Alaska SeaLife Center
Trans-Critical CO2 Heat Pump System
AEA Grant Agreement No. 7310213
AEA Funding: $537,560
Rasmuson Foundation: $50,000
ASLC In-Kind Match: $69,570
Total Project Budget: $657,130
Project Timeline: July 2014-June 2017

Final Report

June 30, 2017

Project Introduction

The goal of this project is to demonstrate the use of innovative seawater source CO2 refrigerant heat pump technology at the Alaska SeaLife Center to meet the medium temperature hydronic perimeter heating, large habitat observation decks snow melt, life support filter room heating to control seasonal condensation, and cooling of the boiler and central motor control rooms using fan coil units.

Key project tasks and relevant activities included the following:

- Installation of four 20-ton Mayekawa CO2 refrigerant heat pumps
- Installation of supporting infrastructure (heat exchangers, pumps, etc.)
- Commissioning of integrated monitoring and controls system
- Reconfiguration and integration of supporting mechanical and electrical systems
- Demonstration of the technology

Project activities commenced in September 2014, with primary system installation and commissioning completed by January 2016 and final commissioning completed by March 2016. The project underwent active performance monitoring from April 1, 2016 through April 30, 2017.

The following organizations were involved in this project:

Alaska SeaLife Center: Located on the shores of Resurrection Bay in Seward, ASLC is Alaska's only public aquarium and ocean wildlife rescue center. ASLC submitted this project to the Alaska Energy Authority for consideration under the Emerging Energy Technology Fund Round Two solicitation. ASLC is the primary stakeholder of this project.

YourCleanEnergy LLC: YourCleanEnergy LCC (YCE) is a clean energy consultant based in Anchorage, Alaska. YCE recommended the CO2 refrigerant heat pumps as a solution to displace an expensive electric boiler and provide heat to existing medium temperature 160F to 180F) hydronic baseboards, unit heaters and air handlers in the facility. YCE, in association with EDC, Inc., designed the system and was instrumental in installing and commissioning it.

Engineering Design and Consulting, Inc.: EDC, Inc. is a professional corporation based in Anchorage that has been registered in the State of Alaska in the fields of Electrical and Mechanical Engineering since 1994. The firm has been providing all aspects of engineering services for a wide variety of governmental, commercial and private concerns throughout the State of Alaska since that time. The firm is owned by four principals: John Faschan, P.E., Kevin L. Hansen, P.E., Ernie Hetrick, P.E., and John Pepe, P.E.

Mayekawa USA: Mayekawa has been manufacturing large-sized air-conditioning heat pumps since 1971. The CO2 refrigerant Unimo W/W uses water as its heat source (including waste hot water) to generate hot water and cold water simultaneously. This industrial heat pump achieves remarkable energy savings by combining simultaneous heating and cooling from one unit boasting a combined coefficient of performance (COP) of 8. This performance is achieved using the trans-critical cycle of its refrigerant CO2, providing hot water outlet temperatures of up to 194F. For example, a heat source water temperature of 71.6F results in a capacity of 26 ton (194F). This makes Unimo W/W ideal for applications that require both heating (high quality hot water) and cooling on a constant basis such as food processing facilities, resorts and hotels.

Trane USA: Trane is a global provider of chillers, heat pumps and other HVAC systems, including its web based Tracer SC and Tracer ES building automation controls. Trane provided and installed the Tracer ES controls for the project.

Alaska Energy Authority: The Alaska Energy Authority provided $537,560 in funding through Round 2 of the Emerging Energy Technology Grant Fund.

Rasmuson Foundation: Rasmuson Foundation provided $50,000 in supplemental funding through a Tier 2 grant.

Alaska Center for Energy and Power: The Alaska Center for Energy and Power (ACEP) an applied energy research program based at the University of Alaska Fairbanks, provided technical support in data collection and will provide an independent performance analysis to AEA.

