T/S Golden Bear Demonstration of the Thermal Energy Harvesting and Conversion System Test Report

Collins Aerospace

September 2023

Prepared by: WP Abrams

William Abrams

Date: 21 January 2024

Table of Contents

Background

The Maritime Administration (MARAD) and Collins Aerospace funded the demonstration of a waste heat driven adsorption chiller on the Training Ship *T/S Golden Bear* during California Maritime Academy's 2023 Summer Cruise. This effort was completed under MARAD contract number 693JF72050001 as part of the Maritime Environmental and Technical Assistance (META) program as a follow up to a previous effort by the U.S. Navy.

Previously, the Thermal Energy Harvesting and Conversion (TEHC) testing on the *T/S Golden Bear* was completed under a Phase 2 effort sponsored by the US Navy under BAA N00167-13-BAA-01. The Naval Surface Warfare Center, Carderock Division (NSWCCD) requested innovative concepts from industry and academia to enable energy conservation and carbon footprint reduction on US Navy ships. The primary focus was to develop concepts with the potential for rapid transition to Fleet operations. All Military Sealift Command (MSC) ship classes and Navy combatant platforms had identifiable opportunities for energy conservation, and all classes were of interest under this BAA.

Figure 1 – 2023 Summer Cruise ITINERARY

Collins Aerospace's TEHC innovative system solution for the 2023 cruise consisted of a state-of-the-art seawater heat exchanger for re-cooling of the adsorption beds and new piping to harvest the ship generators' jacket water wasted energy and provide it to an adsorption chiller for cooling. This system was installed on the *T/S Golden Bear* and evaluated by the California Maritime Academy (CMA) and Collins prior to the start of the 2023 summer cruise. The test period covered approximately two months and covered the area shown in Figure 1.

Executive Summary

Summary results from the cruise showed the waste heat driven heat pump integrated to the generator's jacket water system provided:

1. Reduced fuel consumption by supplementing the ship's cooling loads without consuming electrical power from the generators.
2. A simple installation process to capture a suitable "driving heat source" from all three generators.
3. An effective re-cooling (middle temperature) source of the ship's seawater system. A previous 2021 cruise used the Central Fresh Water (CFW), which was shown to be ineffective due to the higher water temperature of the CFW.
4. The cooling loads provided were free of any CO2 emissions.
5. No maintenance or operator support were required during this 64-day cruise.
6. The system operated 100% of the total cruise without any shutdowns or problems.

The overall success of this test has initiated the planning for a second phase of validation testing, with the U.S. Navy, during the 2024 and 2025 cruises. The initial concept is to scale up the cooling capacity by roughly a factor of 10 times. The 2023 cruise demonstrated a "proof of concept" cooling capacity of roughly three ton. The target for the "scale up demonstration will be roughly 30 tons.

System Design and Installation

The system design and ship installation plan were developed by Glosten and Collins Aerospace. Prior to installation, the design and plans were then reviewed and approved by the American Bureau of Shipping (ABS). Figures 2 through 5 show the TEHC system component installation within the *T/S Golden Bear*. The adsorption chiller was set up to run utilizing hot water generated from the ship's diesel generator. The re-cooling source was provided through a seawater heat exchanger connected to the ship's seawater cooling system.

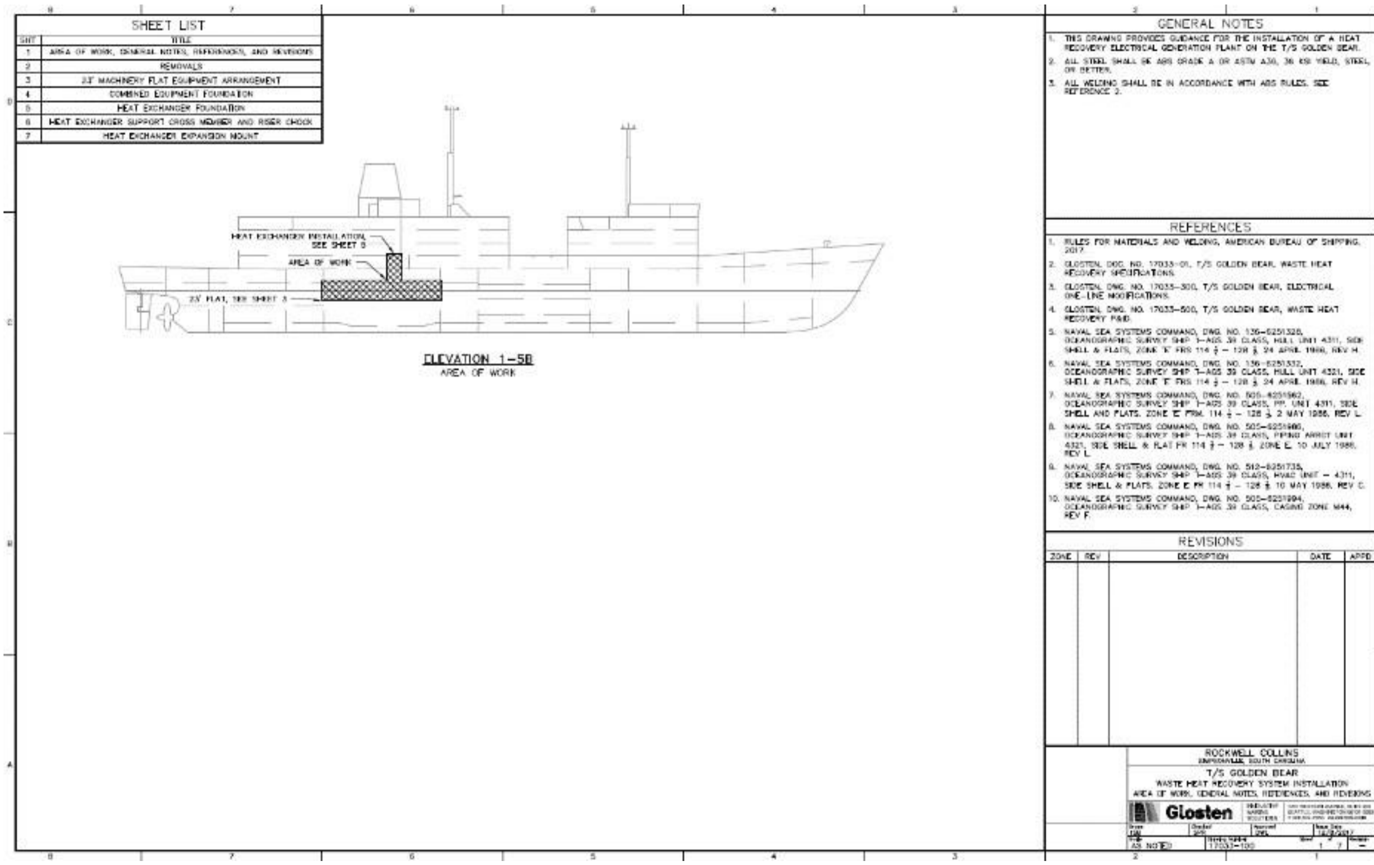


Figure 2 – TEHC System Location

Collins Aerospace

MATERIAL SCHEDULE

PIPING SYSTEM	PIPE SIZE	PIPE MATERIAL	TAKEDOWN JOINTS MATERIAL	TAKEDOWN JOINTS GASKETS	TAKEDOWN JOINTS BOLTING	VALVES BODY	VALVES TRIM	FLEX CONN'S	FITTINGS TYPE & MATERIAL	MAX WORKING CONDITIONS SYSTEM	PRESSURE	TEMP	REMARKS
DIESEL ENGINE COMBUSTION EXHAUST (ABS CLASS I) (USCG CLASS I)	14"	CRES STEEL, TYPE 321 OR 347, ASTM A376, A167 OR A358 SCH 10	CrMo STEEL FLANGES, ASTM A182, GR F11, ANSI B16.5	METALLIC (NON-ASBESTOS)	CrMo ASTM 193, GR B16, ANSI B18.2.1 CrMo ASTM 194, GR 4, ANSI B18.2.2	SS, ASTM A 351, GR CF8 (SEE EQUIPMENT LIST)	ASTM A240 ASTM A276 (SEE EQUIPMENT LIST)	STAINLESS STEEL METAL EXPANSION BELLOWS USCG/ABS APPROVED	NONE	COMBUSTION EXHAUST	10" H20	700 °F	SEE REFERENCE 4
THERMAL OIL (ABS CLASS II) (USCG CLASS II)	2" & BELOW	CARBON STEEL, ASTM A53 OR ASTM A106, GR B, SCH 80, ANSI B36.10, SEAMLESS	STEEL, FLANGE, ASTM A105, ANSI B16.5, CLASS 300, WELD NECK	SS SPIRAL WOUND, API 601, CLASS 300, FLEXIBLE GRAPHITE	STEEL ASTM A193 GR B7 ASTM A194 GR 2H	STEEL, ASTM A105, OR A216, GR WCB, ANSI B16.34, SOCKET WELD, CLASS 300, GRAPHITE PACKING	13 CR, STELLITE SEATS	USCG APPROVED HOSE AND END FITTINGS	STEEL, ASTM A105 OR A234, GR WPB, ANSI B16.11, CLASS 3000, SOCKET WELD	THERMAL OIL	45 PSIG	400 °F	THERMINOL 66
CENTRAL FW COOLING (ABS CLASS III) (USCG CLASS II)	2" & BELOW	CARBON STEEL, ASTM A53 OR ASTM A106, GR B, SCH 80, ANSI B36.10, SEAMLESS	STEEL, UNION, ASTM A105 MSS-SP-83, CLASS 3000, SOCKET WELD	NEOPRENE CLOTH INSERTED, FULL FACE, ANSI B16.21	STEEL ASTM A307 ANSI B18.2.1, GR B STEEL ASTM A563 ANSI B18.2.2, GR A	STEEL, ASTM A105, OR A216, GR WCB, ANSI B16.34, SOCKET WELD, CLASS 150	MONEL OR 316 STAINLESS STEEL	USCG APPROVED HOSE AND END FITTINGS	STEEL, ASTM A105 OR A234, GR WPB, ANSI B16.11, CLASS 3000, SOCKET WELD, CLASS 150, LUGGED	FW COOLING	75 PSIG	140 °F	SEE REFERENCE 5
CHILLED WATER, (ABS CLASS III) (USCG CLASS II)	1-1/4" & BELOW	COPPER, ASTM B88, TYPE K OR L, SEAMLESS	UNION, SOLDER JOINT, COPPER, ASTM B88, ANSI B16.22 OR BRONZE, ASME B62, ANSI B16.18	NEOPRENE CLOTH INSERTED FULL FACE, ANSI B16.21	STEEL ASTM A307 ANSI B18.2.1 GR B STEEL ASTM A563 ANSI B18.2.2, GR A	BRONZE, CLASS 150, ASME SB61 OR SB62, NPT OR SOLDER JOINT, MSS-SP-80	BRONZE	USCG APPROVED HOSE AND END FITTINGS	COPPER, SOLDER JOINT, ASTM B88, ANSI B16.22 OR BRONZE, ASME B62, ANSI B16.18	CHILLED WATER	20 PSIG	90 °F	
GENERATOR JW COOLING (ABS CLASS III) (USCG CLASS II) A4	2" & BELOW	CARBON STEEL, ASTM A53 OR ASTM A106, GR B, SCH 40, ANSI B36.10, SEAMLESS	STEEL, UNION, ASTM A105 MSS-SP-83, CLASS 3000, SOCKET WELD	NEOPRENE CLOTH INSERTED, FULL FACE, ANSI B16.21	STEEL ASTM A307 ANSI B18.2.1, GR B STEEL ASTM A563 ANSI B18.2.2, GR A	STEEL, ASTM A105, OR A216, GR WCB, ANSI B16.34, SOCKET WELD, CLASS 150	MONEL OR 316 STAINLESS STEEL	USCG APPROVED HOSE AND END FITTINGS	STEEL, ASTM A105 OR A234, GR WPB, ANSI B16.11, CLASS 3000, SOCKET WELD, CLASS 150, LUGGED	JW COOLING	53 PSIG	185 °F	SEE REFERENCE 5
AUXILIARY SEAWATER COOLING (ABS CLASS III) (USCG CLASS II) A2	2" & BELOW	CARBON STEEL, ASTM A53 OR ASTM A106, GR B, SCH 80, ANSI B36.10, SEAMLESS	STEEL, UNION, ASTM A105 MSS-SP-83, CLASS 3000, SOCKET WELD	NEOPRENE CLOTH INSERTED, FULL FACE, ANSI B16.21	STEEL ASTM A307 ANSI B18.2.1, GR B STEEL ASTM A563 ANSI B18.2.2, GR A	STEEL, ASTM A105, OR A216, GR WCB, ANSI B16.34, SOCKET WELD, NPT, CLASS 150,	MONEL OR 316 STAINLESS STEEL	USCG APPROVED HOSE AND END FITTINGS	STEEL, ASTM A105 OR A234, GR WPB, ANSI B16.11, CLASS 3000, SOCKET WELD, CLASS 150, LUGGED	SEAWATER	67 PSIG	95 °F	SEE REFERENCE 8

