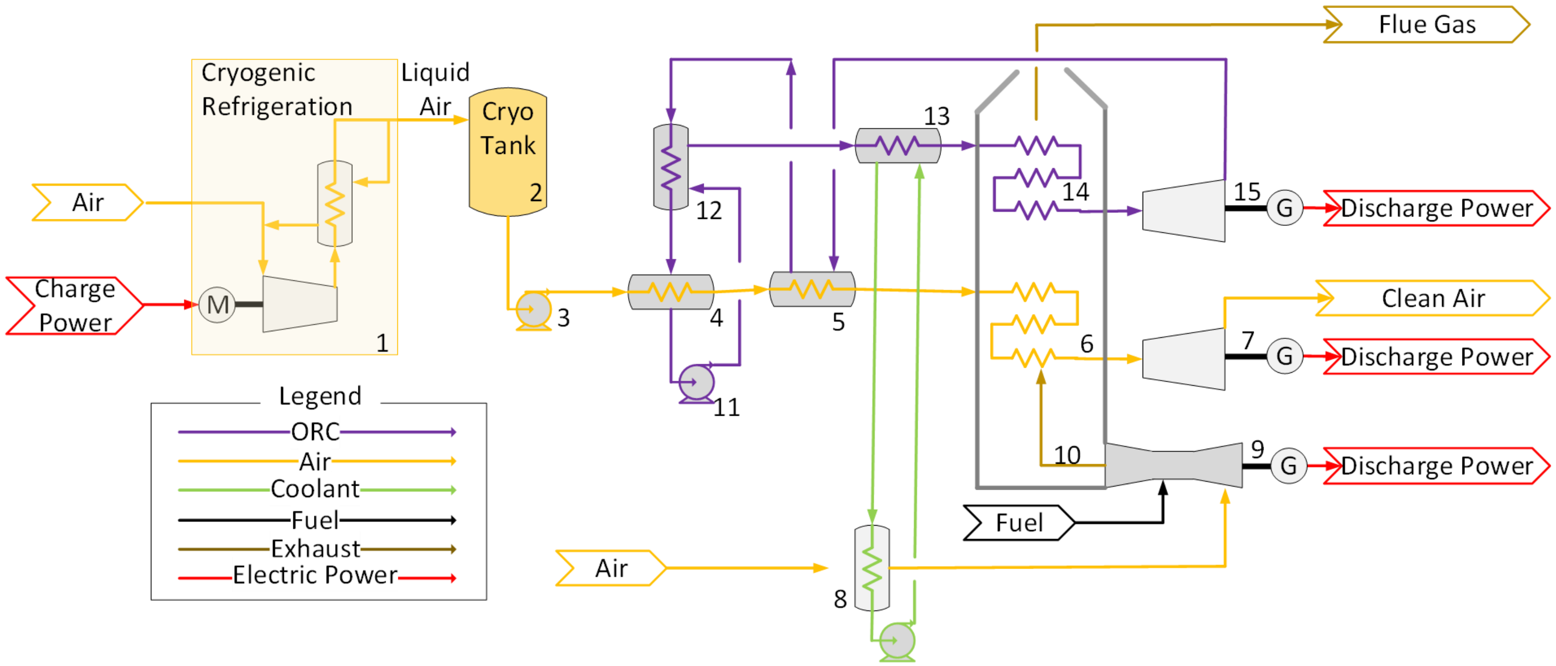
Liquid Air Combined Cycle (LACC) for Power and Storage

FECM Project Review Meeting
5 May 2022



Award No. DE-FE0032002

Southwest Research Institute
San Antonio, TX

PI: Mr. Aaron Rimpel
Dr. Owen Pryor
Dr. Aaron McClung
Dr. Tim Allison

Pintail Power LLC
Palo Alto, CA

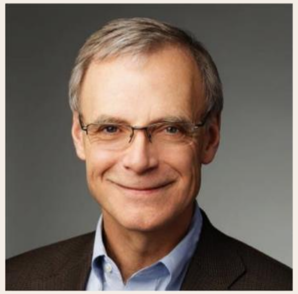
Co-PI: Dr. Bill Conlon
Mr. Milton Venetos

Project Team

(PI) Aaron Rimpel
Group Leader

Owen Pryor, Ph.D.
Research Engineer

- Project management
- Turbomachinery and HX sizing
- TEA data processing, optimization



