DEVELOPMENT OF A 1 MWE SUPERCRITICAL CO_2 BRAYTON CYCLE TEST LOOP

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Project Objectives

- To develop a novel, high-efficiency supercritical CO_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.
- Turbine is designed for 10 MW output in order to achieve industrial scale
- 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
- 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.
- DOE established these goals to make CSP competitive with other energy sources

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 (22 months)
- Phase II – Component fabrication and test loop commissioning (12 months)
- Phase III – Performance and endurance testing (6 months)

Test Loop Layout and Integration

- DOE selected 1-MWe test loop size which offers balance between cost and benefit
- The test loop layout has been designed with the intent of minimizing thermal stress, and maximizing use of existing infrastructure
- Loop piping and components will make use of the recently completed Turbomachinery Research Facility at SwRI
- The test loop is designed around the main and supporting components: expander, heater, pump, compressor, cooler, and dyno
  - Custom engineered air dynamometer will absorb the power produced by the expander during testing

Sunshot Goals

- The Sunshot program is funded by the Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy (EERE) SunShot office under the CSP power block Funding Opportunity Announcement (FOA).
- Co-funding is provided by our partners General Electric, Thar Energy, and Bechtel Marine.
- The thermal-to-electric efficiency of current CSP plants is 35 to 45% (DOE, 2012).
- The goal of this program is to meet these aggressive performance and cost goals:
  - Net cycle efficiency > 50%
  - Dry cooled
  - Cost < $1,200/kWe

