TURBO-COMPRESSION COOLING SYSTEM FOR ULTRA LOW TEMPERATURE WASTE HEAT RECOVERY

2022 CHP/District Energy System Portfolio

Derek Young

June 7, 2022

Barber Nichols

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Colorado State University

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PRESENTATION OVERVIEW

- Motivation
- Turbo-Compression Cooling
- Test Facility
- Planned and Future Work

Motivation

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Waste Heat Recovery

- **Low-grade WHR can substantially improve energy efficiency for a variety of industries**
- **Implementation of heat driven chillers is sparse**
  - **Less than 10% of 4,500 US CHP installations use heat driven chillers**
  - **Commercially available heat driven chillers (absorbers) have operational and economic barriers**
- **Recovering low-grade waste heat and converting it to useful cooling**
  - **US MFG: 54% reduction in CO2 emissions from cooling-related energy use, 6% total reduction**
  - **CHP: 20% reduction in CO2 emissions for cooling related energy use in Commercial Buildings**

US CHP Sector (2021)
Commercial and Industrial

Total Electrical Capacity	81	GW_e
Thermal Energy Available	73	GW_{th}
Heat Driven Cooling Capacity	58	GW_{th}
Electrical Offset	14.5	GW_e
Energy Reduction	76,000	GWh
Electrical Savings	$5.3 billion	$
CO2 Emission Reduction	41	Million metric tons

US Manufacturing Sector (2018)

Recoverable Heat Loss	417,626	GWh
TCCS Cooling	334,101	GWh
Energy Reduction	83,525	GWh
Electrical Savings	$5.9 billion	$
CO2 Emission Reduction	45	Million metric tons

