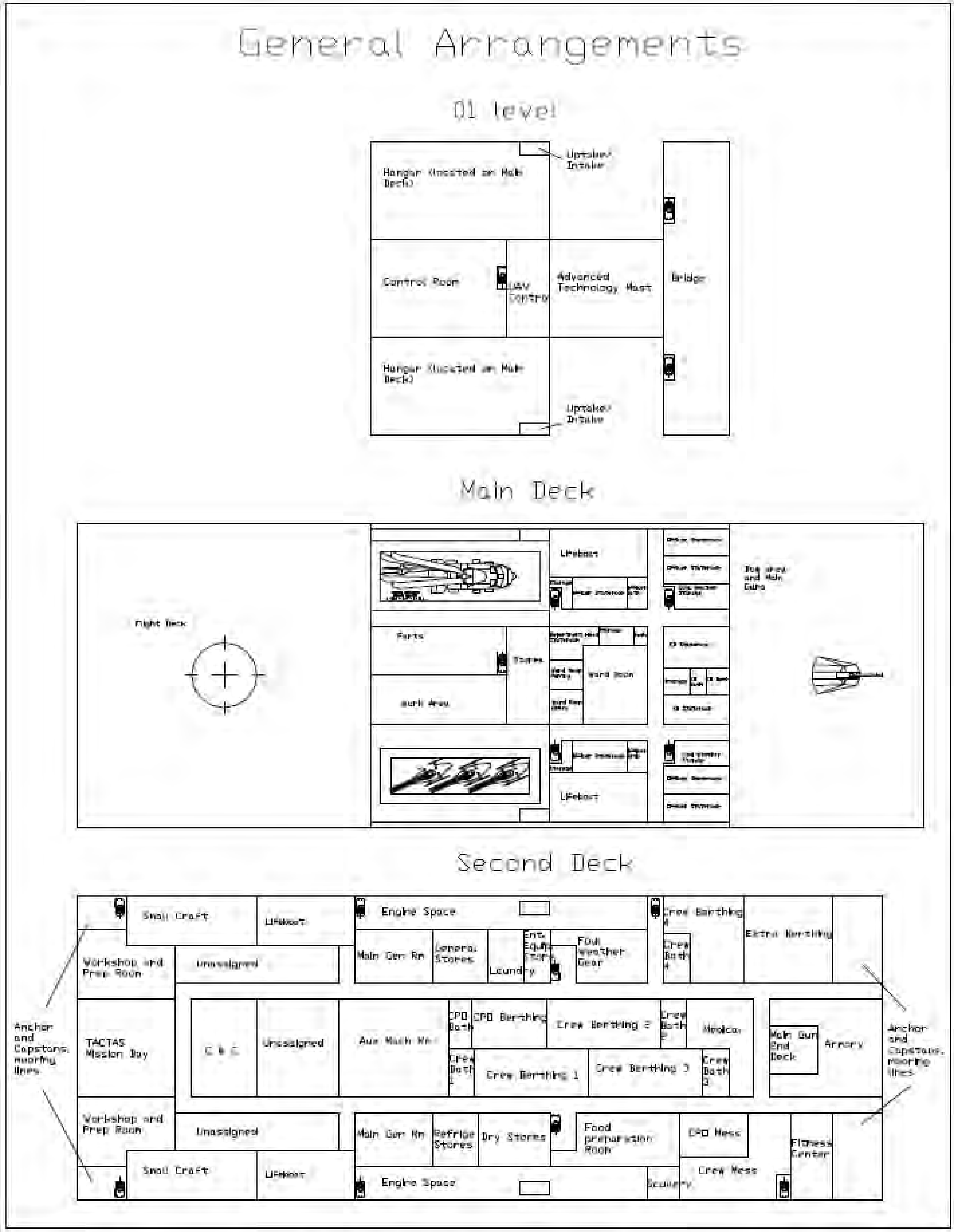
***Step 5: Find the temperatures of the layers***
$T_{Outside}$ = - 40° C = **233.15 K**
$T_{Surface\ Outside}$ = 2° C = **275.15 K**
$T_{Outside\ Middle} = T_{Surface\ Outside} + q_{Overall}/L_o * H_c/(k_c * A)$ = 2.140° C = **275.290 K**
$T_{Surface\ Inside} = T_{Outside\ Middle} + q_{Overall}/L_o * H_s/(k_s * A)$ = 2.149° C = **275.299 K**
$T_{Plate\ Inside}$ = 22° C = **295.15 K**
$T_{Inside}$ = 20° C = **293.15 K**