GENERAL NOTES

1. PIPING SYSTEM DESIGN, MATERIAL, INSTALLATION, TESTING AND WORKMANSHIP SHALL BE IN ACCORDANCE WITH REFERENCE 1 (CONTRACT SPECIFICATIONS) AND REGULATORY BODY REQUIREMENTS OF U.S. COAST GUARD AND THE AMERICAN BUREAU OF SHIPPING.
2. THIS DRAWING IS A DIAGRAMMATIC ILLUSTRATION OF A PIPING SYSTEM. PIPING ARRANGEMENTS WITHIN THE VESSEL SHALL BE DEVELOPED BY THE CONTRACTOR USING EQUIPMENT LOCATIONS PER REFERENCE 2.
3. SYSTEM INSTALLATION SHALL PERMIT CLEAR PASSAGE ALONG WALKWAYS AND LADDERWAYS; CLEAR ACCESS FOR OPERATION AND ROUTINE MAINTENANCE; CLEAR ACCESS TO ALL DOORS, HATCHES AND OPENINGS; AND, AS MUCH AS IS PRACTICABLE, BE FREE OF INTERFERENCE TO THE READY REMOVAL OF EQUIPMENT AND COMPONENTS USING PIPING TAKEDOWN JOINTS.
4. BULKHEAD AND DECK PIPING PENETRATIONS SHALL MAINTAIN THE WATERTIGHT, FUMETIGHT AND FIRE RATING OF THE BOUNDARY PER REGULATORY BODY REQUIREMENTS. REINFORCING PENETRATION SLEEVES SHALL BE FITTED PER GENERAL NOTE 5(e) TO MAINTAIN STRUCTURAL INTEGRITY OF THE BOUNDARY.
5. SYSTEM INSTALLATION SHALL COMPLY WITH THE FOLLOWING ASTM SHIPBUILDING AND MARINE TECHNOLOGY STANDARDS:
   a. SYSTEM THERMAL INSULATION SHALL BE IN ACCORDANCE WITH ASTM F683.
   b. RIGID PIPE HANGERS SHALL BE IN ACCORDANCE WITH ASTM F708. EXCEPTION: PARAGRAPH 1.3 IS NOT APPLICABLE.
   c. PIPE WELDING SHALL BE IN ACCORDANCE WITH ASTM F722. EXCEPTION: NON-CONSUMABLE BACKING RINGS AND MITERED JOINTS NOT PERMITTED (EXCEPT AT EXHAUST CONNECTION).
   d. VALVE LABEL PLATES SHALL BE IN ACCORDANCE WITH ASTM F922. INSTALL TYPE 1, GRADE E, CLASS 2, LETTER SIZE 2, PLATE SIZE TO SUIT.
   e. STRUCTURAL REINFORCING PENETRATION SLEEVES SHALL BE IN ACCORDANCE WITH ASTM F682.
7. FLEXIBLE CONNECTIONS SHALL BE DESIGNED TO ALLOW FOR MAXIMUM EXCURSIONS OF RESILIENTLY MOUNTED EQUIPMENT.
8. PROCESS CONNECTIONS FOR THERMAL WELLS SHALL BE 3/4" NPT.

REFERENCES

1. GLOSTEN, DOC. NO. 17033-01, T/S GOLDEN BEAR, WASTE HEAT RECOVERY SPECIFICATIONS.
2. GLOSTEN, DWG. NO. 17033-100, T/S GOLDEN BEAR, WASTE HEAT RECOVERY SYSTEM INSTALLATION.
3. GLOSTEN, DWG. NO. 17033-300, T/S GOLDEN BEAR, ELECTRICAL ONELINE MODIFICATIONS.
4. NAVAL SEA SYSTEMS COMMAND, DWG. NO. 259-625067, T-AGS 39 CLASS, MACHINERY INTAKE AND EXHAUST SYSTEM, 5 DECEMBER 1989, REV D.
5. NAVAL SEA SYSTEMS COMMAND, DWG. NO. 532-6251462, T-AGS 39 CLASS, PIPING DIAGRAM CENTRAL COOLING SYSTEM, 6 AUGUST 1990, REV H.
6. ECONOTHERM Ltd, DWG NO. 188-01-ASSEMBLY, 10 JULY 2017, REV D.
7. TWIN CITY, DWG NO. 590096, 11 SEPTEMBER 2017, REV B.
8. NAVAL SEA SYSTEMS COMMAND, DWG. NO. 524-6251458, T-AGS 39 CLASS, PIPING DIAGRAM MAIN & AUX SEAWATER SYSTEM, 5 DECEMBER 1989, REV D.

A2

SYMBOL LIST

SYMBOL	DESCRIPTION	SYMBOL	DESCRIPTION
	POWER CABLE		PUMP, CENTRIFUGAL
	CONTROL CABLE		CAP, PIPE END
	PIPE		HOSE, FLEXIBLE
X"	DIRECTION OF FLOW ARROW WITH PIPE SIZE		EXPANSION BELLOWS
	PIPE REDUCER	B	STRAINER, Y-TYPE BASKET
	PIPE FLANGE CONNECTION	P	GAGE, PRESSURE, LOCAL READING
	SPECTACLE FLANGE (SPECTACLE IN LINE)	T	THERMOMETER, LOCAL READING
	VALVE, BALL	TC 01	THERMAL COUPLE
	VALVE, GLOBE		TANK VENT
B	VALVE, BUTTERFLY		
	VALVE, SWING CHECK		
	PRESSURE RELIEF VALVE		

REVIEWED
Details of this review are as indicated in the ABS letter
ABS
WITH ABS AMENDMENTS ON PAGES N/A
WITH ABS COMMENTS #s P-002

REVISIONS

ZONE	REV	DESCRIPTION	DATE	APPD
	–	INITIAL RELEASE	12/8/17	DWL
2-3B 3-6D 3-7D 1-2B 2-8D 3-2B 2-8D 3-2C 1-8C 2-8D 3-4C 3-2B	A	1. UPDATED TO AS-BUILT CONFIGURATION WITH LEVEL SWITCH, HRU OUTLET TC AND DELUGE CONNECTION. 2. CHANGED ADSORPTION CHILLER FROM FRESHWATER TO SEAWATER COOLING. 3. ADDED PUMP TO CHILLED WATER SYSTEM AND CHANGED TO TWO FCUs. 4. CHANGED ADSORPTION CHILLER TO USE JACKET WATER HEAT FROM GENERATORS. 5. REMOVED ELECTRIC CHILLER.	3/22/22	SPR

Digitally Signed 22-Mar-2022

COLLINS AEROSPACE
SIMPSONVILLE, SC

T/S GOLDEN BEAR
WASTE HEAT RECOVERY P&ID
GENERAL NOTES AND MATERIAL SCHEDULE

Glosten
GLOSTEN.COM

Drawn	Checked	Approved	Issue Date
JCP	SPR	DWL	3/22/2022

Scale	Drawing Number	Sheet	of	Revision
AS NOTED	17033-500	1	3	A

Figure 3 – TEHC Material Schedule

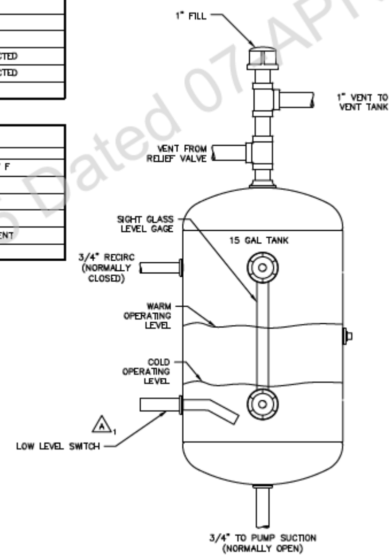
OWNER FURNISHED EQUIPMENT LIST

ID	QTY	SIZE	DESCRIPTION	MATERIAL	SPEC	MFR	PART NO.	REMARKS
A	1		HEAT EXCHANGER	STEEL	105 kW, 5 BAR	ECONOTHERM	188–01	
B	1		HIGH TEMPERATURE BLOWER	STEEL	750 Pa, 7700 m^3/hr	TWIN CITY BLOWER	911	7.5 HP, 460V, 3PH
C	1		ORC HEAT ENGINE		12 kW	VIKING	CRAFT ENGINE 10	12 kW, 400V, 3PH
D	1		ADSORPTION COOLING SYSTEM			FAHRENHEIT	ZEO M10	
E			(REMOVED)					
F	5	3/4"	THERMAL COUPLES AND THERMAL WELLS	SS				
G	1		TEMPERATURE PANEL METERS					MOUNTED IN ENCLOSURE
H	1	1.5"	CIRCULATION PUMP, JACKET WATER	IRON	50 kPA, 2.3 M3/hr	GRUNDFOS	52722513	3 SPEED, 1/6HP, THERMALLY PROTECTED
I	1	1"	CIRCULATION PUMP, CHILLED WATER	IRON	50 kPA, 2.7 M3/hr	GRUNDFOS	52722513	3 SPEED, 1/6HP, THERMALLY PROTECTED

A 2,3,4,5

EQUIPMENT LIST

ID	QTY	SIZE	DESCRIPTION	MATERIAL	SPEC	MFR	PART NO.	REMARKS
1	1	14"	KNIFE GATE VALVE, W HANDWHEEL	A351	MSS SP81, CLASS 150	JASH	ZFI	GRAPHITE PACKING, ANSI B16.5, 700° F
2	1	14"	EXHAUST EXPANSION JOINT	SS	10.75" OAL			
3	1	14"	EXHAUST EXPANSION JOINT	SS	15.25" OAL			
4	1	2"x1.5"	THERMAL OIL PUMP	IRON	100 kPA, 5 M3/hr			
5	1	15 GAL	HEAD TANK	STEEL	400° F	MANCHESTER	304940	W/ LEVEL GAUGE & VENT CONTAINMENT
6	2	2.5 TON	FAN COIL UNIT		9 kW COOLING			



DETAIL 2–2B
HEAD TANK
AT 01 DECK LEVEL
1-1/2"=1'-0"

COLLINS AEROSPACE
SIMPSONVILLE, SC
T/S GOLDEN BEAR
WASTE HEAT RECOVERY P&ID
EQUIPMENT LIST
Glosten
Drawn JCP | Checked SPR | Approved DWL | Issue Date 3/22/2022
Scale AS NOTED | Drawing Number 17033–500 | Sheet 2 of 3 | Revision A

Figure 4 – TEHC Equipment List

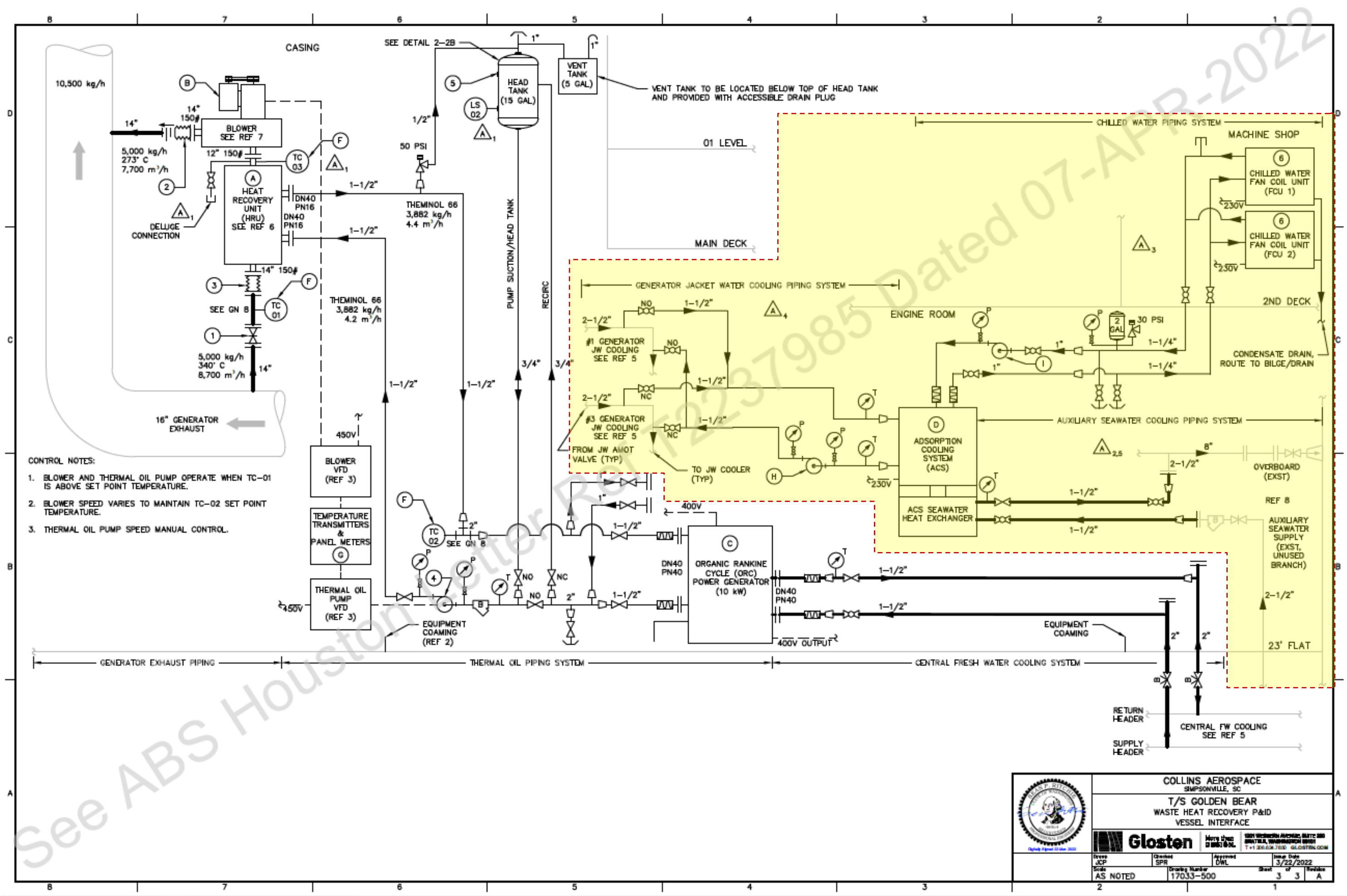
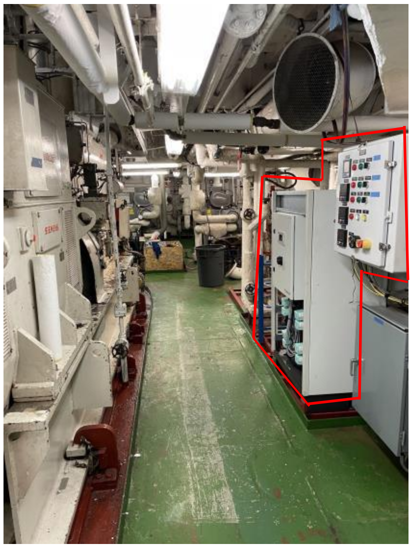


Figure 5 – TEHC Piping (Highlighted)

Note: Drawing shows previous test elements such as an exhaust gas heat recovery unit and organic Rankine cycle power generator which were not part of this test and report.



