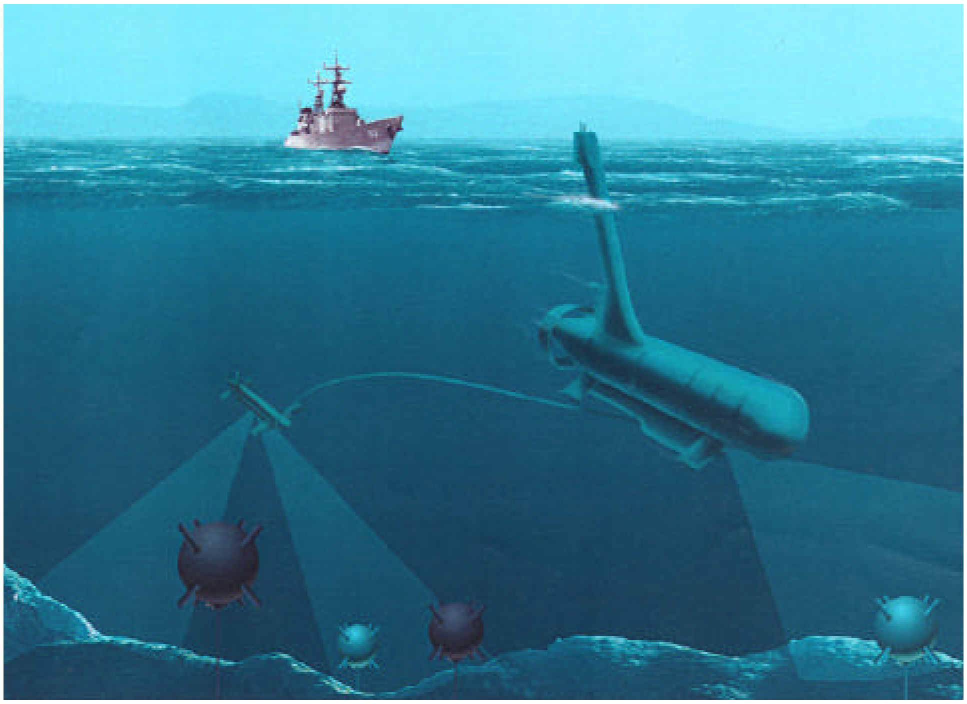
Air Conditioning System
for
AN/WLD-1(V)-1
Navy Remote Minehunting Vehicle

Scott Wrieden
Lockheed Martin, Perry Technologies
Riviera Beach, FL

Ralph Draper
Engineering Technology Program
University of New Hampshire
Durham, NH

Gary Treadwell
Beswick Engineering
Portsmouth, NH

Abstract: The Navy's newest semi-autonomous, remote mine search vehicle has been under development at Lockheed Martin's Perry Technologies division in Riviera Beach, Florida since 1995. This 6.5 ton vehicle is capable of being launched from a Navy ship over the horizon from an enemy mine field, travelling at snorkel depth to the area of interest, mapping the mine field using a towed side scan sonar, relaying the information back to the fleet and then returning to its support ship for recovery. Temperature control is required in the electronics space for both on-deck and underway conditions. Heating is required for cold weather conditions to prevent damage to computer storage devices. 1.3 tons of A/C are required to handle the electronics compartment heat load under worst case conditions. The paper will describe the alternatives considered, methods used for steady state and transient analysis, the system qualification test program and results of sea trial testing.



Section 1.0 Overview

1.1 In 1995 the US Navy selected Perry Technologies of Riviera Beach, Florida, a division of Lockheed Martin, to develop its next version of their Remote Mine Search vehicle.