Overview:

The innovative and sustainable trans-critical CO2 heat pump system of 80 ton capacity was commissioned in January 2016 at the 120,000 square foot Alaska SeaLife Center to displace conventional oil and electric boilers. The CO2 heat pump system was further improved in mid-2016 and has produced significant cost savings thru the sub-arctic winter of Seward, Alaska. The project required a challenging integration of four Mayekawa trans-critical CO2 heat pumps into a large and existing conventional medium temperature hydronic system. A primary goal of the project was to demonstrate the cost savings, operational advantages, and promising market potential of the natural refrigerant CO2 for hydronic heating in colder northern climates. This project is at this time the first known case in the USA of trans-critical CO2 heat pumps replacing hydronic heat from conventional oil and electric boilers in a commercial sized facility. The project has been closely monitored since start up via Tracer ES℠, a web based controls system developed by Trane USA, and results thus far show that heat from the CO2 heat pump system has been produced for less than half of the cost of the heat produced by the original conventional boilers, and without combustion emissions or synthetic refrigerant leaks. Data collected for the winter of 2016/2017 has allowed an efficiency and cost analysis of the system.

This project has the primary goal of evaluating the market potential of this trans-critical CO2 heat pump system to offset and ultimately replace the use of oil boilers in cold climates ,and other heat pump systems that utilize synthetic refrigerants with significantly higher greenhouse warming potential (GWP). A comparison in performance and refrigerant leak events of the new Mayekawa CO2 heat pumps to a pair of older Trane RTWD rotary screw heat pumps operating in the same facility that utilize R-134a refrigerant (GWP=1400) is shown on appended monitoring and performance reports for each heat pump system.

A key innovation of the CO2 refrigerant heat pump system lies in the design of both source side and load side loops which have proven to be reliable and low maintenance. The design is original in that the load side return temperature is reduced through various heat loads that are served in a series arrangement, rather than a single parallel hydronic loop. These heat loads are arranged from higher temperature to lower, such that the load side flow leaving the heat pumps at 194F ultimately returns to the heat pumps in the range of 90F to 120F. This drop in load side temperatures of 70F to 100F is significantly larger than what conventional hydronic heating systems are designed for; this is why trans-critical CO2 heat pump integration into a boiler system has previously gained little traction. The innovative design presented in this project holds lessons that are replicable in other commercial and institutional facilities located in cold climates where adequate open source or ground source water is the available source for CO2 heat pumps.

This demonstration project is tangible and useful in northern climate markets because it's based on a full scale system that has been operating through two successive Alaska winter seasons with complete web based monitoring of key performance data. This data is logged once per minute and includes loop flows, temperature, electrical energy demand (KW) and usage (KWH), heat transfer rates (MBH), total heat production (MMBTU), cooling loads (MBH), outside air temperature, seawater temperature, individual heat pump COP, and total system COP.[1]

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[1] Andy Baker, P.E., YourCleanEnergy LLC

Project Monitoring Period Performance Results

- The CO_2 refrigerant heat pump system consumed 41% of the electricity used for heating and cooling while producing 38% of the heating and cooling energy, achieving a net energy savings of $60,716 with an average COP of 2.11. 586,956 pounds of CO_2 were avoided by operating the heat pumps. [2]

ASLC CO2 Refrigerant Heat Pump System Performance
ACEP Monitoring Period - April 1 2016 - April 30, 2017