TURBO-COMPRESSION COOLING

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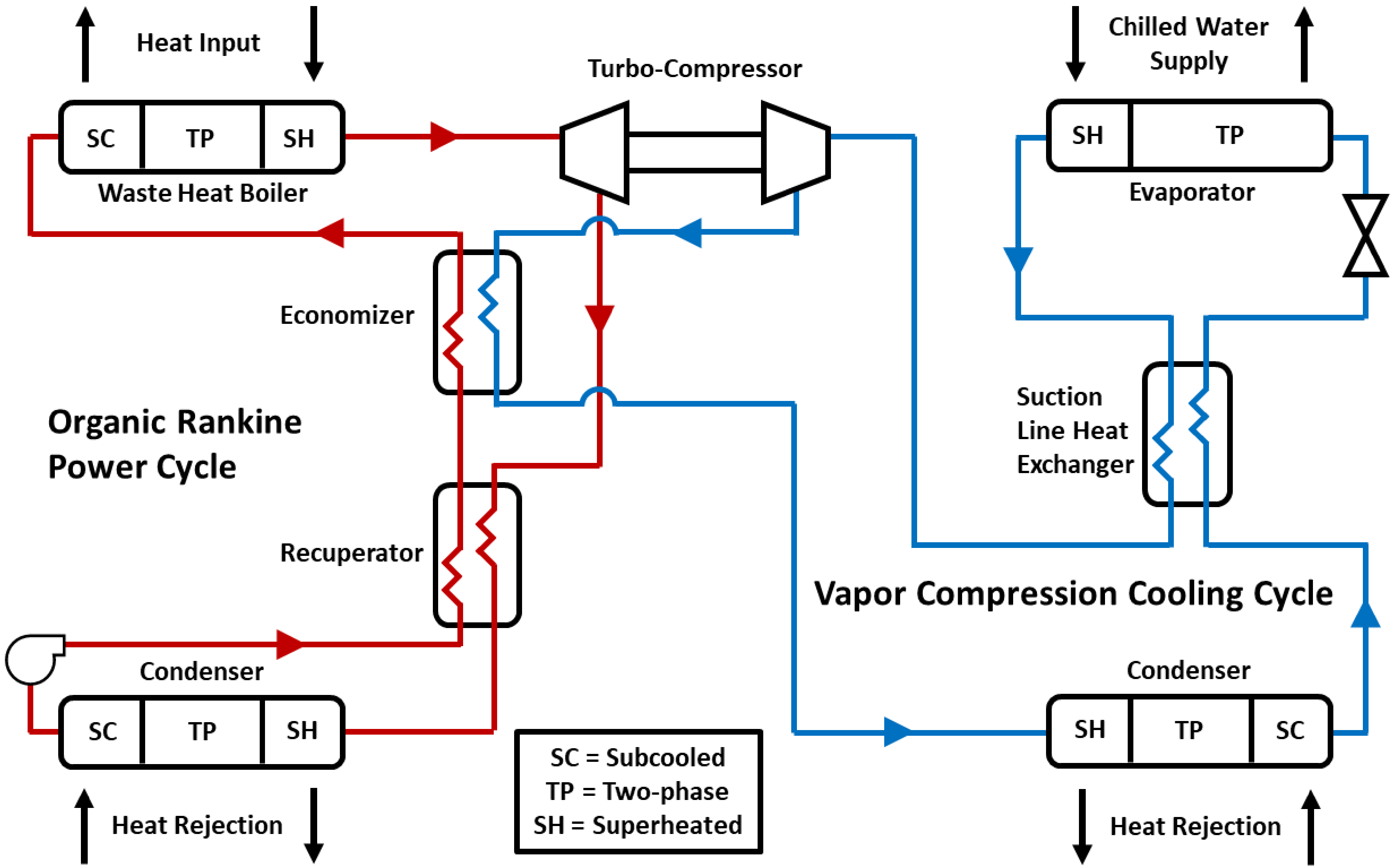
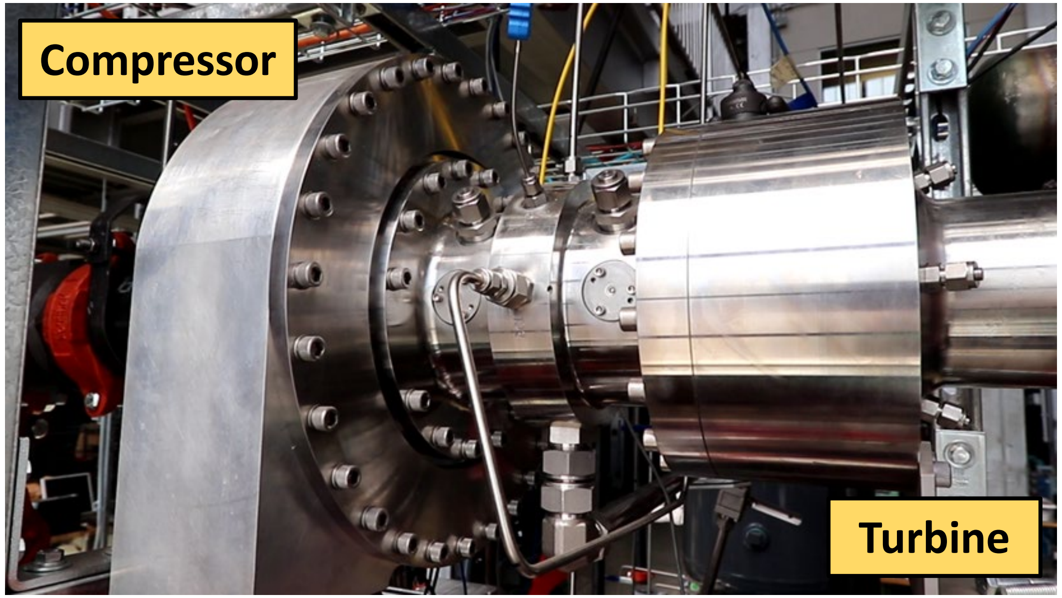
Turbo-Compression Cooling

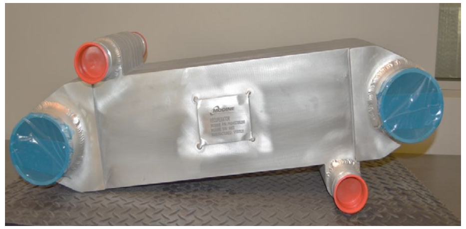


SC = Subcooled
TP = Two-phase
SH = Superheated

Critical Enabling Technologies

- **Turbo-Compressor**
  - High speed, high efficiency (>80% isentropic) centrifugal machine
  - Directly coupled
  - Custom designed for our application with R1234ze(E)
- **Compact Heat Exchangers**
  - Low-cost, aluminum brazed plate style
  - High surface area to volume ratio
  - High effectiveness, low pressure drop