1.2 Unlike earlier versions of this semi-autonomous vehicle, it was determined during the proposal phase that the electronics module, located aft of the bow section and forward of the free flood, fuel and umbilical storage section, would require cooling during warm water operations. The electronics module is 4 feet (1.2 m) in diameter and 3 feet (0.9 m) long and contains heat sensitive electronics components essential to carrying out the mission. A 15,000 Btu/hr (1.25 tons) vapor compression A/C system, operating off the 350 hp Cummins diesel in the engine module, was selected from a range of alternatives to provide underway cooling for the EE space.

1.4 A second cooling system, for use while the vehicle is on deck, when the diesel isn't operating, is required to cool the EE module in order to carry out pre-launch health checks. The refrigerant condenser package for this second cooling system is located in the support area of the surface ship and connects to a second evaporator in the electronics module via hull connections. This second system, because of space limitations, is not capable of carrying the full heat load of the EE space under steady state conditions. Because of this limitation, pre-launch testing is limited to short periods of a couple of hours.

1.5 The prototype vehicle for the V3 configuration has been tested on deck and at sea and these tests confirm the capacity of the cooling system to meet mission requirements.

Section 2.0 Background

2.1 The US Navy selected Perry Technologies, a div of Lockheed Martin, to design and build the V3 and V4 versions of its semi-autonomous mine search vehicle. A prototype for the V3 version has completed sea trails and V4 is in final design.

2.2 During the proposal phase, thermal management of the electronics module was identified as an important consideration. The estimated steady state heat load in the electronics space for V3 was 1,850 watts (6,300 Btu/hr) and for V4 was 4,400 watts (15,000 Btu/hr). Specifications for the vehicle require operation in seawater between 28 °F (-2°C) and 95 °F (35°C). On-deck conditions range from –20 °F (-29°C) to 125 °F (52 °C) for storing and servicing the vehicle. A calculation of the estimated heat transfer rate through the hull and bulkheads into adjacent spaces and seawater during warm water operation showed that an active cooling system would be required. The contract called for all systems for V3 to be sized to handle the requirements for V4 with no increase in the overall envelop of the vehicle. V3 was planned for ships of opportunity, using a portable control van for operations and maintenance. V4 is planned for a new class of ships with dedicated space to store, maintain and operate the RMS. As this was a development contract, any and all approaches that met the mission requirements were to be considered. To keep costs down, commercial, off-the shelf technology (COTS) was to be used wherever feasible. At the time of contract award in 1995 the Navy expected to build 20 of the V3 version and 40 of the V4 version. Contract changes required only two prototypes of the V3 version to be built and the Navy is moving ahead with development of the V4 version, now designated AN/WLD-1(V)1

2.3 In addition to cooling the electronics space during in-water operation, it was determined that the electronics space would also require cooling while the vehicle was in its cradle on deck during pre-launch health checks, when the diesel engine was not running. A transient analysis showed that pre-launch health checks could only be conducted for a short time without exceeding allowable temperature limit. So a second cooling system was designed that would operate without the diesel engine.

2.4 Nitrogen purged. To reduce the risk of fire and preclude condensation from forming in the evaporator or else where, the EE module was to be purged with dry nitrogen when operating.

Section 3.0 Conceptual Design Phase

3.1 Concepts/approaches/trade-off analyses

An initial estimate of the amount of cooling that would be required was just over one ton of A/C or about 15,000 Btu/hr (4,400 watts), which is comparable to a large window A/C unit. An estimate of the amount of heat produced by the electronics space was determined. This equipment load was then reduced by the amount of heat that was expected to be lost through the bulkheads to the two adjacent, free-flooded compartments and through the hull to 95 °F (35°C) seawater at the maximum specified electronics space temperature of 104°F.(40°C). See the appendix for a sample calculation of the hull heat transfer. Following a trade-off analysis, an R 134a, vapor compression system, driven off the diesel engine, located aft in the propulsion module, was selected for underway cooling. Ice storage, an electric powered hermetic compressor, located in either the electronics space or the engine compartment, and thermo-electrics were among the approaches considered. Concept sketches of the approaches are in the appendix.