	Electricity Consumed				Thermal Energy Delivered			HP-3 COP	CO2 HP COP
ACEP Monitoring Period Apr 2016 - Apr 2017	CO2 Refrigerant Sea Water HP kWh Consumed (HP System Monthly Usage Logs	HP-3 (Waterfurnace) kWh Consumed	Electric Immersion Hot Water Tank Heater kWh Consumed	Electric Boiler Total Kwh Consumed (Electric Boiler Monthly Power Usage Logs)	HP-3 (Waterfurnace) MMBTU (Monthly Energy Logs)	CO2 SWHP Thermal MMBTU (HP Monthly Energy Logs (Includes Fan Coil Loop 700)	Electricity saved (Kwh) (293.1*SWHP Thermal MMBTU)	Coefficient of Performance (293.1*SWHP Thermal MMBTU/Total kWh Consumed)	Coefficient of Performance (293.1*SWHP Thermal MMBTU/Total kWh Consumed)
Jan**									
Feb									
Mar									
Apr***	34,262	1,854	102	564	16	235	73,630	2.53	2.01
May	27,937	1,813	976	1,378	16	189	60,158	2.65	1.98
June	15,103	1,296	3,962	5,488	21	128	43,648	4.75	2.48
July	15,560	2,082	3,597	25	35	121	45,744	4.89	2.29
August	16,403	2,443	865	74	40	135	51,480	4.85	2.42
Sept	17,534	1,801	368	395	30	133	47,589	4.85	2.22
Oct	37,090	782	1,057	5,269	13	276	84,586	4.72	2.18
Nov****	45,014	1,115	239	3,328	14	337	102,776	3.68	2.19
Dec	62,020	0	1,005	15,832	0	407	119,292	0.00	1.92
Jan	60,378	0	2,534	26,646	0	313	91,720	0.00	1.52
Feb*****	41,394	0	2,718	36,348	0	318	93,206	0.00	2.25
Mar*****	44,948	0	2,869	56,580	0	354	103,866	0.00	2.31
Apr	45,772	0	3,225	7,359	0	264	77,378	0.00	1.69
Total	**463,414**	**13,188**	**23,516**	**159,286**	**185**	**3,210**	**995,073**	**2.53**	**2.11**

ELECTRICITY CONSUMPTION BY HEAT PUMP SYSTEMS - from Tracer System logs for Period April 1, 2016 - April 30, 2017

kWh	Cost kWh	Energy Cost	Monthly Avg. Cost	
463,414	$0.1171	$54,268	$4,174.48	**CO2 HP's**
13,188	$0.1171	$1,544	$118.79	**HP-3 (Domestic HW)**
476,602		**$55,813**	**$4,293**	

ELECTRICITY CONSUMPTION BY ELECTRIC BOILER AND HOT WATER TANK IMMERSION HEATER - from Tracer System logs for Period April 1, 2016 - April 30, 2017

kWh	Cost kWh	Energy Cost	Monthly Avg. Cost	
159,286	$0.1171	$18,653	$1,434.86	**Electric Boiler**
23,516	$0.1171	$2,754	$211.83	**Immersion Heater (Domestic HW)**
182,802		**$21,407**	**$1,647**	

ENERGY COST SAVINGS

Electricity Saved (kWh)	Cost Of Electricity Saved	Electricity Used (kWh)	Cost of Electricity Used	Net Energy Cost Savings	Monthly Average Cost Savings	
940,854	$110,179	463,414	$54,268	$55,911	$4,300.82	**CO2 Heat Pumps**
54,219	$6,349	13,188	$1,544	$4,805	$369.62	**HP-3 (Domestic HW)**
995,073	**$116,528**	**476,602**	**$55,813**	**$60,716**	**$4,670**	**Combined Systems**

C02 AVOIDED*

Oil Equivalent CO2 Avoided	Lbs C02 Avoided
586,956	**586,956**

*Formula: SWHP Total MMBTU X 1.13 (.87 fuel to hot water efficiency at 195F of 80-HP Cleaver Brooks 4-pass oil boiler) / 136,000 (BTU energy of one gallon of #1 heating oil) X 22 (pounds of CO2 generated by burning one-gallon of #1 fuel oil)

**CO2 Refrigerant Heat Pump System placed in operation on January 21, 2016 significantly reducing the necessity of electric boiler operation

***First month of monitoring data available following commissioning of Tracer ES BAS

****HP-3 (Waterfurnance 7-Ton) failed on November 24, 2016 due to a cracked heat exchanger which resulted in Circuit 1 and Circuit 2 compressor failure. HP will not be replaced.