Recuperator


Economizer

Test Facility

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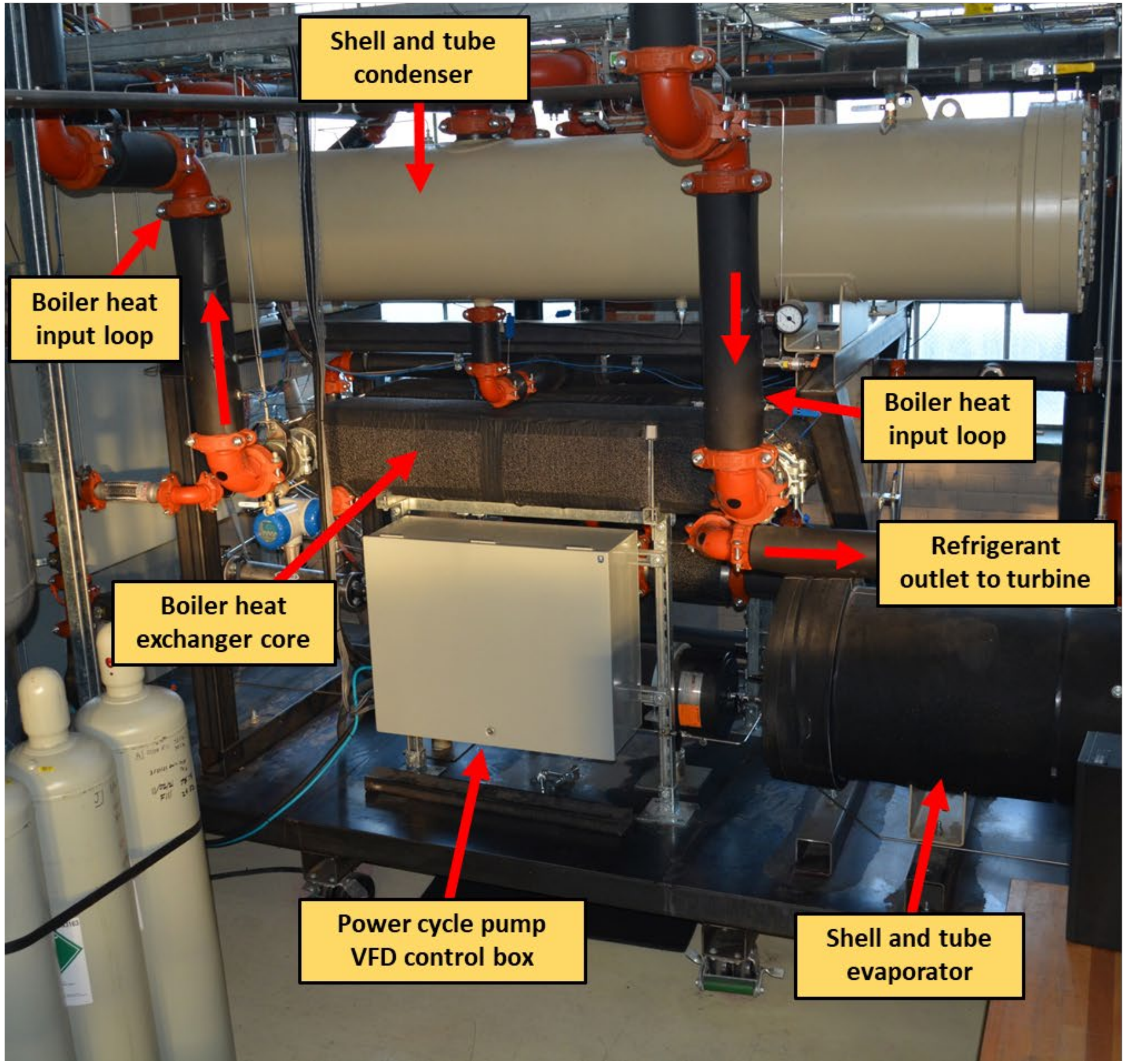