3.2 On-deck thermal issues included the requirement that cooling would be needed in the EE module when the diesel was not operating. It was determined that not all of the equipment in the EE module needed to be tested during pre-launch health checks at the same time and that the reduced number of items would produce only 60% of the full heat load in the space. Since the maximum allowable EE module temperature of 104°F (40°C) would actually be below the ambient temperature of 125°F (52 °C), the A/C system would have to handle heat transfer through the hull into the EE module. The combined equipment and hull heat transfer amounted to 7,270 Btu/hr or 2,130 watts. Due to limited space in the support area for V3 (V3 was planned for ships of opportunity while V4 is planned for a new class of ships with dedicated space for the RMS.) and the desire not to break into the R134a system during routine maintenance of the vehicle, a second R134a system was selected for the on-deck cooling system with the water cooled condenser package located off-hull in the service area, with self-sealing, quick disconnects located behind a removable panel on the hull. 45°F (7.2°C) chilled water from the support ship was also considered but not selected because of potential problems on the support ships. Due to limited space in the electronics module, a full capacity evaporator coil was not feasible. The question of how long this system could maintain a safe temperature in the electronic space during pre-launch health checks was raised. A lumped parameter method, using a technique developed at Perry Offshore in the 1980s for similar situations, was used to predict that the operators would have approximately an hour to conduct testing of essential systems in the electronics module prior to launch. See reference 1.

3.3 Hull heat exchanger. Heat from the refrigerant condenser needed to be rejected to sea water. The diesel engine required cooling water and a closed, water/glycol cooling loop was planned for this purpose. One option, the one finally selected, was to use the same water/glycol cooling loop that served the diesel to condense the refrigerant. But a second option was to circulate refrigerant condenser water through cooling loops made by boxing in frame bays in the hull in the propulsion module. This method was used successfully to reduce the number of seawater hull penetrations in the USS Dolphin (AGSS 555). This approach was analyzed and although the concept would have worked it was rejected as overly complex to build and service and would have required an extra pump. A parallel analysis of the diesel cooling loop option showed that it would work and would be simpler to accomplish.

3.4 A Kepner-Tregoe selection analysis was requested to determine which of several cooling options was the best choice based on several criteria including power, weight, volume, reliability, maintainability, COTS, and cost. Options considered included vapor compression using electrically driven hermetic units located in either the propulsion module or the electronics module, vapor compression using direct drive off the diesel engine, and thermo-electrics. Ice storage was eliminated as not practical because of mission length. During the period of this analysis it became apparent that the diesel driven generator was already at maximum capacity and that the only option for powering the A/C compressor was direct drive off the diesel engine.

Section 4.0 Preliminary Design Phase

4.1 For the water cooled condenser package, to be located in the propulsion module, an automotive style refrigerant compressor and a brazed plate heat exchanger were selected. The RMS's water/glycol cooling system, which rejects heat through a keel cooler, cools the main diesel and the A/C condenser. The estimated load on the cooling loop from the A/C system, based on an assumed coefficient of performance of 3.0, was calculated to be 24,800 Btu/hr (7,270 watts). To provide the coldest possible water to the refrigerant condenser, the 108°F (42°C) cooling water, at design maximum conditions, goes first to the A/C condenser before passing to the diesel engine. The compressor is equipped with an electric clutch controlled by a thermostat located in the EE module.

4.2 Space, weight, power requirements. During preliminary design all major components of the RMS cooling system, including the equipment needed on the support ship, were identified. These items are listed on the bill of materials in the appendix. To provide the capability for underway and on-deck cooling in the limited space allocated to the A/C system in the EE module, a five row evaporator, designed by Super Radiator Coil of Richmond, Virginia, was proposed. Three rows were dedicated to cooling the EE space during underway conditions and only two rows were dedicated to cooling on-deck. To use a single coil of five rows, which would have provided adequate cooling of the EE module underway and on deck, would have required breaking into the R134a refrigerant system through hull valves every time that cooling was required on deck and this was considered unacceptable as a routine way of operating the A/C system.