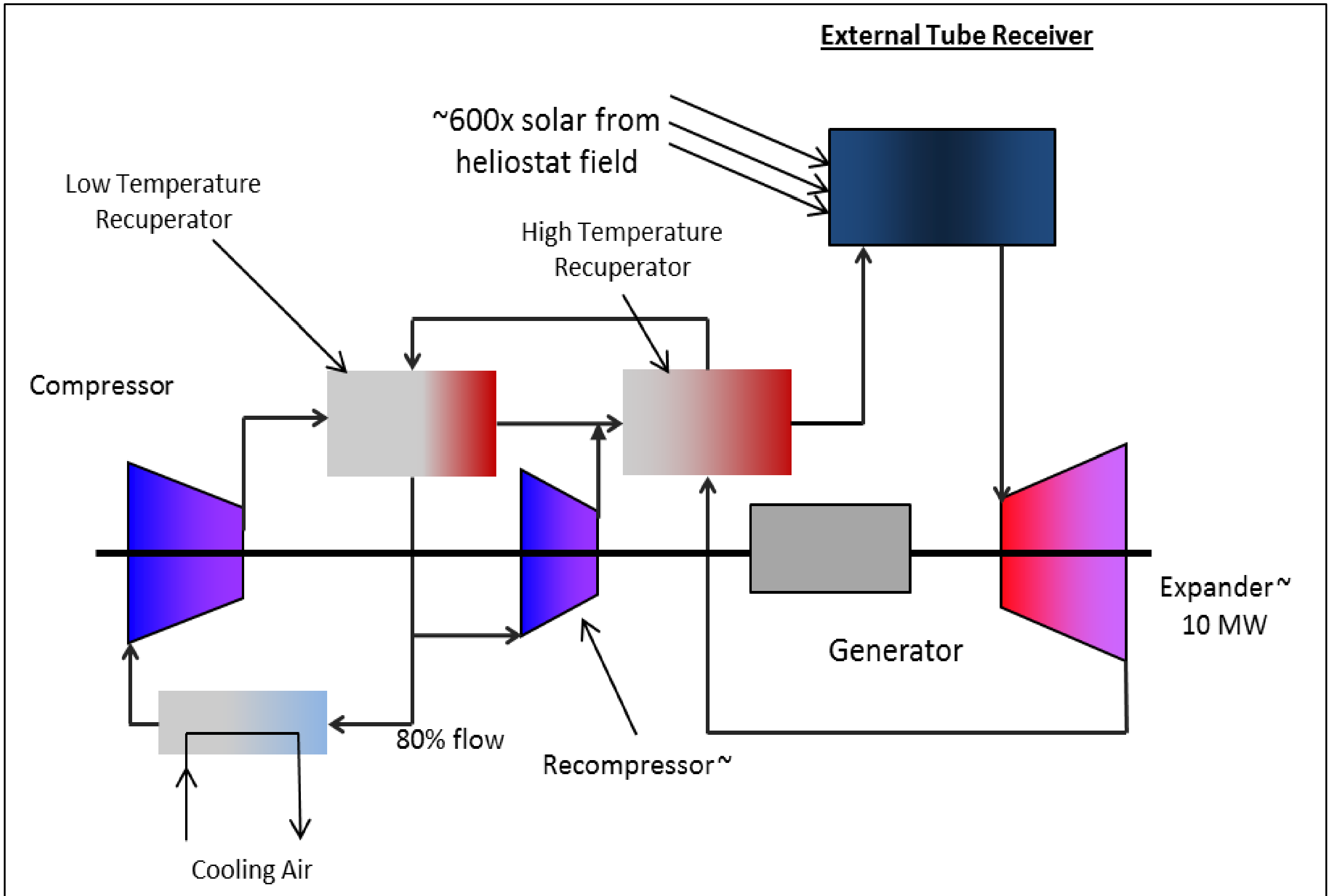
Project Work Breakdown

- Southwest Research Institute (SwRI) in collaboration with General Electric and Thar Energy was awarded a Phase I award on the design and development of these tasks:
- Design Supercritical CO2 Brayton Cycle Power block to achieve FOA goals
- Proposed modular power block in 10 MWe range to meet CAPEX targets
- Compact power block for pre-fabricated tower mounted operation
- SwRI scope includes test loop design and operation, assist GE with expander engineering, manufacturing drawings, and expander fabrication.
- GE is responsible for the power block design, thermo-economic analysis, and test loop cycle design.
- GE to design the sCO2 turbo-generator to meet FOA targets.
- Thar Energy to design recuperator for the power block meeting the FOA efficiency and cost targets.
  - 30% reduction in recuperator cost from current state-of-the-art