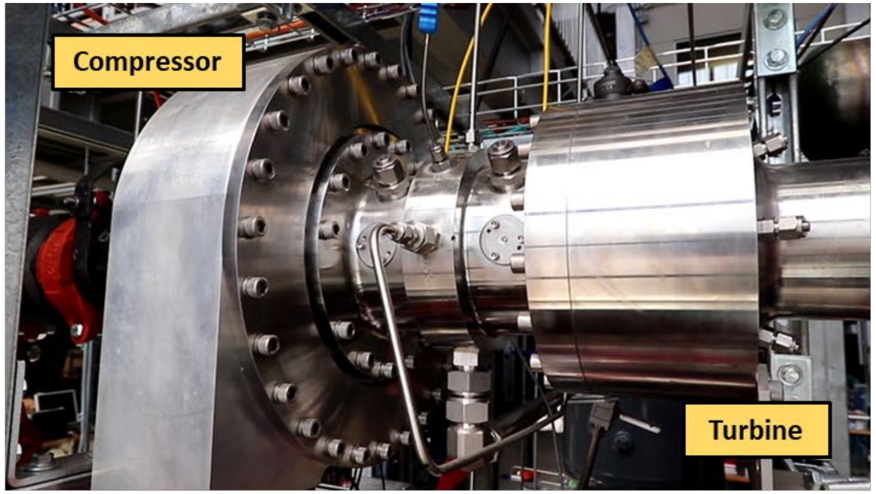
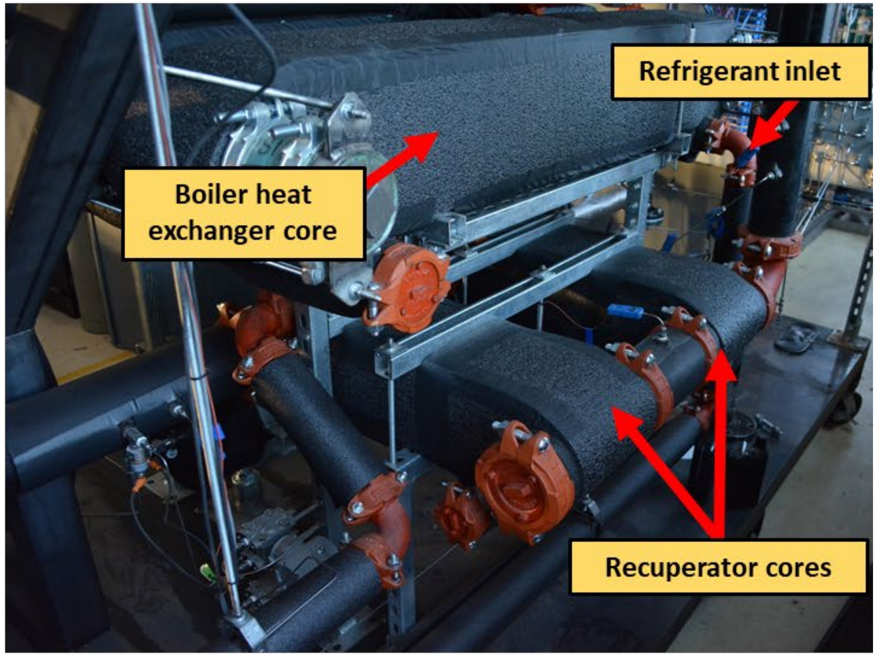
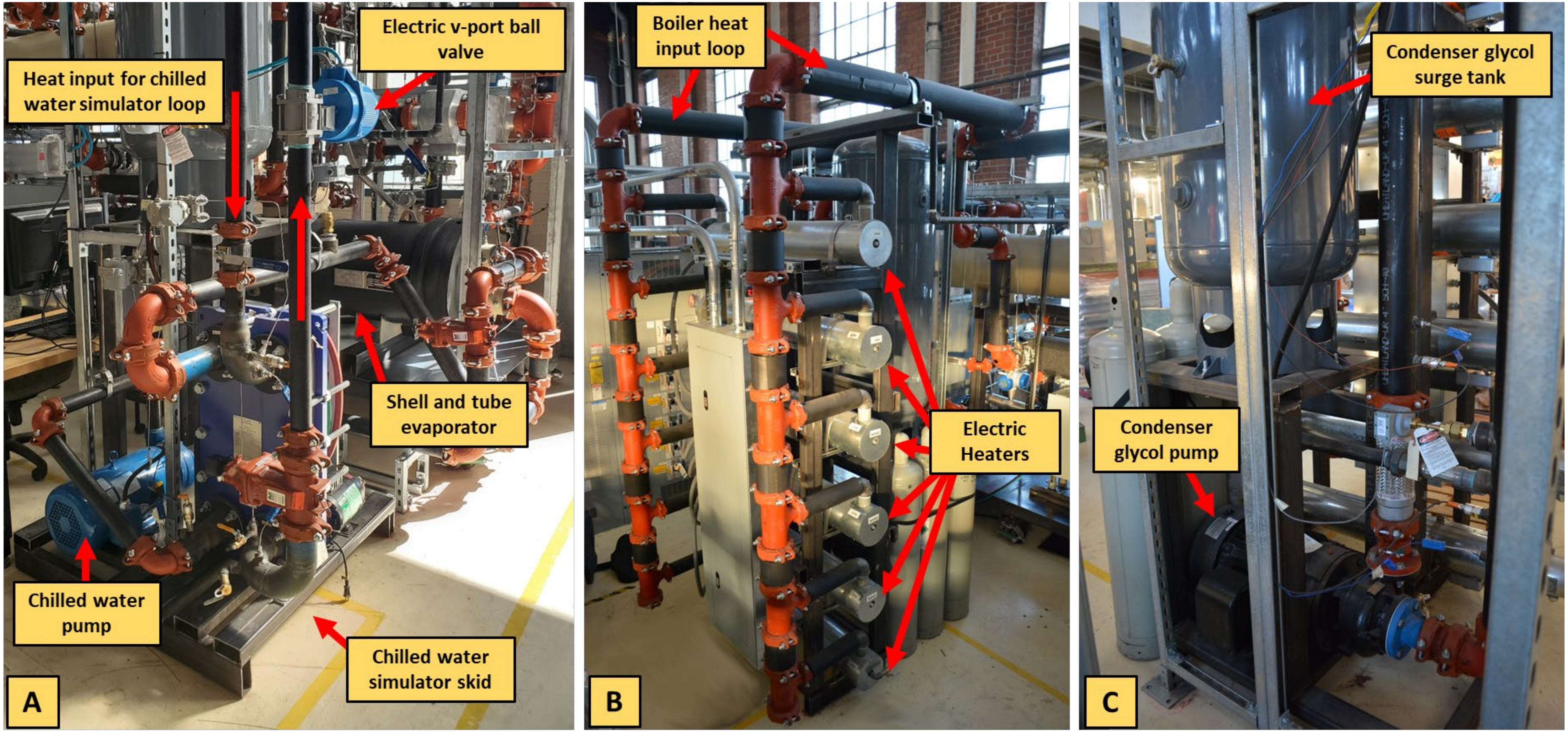
TCCS Test Facility Main Skid