Figures 6 & 7 - Thermal Energy Conversion Equipment (Waste Heat Driven Adsorption Chiller) and Seawater Heat Exchanger installed

The TEHC Component Schematic / Vessel Interface drawing of the installed unit on the *T/S Golden Bear* is shown in Figure 8 below.

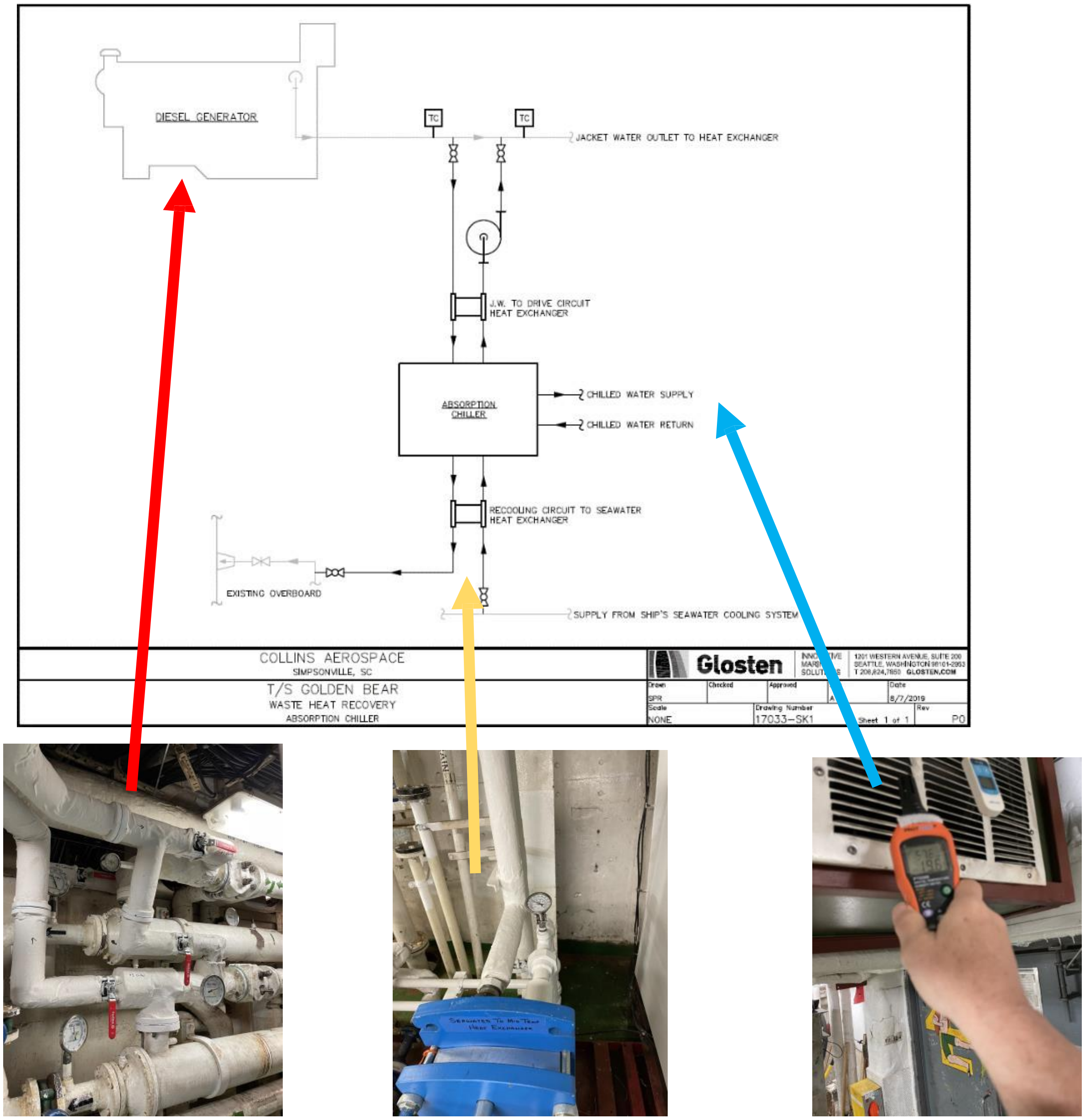


Figure 8: TEHC Vessel Interface

The connections from the ship to the adsorption unit are shown in Figure 9. For the demonstration the chilled water produced by the adsorption chiller was provided to a machine shop directly off from the engine room. A fan coil arrangement was used to transfer the cooling effect throughout the shop. The machine shop had no other cooling source within it. Typically, the shop would be the same temperature of the engine room.

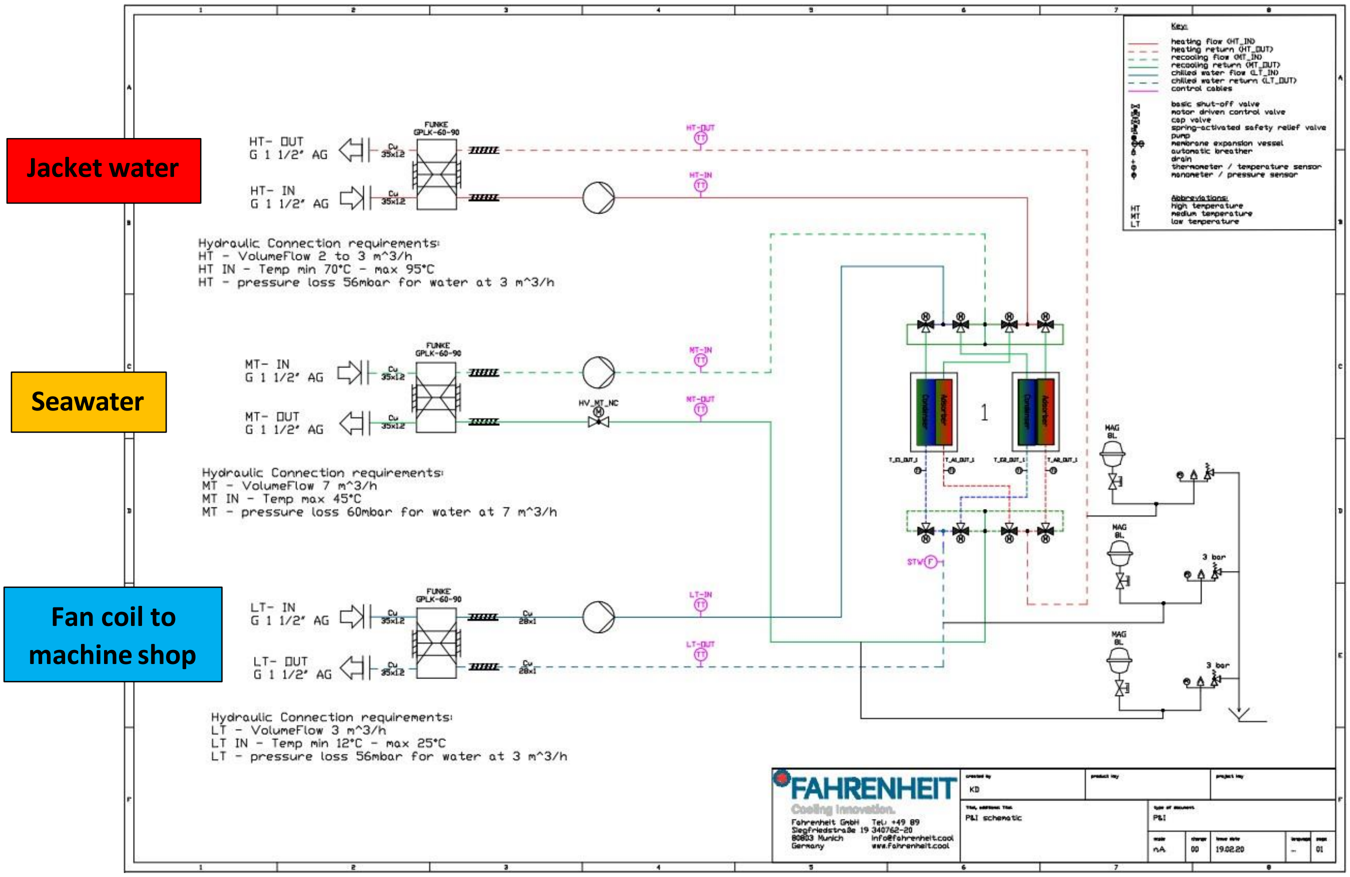


Figure 9: TEHC Component Schematic / Vessel Interface

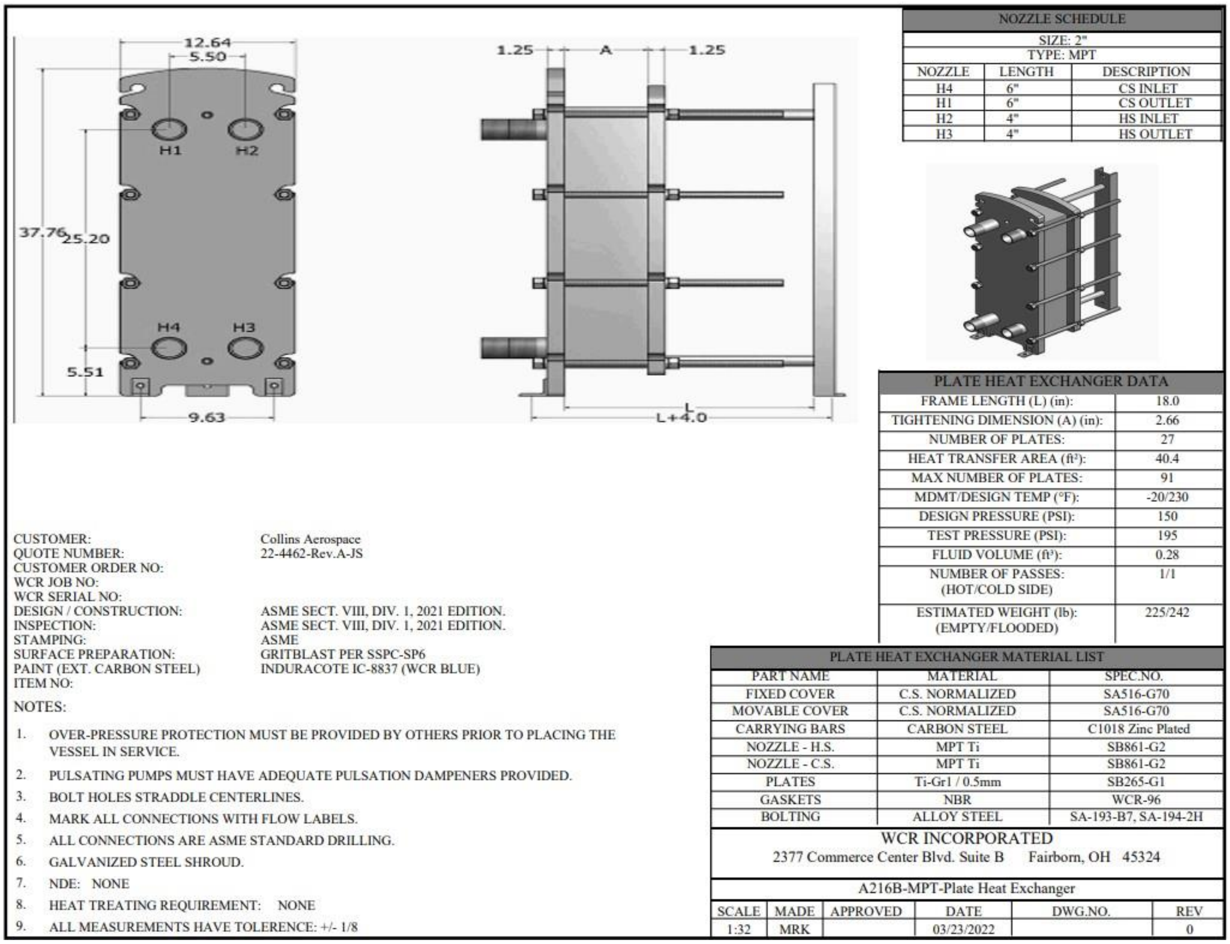


Figure 10: TEHC Seawater Heat Exchanger

Test Objectives

The adsorption chiller was an off-the-shelf product which used silica gel as the adsorbent and water as the refrigerant. The thermal conversion efficiency of the adsorption chiller is roughly 50% at the nominal operating conditions.

The Adsorption Chiller test objective was to demonstrate cooling of the ship's machine shop, located within the engine room of the *T/S Golden Bear*, by using the generators' wasted jacket water energy instead of electrical power from the generators. The TEHC system tested was configured with various sensors to evaluate key system performance parameters. The objectives evaluated included the following:

A. *T/S Golden Bear* ship generator run time vs. TEHC System availability.
B. Hours of required crew operational support vs. total cruise time.
C. Hours of required crew maintenance support vs. total cruise time.
D. Heat exchanger capture effectiveness vs. design to budget/projection.
E. Control system effectiveness - operational time vs. down time.

