## DOE Generation IV Energy Conversion

# Supercritical CO2 Cycle Development

*Paul Pickard (SNL)*

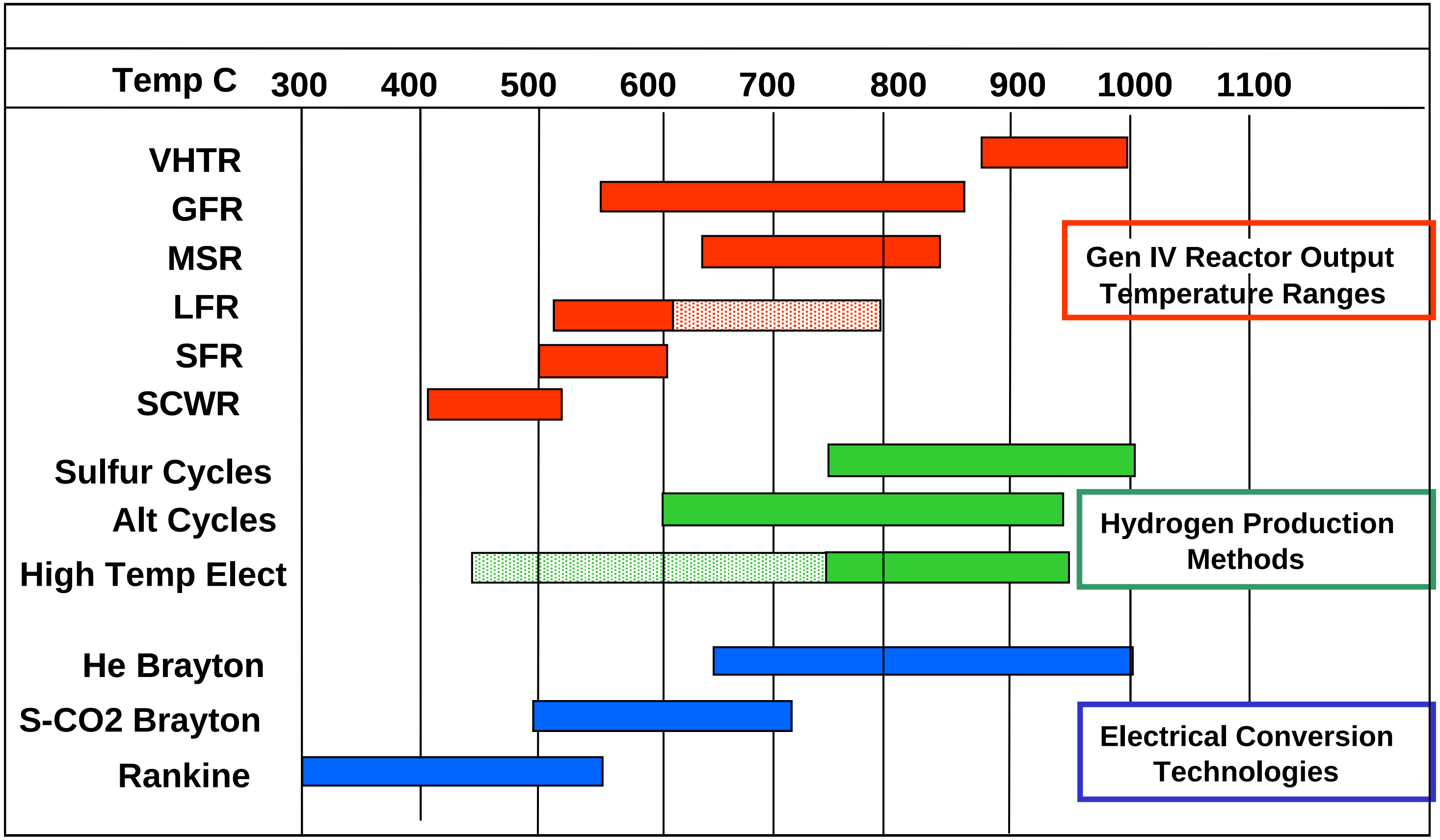
*Technical Director – Gen IV Energy Conversion*

*MIT S-CO2 Symposia*

*March 6, 2007*

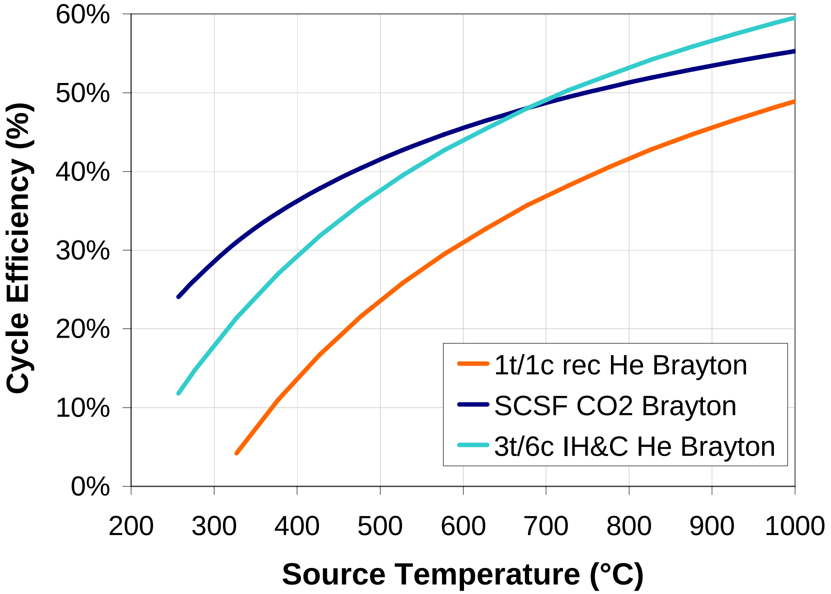
# *Generation IV Energy Conversion*

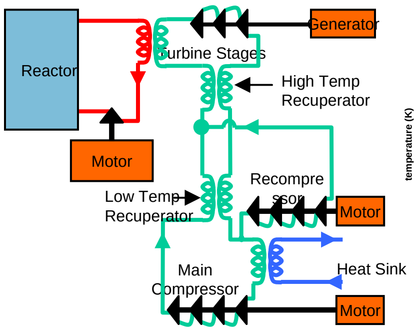
- Electrical generation - ***Gen IV Energy Conversion Program***
- Hydrogen production - ***Nuclear Hydrogen Initiative (NHI)***