TCCS Test Facility – Auxiliary Loops



Baseline Design Point

- **Auxiliary loop temperatures designed to match commercial absorption systems for direct comparison**
- **High efficiencies for turbomachinery based on designs from project partner**

Model Input	*Value*
$\eta_{s,turbine}$	83.1%
$\eta_{s,compressor}$	82.0%
η_{shaft}	94.3%
$T_{boiler,in/out}$	91°C/86°C
$T_{condenser,in/out}$	30°C/35°C
$T_{chiller,in/out}$	12°C/7°C
Working Fluid	R1234ze(E)

Calculated Value	*Value*
$\dot{W}_{turb}$	50.34 kW
$\dot{W}_{comp}$	47.47 kW
COP_{TH}	0.65
η_{ORC}	8.10%
COP_{VCC}	6.32
$\dot{Q}_{boiler}$	459 kW
$\dot{Q}_{condenser, power cycle}$	456 kW
$\dot{Q}_{condenser, cooling cycle}$	315 kW
$\dot{Q}_{recuperator}$	22 kW
$\dot{Q}_{economizer}$	34 kW
$\dot{Q}_{SLHX}$	42 kW
$\dot{m}_{r, power cycle}$	2.79 kg s^{-1}
$\dot{m}_{r, cooling cycle}$	1.83 kg s^{-1}