Project Test Plan

Data was collected during the 2023 cruise. The primary focus was the performance of the system as a stand-alone ship's function and its maturity to deliver cooling energy with minimal downtime or maintenance support. Per the Objectives identified above, three methods were used to monitor and collect the test data:

A. Method #1 - Automated data loggers:
   a. Adsorption Chiller Internal Data
   b. Collins Aerospace data logger
B. Method #2 – CMA Crew Manual Data Collection
C. Method #3 – CMA Visual Inspection Data

Daily digital photos were captured by the crew then emailed to Collins for analysis and recording of key parameters, including: actual generator loads (#1), temperatures inside and outside of the machine shop where the adsorption chiller output was located (#2), and adsorption chiller internal parameters (#3), and Ship HVAC percentage capacity output for each unit (#4) A sample of the daily email information is shown below in Figure 11.

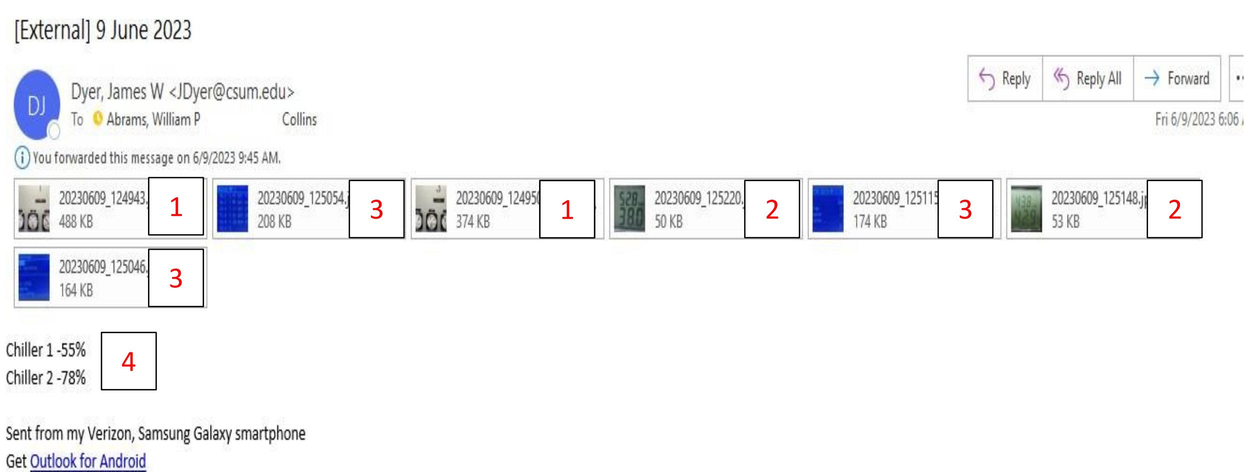


Figure 11 – Daily Data Email Example

The daily inputs were compiled into an Excel file (shown below) by Collins to support the following test parameters.

TS T/S Golden Bear	Generator 1			Generator 3			Chiller Temperatures MP 1												Adsorption Cycle MP 1			Engine Rm Temp.						Shop Temperature	
Date	Volts	Amps	KW	Volts	Amps	KW	Status	HT In	HT Out	MT In	MT Out	LT In	LT Out	A1 Out	E1 Out	A2 Out	E2 Out	HT SP	Phase	Cycles	Phase Time	Time Counter	Time Counter_	dQ LT	dQ HT	Rel Humidity	Temp	Rel Humidity	Temp
9-May			400				OK	62.5	60.6	14.4	19.5	17.3	16.7	18.1	16.5	60.8	17.5	63.2	1	60	217	189	0	6.2	15.7	30.2	34.6	51.6	21.4
10-May			400				OK	62.7	61.1	15.9	21.2	16.8	15.8	20.2	16	61	18.6	64	1	166	217	194	0	5.7	14.1	31	31.7	56.6	18.7
10-May			400				OK	63.4	61.7	16.1	22.3	16.5	15.7	61.6	18.9	21.7	15.3	64.7	3	192	217	181	0	4.9	17.2	27.4	33.5	54.4	18.8
10-May			400			550	OK	70.1	67.4	15.9	23.3	14.6	13.6	22	13.6	67.6	20.8	71.3	1	223	238	127	0	7.2	17.7	35.9	28.8	62.5	16.8
11-May			400				OK	64.8	46.7	16.7	21.8	18.6	18.4	25.9	18.2	61.4	18.7	65.7	3	374	217	31	0	5.3	16.6	32.5	32.7	57.6	19.6
12-May			450			500	OK	70.5	68.5	17.8	26.1	13.8	12.9	68.2	22.3	25.5	12.6	71.6	3	581	226	177	0	5.9	18.3			41.5	28
14-May			400				OK	63.7	61.8	18.7	25.7	17.2	16.3	25.1	16.3	61.6	21.5	64.9	1	971	217	150	0	5.4	14.4	36	30.9	45.6	25.4
15-May			400			450	OK	71.4	56.6	20.7	25	18.2	18.7	29.1	19.3	67.1	20.1	72	3	1168	217	30	0	5.9	17.9	35.3	33.8	45.8	27.6
16-May			400				OK	65.2	60.5	25.8	31.7	21.1	18.8	58.5	29.1	40.3	18.6	69.9	3	1940	217	55	0	4.5	13.9	37.5	32.6	43	29.6
19-May	445	710	400				OK	65.2	60.5	36.8	31.7	21.1	18.8	59.5	29.1	40.3	18.6	69.9	3	1940	217	55	0	4.5	13.90	27.50	32.60	43.00	29.60
20-May				445	675	360	OK	70.2	68.6	23.2	26	18.6	18	25	18	68.9	25.1	71.1	3	2132	217	11	0	5.2	16.20	38.90	34.00	51.80	27.70
21-May	445	740	470	445	760	490	OK	72.1	55.0	26.1	32.5	22.0	21.1	56.9	22.6	43.0	29.7	74.3	1	2341	217	31	0	6.50	13.80	34.00	40.50	46.50	32.60
22-May	445	760	430				OK	68.2	65.6	28.7	34.7	23.6	21.8	64.7	31.5	38.3	21.8	70.7	3	2541	217	75	0	5.7	14.80	37.80	40.40	50.20	33.50
23-May						425	OK	74	72.3	29.2	31.8	25.3	24.8	30.6	24.8	72.5	30.6	74.6	3	2787	217	3	0	5.4	15.30	44.60	38.80	54.50	33.20
24-May			500			500	OK	73.1	71.3	31.8	36.0	26.0	25.1	35.5	25.1	70.9	33.5	73.4	1	2997	217	121	0	6.30	13.80	39.00	42.20	52.30	35.10
27-May			500			500	OK	74.7	72.9	31.5	34.9	26.5	25.7	73	33.2	33.3	25.8	75	3	3606	217	168	0	5.1	14.40	48.30	39.90	59.50	34.90
28-May			500			500	OK	74.6	72.8	31.5	34.8	26.9	26.1	33.0	26.2	72.8	33.2	75.3	1	3781	217	187	0	5.80	13.30	45.40	41.70	58.70	34.90
29-May			500				OK	71.2	66.6	34.4	39.5	29.3	27.3	45.4	27.7	64.2	38.4	74.9	1	3999	217	66	0	5.20	11.80	43.50	42.90	54.00	37.10
30-May						450	OK	74.1	72.9	31.8	34.9	26.5	25.9	72.8	33.2	33.6	25.8	75	3	4192	217	189	0	5	14.10	49.00	40.30	58.30	35.70
3-Jun			500			500	OK	73.3	72.4	32.4	36.7	27.3	26.2	74.4	71.9	34	35.8	74.4	3	4785	217	123	0	4.8	13.60	44.90	40.70	56.20	35.30
4-Jun			550				OK	72.4	71.4	31.2	33.5	30.3	29.7	32.1	29.5	71.5	32.3	73.2	26	5014	217	216	15	4.80	12.30	43.80	40.70	52.10	36.60
8-Jun			500				OK	75.2	73.9	31.8	34.6	28.2	27.8	33.0	27.8	73.9	32.7	75.9	1	5792	217	194	0	5.40	12.10			58.10	36.90
9-Jun			550			550	OK	74.3	73.2	34.1	38.8	28.8	27.8	72.6	35.8	38.5	27.7	75.6	3	5995	217	116	0	5.2	13.00	43.80	42.90	52.80	38.00
11-Jun						500	OK	73.0	71.6	32.9	36.8	28.5	27.7	35.9	27.7	71.1	34.1	73.9	1	6373	217	120	0	5.20	12.40	53.40	38.70	59.70	36.30
12-Jun			550			575	OK	74.9	73.5	32.7	36.3	26.1	25.5	73.1	34.1	35	25.2	75.8	3	6611	217	146	0	4.70	13.70	47.70	41.10	69.50	33.00
13-Jun			450				OK	73.1	57.2	30.4	32.9	29.0	28.8	67.2	29.7	34.5	31.5	73.3	1	6987	217	24	0	5.00	11.60	58.70	35.60	60.90	34.60
14-Jun						500	OK	74.4	72.9	30.6	34.6	24.7	23.8	72.5	32.3	33.5	23.6	75.2	3	7196	217	141	0	4.70	14.70	53.90	35.50	61.50	32.40
15-Jun			500			550	OK	74.3	72.8	29.2	32.3	25.3	24.8	30.4	24.8	72.6	30.0	74.9	1	7378	217	176	0	5.80	13.20	48.00	36.90	55.60	33.50
16-Jun			500				OK	71.5	69.8	30.4	35.7	24.8	23.6	68.7	32.6	30.1	23.4	73.4	3	7590	217	91	0	5.10	13.70	44.90	37.80	53.20	33.80
17-Jun			400			350	OK	71.9	54.4	27.8	33.3	25.8	24.5	58.3	25.4	40.2	31.6	73.6	1	7814	217	32	0	5.30	12.60	40.40	38.30	51.70	32.90
18-Jun			400			350	OK	69.4	64.4	30.1	35.6	25	22.7	61.6	33	47	22.6	73.6	3	7973	217	49	0	4.60	14.00	44.80	34.80	52.10	31.40
19-Jun	No Data	Recoeded																											
20-Jun			450				OK	70.1	69.2	29.8	34.6	24	22.7	68.4	31.6	35.5	22.7	71.1	3	8356	217	105	0	4.50	13.80	48.20	35.80	58.80	31.40
21-Jun			450				OK	73.5	72	29.5	33.5	23.6	22.7	71.8	31.1	32.3	22.7	74.4	3	8566	217	144	0	4.80	14.20	44.30	37.20	51.80	33.00
22-Jun			500				OK	72.2	70.8	28.7	32	25.3	24.6	71	30.2	30.6	24.6	73	3	8746	217	171	0	5.10	13.70	36.90	41.40	43.80	37.10
23-Jun	No Data	Recorded																											

Collins Aerospace

24-Jun						450	OK	73.0	71.0	28.9	32.6	23.6	23.1	31.4	23.0	70.7	30.5	73.9	1	9148.0	217.0	145.0	0.0	5.50	12.90	45.40	35.80	49.00	33.40
25-Jun							OK	72.8	70.3	28.4	33.8	21.9	20.6	35.0	21.1	69.2	31.5	74.4	1	9373.0	217.0	85.0	0.0	5.90	13.70	45.50	35.30	57.50	29.70
26-Jun			500			500	OK	71.9	67.7	26.6	32.8	21.8	19.8	37.8	20.2	65.1	30.7	75.4	1	9566.0	217.0	72.0	0.0	6.30	13.40	33.10	38.50	42.70	32.40
27-Jun						450	OK	70.8	68.7	24.1	28.7	18.7	17.6	27.9	17.8	68.5	25.8	72	1	9731	217	118	0	5.70	13.8				
28-Jun			500				OK	67.3	65.6	20.4	30.9	18.7	17.4	64.8	24.8	34.2	17	68.5	3	9974	217	92	0	5.3	17.7	52.7	30.5	56.8	27.7
29-Jun			450			500	OK	69.6	68.1	19.0	26	16.9	15.9	25.3	15.8	67.8	21.9	70.8	1	10145	217	153	0	6.0	13.9	45.3	30.5	53.5	26.9
30-Jun			500			500	OK	71.1	65.1	20.1	30.1	15.9	14.3	41.2	15.1	60.5	27.7	75.1	1	10348	217	54	0	5.6	13.4	37.6	32.3	47.6	25.8
1-Jul			350			350	OK	69.0	67.8	20.9	24.5	17.8	17.2	67.7	22.6	23.5	17.0	69.6	4	10534.0	217.0	5.0	0.0	5.10	13.30	44.20	28.20	50.60	24.70
5-Jul			500				OK	69.7	68.7	22.1	24.5	19.6	18.9	23.2	19.1	68.8	22.8	70.4	3	11329.0	217.0	10.0	0.0	4.30	13.90	43.20	31.70	55.10	25.90
6-Jul			450				OK	69.7	68.5	13.0	18.6	14.7	13.9	68.5	15.3	17.4	13.8	70.3	3	11509.0	224.0	199.0	0.0	5.90	15.00	39.80	30.00	48.60	25.70
7-Jul			450			450	OK	73.1	72.0	17.3	22.2	14.8	13.9	72.0	19.6	72.0	19.6	73.6	25	11701.0	228.0	208.0	8.0	5.20	14.60	38.60	30.90	51.50	24.10

Figure 12 – Daily Data Excel File

The specific items tested / collected, and the methods used are tabularized in Table 1 below.