# Gen IV Energy Conversion Objectives: Optimize performance and cost effectiveness of Gen IV reactors

## Brayton Cycle Options for Gen IV Reactors





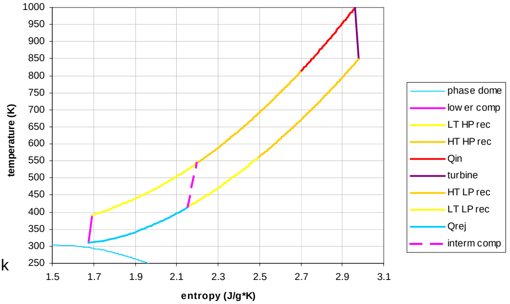
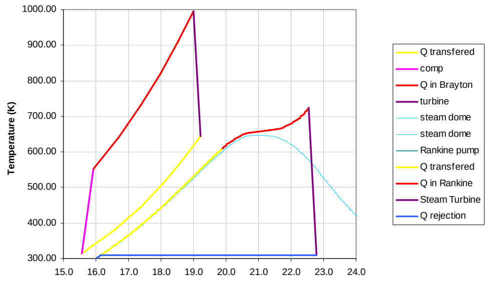
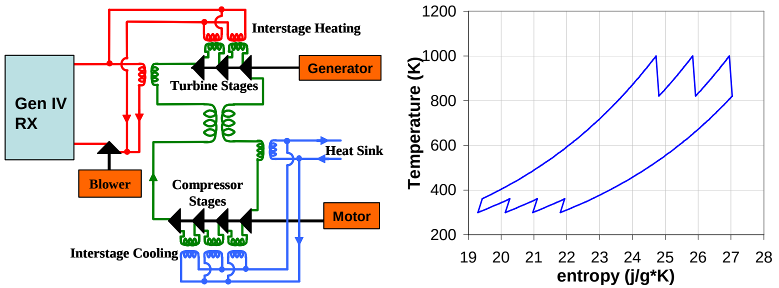


Figure 13: T-s diagram for split flow recuperated Brayton cycle using $CO_2$ beween 7.5 and 22.5 MPa with 29% of the flow diverted by the intermediate compressor (eff=49%)

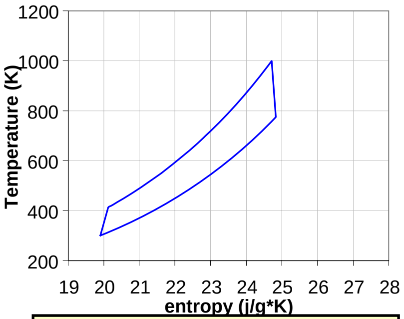
**Split Flow S-CO2 Brayton Cycle**



**Rankine Bottoming Cycle**



**Interstage Heated, Cooled - He Cycle**



**Recuperated He Cycle**

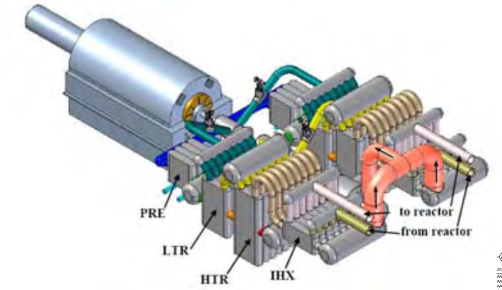
# *FY07 Gen IV Power Conversion*

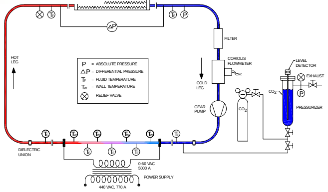
*S-CO2 - intermediate temperature reactors (500-700 C)*

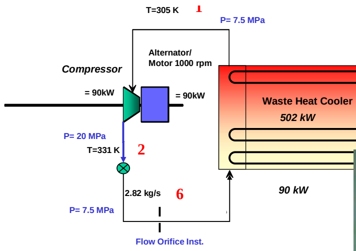
- *High efficiencies in intermediate temperature ranges*
- *Relatively compact, little additional complexity*
- *Potential for reduced capital costs*
- *Key issues – compression near critical point, control strategy for split flow*

***FY07 Task Areas***

1. ***S-CO2 system design (MIT)***
2. ***S-CO2 control analysis (ANL, MIT)***
3. ***PCHE heat transfer experiments (ANL)***
4. ***S-CO2 materials testing (MIT, LANL)***
5. ***Initiate construction of small scale S-CO2 compression exps and (~ MW) class split flow Brayton cycle system (SNL, Industry)***





