Development of a High Efficiency Hot Gas Turbo-expander and Low Cost Heat Exchangers for Optimized CSP Supercritical CO_2 Operation

Southwest Research Institute

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Phase I – Quarter 2

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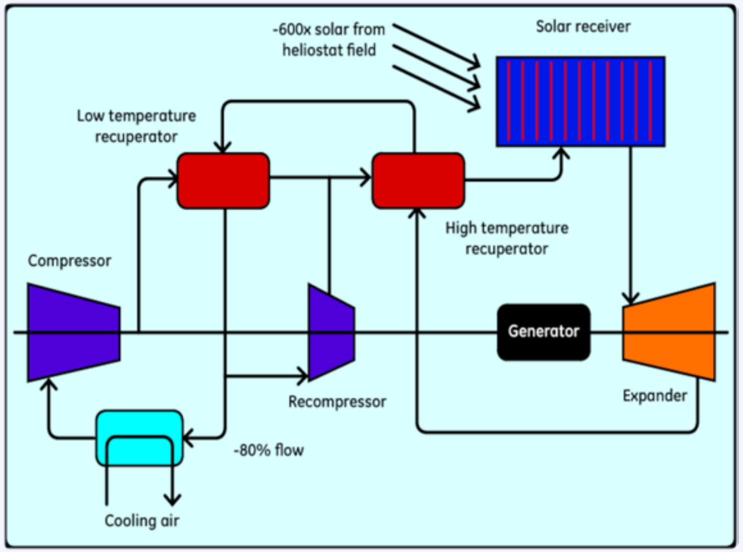
Other Contributors: General Electric