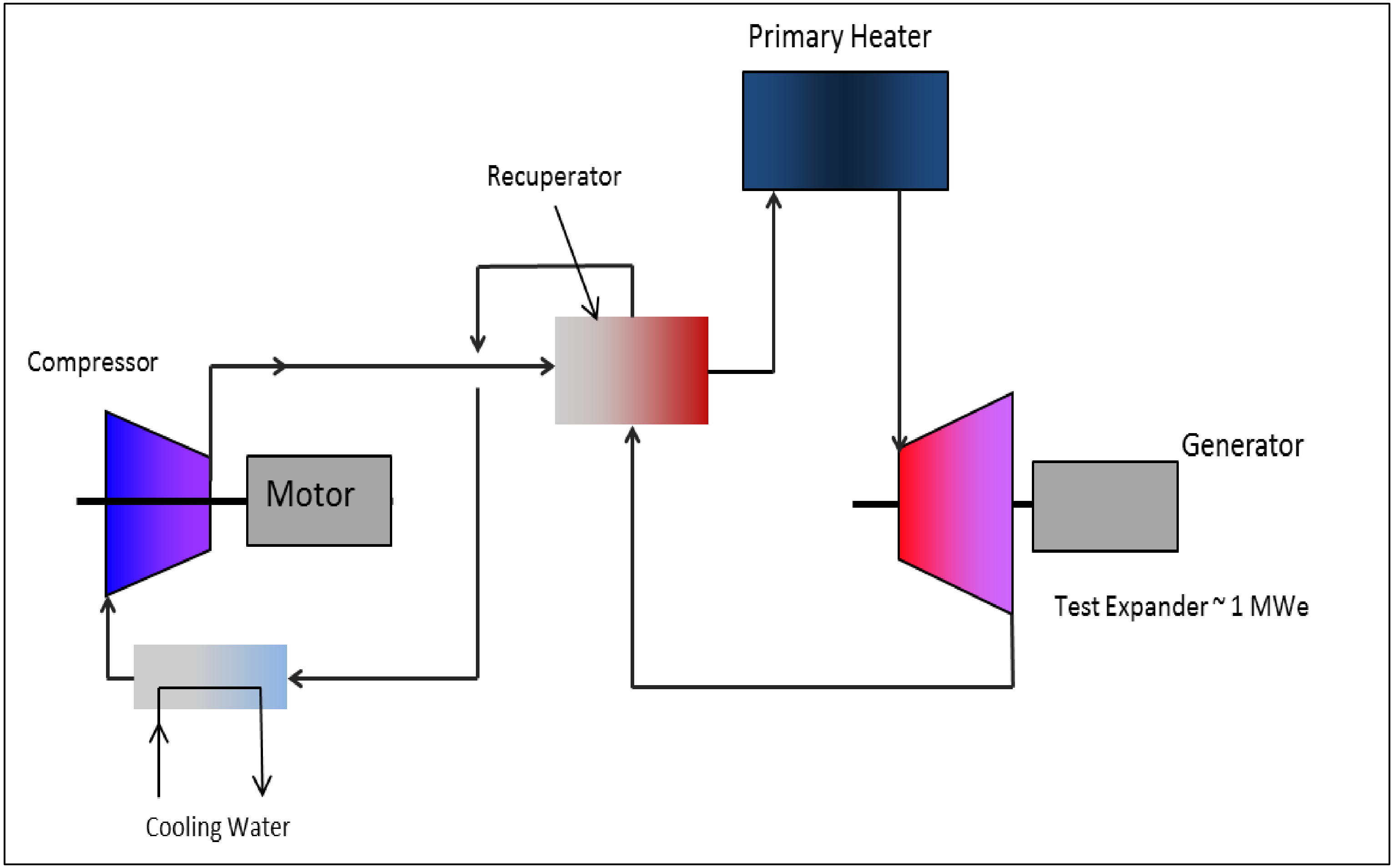
Project Work Breakdown Schedule

22 months	12 months	6 months
Phase 9/12 – 7/14	Phase 2 8/14 – 8/15	Phase 3 8/15 – 2/16
• **Test loop design & component/vendor identification (1 MWe)**	• Test loop fabrication	• Expander assembly and shake-down testing Expander testing off-design at 1MWe scale.
• **Expander engineering**	• (1 MWe)	• Recuperator testing at 5MW-th scale.
• **Test loop and expander manufacturing drawings**	• Expander fabrication	
• **Recuperator design and bench scale testing**	• Recuperator fabrication.	
	• Test loop assembly	

Recompression sCO2 Cycle



Simple sCO2 Recuperated Cycle for Test Loop



Loop Operating Conditions

<table>
<tr><th>Component</th><th>T out (°C[°F])</th><th>P out (bar [psi])</th><th>Flow (kg/s [lb/s])</th></tr>
<tr><td>Pump</td><td>29.22 [84.60]</td><td>255.0 [3698]</td><td>9.910 [21.85]</td></tr>
<tr><td>Recuperator-Heat</td><td>470.0 [878.0]</td><td>252.3 [3659]</td><td rowspan="3">8.410 [18.54]</td></tr>
<tr><td>Heater</td><td>715.0 [1319]</td><td>250.9 [3639]</td></tr>
<tr><td>Expander</td><td>685.7 [1266]</td><td>86 [1247]</td></tr>
<tr><td>Recuperator-Cool</td><td>79.58 [175.2]</td><td>84 [1218]</td><td rowspan="2">9.910 [21.85]</td></tr>
<tr><td>PreCooler</td><td>10.00 [50.00]</td><td>83 [1204]</td></tr>
</table>