A 170 cfm, 24 VDC pancake blower was selected to circulate EE module nitrogen through the evaporator in a space efficient manor. An adapter plate was designed so that the blower could be close coupled to the evaporator.

4.3 Heating requirements. The minimum ambient temperature for the RMS was specified at –20°F (-29°C). It was determined that this temperature is too cold to safely allow computer hard drives to be turned on so an electric heating system was designed for the electronics module but will not be detailed in this paper.

4.4 Compressor RPM determined. To ensure proper capacity of the A/C system at varying diesel engine speeds, the pulley ratio between the compressor and the engine was calculated so that full capacity of the A/C system would occur at engine normal RPM.

Section 5.0 Detail Design

5.1 Steady state cooling underway. The detail design phase included identifying components down to the valves, fittings and tubing. Pressure drop calculations for the refrigerant liquid supply and vapor return lines were also done using Crane Companion software. This calculation was also used to verify that refrigerant velocities were adequate to maintain compressor oil flow around the system.

5.2 On deck cooling. For the on-deck cooling system, the valves, fittings and tubing for the vehicle as well as the support ship subsystems were called out.

5.3 On-deck cooling transient analysis. Because the RMS on-deck cooling system could not handle the projected heat load indefinitely, a transient analysis was requested to estimate the time that the pre-launch health checks could take place without exceeding compartment temperature maximum of 104°F (40°C). Because of the complex geometries of the hull and bulkheads and the heat producing components, a lumped parameter method was chosen for this analysis. Multiple lumps were modeled including the (a) the heat producing equipment, (b) the thermal mass of the nitrogen filling the EE module, (c) the thermal mass of the hull and bulkheads. This technique had been developed in the 1970s at Perry for similar types of systems and circumstances. The model, which runs in Basic, indicated that the EE module temperature would not reach an unacceptable level for about an hour of testing. See the appendix for a sample plot of the transient analysis. This was deemed acceptable but the time period was to be verified during the test phase of the project as the Biot number, that gives confidence in the accuracy of the lumped parameter method, was not << 1.0. Note: In the normal use of the lumped parameter method it is the temperature of the solid that’s in question. In this case it was the temperature of the nitrogen in the EE module that was of primary concern.

Section 6.0 Prototype Testing

6.1 Laboratory mock-up and performance tests

Because the RMS is an un-manned vehicle, it was important to bench test the cooling system components and the assembled cooling system before installing the equipment in the vehicle to verify design flows and performance and to establish normal operating parameters so that problems could be easily identified during dock trials and sea trials.

Since the evaporator and associated condenser and compressor were to be tested in a test loop that had its own dedicated blower, it was necessary to first test the R134a evaporator with the 24 VDC blower that would be attached to the evaporator when it was installed in the vehicle. This test was completed and verified that the blower would supply 170 cfm to the evaporator. The evaporator, compressor and condenser were then mounted in the test loop with all the necessary equipment to make an operational A/C system. This system was operated for 50 hours over a range of expected operating conditions for the RMS and confirmed that the system could provide the required amount of cooling during underway or in water conditions. The on-deck cooling system performance was not tested.

6.2 Dock trials. Dock trials were conducted to check out operation of all auxiliary systems including the A/C system prior to sea trails. These tests confirmed proper operation of the A/C system.

6.3 Sea trails. Sea trails were conducted off the coast of Florida and test data confirmed, when extrapolated to 95°F (35 °C) seawater, the ability of the A/C system to maintain acceptable EE space temperature during design conditions.

Section 7.0 Summary

Although an unexpected complexity at the outset, a cooling system for the electronics module of the RMS vehicle was identified early on in the proposal phase and designed and tested during the development contract of the V3 version. Cooling for both in water operation and on deck during pre-launch health checks has been provided. Some changes to the design are being evaluated during the detail design of V4 (AN/WLD-1(V)-1, including the possible use of chilled water for the on-deck cooling requirements.