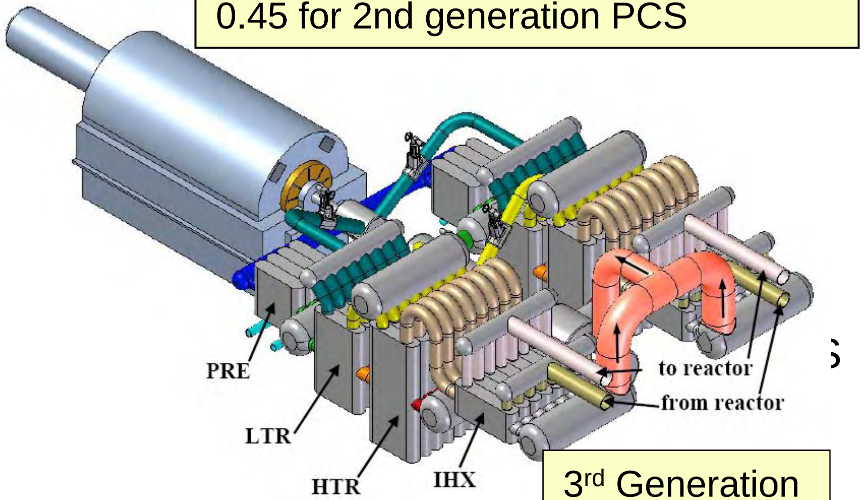


# Supercritical CO2 Cycle Activities

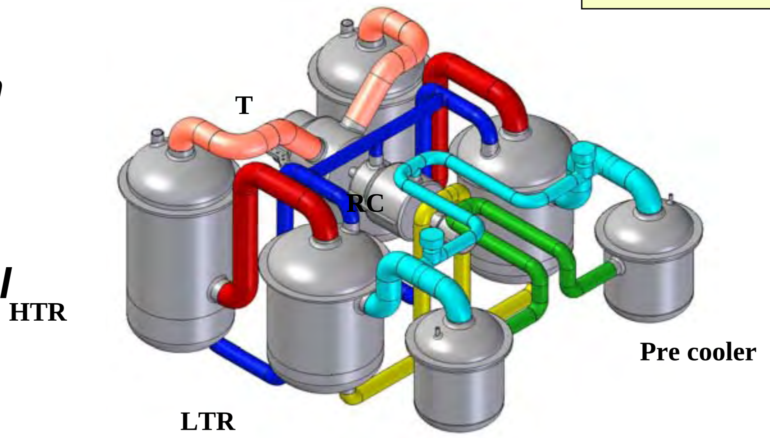
## Power Conversion System Studies (MIT)

- ***FY06 studies developed layouts for PCS ratings ranging from 20 to 1200MWe***
- ***"3rd generation" concepts evolved from earlier MIT studies, addressed impact of ductwork pressure drop on thermodynamic efficiency;***
- ***Radial compressors used for main compressor (1 stage ~0.85) and recompressor (3 stages ~0.89)***
- ***Modular approach to extend power range***
- ***Reference version - 300MWe two-train recuperator configuration using parallel clusters of commercial HEATRIC™ PCHE***
- ***FY07 activities at MIT focus on control simulations***

Net efficiency = 0.47 @650 C versus 0.45 for 2nd generation PCS



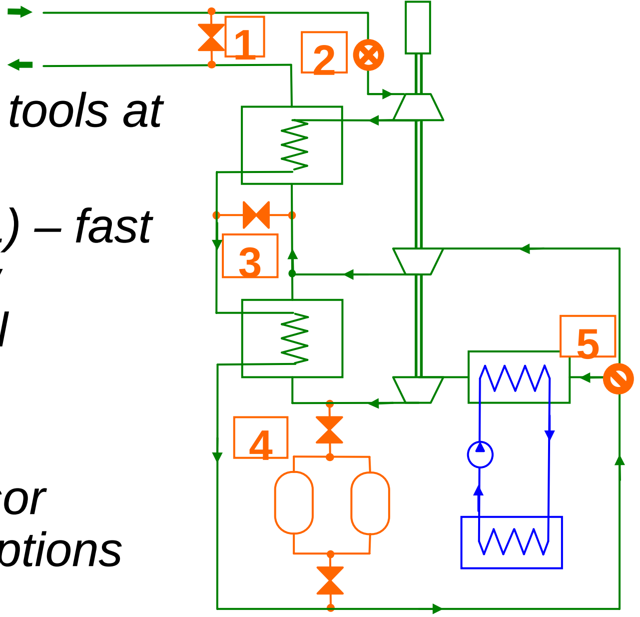
3rd Generation



2nd Generation S- CO2 300Mwe PCS

# S-CO2 Controls – Model Development, Simulation (ANL, MIT)

- ***S-CO2 control strategy Options***
- *Earlier tasks refined analysis tools at MIT and ANL*
- *GASS-PASS/CO2 (MIT, ANL) – fast running, adaptable code now operational – including radial compressor models*
- *ANL Plant Dynamics Code – incorporated radial compressor models – simulated control options for LFR/S-CO2*
- *FY07 studies use updated models to simulate range of control strategies for S-CO2 cycle*



**1 – In-reactor heat exchanger bypass valve**

**2 – Turbine inlet/throttle valve**

**3 – Turbine bypass valve**

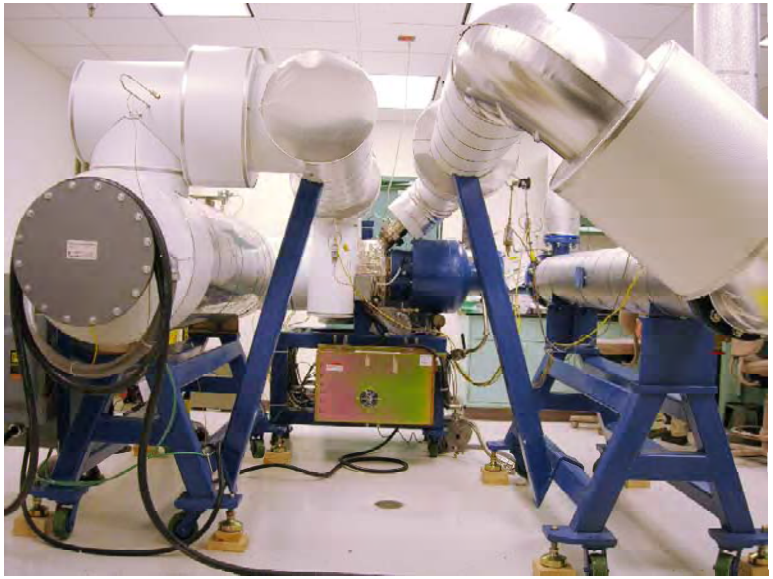
**4 – Inventory control tanks and valves**

**5 – Flow split valve**

# Closed Brayton Cycle Testing

*CBC operational data for model comparisons*

- Transient, steady state operations
- Working fluids -- N2, He, Ar, CO2, mixtures
- Operational data for -- Inventory, temperature changes, startup, shutdown, power changes