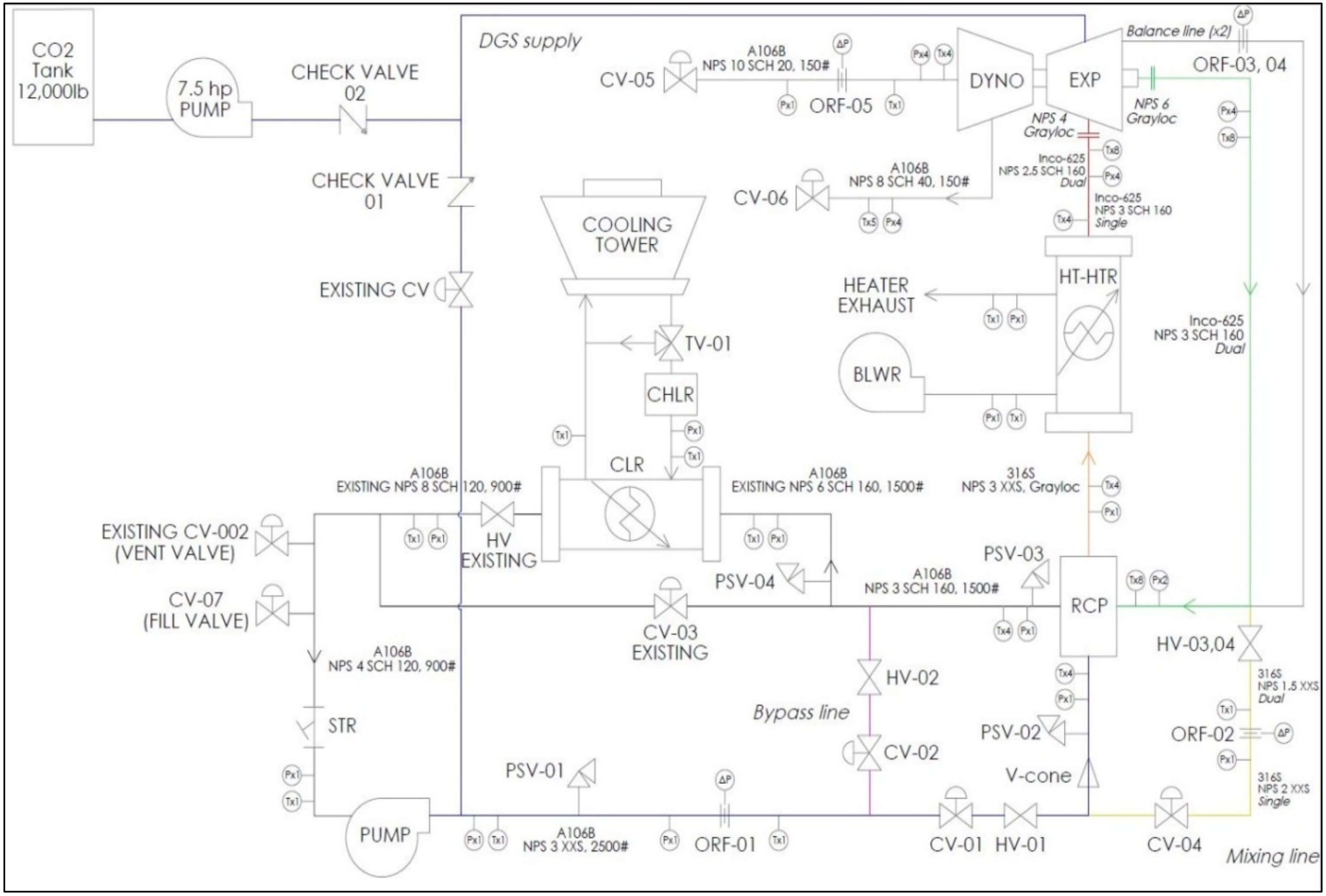
Pipe Specifications

Section	NPS	Schedule	Thickness	Material	Predicted V (ft/s)	Flanges
Pump out	3	XXS	0.6	A106B	13.07	ANSI 2500#
Mixing line	1.5	XXS	0.4	316s	28.56	ANSI 2500#
Recuperator hot out	3	XXS	0.6	316s	59.19	Grayloc
Heater out	3	160	0.438	Inco 625	62.26	Grayloc
Heater out dual	2.5	160	0.375	Inco 625	47.47	Grayloc
Expander out double	3	160	0.438	Inco 625	84.73	Grayloc
Recuperator cool out	3	160	0.438	A106B	54.13	ANSI 1500#
6” to cooler	6	160	0.718	A106B	13.84	ANSI 1500#
Cooler out	8	120	0.718	A106B	1.37	ANSI 900#
Pump inlet	4	120	0.437	A106B	5.39	ANSI 900#