References:

1. Principles of Heat Transfer by Frank Kreith, International Textbook Co., Scranton, 1963, Page 117

Appendix:

A. Bill of material
B. Hull and bulkhead estimated heat transfer rates
C. Concept figures
D. Transient model results

Appendix B Hull and Bulkhead Transmission Calculations

Estimating heat loss or gain through the hull of the Electronic Module:

Case 1.—In water condition, heat loss.

Assuming compartment temperature = 104°F and sea water temperature is 95°F.

66 sqft x 2.0 Btu/hr-sqft-°F x (104-95°F)= 1,190 Btu/hr

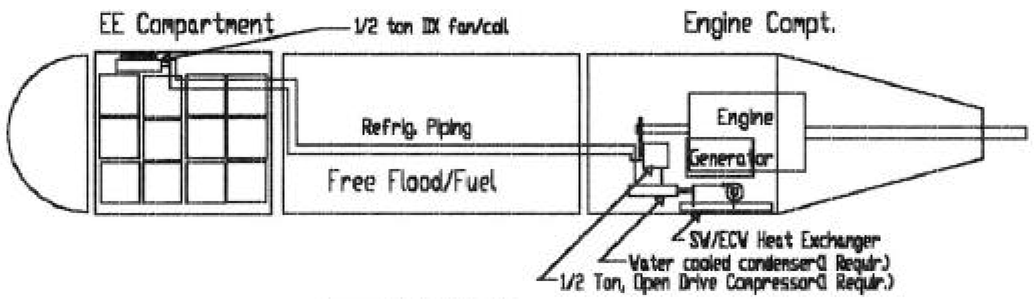
Case 2. –In air/on deck condition, heat gain.

Assuming compartment temperature = 108°F and air temperature is 125 F and neglecting solar gain (from direct sunlight), the T is only 3 F° and the overall heat transfer coefficient will be approximately 1.0 Btu/hr-°F-sqft:

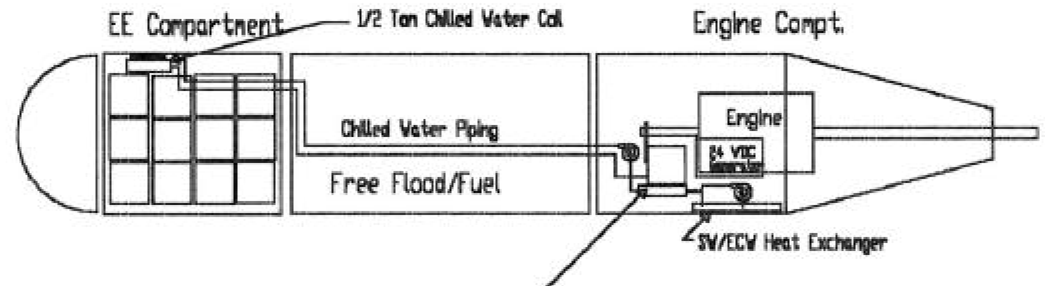
66 sqft x 1.0 Btu/hr-sqft-°F x (125-108°F) = 1,122 Btu/hr

V3 plus upgrades 1,2 & 3, open drive, split-DX system   Appendix A   3/4 ton A/C capacity