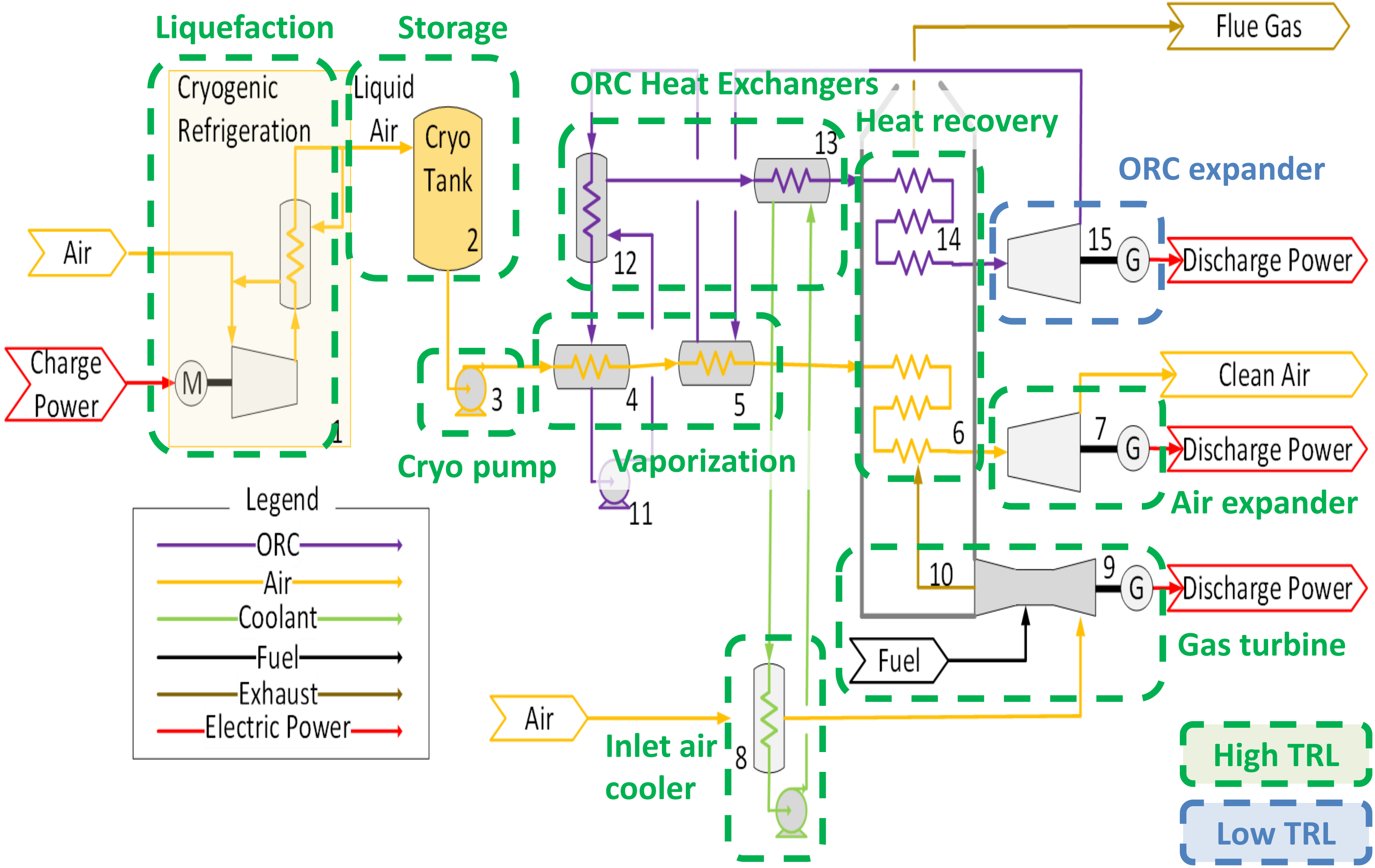
(Co-PI) Bill Conlon, Ph.D.
President

Milton Venetos
VP, Systems

- Technology
- Requirements analysis
- Performance modeling
- Manage subcontractor, Wood PLC

LACC can be applied to existing or new combustion turbine assets

- Advantages
  - Any CT
  - Site anywhere
  - High-TRL components
  - Valuable at large scale
  - Lower CAPEX
- DOE project objectives
  - Identify application
  - LACC conceptual design
  - Demo-scale LACC