P&ID Equipment List

Component	Symbol	Description
Pump	PUMP	$sC0_2$ pump: GE Nuovo Pignone
Recuperator	RCP	Heat exchanger: Thar Energy
Heater	HTR	Gas-fired heater: Thar Energy
Blower	BLWR	Heater air supply blower
Expander	EXP	$sC0_2$ turbine: GE
Dynamometer	DYNO	Load absorbing centrifugal compressor: SwRI
Chiller	CHLR	800 gpm cold water
Loop throttle	CV-01	Main loop throttle control valve
Compressor recycle	CV-02	$sC0_2$ pump recycle control valve
Cooler bypass	CV-03	Existing 3" Dyna-Flo, 900# process bypass
Dilution valve	CV-04	Mixing valve to control RCP-H inlet temp.
Dyno suction valve	CV-05	Dyno compressor suction throttle valve
Dyno discharge	CV-06	Dyno compressor discharge throttle valve
Cooling water bypass	TV-01	Existing 3-way cooling water bypass hand valve
Flow meter	ORF	Orifice plate flow meter
V-cone	V-CONE	Flow meter
Strainer	STR	4" Y-strainer
Relief valve	PSV-01	Set pressure = 4000 psig
Relief valve	PSV-02	Set pressure = 4000 psig
Relief valve	PSV-03	Set pressure = 1975 psig
Relief valve	PSV-04	Existing 2x3", set pressure = 1975 psig

Test Loop Process and Instrumentation Diagram



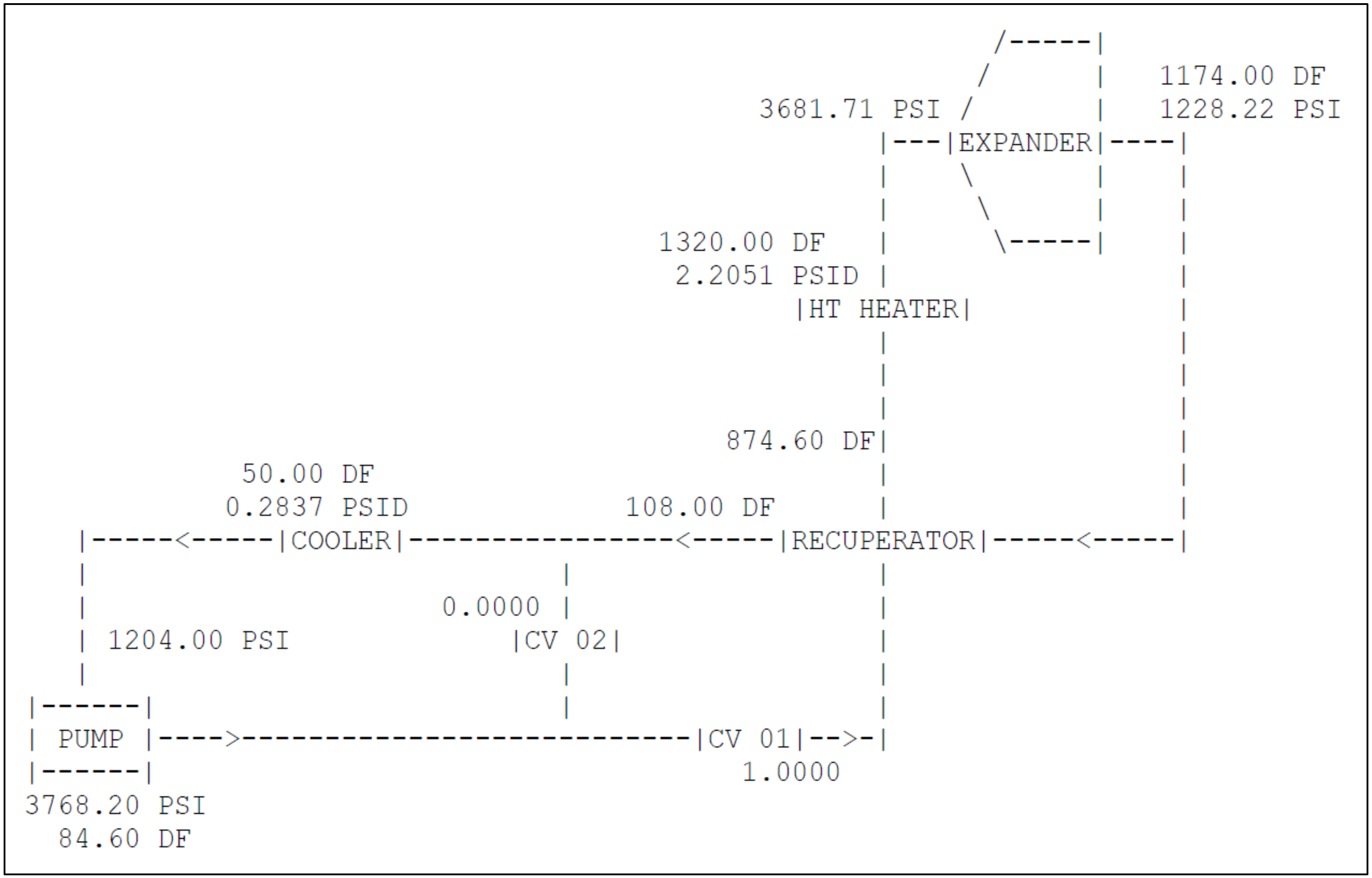
Comparison of CO_2 Density – Stoner Pipeline Simulator and REFPROP