*****Fouled flow transmitters resulted in CO2 heat pump system energy being recorded by Tracer ES system less than actual during periods in February and March 2017. This will br permamently addressed by the installation of micro-screen bag filters in fall 2017. In the interim, the indvidual flow meters are periodically removed and cleaned. February and March 2017 CO2 heat pump energy delivered was calculated using actual energy recorded of 10 MMBTU on February 28, 2017 with HP-4, 5, and 6 flow tranmitters cleaned and operating. HP-7 was off-line in February 1 through April 13 due to a failed high pressure tranducer resulting in the electric boiler operating significantly more.

Figure 1 ASLC CO2 Refrigerant Heat Pump Performance

Case Study for Submission for ATMOSPHERE America 2017, June 5-7, 2017, San Diego, CA
Title: INNOVATIVE TRANS-CRITICAL CO2 HEAT PUMP SYSTEM PROVIDES LOWER COST HYDRONIC HEAT THAN OIL BOILERS IN SEWARD, ALASKA. Used by Permission

[2] See Figure 1

- The RTWD heat pump system consumed 42% of the electricity used for heating and cooling while producing 53% of the heating energy, achieving a net energy savings of $89,404 with an average COP of 2.98. 716,192 pounds of CO2 were avoided by operating the heat pumps. [3]

Alaska SeaLife Center Seawater RTWD Heat Pump System Performance
ACEP Monitoring Period - April 1, 2016 - April 30, 2017

	Electricity Consumed	Thermal Energy Delivered		HP System COP
ACEP Monitoring Period Apr 1, 2016- Apr 30, 2017	Sea Water HP System Total kWh Consumed (HP System Monthly Power Usage Logs)	SWHP Thermal MMBTU (HP Monthly Energy Logs)	Electricity saved (Kwh) (293.1*SWHP Thermal MMBTU)	Coefficient of Performance (293.1*SWHP Thermal MMBTU/Total kWh Consumed)**
Apr**	36,813	279	81,775	2.22
May	26,622	144	42,206	1.59
June	17,065	87	25,588	1.50
July	9,514	46	13,359	1.40
Aug	13,301	88	25,872	1.95
Sept	15,932	133	38,890	2.44
Oct	27,661	289	84,706	3.06
Nov	40,259	430	126,030	3.13
Dec	66,737	674	197,549	2.96
Jan	70,226	684	200,463	2.85
Feb	57,335	593	173,715	3.03
Mar	56,580	722	211,648	3.74
Apr	36,890	305	89,501	2.43
Total	**384,920**	**3,918**	**1,148,374**	**2.98**

ELECTRIC CONSUMPTION BY HEAT PUMP SYSTEM - from Tracer System logs for Period April 1- April 30, 2017

kWh	Cost kWh	Energy Cost
384,920	$0.1171	$45,076

ENERGY COST SAVINGS

Electricity Saved (kWh)	Cost Of Electricity Saved	Electricity Used (kWh)	Cost of Electricity Used	Net Energy Cost Savings	Monthly Average Cost Savings
1,148,374	$134,481	384,920	$45,076	$89,404	$6,877.26

C02 AVOIDED*

Oil Equivalent CO2 Avoided	Lbs C02 Avoided
716,192	**716,192**

*Formula: SWHP Total MMBTU X 1.13 (.87 fuel to hot water efficiency at 195F of 80-HP Cleaver Brooks 4-pass oil boiler) / 136,000 (BTU energy of one gallon of #1 heating oil) X 22 (punds of CO2 generated by burning one-gallon of #1 fuel oil)

** COP January-March 2017 is higher due to Pump 100 being off-line so salt water pumping electric energy not included

Figure 2 ASLC RTWD Heat Pump System Performance

- The remainder of the electricity used for heating was consumed by the electric boiler (14%), domestic hot water tank immersion heater (2%), and Waterfurnace domestic hot water heat pump (1%). These devises contributed 9% of the energy production at a cost of $21,407. [4]