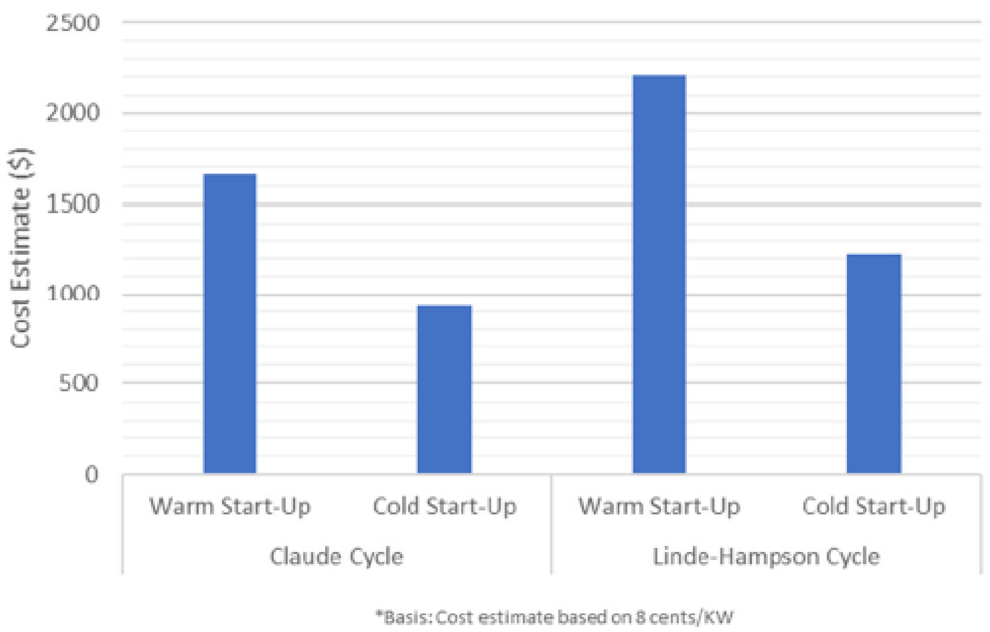
Capital and Operating Cost Trade-offs

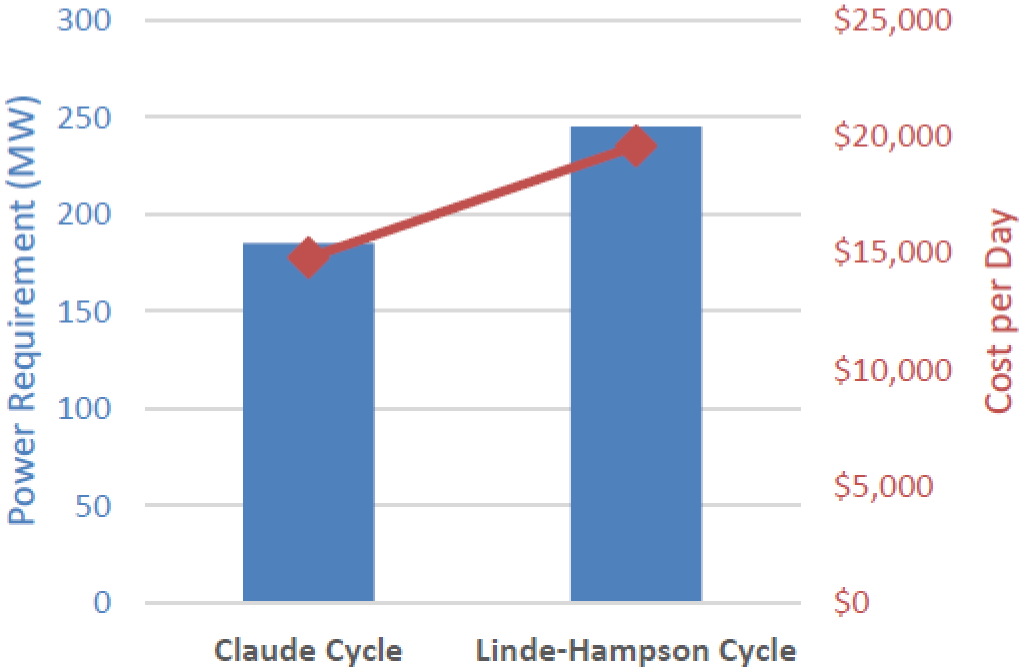
- Capital Cost ($): Discharge + Charge + Storage
  - $C_{ESS} = C_D + C_S + C_C$
- Cost of Energy Delivered ($/MWh)
  - Capital Cost of Energy: $\boldsymbol{CCOE}\ (\frac{\$}{MWh}) = \frac{c_{ESS} \text{ x } AF}{[8760\ (\text{hours/year}) \text{ x } P_D \text{ x } CF]}$
    - Amortization: $AF = \frac{i(1+i)^n}{(1+i)^n - 1}$, i = WACC, n = term
    - P_D: Discharge power (MW)
    - Capacity Factor: CF depends on marginal cost of energy and the market
  - Marginal Cost of Energy: $OC_{MCOE} = [\,FHR\ c_F + SER\ c_P\,]$
    - FHR: Fuel Heat Rate (MJ/MWh)
    - c_F: Cost of Fuel ($/MJ)
    - SER: Stored Energy Rate (MWh/MWh) – inverse Round Trip Efficiency
    - c_P: Cost of Energy used to charge storage tank ($/MWh)

Liquefaction System

- Claude Cycle vs. Linde-Hampson Cycle
  - Commercial size limits for single train
    - Motors < 75 MWe → 6,480 tonnes per day
  - Compared overnight capital costs, power consumption, reliability, operating costs, and additional expenses

	Claude Cycle	Linde-Hampson Cycle
Equipment Costs	$129.7MM	$612.1MM
Construction Costs	$324.0MM	$385.5MM
O&M Costs per year	$10.52MM	$12.24MM