Device	P (psia)	T (°F)	Density [lb/ft3]		Error
			Stoner	REFPROP	
Pump out	3697.91	143.17	49.387	48.883	1.03%
LT-HTR out	3690.28	356.90	22.9	22.554	1.53%
RCP 1 out	3681.14	988.00	10.306	9.9871	3.19%
HT-HTR out	3678.02	1320.00	8.259	8.0043	3.18%
EXP out	1213.73	1190.00	3.014	2.9711	1.44%
RCP 2 out	1205.08	366.10	6.621	6.5232	1.50%
CLR out	1204.00	86.00	47.988	44.789	7.14%

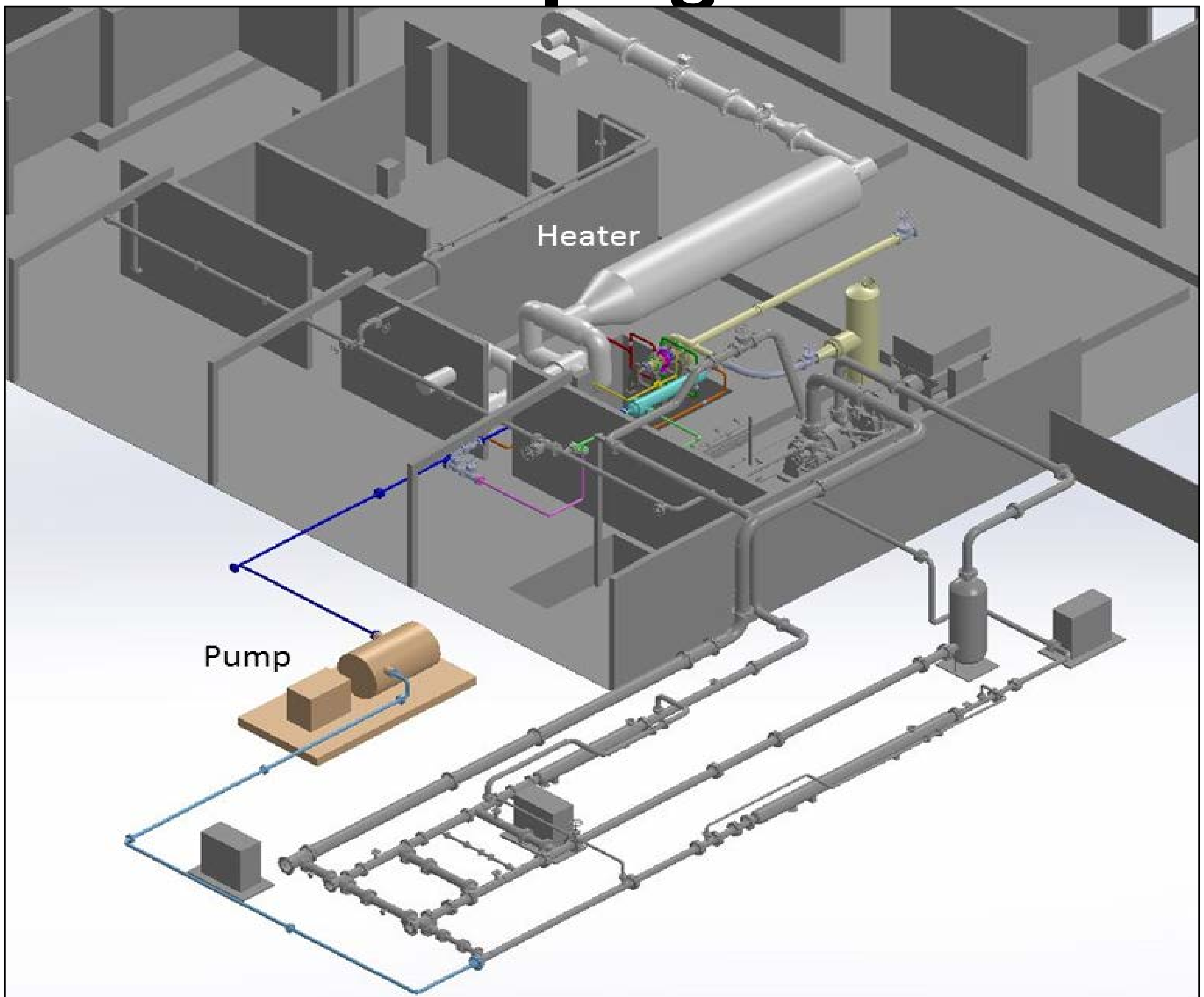
Predicted Nozzle Loads

	Fx (lb)	Fy	Fz	Mx (ft-lb)	My	Mz
RCP-C in	66	-50	-120	-144.3	-130.8	-89
RCP-H out	74	-305	-129	456.2	48.7	-185.4
HTR in	17	-92	-85	143.4	290.4	-253.4
HTR out	305	605	-252	-325.4	1166.5	490.7
EXP in, top	670	-143	-143	-105.6	-457	-777.2
EXP in, bottom	-365	-149	-109	53.1	-393.1	-477.7
EXP out, top	333	898	-170	-1613.1	175.1	164.8
EXP out, bottom	102	-781	-82	1414.5	121.9	-618.3
RCP-H in, top	232	-2537	101	2405	-386.2	287.4
RCP-H in, bottom	118	2271	-94	-2334.2	-292.2	-522.7
RCP-C out	55	169	165	195.3	-686.6	457.4