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[3] See Figure 2
[4] See Figure 3

ASLC HEATING SYSTEM PERFORMANCE - ACEP Monitoring Period Performance April 1, 2016 - April 30, 2017 - compiled by Darryl Schaefermeyer, Special Projects Director, Alaska SeaLife Center			
Pie Chart Of Electricity Usage	KWH	Pie Chart Of Heating & Cooling Production	MMBTU
RTWD HP System	474,934.00	RTWD HP Heat Energy	4,474.00
CO2 HP System	463,414.00	CO2 HPs Heat Energy	2,802.47
Electric boiler	159,286.00	CO2 HPs Cooling Energy	407.53
DHW Immers Htr	23,516.00	Electric Boiler Heat Energy	543.64
DHW HP-3 System*	13,188.00	DHW Immersion Heater Energy	80.26
		DHW HP-3 Heat Energy*	185.00

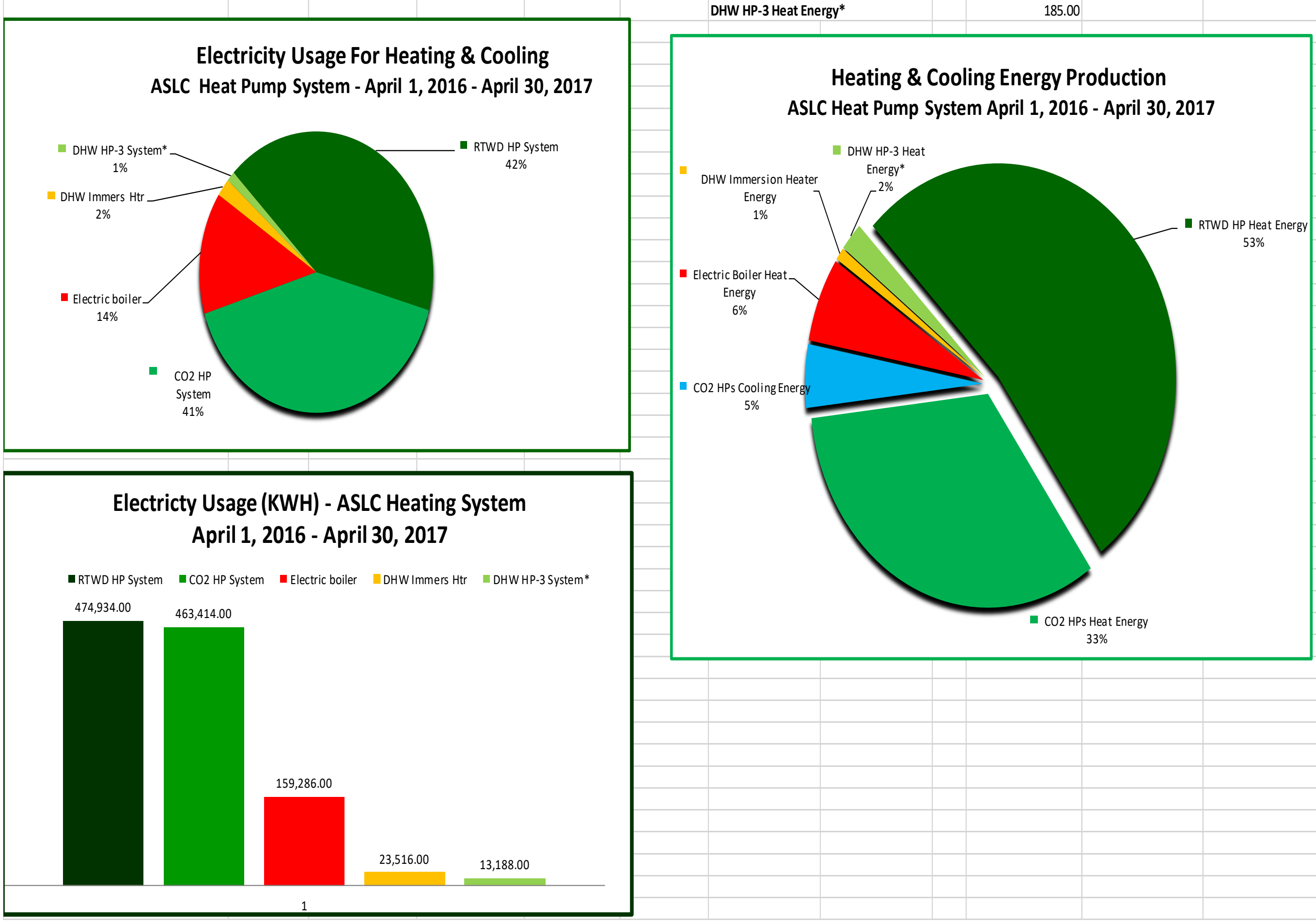

Figure 3 ASLC Heat Pump System Performance

Problems Encountered during the monitoring period

- On January 30, 2017, one of the four CO2 refrigerant heat pumps (HP-7) shutdown due to a faulty pressure transducer. A replacement transducer was supplied by Mayekawa along with tools to assist in the repair. ASLC personnel with the assistance of the AVTEC refrigeration class were able to replace the transducer and restore operation of the heat pump on April 13, 2017. With the heat pump off-line, greater operation of the electric boiler was necessary which was reflected in lower CO2 heat pump system energy performance and a lower system COP.

- During February and March 2017, fouling of the Seametrics flow meter paddle-wheels caused the flow meters for the CO2 refrigerant heat pumps to record incorrectly or not record at all. This has resulted in periods of lower than actual heat production recording and consequential lower than actual COP recording. During affected months, energy delivered by the CO2 heat pumps was extrapolated using actual energy recorded of 10 MMBTU on February 28, 2017 with the flow transmitters cleaned and operating. The ASLC facilities staff have periodically removed and cleaned the paddle wheels. As a permanent solution a micro-screen bag filter to catch the material fouling the meters has been purchased for installation following the busy 2017 summer season.