Table 1: Data Collection Items

ITEM TO BE TESTED	TEST DESCRIPTION/OBJECTIVE TARGETED	TEST FREQUENCY	COLLECTION PARTY	SOURCE TEST TYPE OR EQUIPMENT
Ship Generator Output	Voltage vs. Time / Objective A	Daily	Crew	Visual reading
Heat Exchanger Output	Temperature / Objective A & D	Daily	Crew	Visual reading
Ship current chiller Output	Percentage of full Capacity / Objective A	Daily	Crew	Visual reading
Seawater Temperature	Temperature/ Objective D	Daily	Crew	Visual Reading
Adsorption Chiller Parameters	Cycles, temperatures, run time / Objective D	Continuous	Crew	Visual of Chiller Display and data logger
Maintenance Support	Crew Survey / Objective C	As required	Crew	Logbook
Operational Support	Crew Survey / Objective B	As Required	Crew	Logbook
Control System Data	Control Panel Data / Objective E	Daily	Crew	Logbook
System Inspection	Visual Inspection and Data Review / Parameter B & C	At CMA Pre and Post Cruise	Collins	Logbook

Test Results / Analyses

The following subsections provide recorded data, some initial data processing of the information, and analyses addressing each of the seven technical parameter targets.

Objective A: *T/S Golden Bear* Ship Generator Run Time vs. TEHC System Availability

The data collection period associated with the TEHC operational validation during the 2023 *T/S Golden Bear* cruise began May 9th and was completed July 7th. During this 60-day period the ship's three generators' output power was monitored and recorded daily as shown in Figure 12. The maximum operating output of the onboard MAK generators was stated to be ~900KW. A sample of the daily information collected by the crew is shown in Figure 13 below (Generator Output Power). The number at the top of the photo shows which generators were running. The No.1 and No.3 generators were connected to the TEHC. One or both generators were operated in parallel for all but two days of the cruise. The offline generator(s) was/were not included in the daily data.

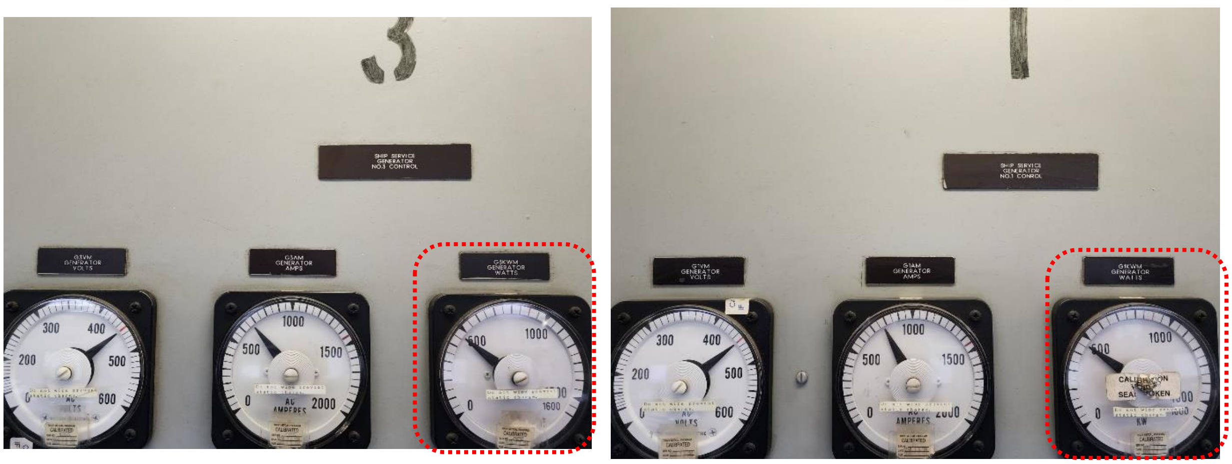


Figure 13 – Daily Generator Output in KW (meter on right)

Likewise, the status of the adsorption chiller was also observed and photographed at the same time as the generator output each day and recorded during the cruise. The data captured from the chiller's main display screen indicated the operational status of the chiller. An example of the daily chiller status is shown in Figure 14 below.

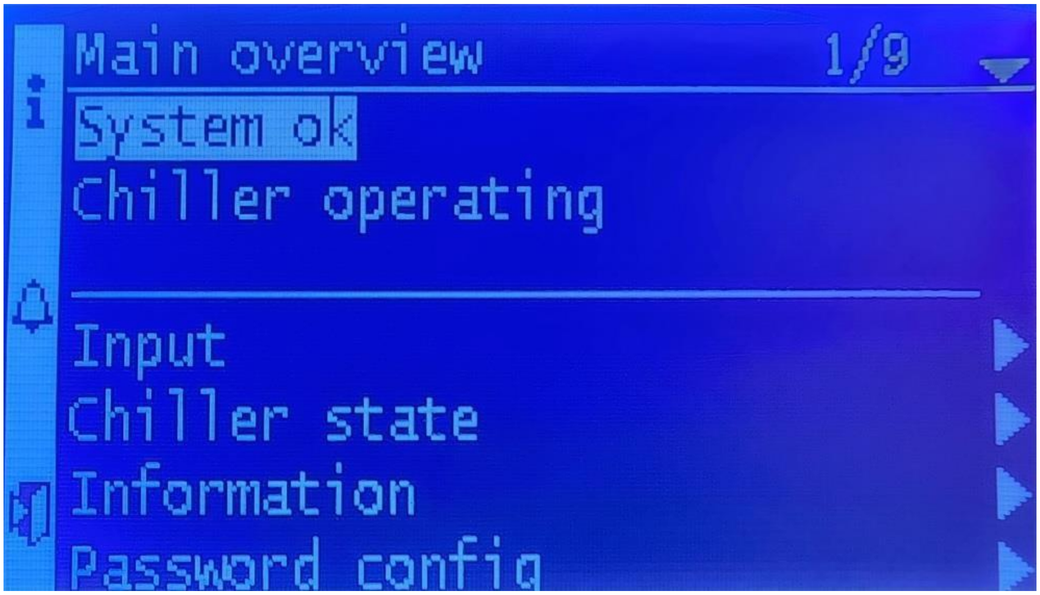


Figure 14 – Daily Adsorption Chiller Status Data

The results of this data showed that the adsorption chiller operated 100% of the time during the 2023 cruise.

Objective B: Hours of Required Crew Operational Support vs. Total Cruise Time

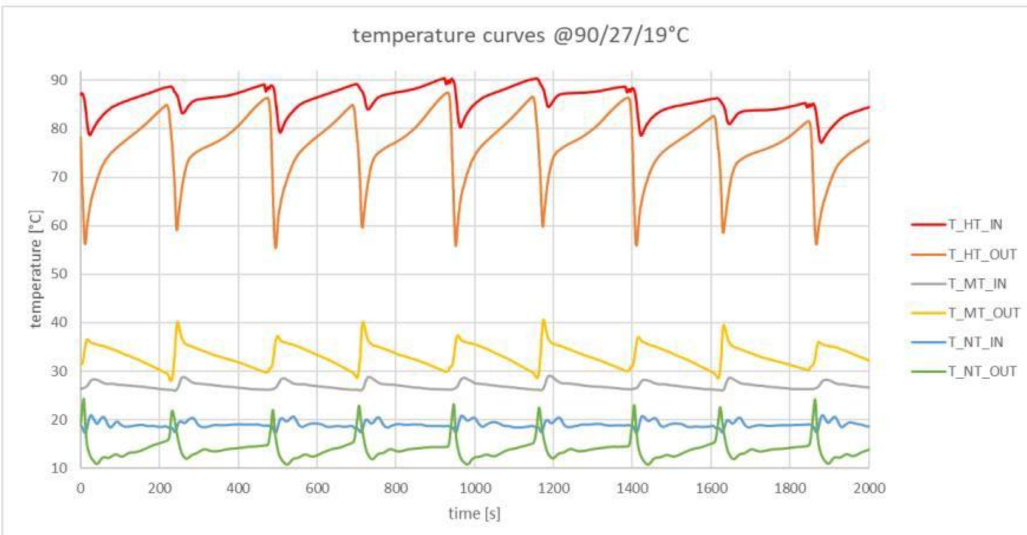
Total cruise time for the test period on the *T/S Golden Bear* was 60 days or a total of 1440 hours. The crew's log reported no operational support time was needed for the adsorption cooling unit. This indicated that the TEHC operated independently during all cycles of generator operation as reflected in the results presented for Parameter A. The Adsorption chiller was not connected to the Number 2 generator; however, it continued to function whether waste heat was provided from either the first or third generators. This data confirms the ease-of-use capability of the adsorption technology, thus making it suitable for shipboard applications.

Objective C: Hours of Required Crew Maintenance Support vs. Total Cruise Time

As stated in the discussion for parameter B, total cruise time for the test period on the *T/S Golden Bear* was 60 days, or a total of 1440 hours. The crew reported no down time resulting in required crew maintenance efforts for the TEHC's adsorption chiller.

Objective D: Heat Exchangers Capture Effectiveness vs. Design to Budget/Projection
The adsorption chiller operates by having a heat source or "driving" temperature that warms the adsorbent bed, in this case zeolite, to "drive" the refrigerant (water) to a higher pressure in the bed. This in effect does the same function as the vapor compressor, but without the use of electrical power. Once the refrigerant in the bed is transferred to the condenser, it is then "re-cooled" to allow the bed to adsorb more refrigerant. The adsorption unit operates on a pair of modules. Therefore, at any point in time one module is heating up or desorbing while the other module is cooling down to allow for adsorbing.

This operation, in pairs, allow for a smooth cooling performance to be obtained. The cyclic performance within the module is shown in Figure 15.



Cycling process on the adsorption phases with dynamic temperature profile

Figure 15 – Temperature Cycling of Adsorption Modules

The demonstration adsorption chiller unit installed for this test had a nominal driving temperature range requirement of 70 °C to 90 °C. The re-cooling temperature requirement was from 20 °C to 34 °C. Figure 16 shows the high temperature (HT) and re-cooling temperature (MT) plotted against the cooling capacity during the 2023 cruise.

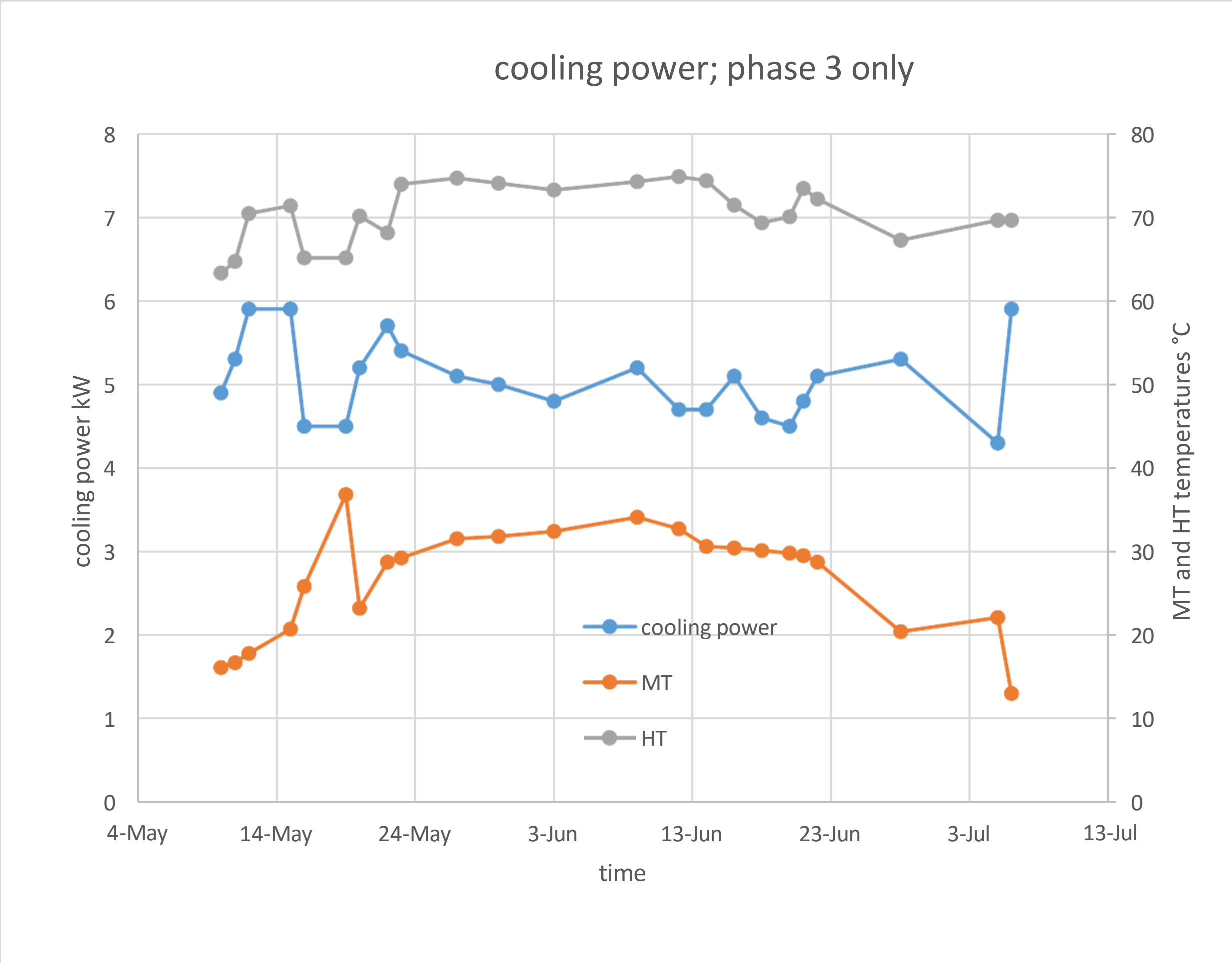


Figure 16 – Adsorption Chiller Temperature and Cooling Power

The actual nominal operating temperatures needed for the adsorption chiller were obtained throughout the cruise, once the ship was underway. Both the driving heat needed to heat the adsorbent material and the re-cooling temperatures needed to lower the adsorption bed temperatures were within the acceptable range. The seawater proved to be a very effective re-cooling energy source. The high temperature or jacket water source was at the low end of the range. Our design projection was that this would have been near the mid-range or 80 °C. The *T/S Golden Bear* has a "keep warm" feature that uses the waste heat from the two operating generators to keep the offline stand-by generator warm. The jacket water passes through an AMOT valve, which regulates the flow to either the keep warm generator or to the Central Fresh Water (CFW) cooling system, so that it returns the operating generator to the desired temperature. This system will be further analyzed to determine a high temperature and optimized flow rate for the adsorption unit to achieve a high cooling capacity. By improving the integration to this ship system, a smaller footprint will result.