Thar

Knolls Atomic Power Lab



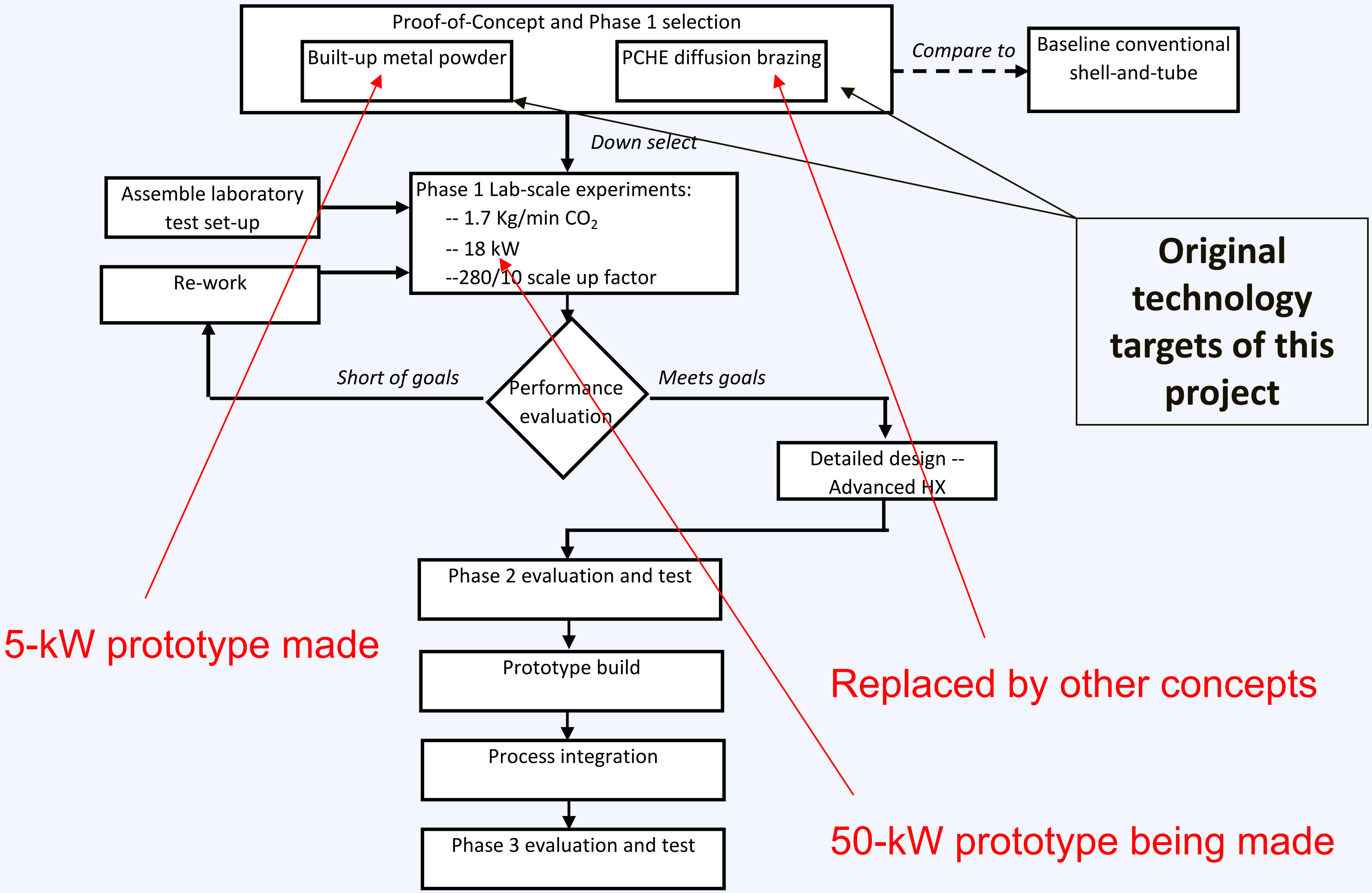
Project Objectives

- To develop a novel, high-efficiency supercritical sCO_2 turbo-expander optimized for the highly transient solar power plant duty cycle profile.
  - This MW-scale design advances the state-of-the-art of sCO_2 turbo-expanders from TRL3 to TRL6.
- To optimize compact heat exchangers for sCO_2 applications to drastically reduce their manufacturing costs.
- The turbo-expander and heat exchanger will be tested in a 1-MWe test loop fabricated to demonstrate component performance and endurance.
- The scalable sCO_2 expander design and improved heat exchanger address and close two critical technology gaps required for an optimized CSP sCO_2 power plant and provide a major stepping stone on the pathway to achieving CSP power at $0.06/kW-hr levelized cost of electricity (LCOE), increasing energy conversion efficiency to greater than 50% and reducing total power block cost to below $1,200/kW installed.

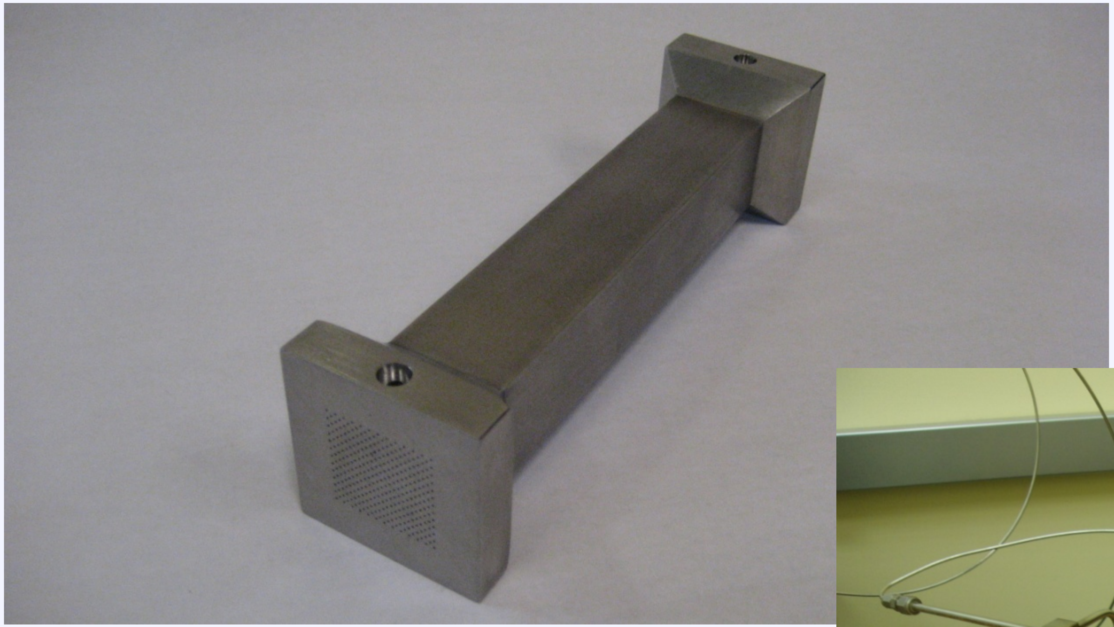
Project Approach

- Work has been divided into three phases that emulate development process from TRL3 to TRL6
- Phase I – Turbomachinery, HX, and flow loop design (18 months)
- Phase II – Component fabrication and test loop commissioning (12 months)
- Phase III – Performance and endurance testing (6 months)