Liquefaction System

- Claude Cycle recommended for LACC
  - Less complex
  - Higher power efficiency
  - Lower capital costs
  - Lower operating expenses and start-up costs

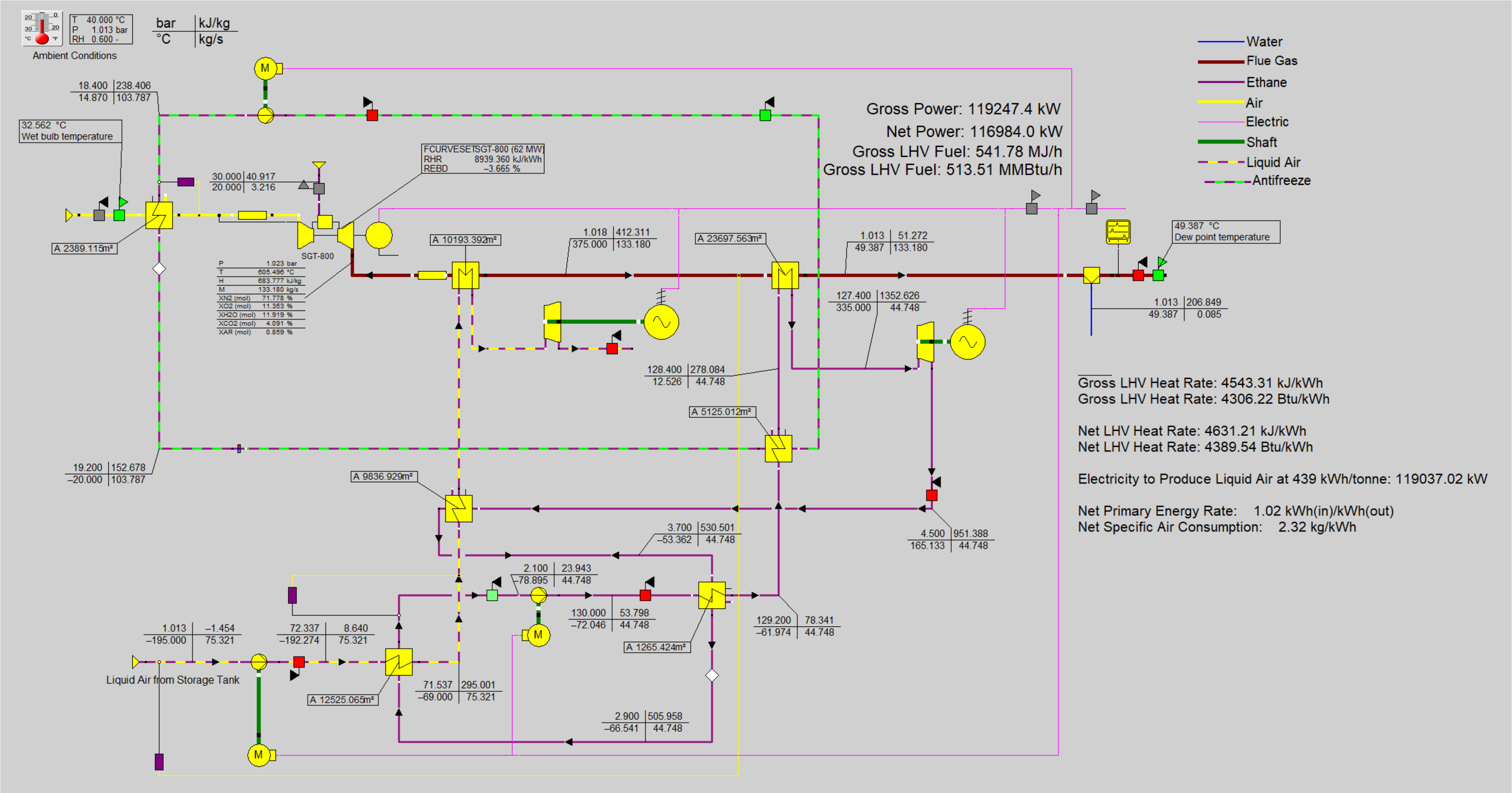
	Claude Cycle	Linde-Hampson Cycle
Feasibility	Feasible	Feasible
Reliability	High	High
Operability	Easy to Operate	Easy to Operate
Power Efficiency	Higher	Lower
Capital Costs	Lower	Higher
Operating Expenses	Lower	Higher
Additional Expenses	Licensing	Mixed Refrigerant & Licensing

Liquid Air Storage System

- Liquid air is an ideal storage medium
  - Zero-cost storage medium reduces CAPEX
  - Air is safe, non-toxic, and non-corrosive
  - Benefits from economy of scale

- Cryogenic Tanks
  - Known technology
  - Low loss: < 0.1% per day boil-off
  - \$360 to \$480 per m^3 for tanks between 100,000 to 200,000 m^3