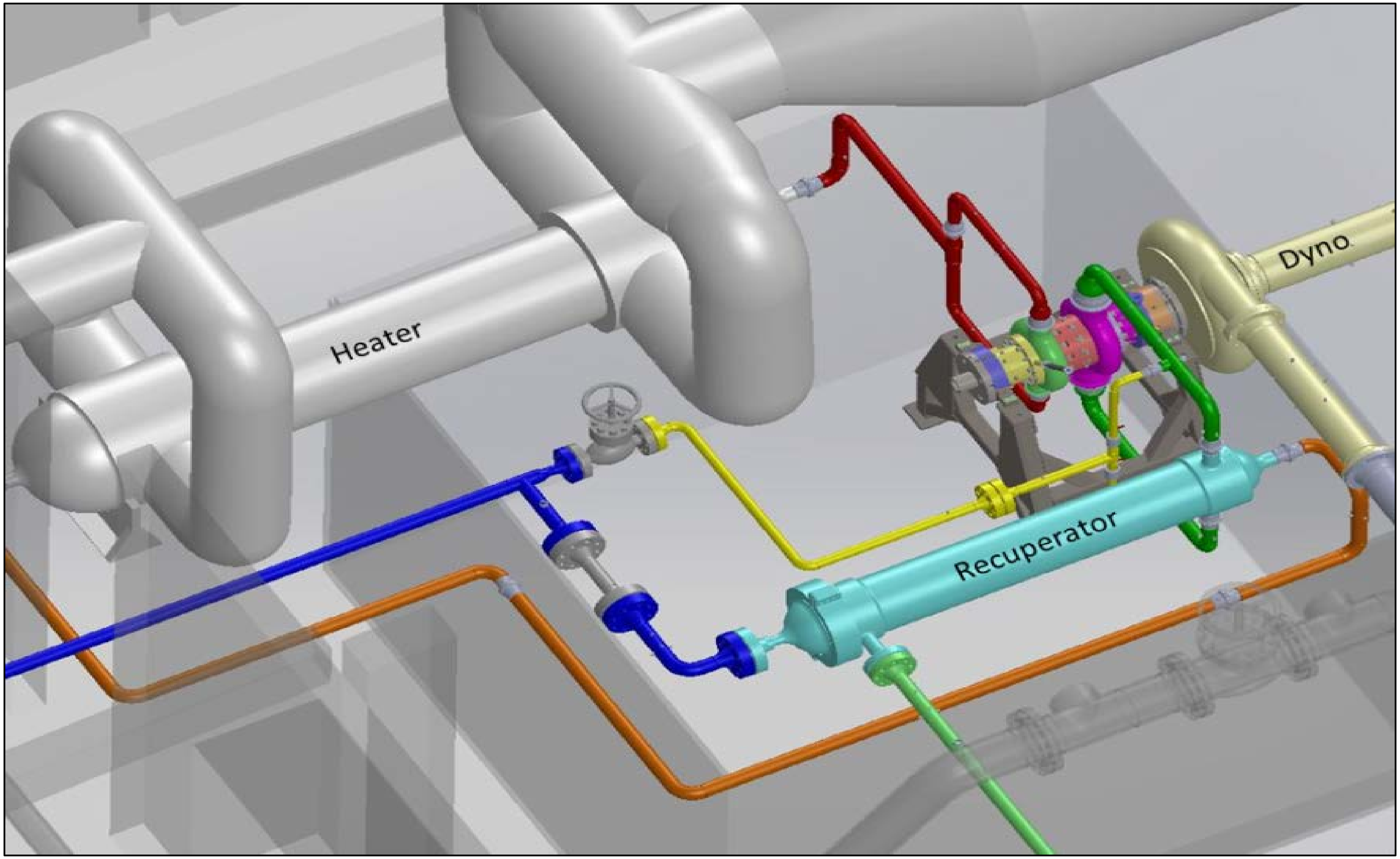
Stoner Pipeline Simulator Model Schematic



Existing Facility Piping and Expander Piping



Expander Piping Detail



Existing 3 MW CO2 Compressor

Existing CO2 Pipe Loop

Conclusions

- Design of a high-pressure, high-temperature ${}_{S}CO_2$ flow loop has been completed to measure the mechanical and flow performance of a custom ${}_{S}CO_2$ turbine expander and recuperator.
- The flow capacity of the loop is equivalent to a 1 MWe size.
- Test loop provides a platform to perform mechanical and performance testing of the expander and recuperator.
- The test loop design has sized the pipe to maintain acceptable flow velocities and pressure drop.
- A thermal piping analysis was performed to demonstrate acceptable pipe loading on the expander and recuperator nozzles.
- All of the test loop design objectives were satisfied.
- Manufacturing will commence in Phase 2 of the program.