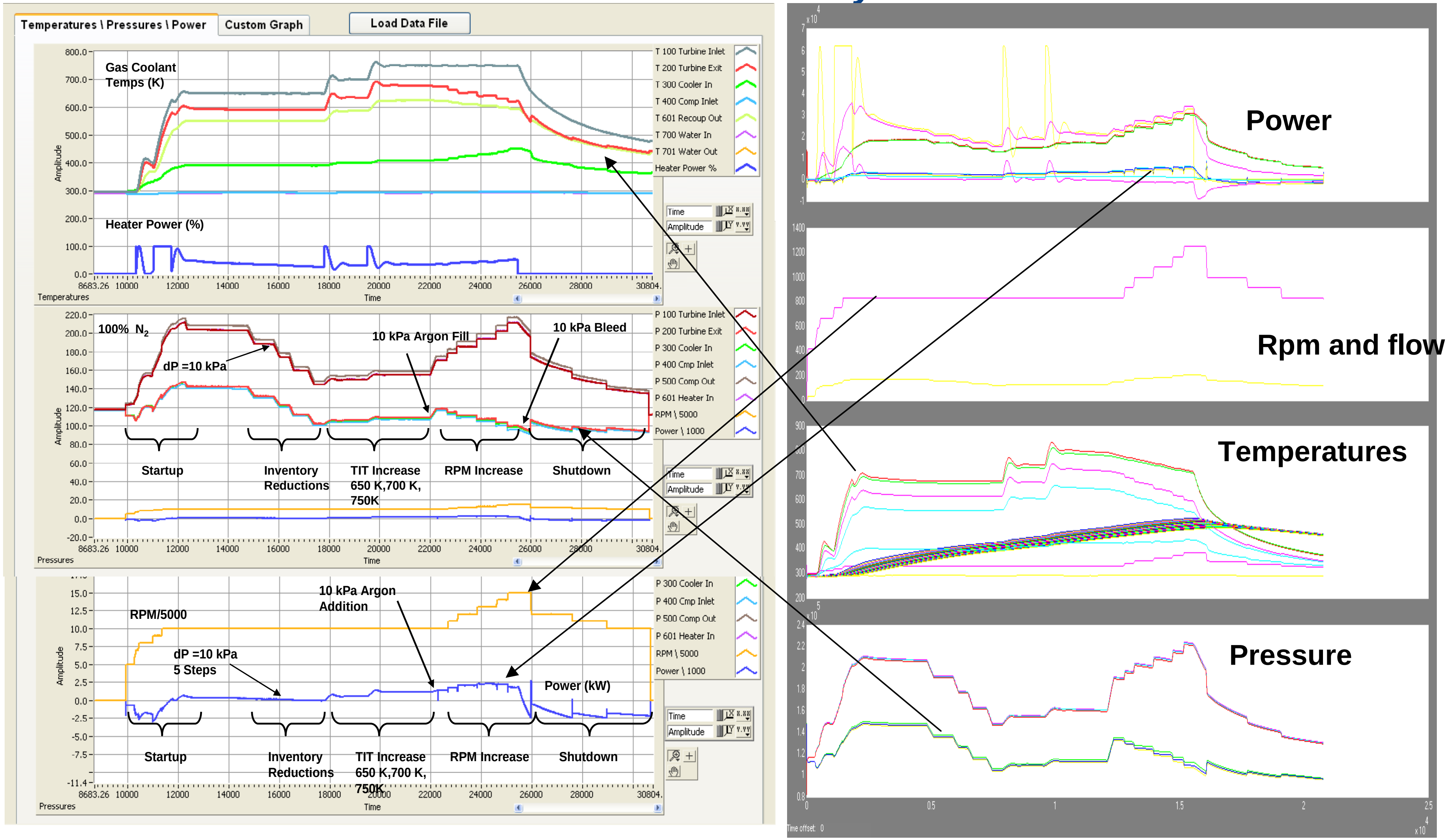


| SNL CBC Testing For Gen IV | | Pure Gases | | | | Gas Mixtures | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Test Date | 1/11/2006<br>10/17/2006 | 3/16/2006 | 5/25/2006 | | 1/11/2006 | 3/16/2005 | 3/16/2005 | 3/23/2006 |
| Gas Type | Description | N2 | Ar | CO2 | He | 90N2-10Ar | 90Ar-10He | 80Ar-20He | 70N2-30He |
| | Cp J/kg*K | 1026 | → 518 | 844 | 5378 | 941.4 | 571 | 634 | 1221 |
| | k(300K) mW/m*K | 26 | 18 | 16 | 154 | 26 | 24 | 33.1 | 46 |
| | k(1000K) mW/m*K | 60 | 42 | 54 | 336 | 59 | 56 | 72 | 105 |
| | Ro (J/kg*K) | 297 | 208 | 188.9 | 2079 | 284 | 229 | 254 | 399 |
| | MW (gm/mole) | 28 | 39.9 | 44.01 | 4 | 29 | 36.4 | 32.7 | 21 |
| | Gamma | 1.407 | → 1.66 | 1.316 | 1.66 | 1.433 | 1.66 | 1.66 | 1.486 |
| SS | Inventory Test | x | x | | Mix | | | | x |
| SS | Temperature Increase | x | x | x | Mix | | | | x |
| SS | Flow and RPM Op-Curves | x | | x | Mix | x | | x | x |
| SS | Operating Pwr Curve | x | | x | Mix | x | | x | x |
| SS | Operating Pressure Ratio | x | | x | Mix | x | | x | x |
| Transient | RPM Step Decrease (5000 rpm) | x | | | Mix | x | | x | x |
| Transient | RPM Step Increase (1000 rpm) | x | x | x | Mix | | x | x | x |
| Transient | Startup | x | x | x | Mix | | | | x |
| Transient | Shutdown | x | | x | Mix | x | | | x |
| SS | MW Increase | x | | | | | | | |
| SS | MW Decrease | | x | | | | x | | |