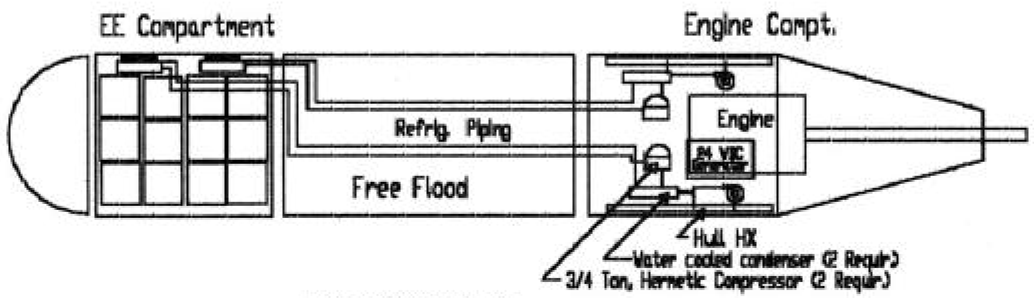
No.	Description	Make	Model	Location	ÅWt(lbm)	Size: L"xW"xH"	ROM Cost	Vendor, Stock No., cat. page
1	1-134a Compressor, 3/4 ton, note 2	Seltec	EM 15	Eng. Sp	10.0	5 Ø x 9.5	$400	Seltec
2	1 Brazed plate condenser, 6 gpm	ITT Standard	BPR 410	Eng. Sp	9.0	4 x 4 x 12	$350	30 plates, 316 ss
3	1 Liquid reservoir,	Refrig. Research	1920	Eng. Sp	4.0	3.5 Ø x 7.5	$30	Johnstone, B81-385
4	1 low pressure switch	Johnson(Penn)	P70AB-2C	Eng. Sp	1.0	5 x 3 x 3	$44	Johnstone, B11-561
5	Time delay relay	Macromatic	SS60228	Eng. Sp.	negl	2.5 x1.7 x 2.8	$52	Newark, 46F5881
6	Copper tubing, 6' ¾", 6' 3/8"	Johnstone	B92-178	Eng. Sp	8.0	N/A	$100	Johnstone Supply, P-719
7	134a Refrigerant	Johnstone	B92-373	Eng. Sp	2.3	N/A	$25	Johnstone, B92-373
8	Refrig. Filter/Dryer, liquid line	Parker	053(s)	Eng. Sp	1.0	2.5 Ø x 5-3/16	$7	Johnstone, B10-117
9								
10	1 Compressor wrap around heater	Raychem	CCH1	Eng. Sp	1.0	N/A		United Refrig. P-284
11a	2 Press. gauges, 30" Hg to 150 psig	Marsh	J1118	Eng. Sp	3.0	2 Ø x 1/8 NPT	$60	United Refrig., P-315
11b	4 Press. gauges, 30" Hg to 150 psig	Marsh	J1118	EE Sp.	3.0	2 Ø x 1/8 NPT	$120	United Refrig., P-315
12	1-dual circuit, evap. coil	Super Radiator	RS02197P	EE Sp.	10.0	11.5 x 5.5 x 12.5	$300	10x9(6R)38/96/48
13	24 VDC, 270 cfm blower	Rotron	mil 901	EE Sp.	3.0	6.5 Ø x 2	$1,300	Rotron, motor 3381SF
14	Sight glass, liquid line	Parker	PSG-3S	Eng. Sp.	negl.	2 Ø x 1	$9	Johnstone, B10-091
15	Copper tubing, 6' ¾", 6' 3/8"	Johnstone	B92-181	EE Sp.	8.0	N/A	$25	Johnstone Supply, P-719
16	1 Expansion valve, 1 ton 134a, ext. comp.	Parker	GE1FW	EE Sp.	2.0	2 Ø x 3	$40	Johnstone, B12-078
17	134a Refrigerant	Johnstone	B92-373	EE Sp.	2.3	N/A	$25	Johnstone, B92-373
18	Refrig. line QDs for off hull cooling	Hansen		Free fl				
19	Thermostat w/remote sensing bulb	Johnson(Penn)	A19ABC-24	EE Sp.	negl.	2 x 2 x 4	$40	Johnstone, L36-931
20a	2 5/8" Packless refrig. valve	Superior VIv	216-10S	Eng. Sp	0.5	2 Ø x 3	$60	Johnstone, B12-029
20b	~~1 3/4" Packless refrig. valve~~			Eng. Sp	0.5	~~2 Ø x 3~~		
20c	2 1/4" Packless refrig. valves	Superior VIv	214-4S	Eng. Sp	0.5	2 Ø x 3	$24	Johnstone, B12-026
				Tot. =	68.6 lbm	0.96 cuft	$2,987	components/material
							$6,500	130 hrs labor-inst/tst
						Tot cost=	**$9,487**	