To understand the performance of the system during the cruise, various parameters from inside the adsorption unit were obtained daily. Each of the three temperatures (HT, MT, and LT) were obtained by a daily "screenshot" of the chiller. Figure 17 shows the internal temperatures.

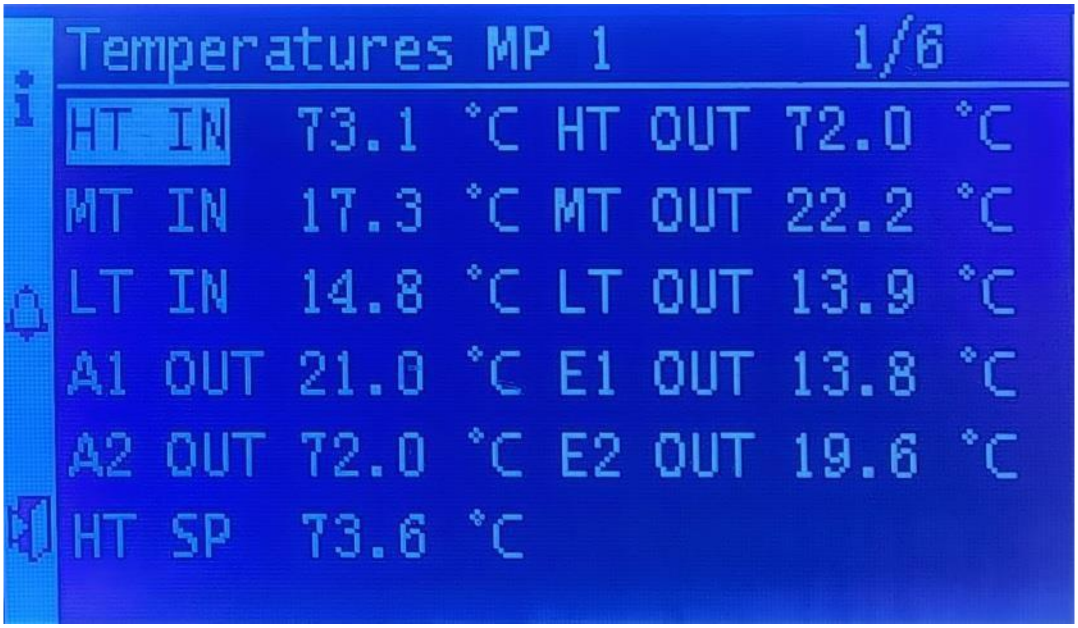
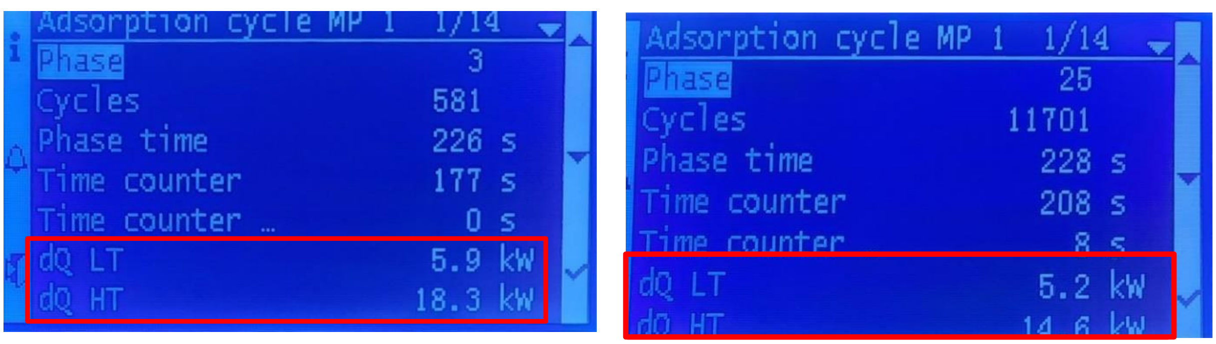


Figure 17 – Temperatures in Adsorption Chiller

The actual cooling capacity in kilowatts thermal and the energy in the high temperature driving source are also calculated from within the adsorption chiller. Two different screenshots are shown in Figure18. The first is from the beginning of the cruise in early May, and the second is from the end of the cruise in early July. The cooling capacity or power is shown as dQ LT, and the driving energy is dQ HT. In addition to this information the number of cycles performed by the module pair is shown in Figure 18.



Start of Cruise in May 2023

End of Cruise in July 2023

Figure 18 - Cooling Capacity, Driving Energy, and Number of Cycles

In addition to this information, the actual temperature was recorded for both the machine shop and the engine room. This provided a second verification method of the actual absorption chiller operations, with data independent of the chiller itself. Figure 19 shows the instrument which was used in each of the two locations each day. The machine shop was an average of 5.1°C (9.2°F) cooler than the engine room over the period of the cruise.

Machine Shop Temperature Location

Engine Room Temperature Location

Figure 19 – Temperature Measurement Areas on *TS T/S Golden Bear*

Figure 20 shows the above conditions, illustrated on the performance curves, for the chiller. The star shows the approximate operational parameters during the 2023 cruise. The curves show the performance with higher driving temperatures. Given the operational parameters, it is to be expected that a low cooling capacity was achieved. The re-cooling temperature is controlled by the ambient seawater temperature, which can fluctuate. The zeolite's high temperature performance was confirmed during the cruise when the ship crossed the equator and a 31°C (88°F) seawater temperature was observed with the chiller, while still producing the cooling effect, even though it was in warm seawater.

As previously discussed, the high temperature driving energy (from the jacket water) will be investigated to improve both temperature and flow rate to the adsorption chiller. The configuration of this loop, during the cruise, only had two flow rates that could be selected. These flow rates can be optimized given the data from the 2023 cruise. The operation of the AMOT valve and "keep warm circuit" for the generators will be further investigated to raise the temperature up to the expected high temperature of 80°C (180° F).

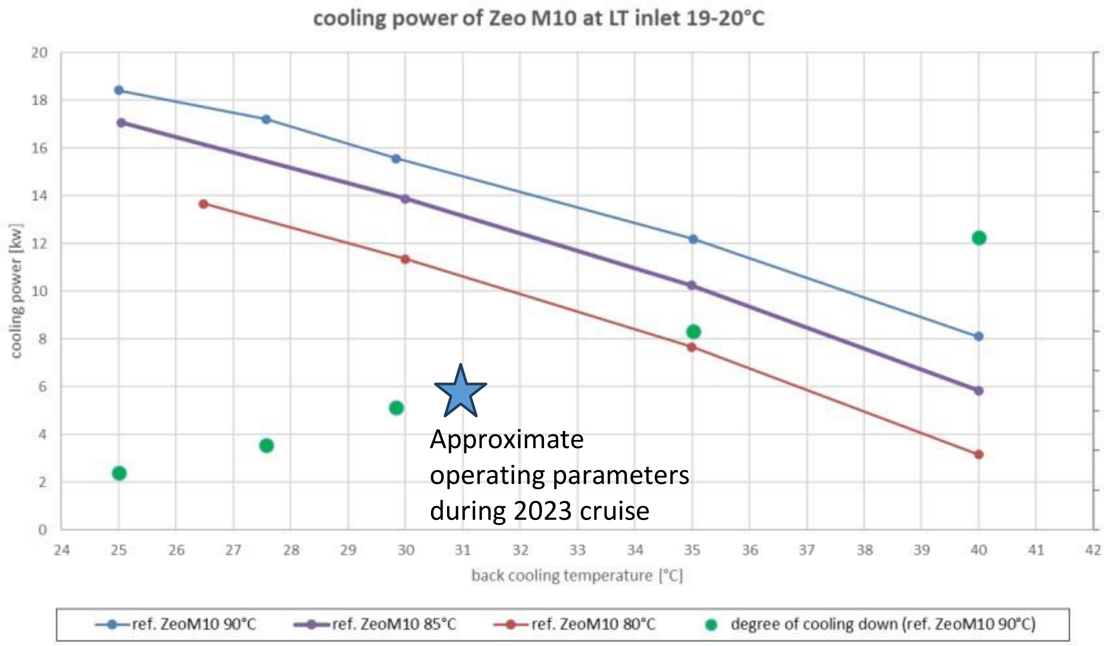


Figure 20 – Predicted Operational Performance Curves of the Adsorption Chiller

Two additional pieces of data were recorded during the cruise to provide further insight into the operating mode of the *T/S Golden Bear*. The first was the seawater temperature at the various locations during the cruise. The second was to obtain the current electrical (vapor compression) chillers' performance at those same locations and corresponding temperatures. Figure 21 shows the same temperature of the seawater at the various time of the cruise and location.

Figure 21 – Seawater Temperatures During the 2023 Cruise

Objective E: Control System Effectiveness - Projected Operational Time vs. Down Time

A key aspect of the shipboard suitability is the ability to supply cooling which can be used for a high percentage of the underway time of the ship. To understand this for the *T/S Golden Bear*, data was collected for each of the two electric vapor compressor chillers on the ship. This was accomplished using a display on each of the Carrier chillers. Figure 22 shows the display and its location in respect to the chiller itself. It was observed that, in most of the climate conditions, only one chiller operated. The typical minimum load was found to be 22% of the current ship chiller maximum capacity of 150 tons equivalent to 34 tons of cooling.

The data sheet in Figure 23 shows the full capacity power draw for the 155-ton unit which is circled in the figure. The power required for the full capacity amount of cooling appears to be roughly 111 kW of power draw at full capacity. As shown earlier in Figure 16, there were no failures or down time events during the entire cruise and all components of the system performed as expected. By operating the adsorption chiller in the “baseload” cooling mode, the maximum number of usage hours from the adsorption units can be obtained. Figure 24 shows the ship’s vapor compression chillers’ capacity output percentages during the various days of the at sea demonstration. This information gives an estimation of the actual cooling loads for the *T/S Golden Bear* of which a simplified business case model can be created using the generator kWh per gallon of fuel can be applied.

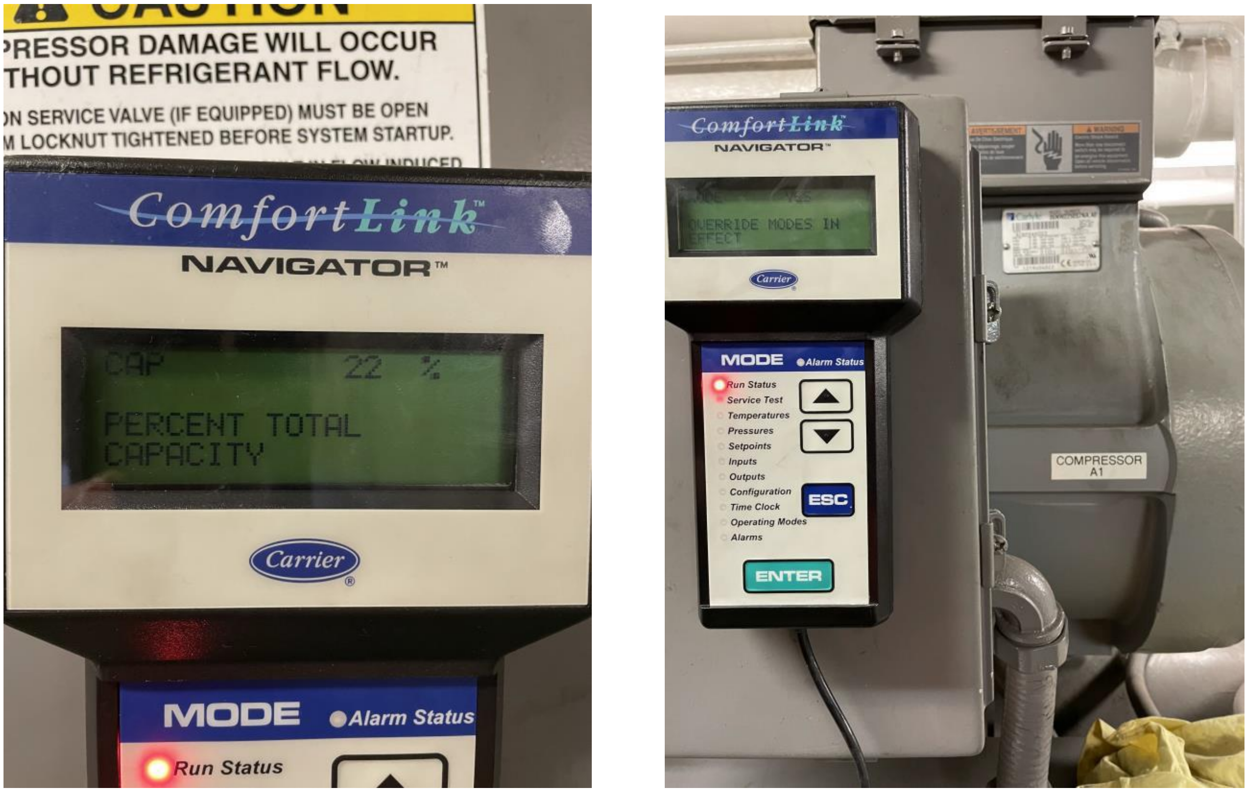


Figure 22 – *T/S Golden Bear* Onboard Carrier Chiller Display

Electrical data 460 V – 60 Hz – option 60

30HXC		080	090	100	110	120	130	140	155	175	190	200	230	260	285	310	345	375
Power circuit																		
Nominal power supply (Un)*	V-ph-Hz	460-3-60																
Voltage range	V	414-506																
Control circuit supply		The control circuit is supplied via the factory-installed transformer																
Nominal power input*	kW	56	63	69	78	82	91	103	111	123	129	142	166	189	198	223	249	261
Nominal current drawn*	A	94	101	109	121	133	147	164	178	194	213	228	260	291	319	355	388	425
Max. power input**	kW	87	96	105	118	130	144	159	172	187	212	223	253	281	318	344	374	424
Circuit A	kW	-	-	-	-	-	-	-	-	-	-	144	159	187	212	172	187	212
Circuit B	kW	-	-	-	-	-	-	-	-	-	-	79	94	94	106	172	187	212