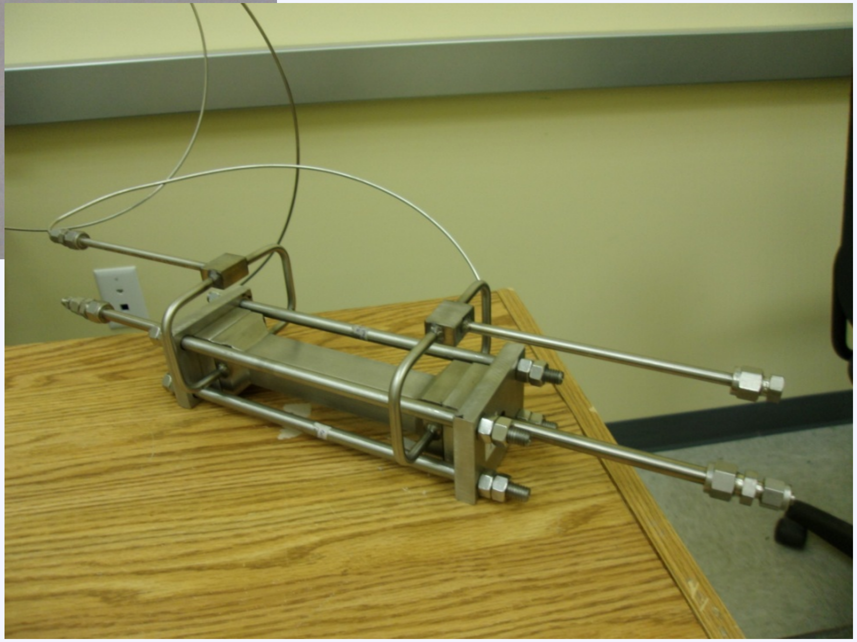
Heat Exchanger Design – Changes to Scope



5-kW DMLS Prototype



Expensive and slow to build
-- but highly automated



Pressure tested to 7,250 psi
Performance testing ongoing at KAPL

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Second Prototype

- Key Figures of Merit:
  - Areal density greater than 1,500 m2/m3
  - Cost less than $50 kWt
  - Opacity (cross-sectional metal area) less than 35%
- Design concept
  - Not diffusion bonded PCHE
  - Automated manufacturing
  - Retains checkerboard flow concept of Prototype 1
  - No cross-flow pattern; all counter-flow
  - Unique header configuration

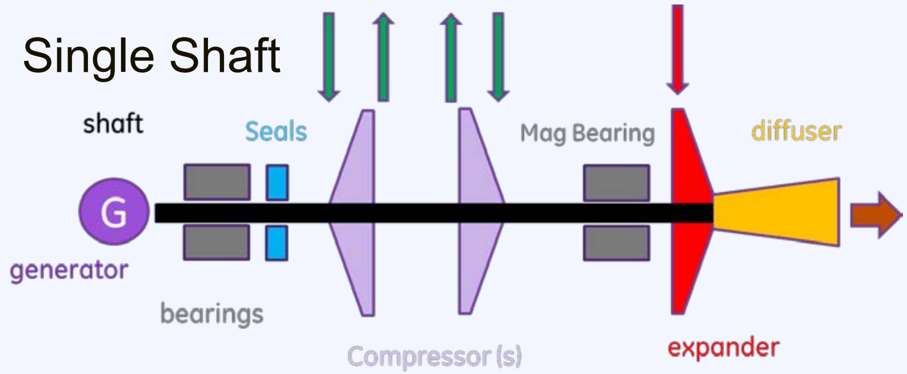
Turbomachinery Concepts

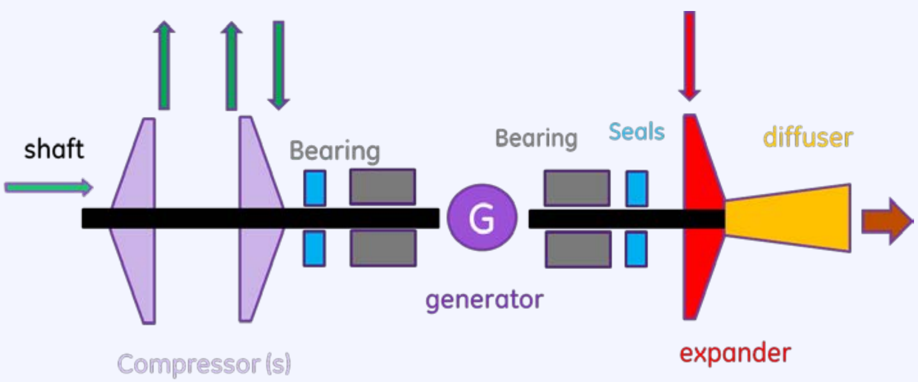
- Concepts being explored include high-speed, low-speed, and geared layouts.