Experimental Testing

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DESIGN POINT RESULTS

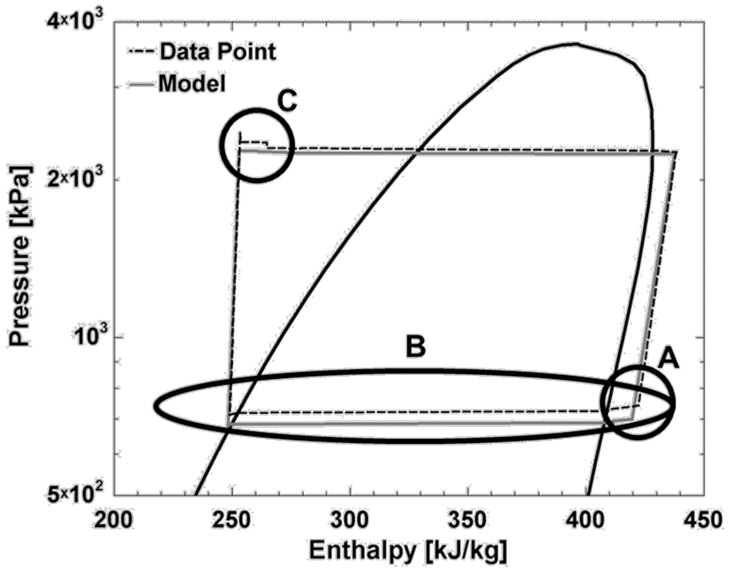
- **Boiler Temperature Inlet/Outlet**
  - **91°C to 86°C**
- **PC and CC Condenser Temperature Inlet/Outlet**
  - **30°C to 37°C**
- **Evaporator Temperature Inlet/Outlet**
  - **12°C to 7°C**

Experimental Performance	***Value***
Boiler Heat Duty [kW]	473.0 ± 10.6
Power Condenser Heat Duty [kW]	435.7 ± 9.5
Cooling Condenser Heat Duty [kW]	291.8 ± 4.0
Evaporator Heat Duty [kW]	263.8 ± 3.5
Turbine Work [kW]	50.07 ± 0.57
Compressor Work [kW]	50.24 ± 0.48
Transfer Efficiency [%]	100.3 ± 1.5
Turbine Efficiency [%]	76.70 ± 0.90
Compressor Efficiency [%]	84.75 ± 0.54
Turbo-compressor speed [RPM]	31,500 ± 300
Thermal COP [-]	0.56 ± 0.01
Organic Rankine Cycle Efficiency [%]	7.71 ± 0.22
Vapor Compression Cycle COP [-]	5.23 ± 0.09