Figure 23 – *T/S Golden Bear* Onboard Carrier Chiller Power Use

DATE	Chiller #1 Capcity(%)	Chiller #2 Capacity (%)	SEAWATER TEMP (°C)
9-May	22	0	14
11-May	22	0	20
	DATA NOT RECORDED FOR THIS PERIOD		
29-May			28
3-Jun	38	44	
4-Jun	43	38	
8-Jun	38	55	
9-Jun	55	78	
11-Jun	55	70	29
12-Jun	55	66	
13-Jun	34	22	
14-Jun	38	70	31
15-Jun	28	38	
16-Jun	24	44	
17-Jun	70	0	
20-Jun	70	0	24
21-Jun	70	0	
22-Jun	70	0	
24-Jun	70	0	
25-Jun	67	0	23
26-Jun	42	0	21
27-Jun	45	0	
28-Jun	45	0	16
29-Jun	45	0	16
1-Jul	45	0	18
5-Jul	45	0	
6-Jul	31	0	
7-Jul	22	0	14

Figure 24 – *T/S Golden Bear* Vapor Compression Chiller Percentage Capacity Output

In addition to the manual daily data information, two temperature data loggers were installed inside the machine shop to verify the chillers performance on a continuous basis. These were placed directly in the cool air from the fan coil as shown in Figure 25.

Figure 25 - Data Logger Location

Figure 26 shows the data obtained during the cruise. This data shows the continuous output from the chiller during the cruise. The data was captured every 4 minutes during the cruise. This data correlated very closely with the temperatures recorded internally by the chiller and shown in the display during the cruise. The area in the chart to the left of the of the indicated “period of the cruise” was the start of a second unplanned 2023 cruise with another state maritime academy. This showed the chiller continued to operate until the data logger ran out of recording space in August.

Summary

Maximum:	37.3°C	**Start Time:**	2023-05-08 20:47:51
Minimum:	15.7°C	**Stop Time:**	2023-08-05 18:03:51
Average:	25.5°C	**Logging Duration:**	88d 21h 16m
MKT:	26.4°C	**Total Memory:**	32000
Alarm Time(Te):	N/A	**Current Readings:**	32000

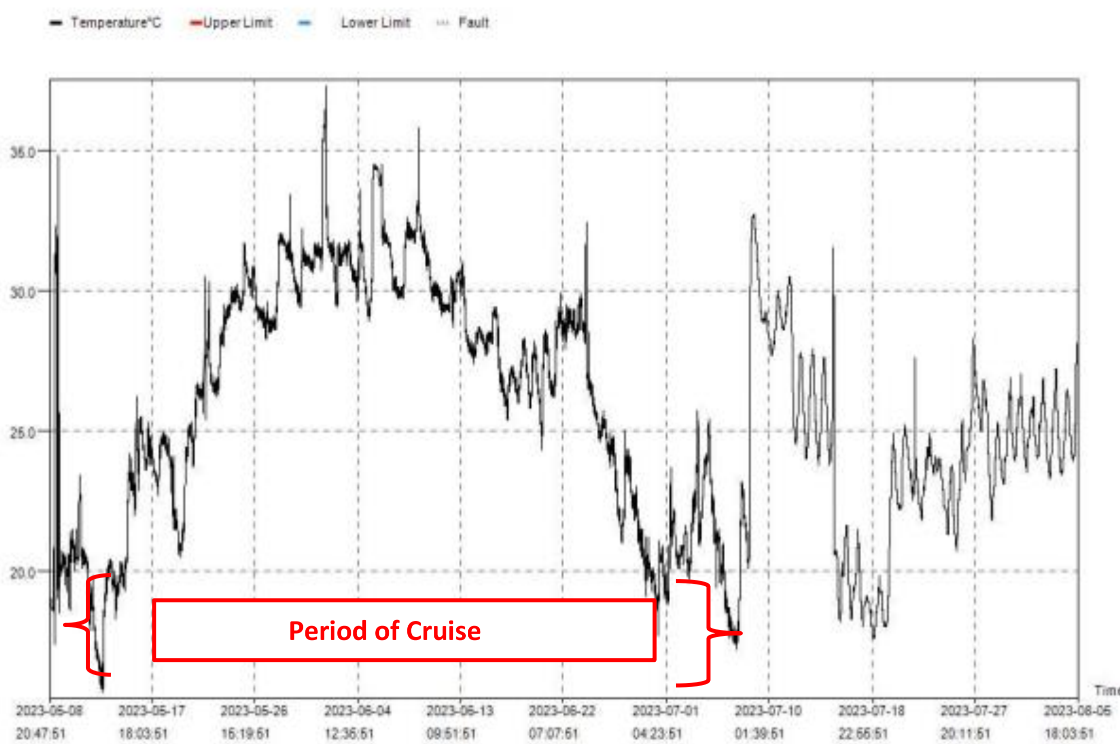
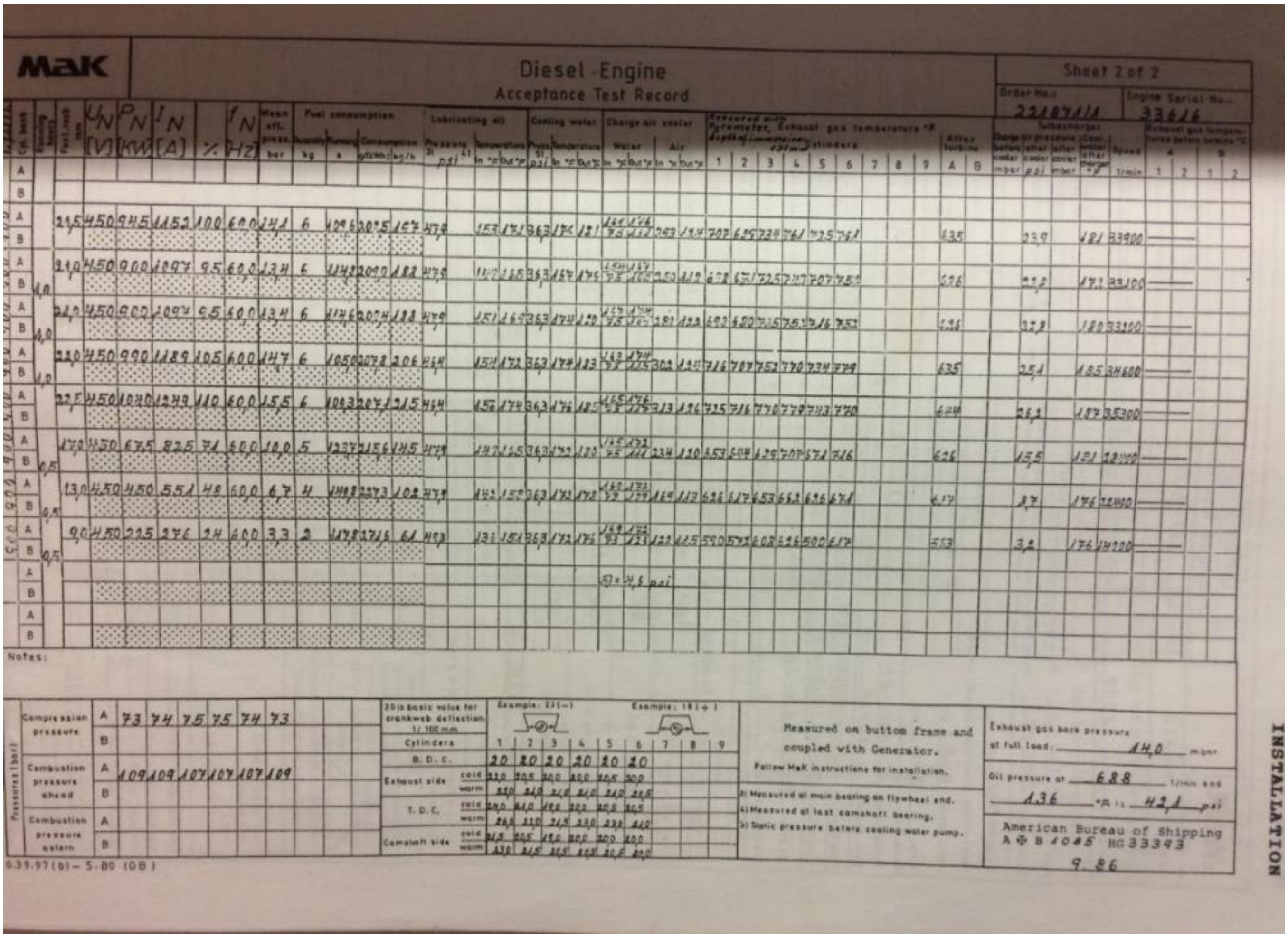


Figure 26 - Fan coil temperatures within the machine shop

Business Model Analyses

One of the objectives of the cruise was to produce data that could be used to establish an initial assessment of the potential level of sustainable savings. The following method was used to develop this business model:

First, the generator's Acceptance Test Record (ATR) was utilized to determine the fuel consumed by the ship's generators for the actual electrical power generated on the *T/S Golden Bear*. Table 2 (below) is the ATR for one of the three on-board MAK generators.



MaK — Diesel-Engine Acceptance Test Record — Sheet 2 of 2 — Order No.: 22187/1/1 — Engine Serial No.: 33616

Running hours	U_N [V]	P_N [kW]	I_N [A]	%	f_N [Hz]	Mean eff. press. bar	Fuel quantity kg	Runtime s	Consumption g/kWh	Consumption kg/h	Lub. oil pressure psi	Lub. oil temp. in °F	Lub. oil temp. out °F	Cooling water press. psi	Cooling water temp. in °F	Cooling water temp. out °F	Charge air cooler water in/out °F	Charge air cooler air in °F	Charge air cooler air out °F	Exhaust cyl. 1	2	3	4	5	6	After turbine A	Charge air pressure after cooler psi	Temp. after charger °F	Speed 1/min
21,5	450	945	1152	100	60,0	14,1	6	109,6	200,5	[illegible]	479	153	171	363	176	121	[illegible]	243	114	707	695	734	761	725	761	635	23,9	181	33900
21,0	450	900	1097	95	60,0	13,4	6	114,2	209,0	188	479	112	155	363	157	175	[illegible]	250	119	678	671	725	717	707	75?	576	22,2	171	33100
21,0	450	900	1097	95	60,0	13,4	6	114,6	207,4	188	479	151	169	363	174	120	[illegible]	181	122	693	680	715	751	716	752	616	22,8	180	33100
22,0	450	990	1189	105	60,0	14,7	6	105,0	207,8	206	464	154	172	363	174	123	[illegible]	302	125	716	707	752	770	734	779	635	25,1	185	34600
22,5	450	1040	1249	110	60,0	15,5	6	100,3	207,1	215	464	156	174	363	176	125	[illegible]	313	126	725	716	770	779	743	770	644	26,1	187	35300
17,0	450	675	825	71	60,0	10,0	5	123,7	215,6	145	479	147	125	363	172	120	[illegible]	234	120	553	594	625	707	571	716	626	15,5	181	28000
13,0	450	450	551	48	60,0	6,7	4	140,8	227,3	102	479	142	150	363	172	178	[illegible]	169	113	626	617	653	662	626	671	617	8,7	176	22400
9,0	450	225	276	24	60,0	3,3	2	117,8	271,6	61	493	131	151	363	172	175	[illegible]	122	115	590	572	608	626	500	617	553	3,2	176	14000

Compression pressure A: 73 74 75 75 74 73
Combustion pressure ahead A: 109 109 107 107 107 109
B.D.C.: 20 20 20 20 20 20
Measured on bottom frame and coupled with Generator.
Exhaust gas back pressure at full load: 14,0 mbar
Oil pressure at 688 1/min and 136 °F is 42,1 psi
American Bureau of Shipping

Table 2: MAK Generator ATR

As can be seen in Table 2, there were eight tests performed at various output loads on the generator. Five tests evaluated between ~ 110% and 95% capacity or ~900 kW. These are the top five rows in the table. The lower three rows, evaluated at three-quarters capacity (~675 kW), half capacity (~450 kW) and one-quarter capacity (~225 kW). The data obtain on the generators output, during the 2023 cruise period, showed that it operated at roughly 50% load or 450 kW, as previously shown in Figure 13.

The fuel consumption per kWh at 450 kW load was 227.3 grams per kWh, as shown on Table 2. Given a density of 3,150 grams/gallon for diesel, the result is 13.85 kWh per gallon of diesel is produced by the ship's generator. As of February 2023, the Defense Logistics Agency (DLA) price of diesel is $3.90 per gallon. This would result in a fuel cost of $0.281 per kWh.