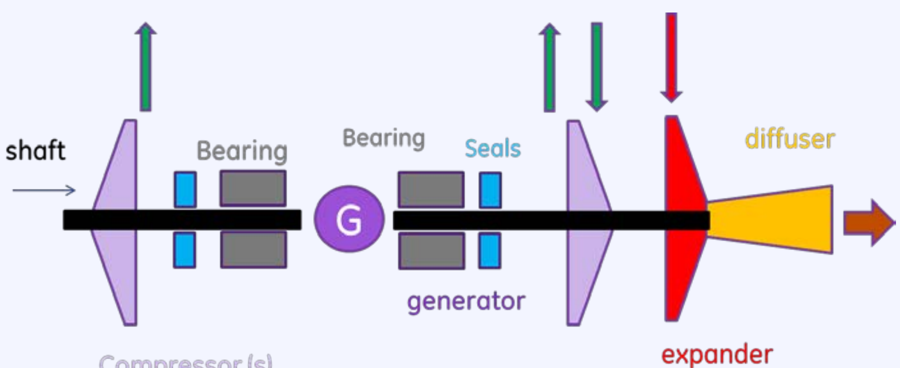
Option	Generator	Compressor	Turbine	RPM
High-speed, Optimal	A. IC B. PM	A. Single-stage centrifugal B. Multi-stage pump	A. Radial B. Axial	Optimized for compressor
High-speed, expander only	A. IC B. PM	None	A. Radial B. Axial	Optimized for expander
High speed, Geared	A. IC B. PM C. 3,600 rpm	A. Single-stage centrifugal B. Multi-stage pump	A. Radial B. Axial	Both expander and compressor run at optimal speed
3,600 rpm – integrated	3,600 rpm	Multi-stage pump or compressor	Multi-stage Axial at 3,600 rpm	3,600 rpm
3,600 rpm – expander only	3,600 rpm	None	Multi-stage Axial at 3,600 rpm	3,600 rpm

Turbomachinery Concepts

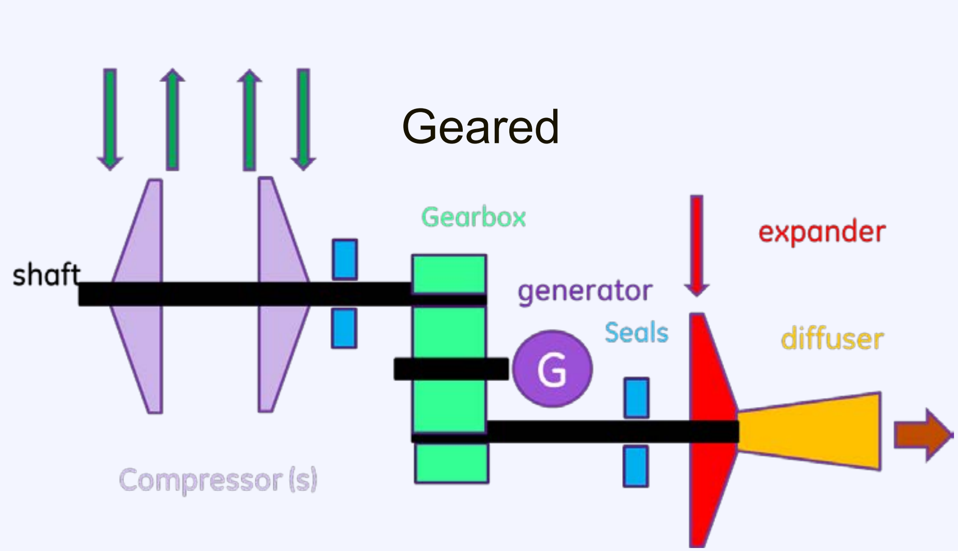
Single Shaft



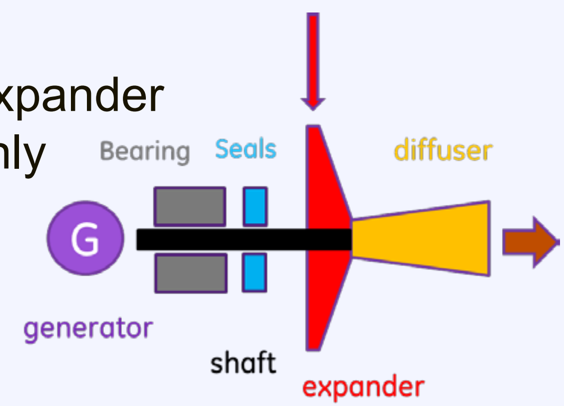




Geared



Expander only



Analysis completed

Generator Design

- Low-speed Synchronous
  - Low cost
  - Commercially available
  - Need to be combined with gearbox
- High-speed
  - May drive turbomachinery directly or use small gearbox if needed
  - Limited to 20,000 rpm
  - Lighter than low-speed option
  - More expensive