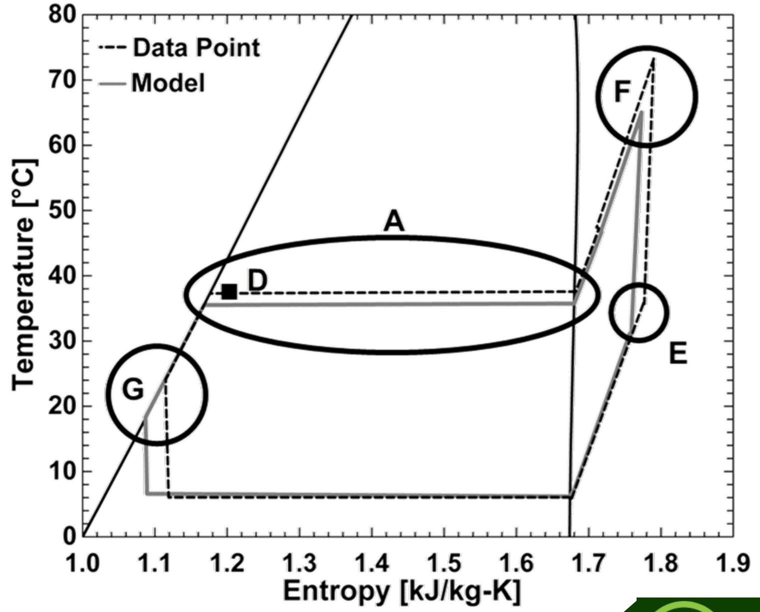
DESIGN POINT RESULT ANALYSIS

- COP = 0.56 experimental, compared to 0.6 modeled
- Lower than design turbine η caused:
  - Higher mass flow through PC to get desired power output
  - Greater delta P through cycle
  - Choked flow through turbine
- Undersized condenser meant lower turbine PR and higher compressor PR
  - Lower turbine PR = less power output
  - Higher compressor PR = less flow delivered and reduced cooling capacity in evaporator
  - Two-phase fluid exiting CC condenser (less h_{vap}) available in evaporator for chilling
- Some of these challenges were outweighed by performance improvements from heat integration
  - 19.6% increase to COP from SLHX (0.45 to 0.56)
  - 9% increase to COP from Economizer (0.51 to 0.56)
  - 7% increase to COP from Recuperator (0.52 to 0.56)

Power Cycle P-h Diagram



Cooling Cycle T-s Diagram



Next Steps for TCCS

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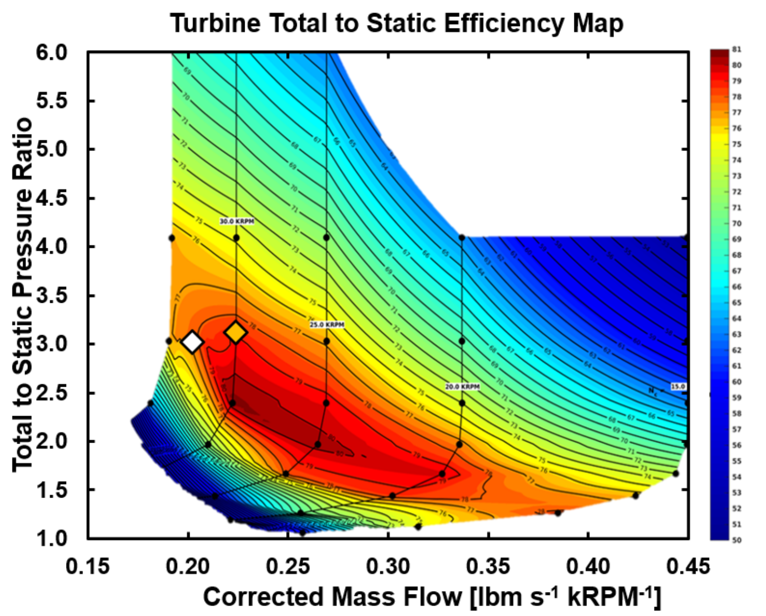
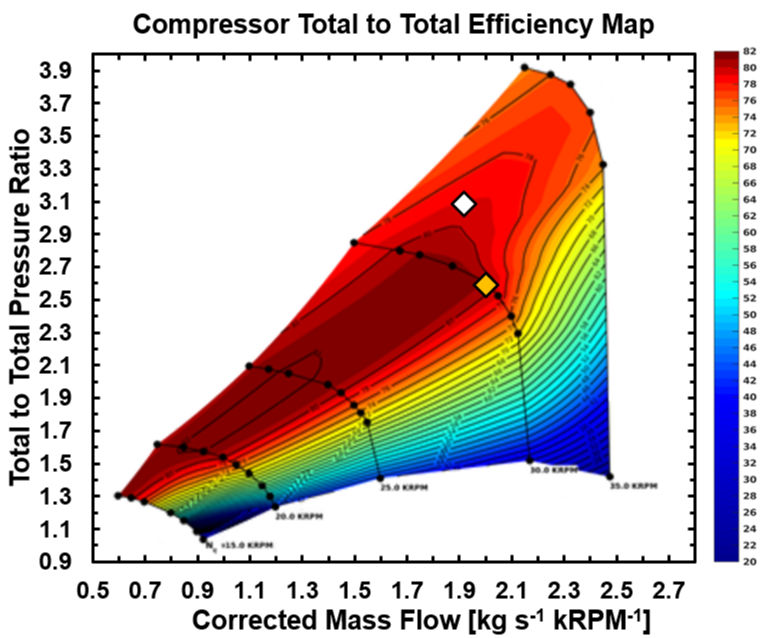
PLANNED AND FUTURE WORK