Average generator load (50%) = 450 kW

Fuel consumption at 50% load: 227.3 grams per kWh
Density of diesel fuel: 3,150 grams per gallon

kWh produced per gallon of diesel fuel by generator at 50% load =
3,150 g/gal ÷ 227.3 g/kWh = **13.85 kWh per gallon**

Price of diesel fuel (February 2023 DLA price): $3.90 per gallon

Fuel cost per kWh produced at 50% load = $3.90 per gallon ÷ 13.85 kWh per gallon = **$0.281 per kWh**

Second, the cooling electrical power displacement was estimated for the model based on an actively sailing vessel. The business model used a yearly underway time of 7,600 hours to represent an active vessel profile. The adsorption chiller, operating in baseload conditions, will reduce the number of kWh produced by the generator for powering the HVAC.

To estimate the cooling load replacement by the adsorption system, the current ship's chillers full load power consumption (shown by the circle in Figure 23) of 111 kW to produce 155 tons of cooling was used. This results in 0.72 kW electrical power per ton of cooling.

111 kW electrical power / 155 cooling tons = 0.72 kW/ cooling ton for the vapor compression chiller

To verify the electrical load per cooling ton value was in-line with the stated value (Figure 23) the compressor load and electrical load on the days with the highest and lowest cooling loads were compared assuming that the only major electrical load change was for air conditioning. On May 10 (lowest cooling load) the two-generator output was 950 kW (400 kW + 550 kW) and the corresponding observed cooling capacity was 34 tons (155 tons X 22%). On June 9 (highest cooling load) the two-generator output was 1,100 kW and the observed cooling capacity of 205 tons (155 tons X 55% + 155 tons X 78%).

Change in cooling load = 205 tons (highest load) – 34 tons (lowest load) = 171 tons cooling
Change in electrical load = 1,100 kW (highest A/C load day) – 950 kW (lowest A/C load day) = 150 kW

Calculated electrical load = 150 kW / 171 tons = **0.88 kW/ cooling ton (approximate) observed**

The observed electrical power per ton of cooling value is reasonable given that the chillers were operating at partial load, which is less efficient than operating at full load. The amount of time spent at a significantly lower load than the maximum load would result in a higher kW per ton value. This effect was not included in the model. The ship chillers operated in the range between 11% to 66% of the full load condition over the cruise period. The concept of operation would be to use the adsorption technology as a pre-cooler to augment the ship's vapor compression chiller at all times during the cruise similar to how it operated continuously on the 2023 cruise.

Third, the actual adsorption chiller produced roughly 1.43 tons (5 kW) of cooling power per hour during the cruise and operated continuously. This relatively small cooling output was a result of the less-than-optimal high temperature driving conditions (jacket water temperature at the chiller was less than expected). It is noted here that the proof-of-concept unit's performance under the nominal design parameters conditions, would have produced an estimated 4 tons (14 kW) of cooling. Applying the existing *T/S Golden Bear*'s chillers performance and the adsorption chiller performance a simplified rough order of magnitude return on investment (ROI) is calculated as shown below. Note: the adsorption chiller does utilize a small amount of power to operate solenoids and a small pump. This value is not included in the simplified ROI.

The value of a ton of cooling on the *T/S Golden Bear* is determined by using the 0.88 kW/ton multiplied by the average per hour cooling capacity of the prototype adsorption chiller and then multiplied by the assumed annual operating hours of 7,600 for an active vessel and finally multiplied by the cost of a kWh of power produced on the *T/S Golden Bear*.

kWh Savings = 0.88 kW/ton X 1.43 tons X 7,600 hours **= 9,564 kWh electrical power saved per year**
Cost savings = 9564 kWh X $ 0.281 kWh = **$2,687 per year** as installed and observed

Increasing the jacket water temperature to the chiller to 80°C (176°F) would increase the cooling capacity of the chiller from the observed 1.43 tons to 4 tons. Utilizing this higher cooling capacity, the annual electrical savings can be calculated as:

kWh Savings = .88 kW/ton X 4 tons X 7,600 hours = **26,752 kWh electrical power saved per year**
Cost savings = 26,752 kWh X $ 0.281 kWh = **$7,517 per year** (with higher jacket water inlet temp)

Finally, the total investment cost was estimated. The actual proof of concept unit was procured for $30,500. The estimated installation cost based the actual cost of the recurring installation tasks only and on our lessons learned from the 2023 cruise. By removing the engineering costs and first-time installation inefficiencies, an estimated installation cost of $22,500 was used in the model. The total estimated investment of $30,500 + $22,500 was included in the model. In addition, $500 per year was included for yearly maintenance.

One-time Investment = $30,500 (procurement) + $22,500 (installation) = **$53,000 install cost**
Annual operating costs were estimated at **$500 per year.**

The simple payback analysis resulted in a payback period of roughly 24 years as demonstrated (this does not consider improved efficiency modifications which could considerably reduce the payback period). Given these assumptions and rough order of magnitude for installed cost, and the actual demonstrated performance of the adsorption chiller during the 2023 cruise the simple payback period is excessively long to attract investment if only cost is considered. Further savings in maintenance and life cycle costs are expected but not included. Note that the small capacity of this prototype chiller was for a proof-of-concept test.

However, as mentioned previously the performance of the prototype unit should be able to be increased considerably through better ship integration. With a higher hot driving temperature, the expected simple return would be 7.66 years which would be in the acceptable range to consider the technology affordable at this stage of market deployment. The result from the business model is shown in Figure 27. The payback period is shown in the red figures in the cash flow calculations chart and in graphic form below that.

As Demonstrated in 2023 Cruise

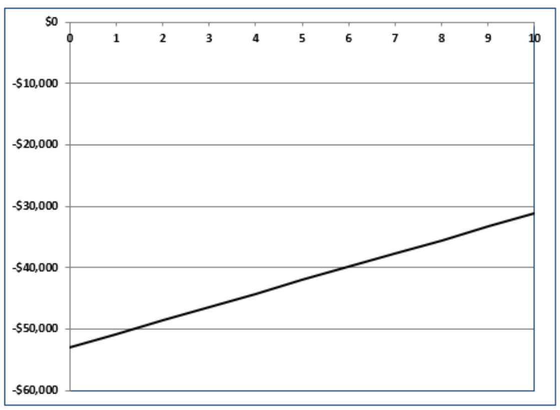
CASHFLOW WITHOUT TAX INCENTIVES

MARKET INPUT PARAMETERS		
Sales value of heating and cooling	$/kWh	**0.281**
Sales value of electricity		

POWER PACK - SALE OF HEAT & ELECTRICITY

	Year	0	1	2	3	4	5	6	7	8	9	10
Heating and Cooling power savings	9,564 kWh											
Electricity production	kWh											
Value of electricity			0	0	0	0	0	0	0	0	0	0
Value of heating and cooling	$0.281		2,687	2,687	2,687	2,687	2,687	2,687	2,687	2,687	2,687	2,687
Operating costs			-500	-500	-500	-500	-500	-500	-500	-500	-500	-500
Cash from operations			2,187	2,187	2,187	2,187	2,187	2,187	2,187	2,187	2,187	2,187
Investment		-53,000	0	0	0	0	0	0	0	0	0	0
Net cash		-53,000	2,187	2,187	2,187	2,187	2,187	2,187	2,187	2,187	2,187	2,187
Accumulated cash		-53,000	-50,813	-48,625	-46,438	-44,250	-42,063	-39,875	-37,688	-35,500	-33,313	-31,125
IRR	-13.53%											

PAYBACK: 24.23 YEARS



Expected with Improved Ship Integration

CASHFLOW WITHOUT TAX INCENTIVES

MARKET INPUT PARAMETERS		
Sales value of heating and cooling	$/kWh	**0.281**
Sales value of electricity		

POWER PACK - SALE OF HEAT & ELECTRICITY

	Year	0	1	2	3	4	5	6	7	8	9	10
Heating and Cooling power savings	26,572 kWh											
Electricity production	kWh											
Value of electricity			0	0	0	0	0	0	0	0	0	0
Value of heating and cooling	$0.281		7,467	7,467	7,467	7,467	7,467	7,467	7,467	7,467	7,467	7,467
Operating costs			-500	-500	-500	-500	-500	-500	-500	-500	-500	-500
Cash from operations			6,967	6,967	6,967	6,967	6,967	6,967	6,967	6,967	6,967	6,967
Investment		-53,000	0	0	0	0	0	0	0	0	0	0
Net cash		-53,000	6,967	6,967	6,967	6,967	6,967	6,967	6,967	6,967	6,967	6,967
Accumulated cash		-53,000	-46,033	-39,067	-32,100	-25,133	-18,166	-11,200	-4,233	2,734	9,701	16,667
IRR	5.31%											

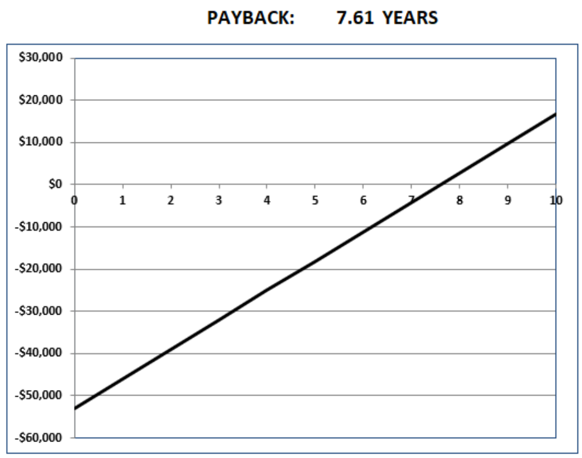


Figure 27 – Business Model for 2023 Cruise Adsorption Cooling Demonstration

Conclusions / Recommendations

Waste heat generated cooling capacity was successfully installed and demonstration, at sea, during the May 9, 2023, to July 7, 2023, timeframe. This demonstration project was relatively small, providing 1.43 tons of cooling capacity, but the results obtained from the *T/S Golden Bear* 2023 cruise indicated that the waste heat driven heat pump is a viable technical solution for military and commercial vessels. By using waste heat from the generator's jacket water system and a connection to the ship's seawater cooling system, adsorption cooling driven by waste heat energy already on the ship can be successfully and affordability implemented on ships. This method provides ship cooling without the combustion of fuel and thereby minimizes CO_2 emissions by the ship.

The data captured during the *T/S Golden Bear's* cruise indicated that the driving heat for the adsorption technology can be obtained from the roughly 950 kW of electrical load delivered from the ship's generators while the *T/S Golden Bear* was underway. An example of this is shown in Figure 28. The waste thermal energy available from a data sheet for a similar diesel generator's jacket water, assumed to be operating at 50% load, like the T/S Golden Bear and many ships operate, shows a 43% heat rejection rate to the jacket water as compared to electrical output of a diesel generator operating at 50% load (875 kW/378 kW_{th}). The blue arrow indicates the 50% load performance which gives an electrical output like the two generators usage on the *T/S Golden Bear*. This would result in approximately 400 kW of thermal energy available for conversion to cooling. Since the adsorption chiller's efficiency at the specified optimal parameters is roughly 50%, then an expected cooling capacity of 200 kW or 57 tons of cooling potentially could be available. A scaled-up chiller could take advantage of this available heat source for cooling.

Properties for Single Genset at Rated Altitude and Temperature	Unit	100%	90%	75%	50%
Energy input (LHV)	kW	4799	4334	3708	2655
Electrical Output	kW	1750	1575	1313	875
Total heat rejected to LT. Circuit	kWth	422	382	348	283
Total heat rejected to H.T Circuit	kWth	708	634	524	378
Available Exhaust Heat To 105 deg.C	kWth	1200	1079	946	698
Maximum LT. engine water inlet temperature	°C	50	50	50	50
Maximum LT. engine water outlet temperature	°C	60	60	60	60
Maximum HT engine water inlet temperature	°C	82	82	82	82
Maximum HT engine water outlet temperature	°C	95	95	95	95
Exhaust gas temperature after turbine	°C	507	514	528	549

Figure 28 – Thermal Energy Distribution in Typical Gen Set

.

The 57 tons of cooling would represent 100% of the ship's cooling loads in 21° C(70°F) seawater and roughly 30% of the total cooling observed in 32°C (90°F) seawater. The amount of cooling capacity could be further increased by using the exhaust energy shown on the chart. This would provide another estimated 700 kW of exhaust waste heat that could be used with the jacket water. In this combined configuration, a total of 157 tons of cooling potentially would be available from waste heat. The maximum cooling capacity observed during the *T/S Golden Bear's* 2023 cruise was 199 tons. An exhaust heat exchanger was successfully demonstrated on the *T/S Golden Bear* at sea in both the 2019 and 2021 cruises. The 2023 jacket water application was able to produce a positive business model on the small-scale demonstration with a simple payback period of 3.66 years, assuming higher driving heat can be provided to the prototype unit through improved integration to the ship.

By reducing the fuel combusted for ship's cooling needs, as described above, an estimated corresponding greenhouse gas reduction of 1,469 tons of Carbon Dioxide Equivalent could be achieved annually, based on the EPA's website calculator. Since the electrical power avoided is from petroleum-based fuel, the emissions are higher per kwh than landed based power plants. The carbon footprint reduction results from avoiding the annual combustion of 121,612 gallons of diesel fuel on the ship and instead harvesting wasted thermal energy from the ship's generator to produce an equivalent amount of "fuel free" cooling. If widely adopted, this can result in a significant carbon footprint reduction across the Navy's and commercial maritime fleets.

Given the potential operational benefits demonstrated during this project and the ability to use the *T/S Golden Bear* as a shipboard sea trail asset, it is recommended that this project continue. The data obtained from follow-on efforts would facilitate the analysis to determine the applicability to other various type of vessels used in maritime operations today and in the future.

Collins Aerospace would like to recognize the contributions from both MARAD and the California Maritime Academy for making the 2023 Cruise a successful demonstration.