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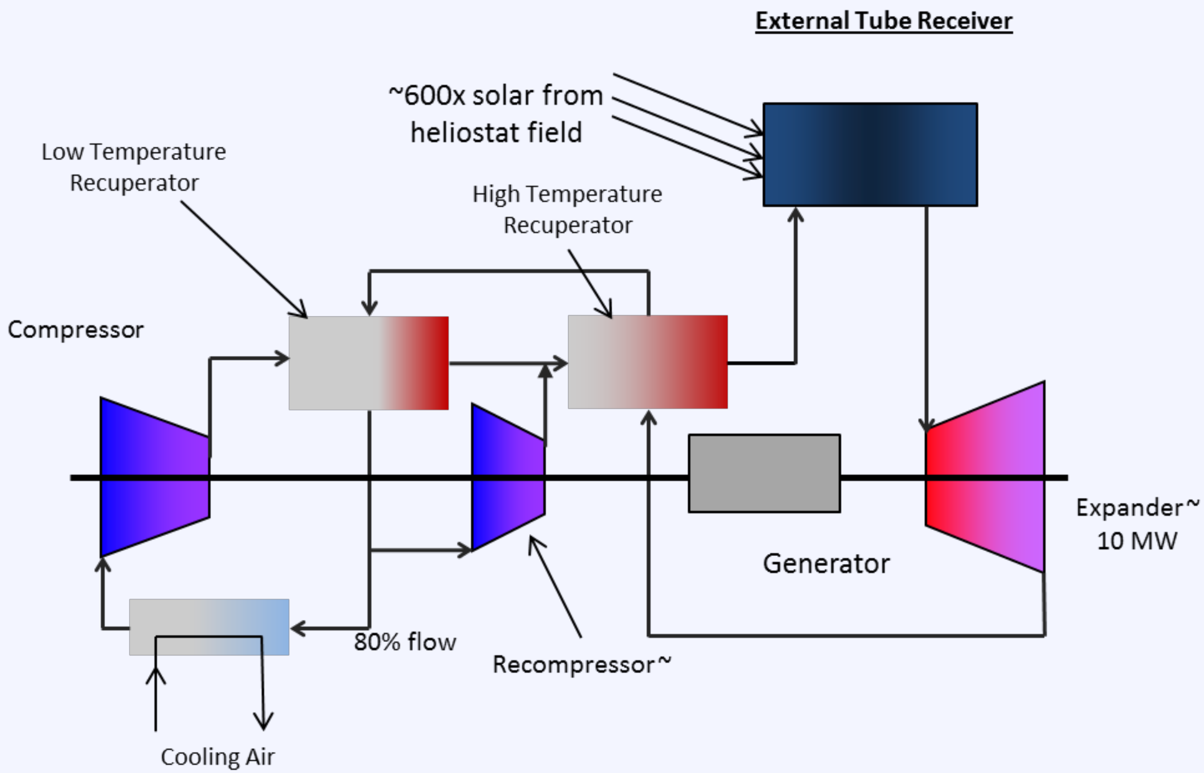
Test Loop Design

- Recompression Supercritical CO_2 Cycle Model

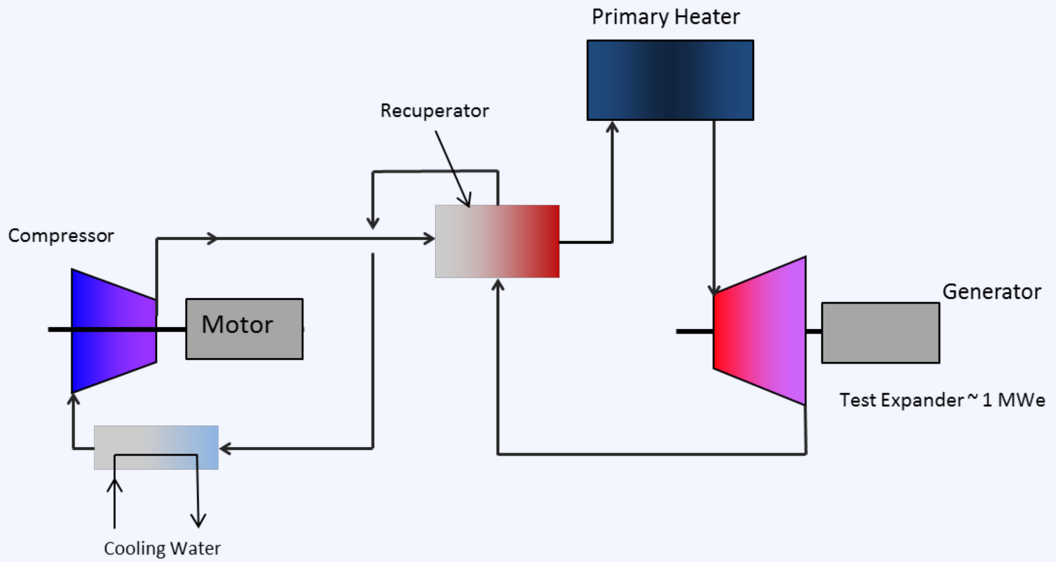
The proposed CSP system uses sCO_2 as both, the heat transfer fluid and the working fluid.