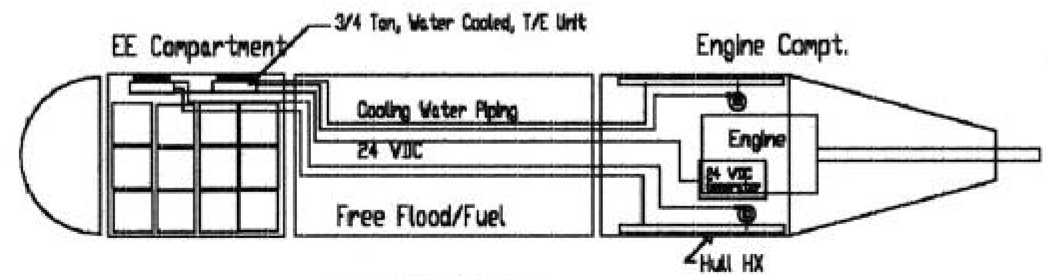
Concept Sketch #1a



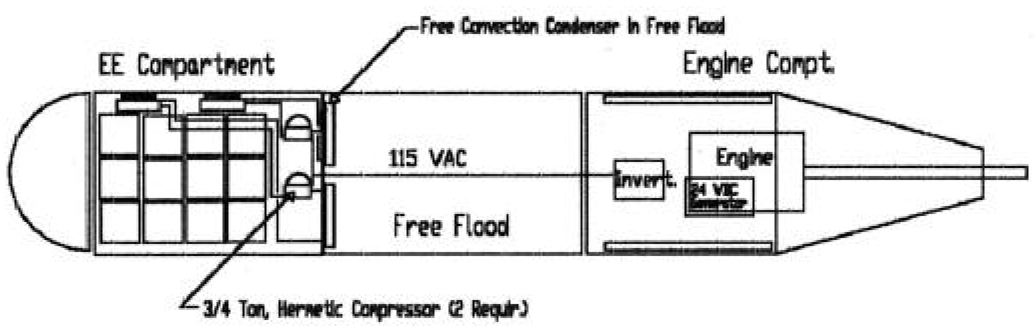
Concept Sketch #3a



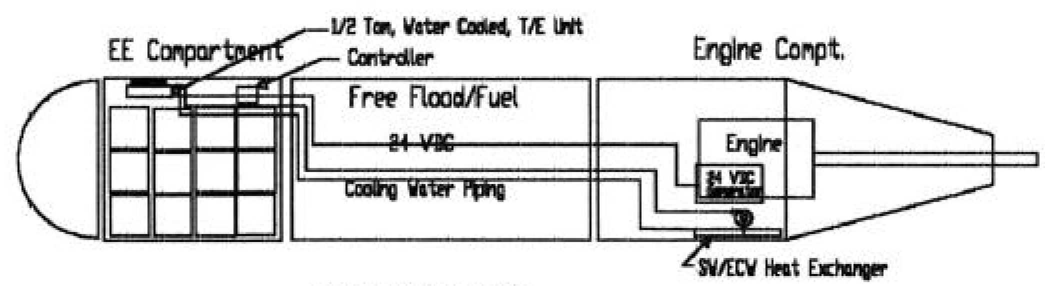