- On March 1, 2017, the Tracer SC and ES controls ceased logging the system operating data. This resulted in no data being transmitted to ACEP between March 1st and April 13th when the problem was corrected by Trane. The issue was that the SQL database on the Tracer server had gotten full and the trending stopped. It was not a physical hard drive issue or a report template/emailing issue. Trane came to Seward, installed an external hard drive, made a backup of the existing SQL and then purged the active one and trending re-started. Unfortunately Trane cannot recreate the lost data.

- When the heat pumps are attempting to heat up the boiler loop after a cooling period, or at start up, they chill the source loop significantly. This caused the heat pumps to cycle on and off to prevent a freeze event inside the evaporator heat exchangers. This required increasing the source loop propylene glycol to a 20% concentration to permit lowering the freeze protection setting from 36F to 34F.

Lessons Learned

- **Unit COP is most impacted by load entering temperature.** The output is a constant 194 F load side leaving temperature, however the load side entering temperature can vary significantly depending on heat loads and loop design. The ideal range of load side entering temperature is 80F to 100F which allows the units to make the most of electricity consumed by compressor work. In order to provide a load side entering temperature that is 80F lower than the building loop at 160F, a smaller volume side loop must be routed thru a series of heat loads that sequentially cool this side loop down to 100F or less.

- **Unit COP is moderately impacted by source side entering temperature.** Sea water from Resurrection Bay is used as the primary source of heat on the cold side of the heat pump units. The colder sea water temperatures of late spring and early summer can be as low as 38F which forces the compressors to do more work to lift on the hot side. A simple and effective method of adding heat to the source side of the CO2 heat pumps is to install branch loops off the main source loop that is routed to fan coils in over heating mechanical or electrical rooms. Waste heat from these rooms is then effectively recovered back into the heating system; the rooms are cooled with minimal energy input; and the unit COP is improved due to warmer source entering temperature.