# *Comparison of Measurements and Predictions*

## *SNL 30 kWe CBC Measurements*

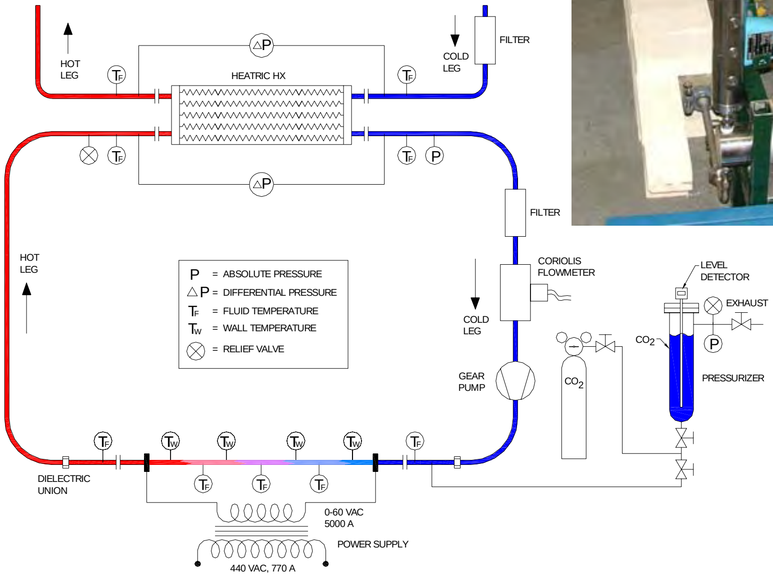
## *Dynamic Model Predictions*



# *S-CO2 PCHE Heat Transfer Testing Facility -- ANL*

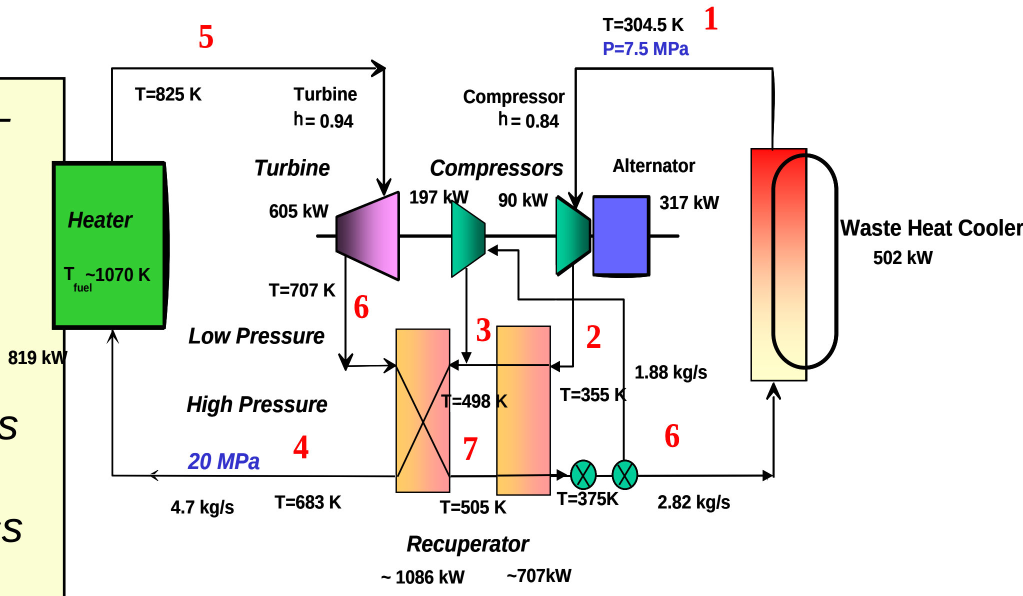
- *Initial configuration - $CO_2$-to-water heat exchange tests*
- *17.5 KW heat duty PCHE represents section of cooler for S-$CO_2$ Brayton cycle*
- *FY07 upgrade to $CO_2$ to $CO_2$ configuration (started in FY06). (low temperature recuperator).*

- *Conducted initial series of CO2-to-water steady state under prototypical conditions.*
- *Determined average heat transfer coefficients on the water and CO2 sides. Compared ANL PCHE modeling with test data*
- *Good agreement is obtained for the heat exchange rate, Q, or CO2 and H2O outlet temperatures. CO2 side pressure drop is overpredicted*



# Small Scale S-CO2 Cycle Demonstration Loop

- *Next stage of S-$CO_2$ development – construct small scale S-$CO_2$ power conversion system to demonstrate key technology issues*
- *Phased approach – key technical issues first -- and budget constraints*
- *First stage – experiments to address compression near critical point*
- *Progress to split flow recuperated Brayton cycle demo*
- *Contracts (FY06) solicited TM Industry input on small scale test loop to test key technical features (BNI, P&W-Rocketdyne)*



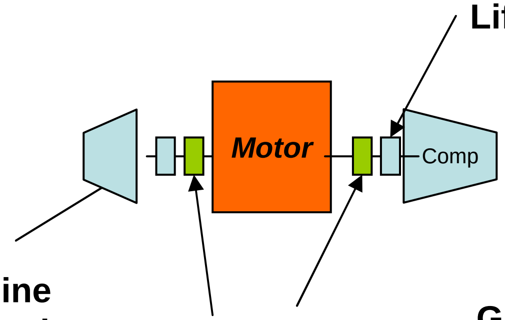
## Primary FY06 SOW Tasks

- *Review key technical issues for full scale system*
- *Examine approach for S-CO2 compression tests*
- *Phased approach to develop full cycle, preliminary cost and schedule*