LACC Discharge Cycle: Ebsilon Professional Model

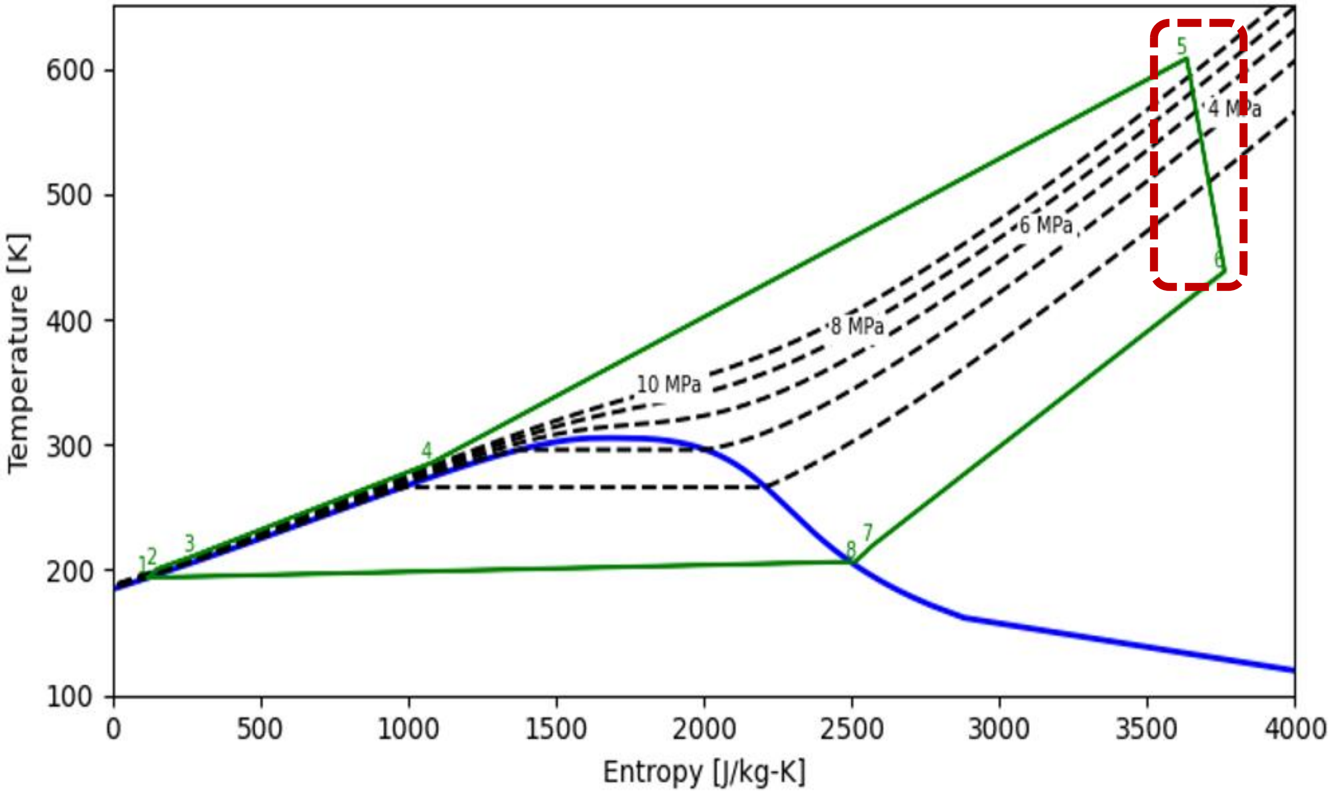


LACC Discharge Cycle: Trade Studies

- Trade studies
  - Gas turbine: Aero-derivative vs. **Heavy Frame**
  - Fuel: **Natural gas** vs. Hydrogen
  - ORC Working Fluid: **R-170 (ethane)** vs. R-290 (propane)
  - Ambient temperature: ISO vs. **Hot Summer Day (40°C)**
  - Inlet Air chiller coupling location: Vaporized air vs. **ORC**
- Reference plant
  - Net Power: 116,979 kW
  - Specific air consumption: 2.32 kg/kWh
  - Net Fuel Heat Rate: 5138 kJ/kWh HHV
  - Specific Cost: $1500/kW (ballpark)

ORC Discharge Cycle

- Radial and axial turbines were explored for the baseline case
- 3 heat exchangers were examined fir the air vaporizer, air preheater and ORC recuperator