# Appendix Q – 2015 GAPV Weights and General Arrangements

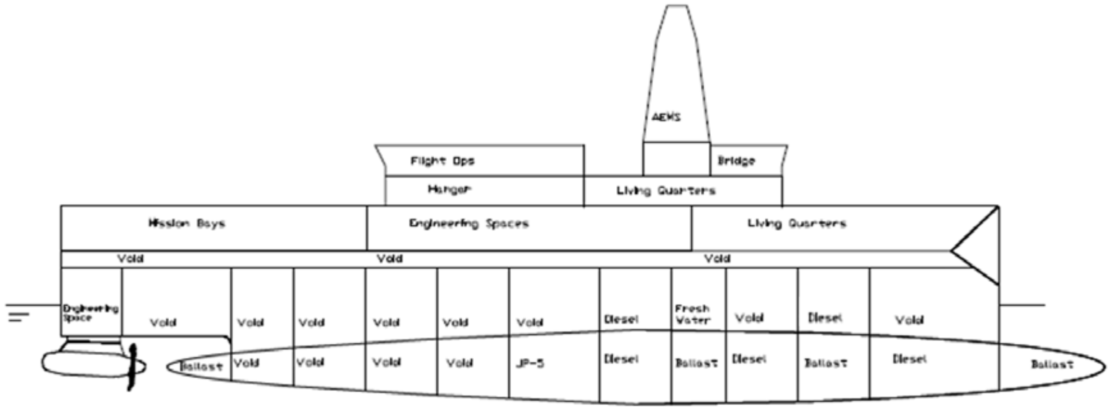
| Principal Characteristics | |
|---|---|
| Displacement – Full Load (LT) | 6,088 |
| Length Overall (ft) | 260.0 |
| Draft (ft) | 28.0 |
| Trim (ft) | 0.1 |
| $BM_L$ (ft) | 89.2 |
| $BM_T$ (ft) | 34.2 |
| KB (ft) | 13.4 |
| $KM_L$ (ft) | 102.6 |
| $KM_T$ (ft) | 49.6 |
| KG (ft) | 34.3 |
| $GM_L$ (ft) | 68.3 |
| $GM_T$ (ft) | 15.3 |
| LCB (ft) | 106.5 |
| LCG (ft) | 106.5 |
| TPI (LT/inch) | 11.1 |

| Principal Characteristics with Icing (ft) | |
|---|---|
| $BM_L$ | 80.6 |
| $BM_T$ | 32.7 |
| LCB | 106.5 |
| KB | 13.4 |
| $KM_L$ | 94.0 |
| $KM_T$ | 46.1 |
| KG | 37.9 |
| $GM_L$ | 56.1 |
| $GM_T$ | 8.2 |
| LCG | 107.7 |

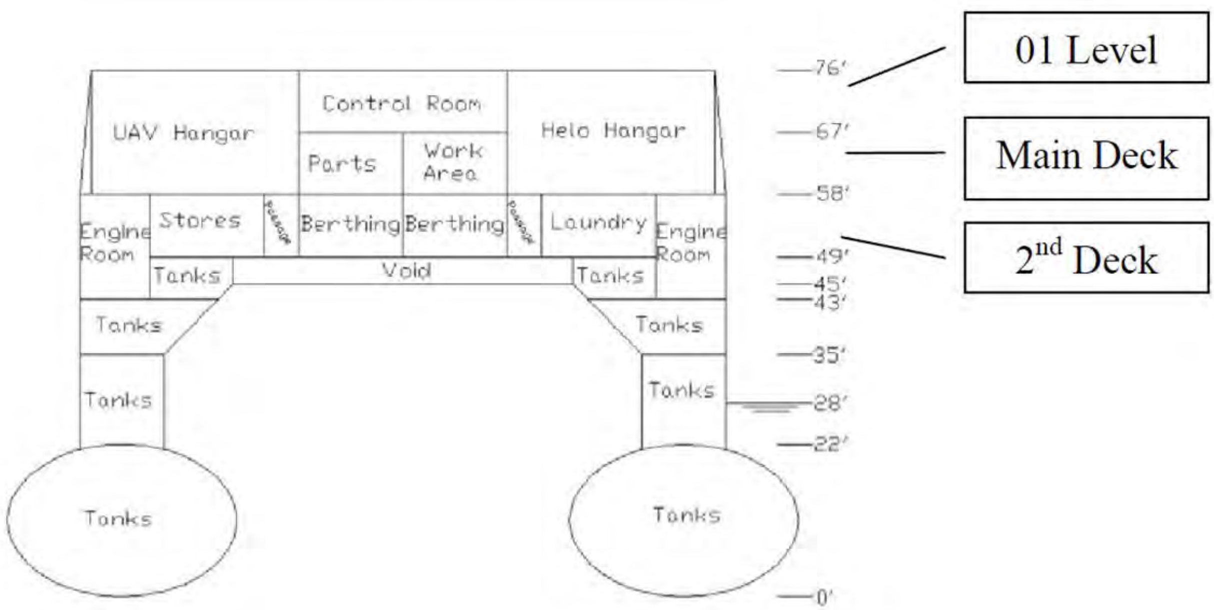
| SWBS GROUPS SUMMARY | | | |
|---|---|---|---|
| **SWBS Group** | **Total Weight (LT)** | **Vertical Center of Gravity (ft)** | **Longitudinal Center of Gravity(ft)** |
| 100 | 2,405 | 34.4 | 111.5 |
| 200 | 594 | 43.5 | 167.0 |
| 300 | 151 | 45.2 | 115.0 |
| 400 | 154 | 45.7 | 71.8 |
| 500 | 473 | 40.8 | 113.5 |
| 600 | 350 | 42.8 | 93.9 |
| 700 | 83 | 55.3 | 10.0 |
| Margin | 446 | 35.5 | 107.0 |
| Variable Weights | 854 | 17.0 | 72.5 |
| Service Life Margin | 579 | 30.0 | 106.5 |
| Topside Icing | 647 | 72.0 | 108.4 |
| | | | |
| Lightship | 5,234 | 33.8 | 106.5 |
| Total | 6,088 | 34.3 | |
| Total with Icing | 6,735 | 37.9 | |




**General arrangements**[1]




**Updated inboard profile of general arrangements**




**Cross-sectional amidships view[1]**