# Key Technology for S-$CO_2$ Development
# SNL LDRD -- S-$CO_2$ other working fluids

## *S-$CO_2$ Main Compressor Test*
## *Electric Motor Driven Option*

**Phase 1-LS: Turbo Assisted Main Compressor Study SC-$CO_2$ Flow Compression (3 kg/s)**

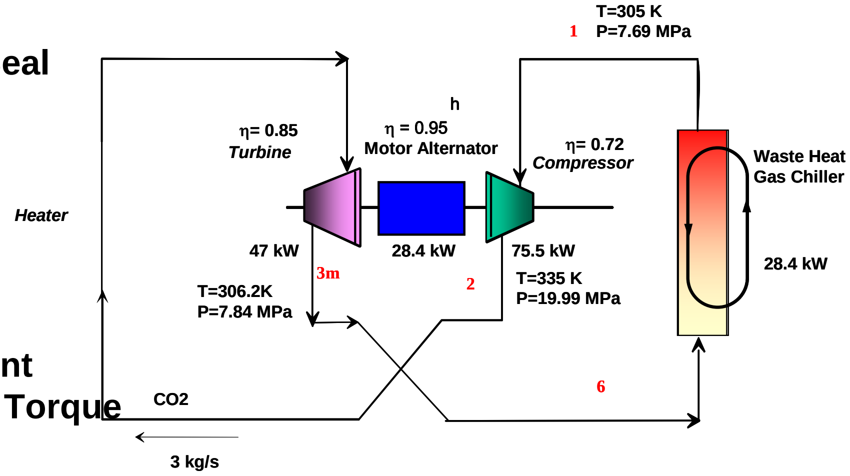


**Liftoff Gas Seal**

**Turbine Expander**

**Ball Bearings**

**Gimbal Mount To Measure Torque**



### *Major Technology Issues*

*Gas Liftoff Seals*

*Efficiency of Compression*

*Thermal Input Control*

*Bearings and Thrust Loads*

*Off-Normal behavior (wet)*

### *Turbo Assisted Motor/ Compressor*

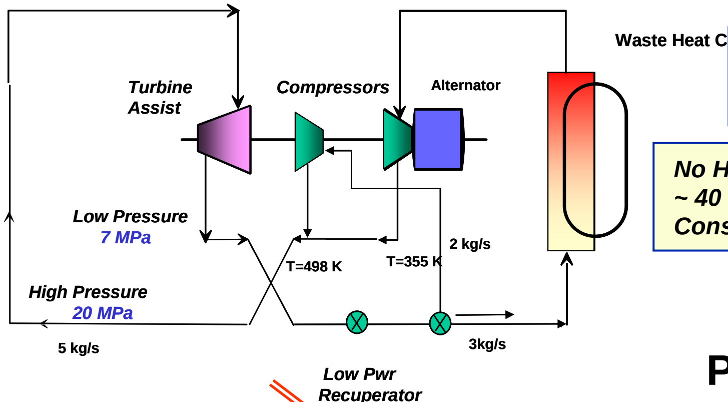
*Reduces motor power requirements*

*Allow modification – wheels, housings could be replaced with different designs.*

# Gen IV S-CO2

## (1 $MW_{th}$ => 300 $kW_e$ with Split Flow)

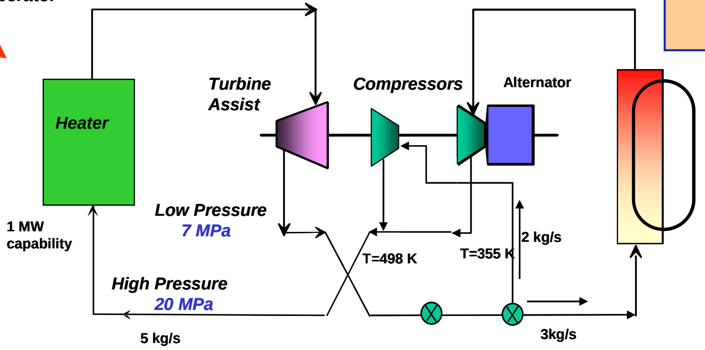
## Phase 1



**Phase 1 - Split flow (Main and Recompressor) Study**

*No Heater*
*~ 40 kWe Motor*
*Consumes Electricity*

## Phase 2



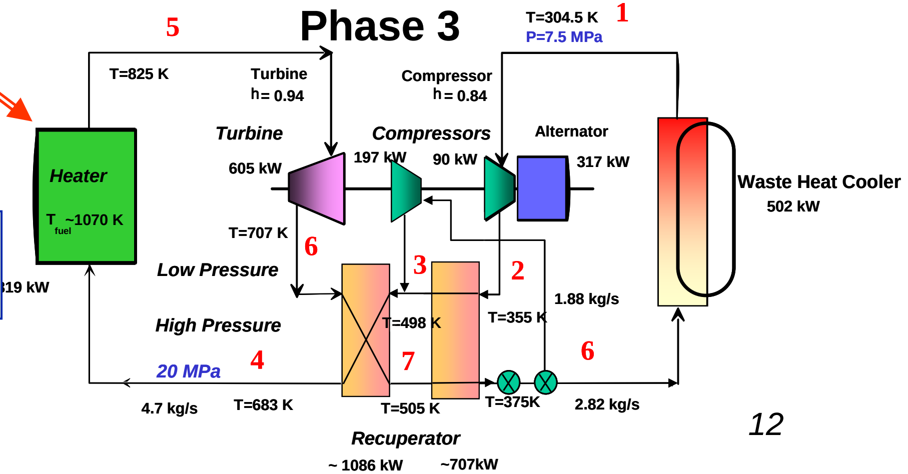
**Phase 2 - Non-recuperated Brayton split flow**

*Up to 1 MW Heater*
*~ 40 kWe Alternator Pwr*
*Produces Electricity*

**Phase 3 – Recuperated split flow S-$CO_2$ cycle**

*Low Pwr Recuperator*

## Phase 3



*~1 MW Heater & ~40 kWe Motor/Alternator*
*+ 300 kW Dynometer or 300 kWe Alt. is an Option*
*Produces Electricity*

# Gen IV Energy Conversion

## *FY07 S-CO2 Summary*

***Develop experimental capability to address key technical issues***

- *Main compressor operation,*
- *System control strategies*
- *Heat transfer experiments*