Concept Sketch #2



Concept Sketch #4

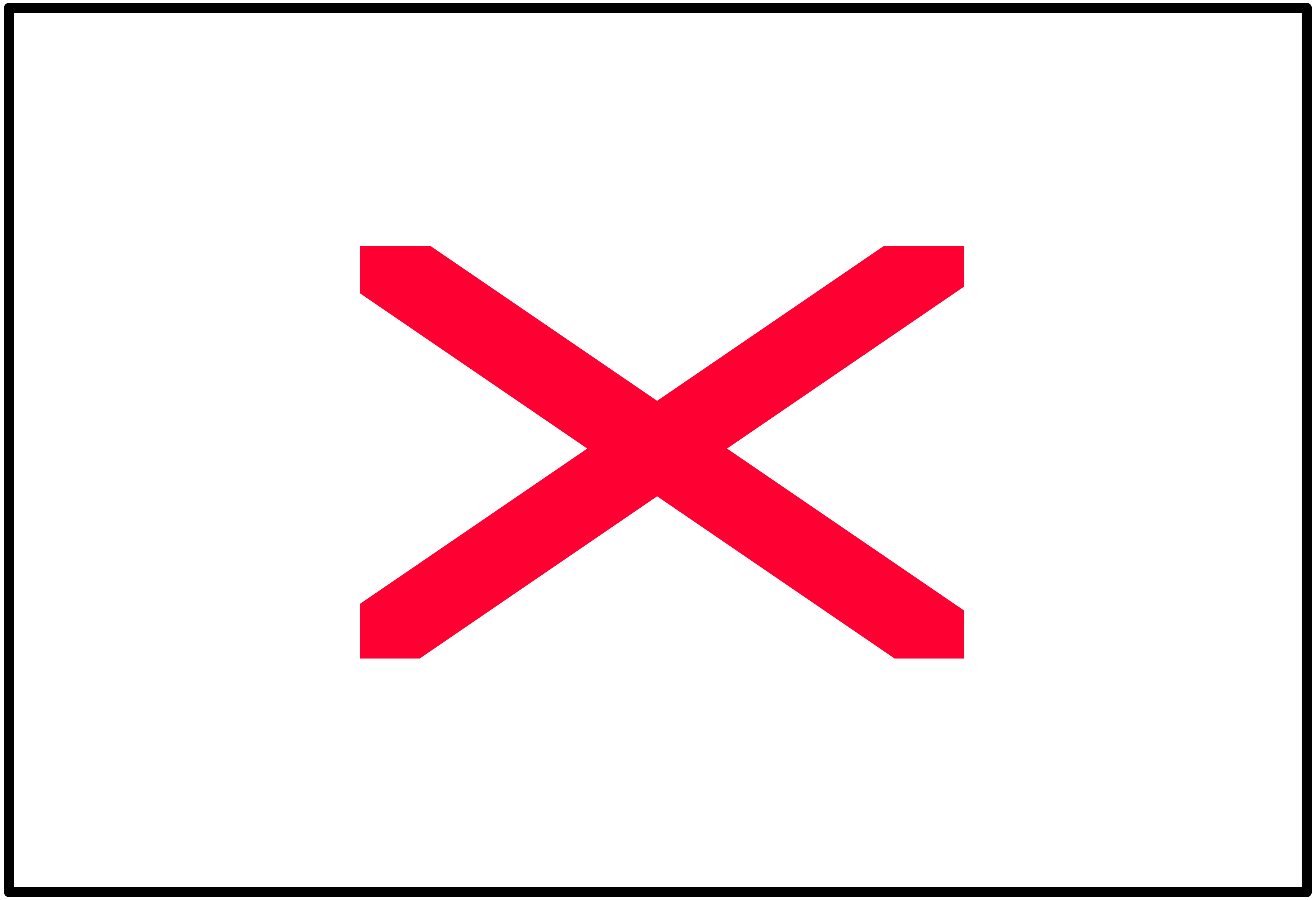


Concept Sketch #2a



Concept Sketch #4a

APPENDIX C



Appendix D