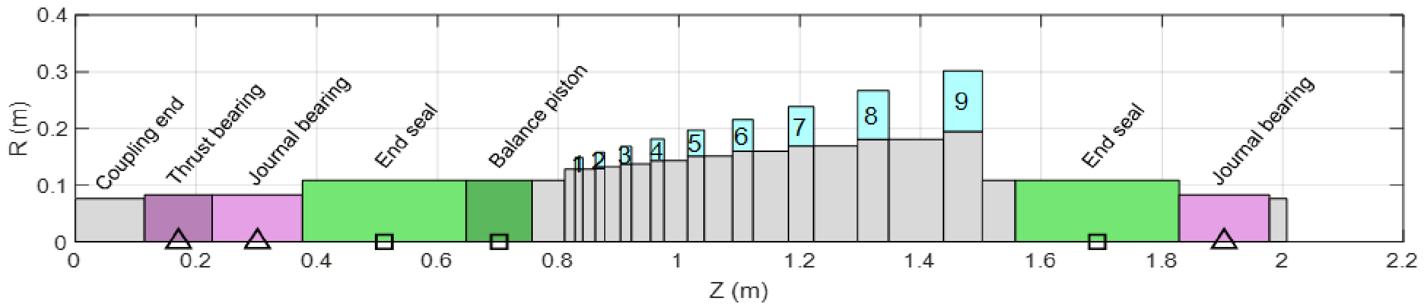


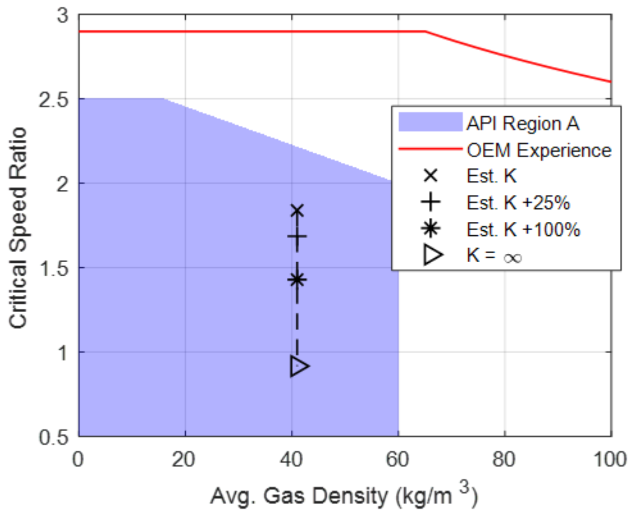
Turbine Inlet Conditions

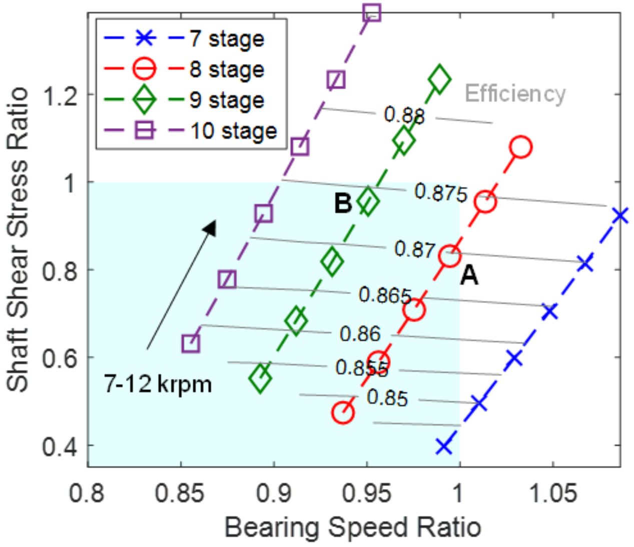
Inlet Total Pressure [MPa]	12.7
Inlet Total Temperature [K]	608
Outlet Total Pressure [MPa]	0.45
Mass Flow Rate [kg/s]	44.7
Fluid Composition	Ethane

ORC Axial Turbine

- Conceptual aero sizing based on Balje plot correlations
- Rotor layout based on assumed dimension ratios
- Screening criteria
  - Shaft stress (torque)
  - Surface velocities
  - Bearing unit loads
  - Rotordynamic stability