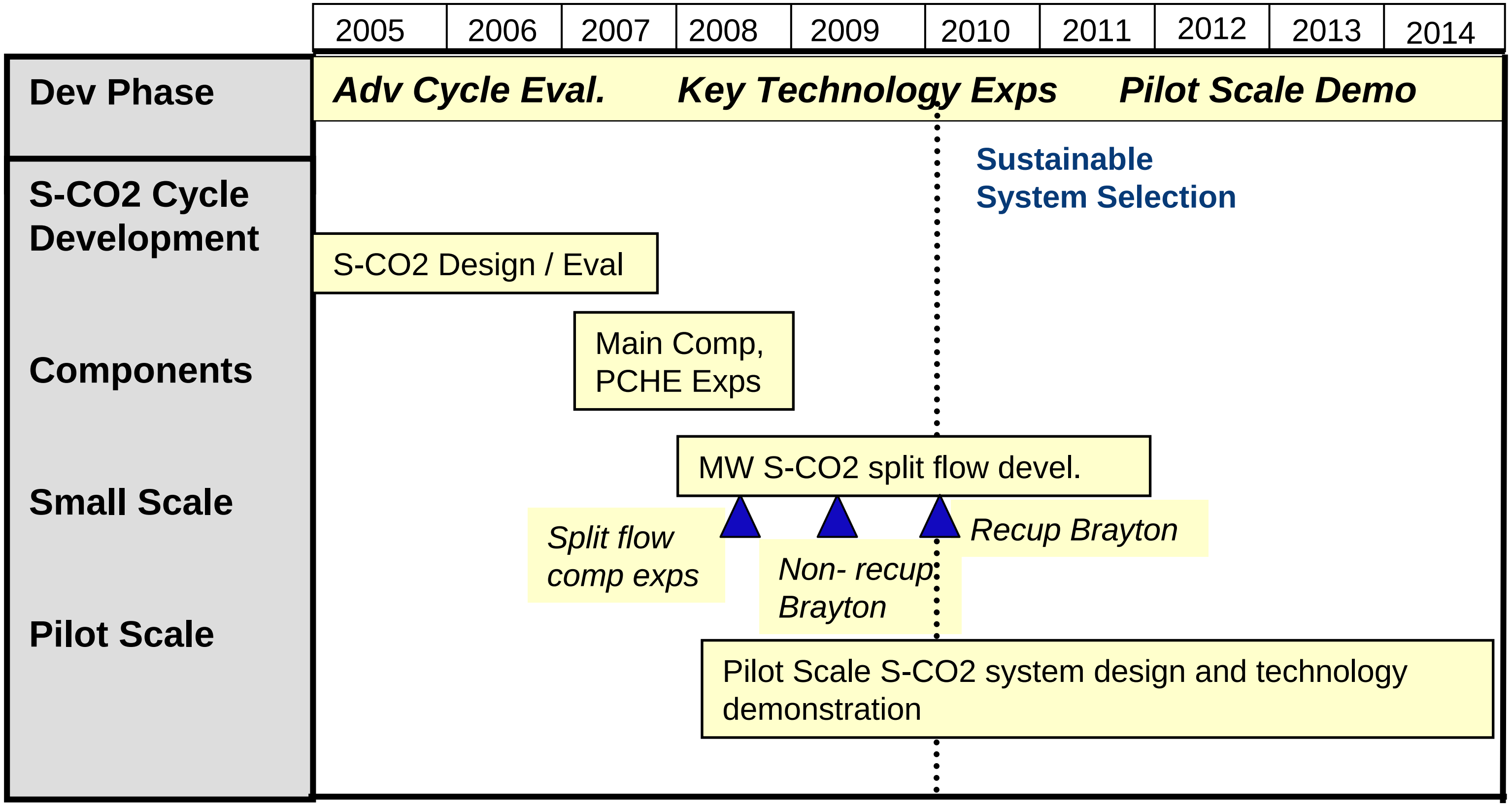
***Approach: phased design, construction***

- *Address main compressor exps first*
- *Split flow compression as first stage of small scale system*
- *Optimize construction sequence to provide early results and leverage previous phase*

***Planning Schedule for Gen IV scope***

- *Gen IV funding - ~ 4 year schedule*
- *Other SC fluids work on supercritical compression studies*
- *GNEP – other program involvement*

# Gen IV Energy Conversion
# S-CO2 cycle phases, proposed schedule



2005 2006 2007 2008 2009 2010 2011 2012 2013 2014

**Dev Phase**

*Adv Cycle Eval.* *Key Technology Exps* *Pilot Scale Demo*

**Sustainable System Selection**

**S-CO2 Cycle Development**

S-CO2 Design / Eval

**Components**

Main Comp, PCHE Exps

**Small Scale**

MW S-CO2 split flow devel.