Note: Wet cooling is used to use existing heat exchanger.



Test Loop Design

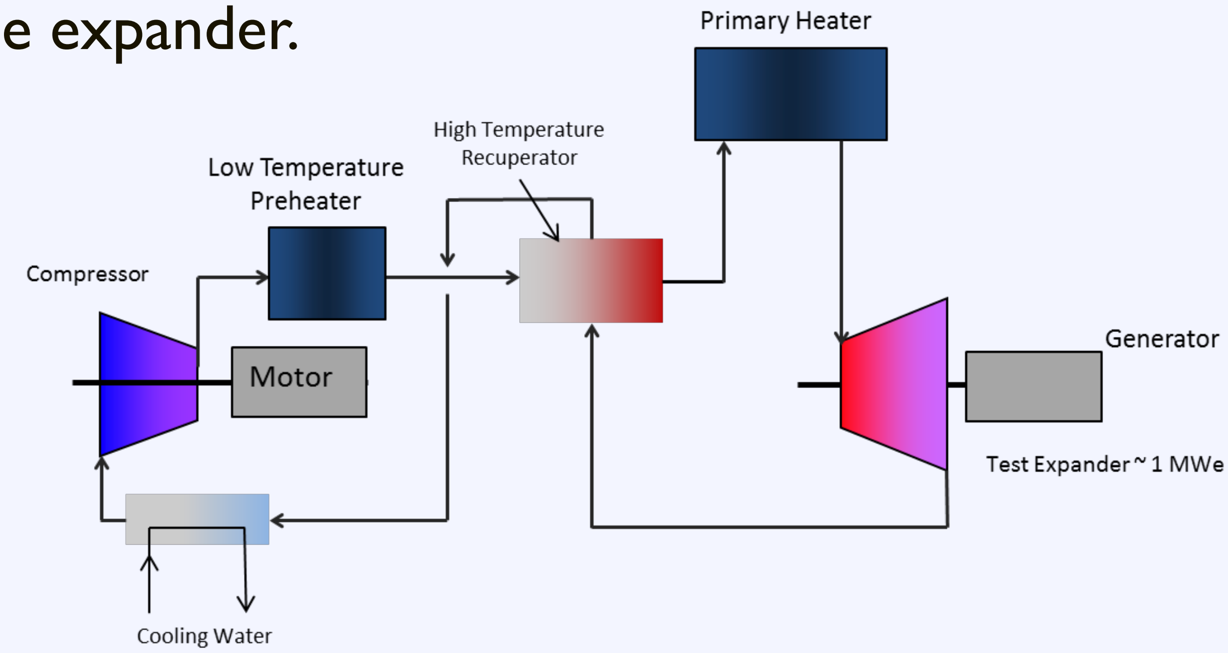
- First configuration was a simple cycle with a primary recuperator and an external heater (electric or gas fired) to provide high temperature and high pressure CO_2



- Limited flexibility with respect to recuperator testing.
- It may not be possible to replicate exactly the conditions of the high-temperature recuperator in the recompression cycle.

Test Loop Design

- A low-temperature heater is added before the recuperator to replicate the recompression loop and low temperature recuperator.
- This significantly extends the recuperator test conditions while providing a reliable test environment for the 1 MWe scale expander.