- **Overall COP can be improved by turning off CO2 heat pump system sea water supply pumps, and utilizing waste heat loops instead.** ASLC is planning to undertake construction of an additional closed run around loop style heat recovery system in the near future. There is enough waste heat available in the facility's IT room, tissue storage room and exhaust fan ducts to displace the need for raw sea water heat source for most of the year. It is far less costly to operate a closed run around loop to gather source heat, than to lift sea water 40 feet vertically from the wet well and pump it across the basement.

- **Adequate freeze protection is required in the glycol source loop.** When the units are attempting to heat up the boiler loop after a cooling period, or at start up, they will chill the source loop significantly. Glycol concentration must be high enough to prevent a freeze event inside the heat pump evaporator heat exchangers, or the heat exchangers will be damaged and compromised. Again making use of waste heat to warm the source loop will reduce the concentration of glycol needed to prevent freezing.

- **Delay time to add or subtract a heat pump must be generous to avoid over cycling.** When a single heat pump is added by the control logic, it took about 30 minutes for this heat pump to lift the boiler loop to a stable temperature. Conversely, when a heat pump is turned off, it takes about 30 minutes for the boiler loop to cool to a stable temperature. Thus it is necessary to add and subtract heat pump units with enough time delay so that the boiler loop was not dramatically over and under shooting its target temperature. The larger the volume of the boiler loop, the less over cycling will occur as the loop will act as a buffer tank and reduce rapid temperature changes.

- **Leakage of refrigerant is far less common in CO2 units in comparison to R-134a units.** Over the operating period of January 2016 thru June 2017, no leakage of CO2 was detected from the units installed under this project. During the same period of time several leaks occurred from the Trane RTWD units that totaled 156 lbs of refrigerant. Given that R-134a has greenhouse warming potential (GWP) that is 1400 times that of CO2, the CO2 units so far are the preferred choice in regards to refrigerant liability.[5]

Media Publications

[5] Most likely due to the CO2 units manufactured to withstand 2,000 psi operating pressures not required of the Trane RTWD units, coupled with the much lower operating hours of the Co2 units.

- Michael Garry, Accelerate America (May 2016) CO2 Heat Pumps Help Save Alaska SeaLife Center. http://publication.shecco.com/upload/file/org/573c87fe3e7531463584766ugtll.pdf

- Caslon Hatch & David Brooks, KTUU-TV (April 27, 2016) How Cold Ocean Water Heats the Alaska SeaLife Center. https://vimeo.com/174077060

- Eric Keto, Alaska Public Media News (July 7, 2016) How Cold Ocean Water Heats the Alaska SeaLife Center. https://www.youtube.com/watch?v=UgxwDPcsZeQ&feature=youtu.be&platform=hootsuite

References and Notes

- See the Alaska Center for Energy and Power (ACEP) independent project performance analysis provided to the Alaska Energy Authority attached as Appendix A.

- For a complete review of the Trane RTWD heat pump system at the Alaska SeaLife Center, see An Investigation of the Alaska SeaLife Center Seawater Heat Pump Demonstration, Alaska Center for Energy and Power. http://acep.uaf.edu/media/60835/ACEP-Final-Project-Report.pdf

Photos

Figure 4 ASLC Life Support Staff with Mayekawa USA Engineer Troy Davis Photo: Chip Arnold

Figure 5 Andy Baker, YCE; Kody Bull, Trane USA; Troy Davis, Mayekawa USA; Darryl Schaefermeyer, ASLC

Figure 6 Andy Baker, YCE   Photo: Chip Arnold

Figure 7 Governor Bill Walker discussing CO2 Heat Pumps with Darryl Schaefermeyer Photo: Tara Riemer