- **Test Facility Modifications**
  - Changes to enable repeatable startup and shutdown
  - More testing to generate detailed turbomachinery performance maps
  - Turndown testing
- **Future Work**
  - Replace shell and tube condenser with larger surface area HX
  - Transition to commercialization: CHP packaging and marine sectors





Planned and Future Work – US Navy STTR

- **Partnering with small business Mantel Technologies on a Phase II DOD STTR grant to design and test a turbo-compression cooling system for US Navy Ships**
- **Capture low-grade waste heat from ship service diesel gensets to improve fuel efficiency by 10%**
- **TCCS fits into existing chiller footprint by using compact heat exchangers**

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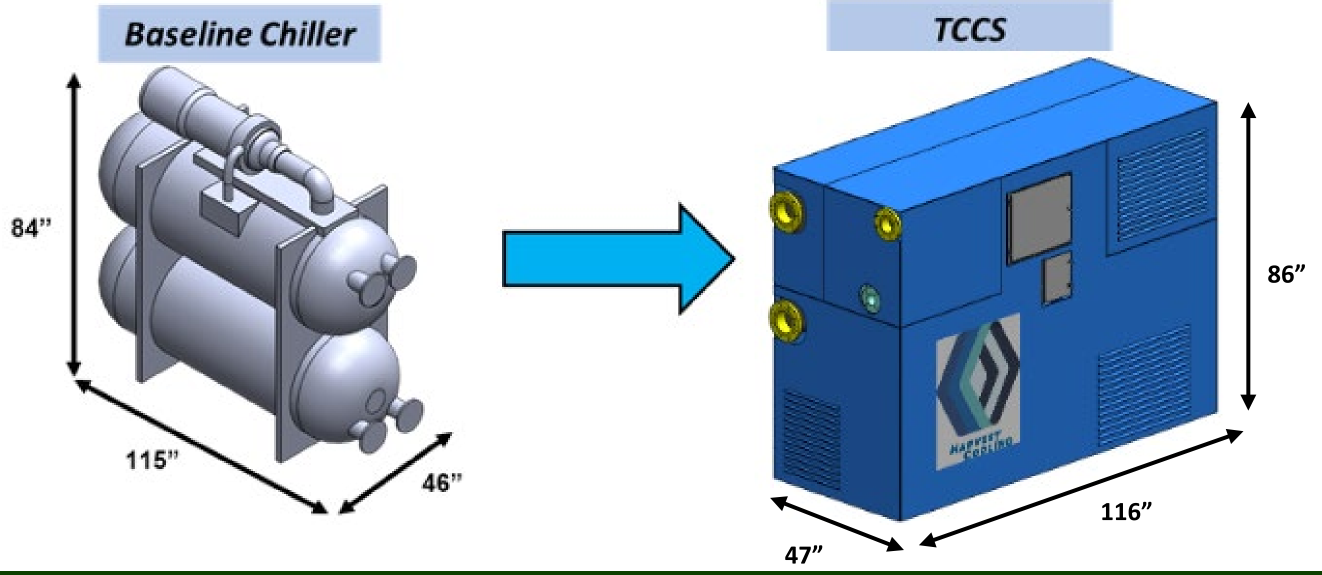

System	Baseline Chiller	TCCS
Nominal Cooling Capacity	200-tons	200-tons
System Weight	20,000 lbs	20,000 lbs
Annual Electricity Consumption	789,000 kWh	387,000 kWh

Acknowledgements

- **Funding Sources**
  - ARPA-e ARID Program
  - DOE EERE AMO Funding, DE-EE0008325
  - DOD STTR Phase I-II with US Navy
- **Project Partners**
  - Colorado State University
  - Barber-Nichols, Inc.
  - Modine Manufacturing Co.
  - Mantel Technologies
- **Key Advisers**
  - DOE: Bob Gemmer, John Winkel
  - BNI: Bob Fuller, Kevin Eisemann, Jeff Noall
  - Modine: Rob Bedard, Mike Reinke, Thomas Grotophorst

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