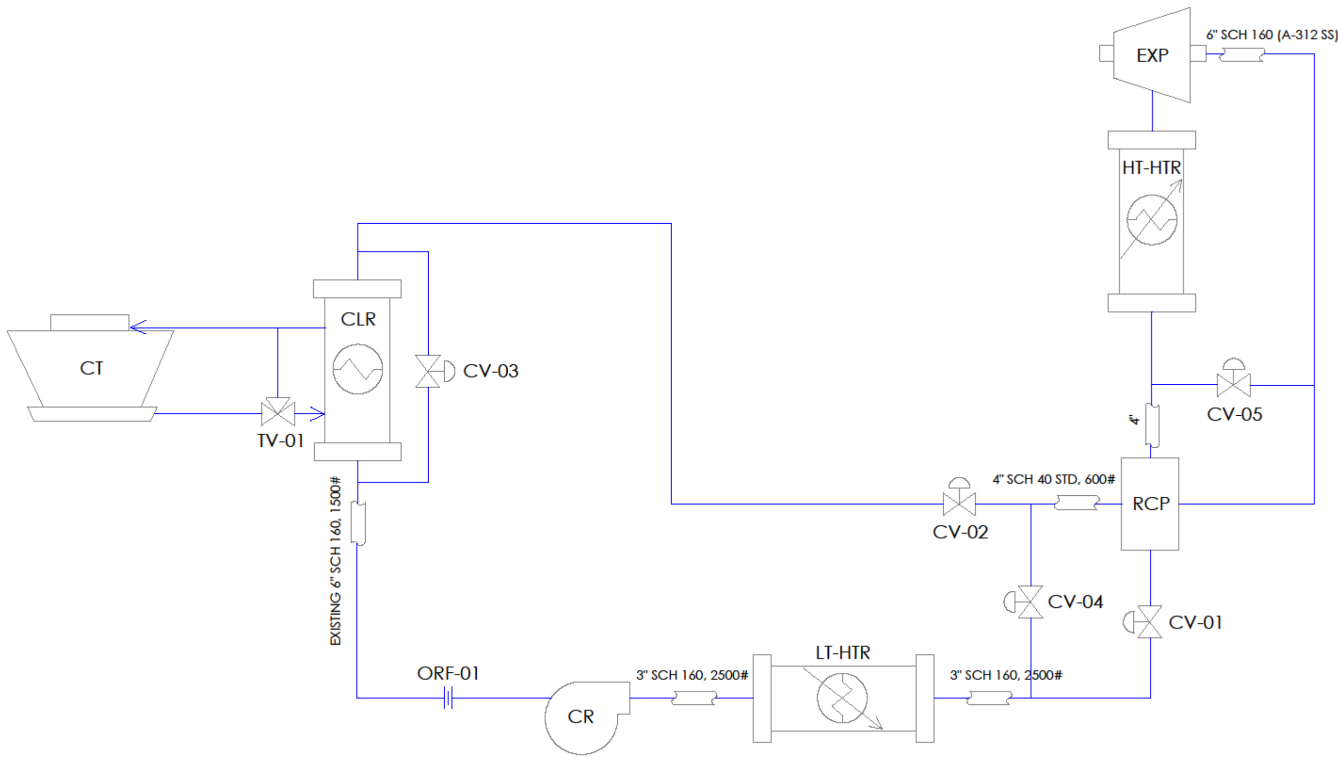
Equipment Procurement

- Supercritical CO_2 pump/compressor
  - Contacted several companies to obtain quotes
  - Several pump companies indicated our conditions were outside the capabilities of their current products
    - Recommend to reduce temperature or increase inlet pressure
    - Need to consider impact in the cycle
  - Also considering integrating compressor into the turbine design

Equipment Procurement

- Heater
  - heat CO_2 from 1000-1200 F at 4500 psi
  - Resistive heaters:
    - Screen heaters available up to 2500 F/ 5000 psi
    - Heater and power conditioner are expensive
  - Electric heaters may require some R&D effort to work with sCO2
  - Gas fired solution may be less expensive and is being investigated

P&ID



EQUIPMENT LIST

Component	Symbol	Description
Compressor	CR	
Recuperator	RCP	
High temp. heater	HT-HTR	
Low temp. heater	LT-HTR	
Expander	EXP	
Cooler	CLR	Shell-and-tube; 1500# flanges
Cooling tower	CT	800 gpm, 83°F cold water
Control valve	CV-01	
Loop throttle	CV-02	
Cooler bypass	CV-03	3" Dyna-Flo, 900#
Recuperator bypass	CV-04	
Heater bypass	CV-05	
Cooling water bypass	TV-01	
Orifice flow meter	ORF-01	