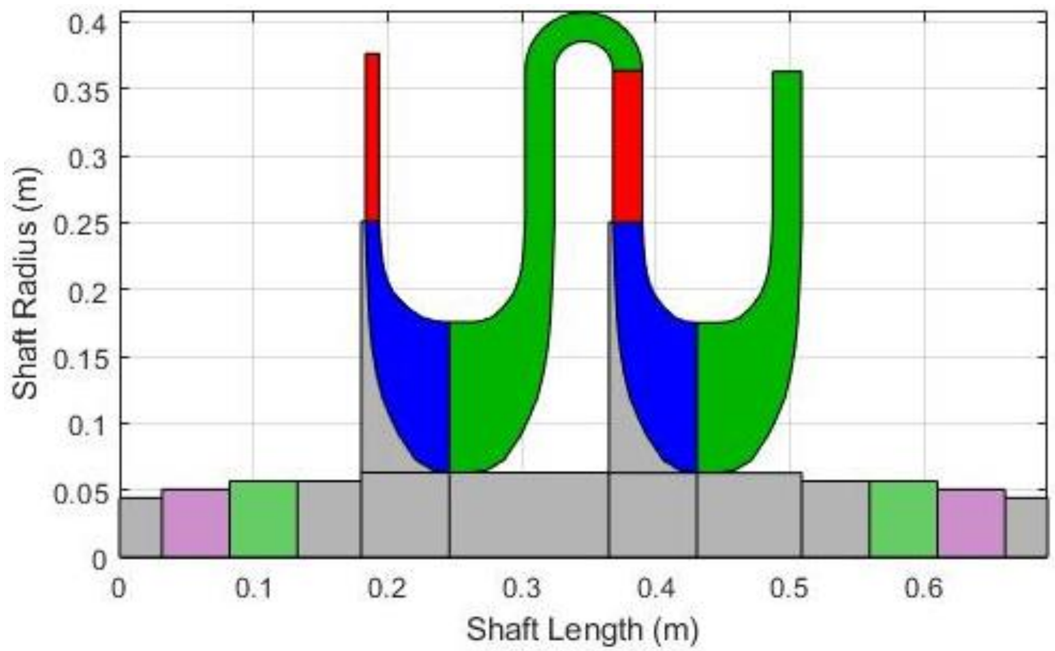


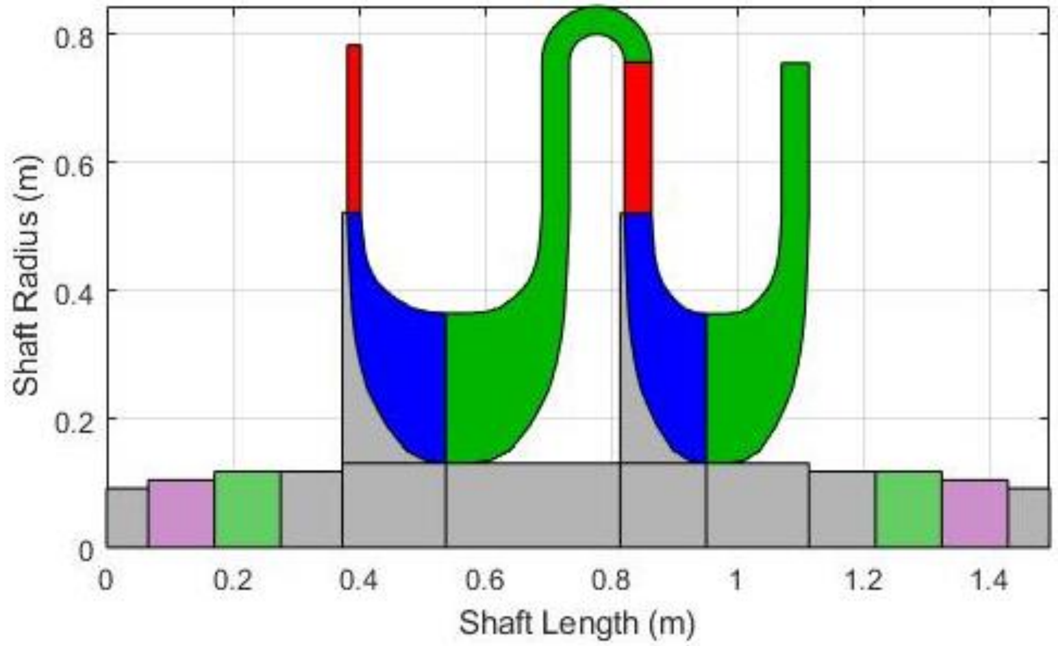




ORC Radial Turbine

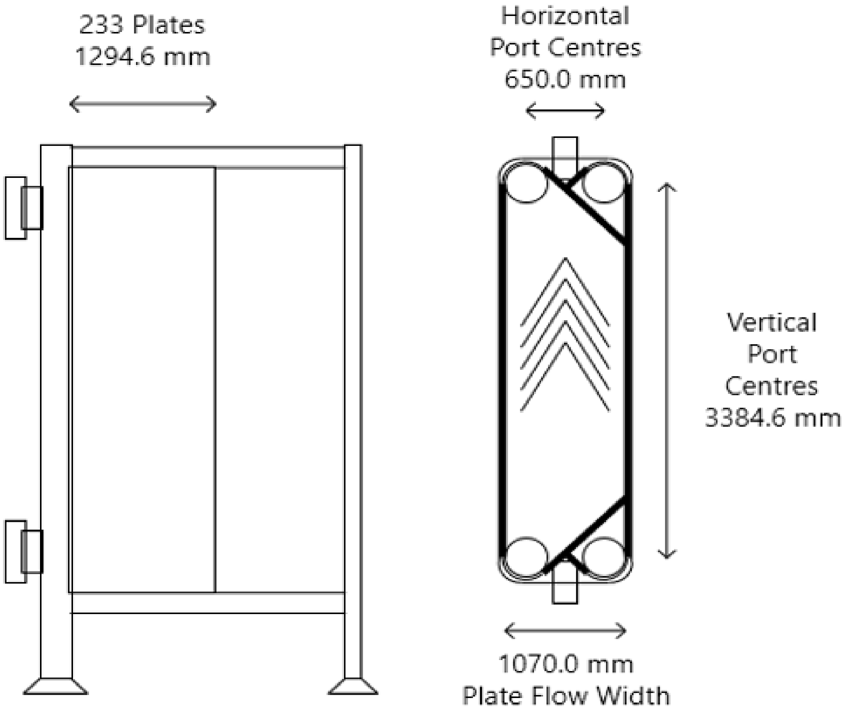
- Two-shaft, each with 2 stages, solution was created using the NASA RTD Code
  - Aerodynamic Efficiencies for each stage over 93%
  - 1st Shaft: 26.5 krpm, 9.64 MW
  - 2nd Shaft: 11.5 krpm, 7.98 MW