OPERATING CONDITIONS

Component	T in (°F [°C])	T out (°F [°C])	P in (psi [bar])	P out (psi [bar])
CR	127 [53]	240 [115]	1168 [80.5]	3698 [255]
LT-HTR	240 [115]	410 [210]	3698 [255]	3684 [254]
RCP-H	410 [210]	1034 [557]	3684 [254]	3655 [252]
HT-HTR	1034 [557]	1320 [715]	3655 [252]	3640 [251]
EXP	1320 [715]	1049 [565]	3640 [251]	1211 [83.5]
RCP-L	1049 [565]	419 [215]	1211 [83.5]	1182 [81.5]
CLR	419 [215]	127 [53]	1182 [81.5]	1168 [80.5]

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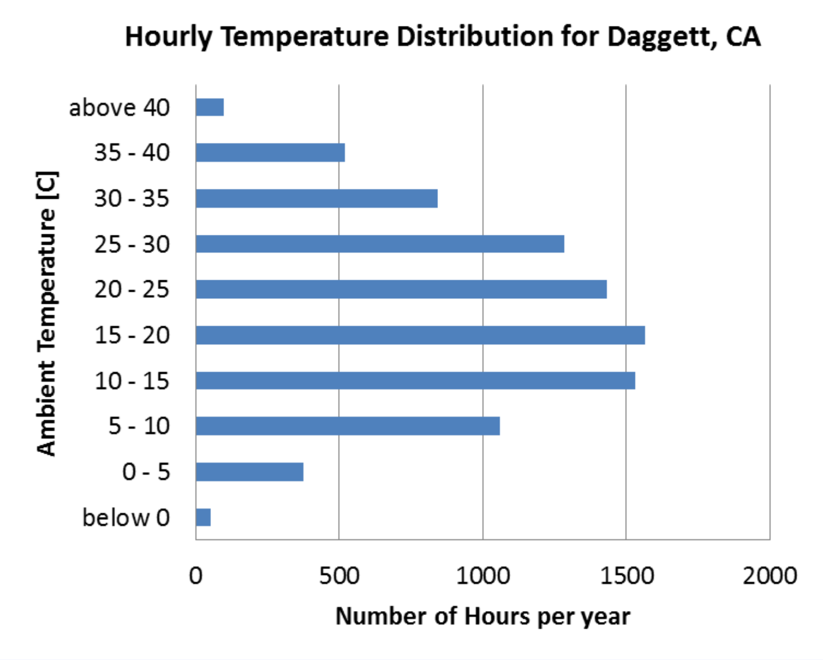
CSP Expander Test Loop

Rev 06

A2

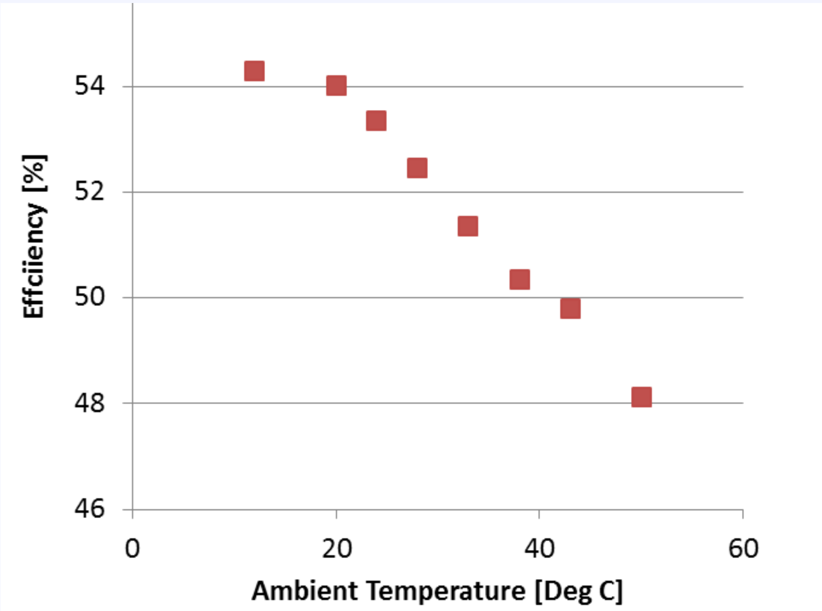
Thermo-economic Cycle Analysis

- Initial assessment uses Dagget, CA as the possible location for a CSP plant.
- For cooling purposes, the program calls for air at 43 C to achieve 50% efficiency.
- However, 24 C is a more realistic temperature for this location



Thermo-economic Cycle Analysis

- At 24 C, the power block will have an efficiency of 54%
- At 43 C, the efficiency will be 50%, thus meeting the program goals



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Future Work

- Test heat exchanger prototypes
- Heat exchanger CFD
- Down-select Turbomachinery Layout
- Complete Aero design
- Procure long lead items for expander and test loop
- Finalize test loop design