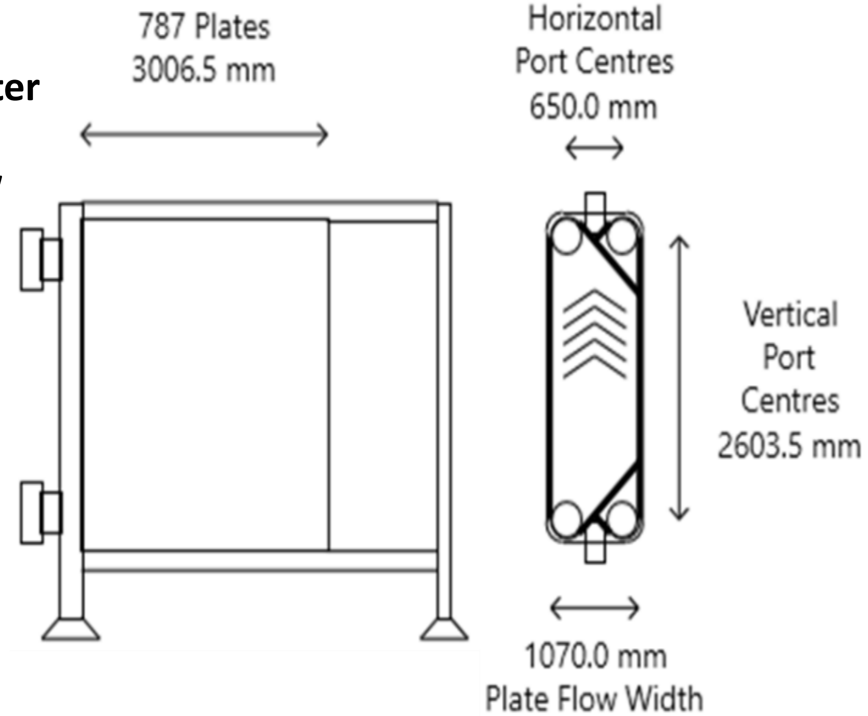




ORC Heat Exchangers

- The air vaporizer, ORC recuperator and air-preheater have been sized for the baseline conditions
  - Material – Stainless Steel
  - Types of heat exchangers: Plate-fin, gasketed plate and shell-and-tube





System Cost Modeling

- Multiple charge and discharge trains were evaluated
  - All arrangements would reduce installed costs by more than 90% compared to Li-ion batteries

Number of Tanks	1	1	2	4
Number of Charge Trains	1	1	2	2
Number of Discharge Trains	1	8	8	16
Power (MW)	117	936	936	1,872
Energy (GWh)	75	75	150	300
Duration (h)	650	80	160	160
Capital Costs ($MM)	$709	$2,018	$2,541	$4,181
Cost of Electricity ($/kW)	$6,062	$2,156	$2,714	$2,234
Cost of Energy ($/kWh)	$9.46	$26.91	$16.94	$13.94

Future Work

- Finalize the discharge cost model and trade studies
- Demonstration-scale conceptual design of LACC
  - Lab-scale ORC cycle demonstration
  - 10 MW scale discharge cycle
- Commercial-scale conceptual design of LACC
  - Use for market assessment
- Hydrogen Fuel
  - Cycle modification to recover/recycle water of combustion

Summary & Conclusions

- Technically feasible
- Economically attractive at very large scale
- Initial results to be presented at ASME GT2022
  - 80426 Liquid Air Combined Cycle (Conlon, Venetos, Rimpel)
  - 82263 Organic Rankine Cycle Turbine and Heat Exchanger Sizing for Liquid Air Combined Cycle (Pryor, Rimpel, Conlon)

Acknowledgement & Disclaimer

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Questions?

Aaron Rimpel
aaron.rimpel@swri.org

William Conlon
bill.conlon@pintailpower.com