*Split flow comp exps*

*Non- recup Brayton*

*Recup Brayton*

**Pilot Scale**

Pilot Scale S-CO2 system design and technology demonstration

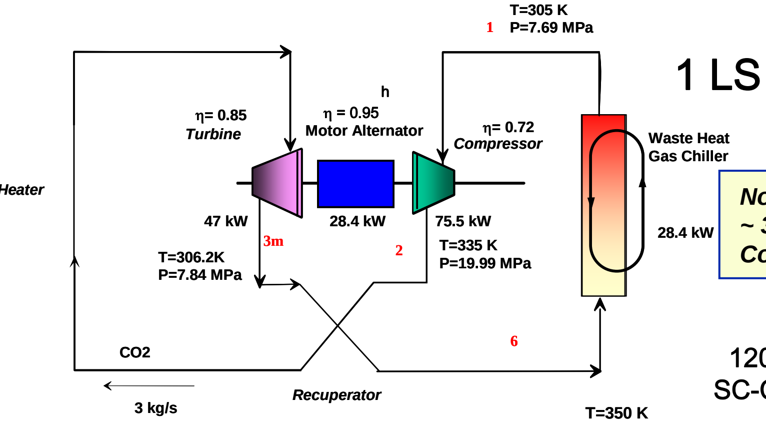
# Extra VGs

# *SNL LDRD Single Shaft SC-CO$_2$ opt for SC-Xe*

## *Lab-Scale 120 kW$_{th}$ Heater Power : 7 kWe SC-CO$_2$ : 33 kWe SC-Xe*

Nuclear Energy Systems

SC-CO2 Comp. LDRD

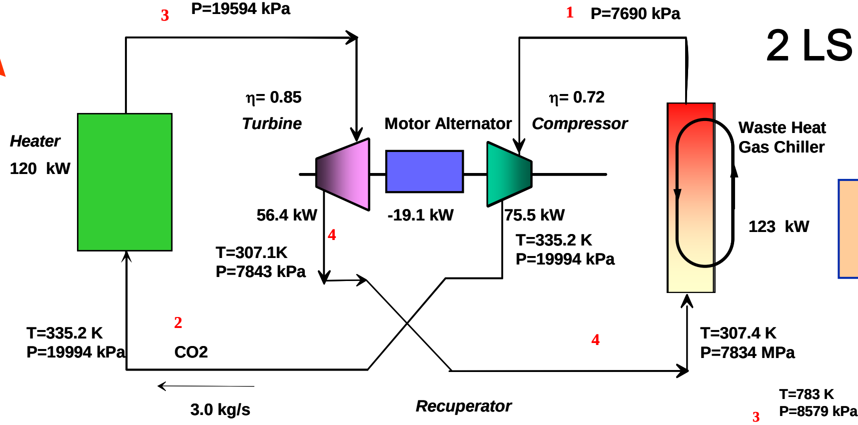


**Phase 1-LS: Turbo Assisted Main Compressor Study SC-CO$_2$ Flow Compression (3 kg/s)**

*No Heater*
*~ 30 kWe Motor*
*Consumes Electricity*

**Phase 2-LS: Un-Recup. Brayton Cycle**
**SC-CO$_2$ & SC-Xe Compression**
**Higher TIT various RPMs**
**SC-CO$_2$ and SC-Xe**

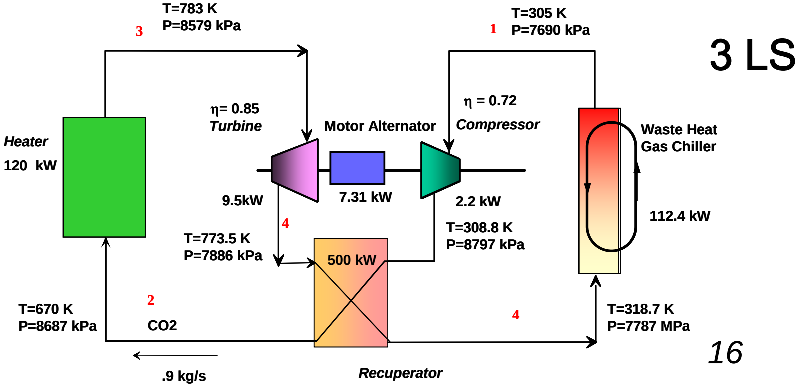
120 kW LDRD
SC-CO2 / SC-Xe



*120 kW Lab-Scale Heater*
*~ 20 kWe Motor Pwr CO2*
*~ 10 kWe Alternator Pwr Xe*
*Consumse &Produces Electricity*

**Phase 3-LS: Split Flow S-CO$_2$ & Xe Brayton Cycle with Recup.**

120 kW LDRD
SC-CO2 / SC-Xe

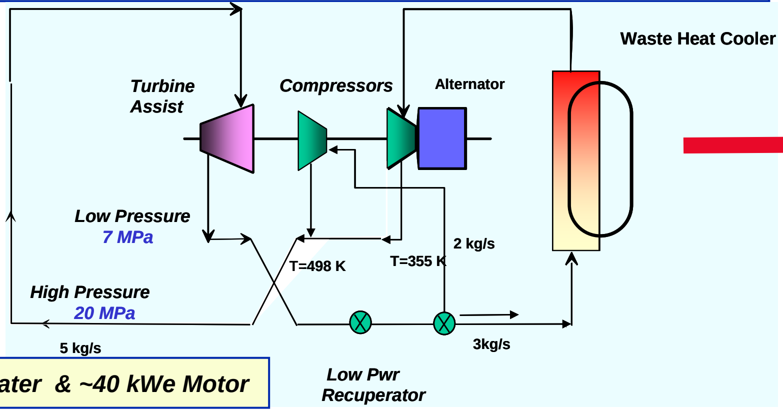


*~120 kW Heater & ~40 kWe Motor/Alternator*
*+ 300 kW Dynometer*
*300 kWe Alt. is an Option*
*Produces Limited Electricity 7- 32 kWe (CO2/Xe)*

# Small Scale S-CO2 Demo Unit

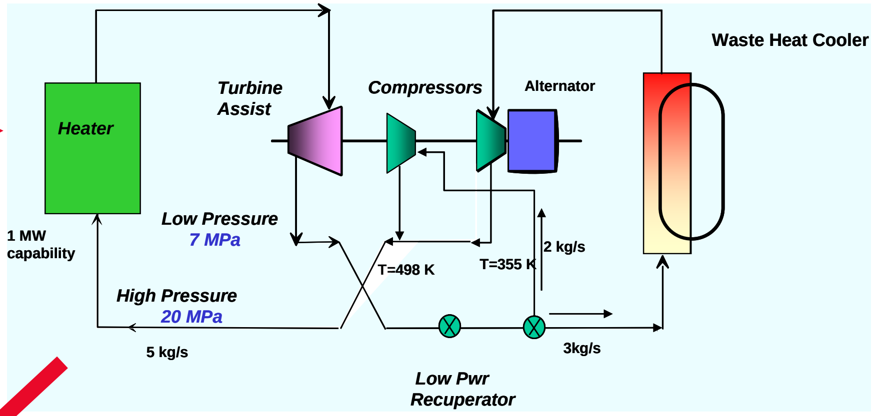
## Conceptual Approach

Phase 1 - Main compressor and/or Recompressor with/without split flow



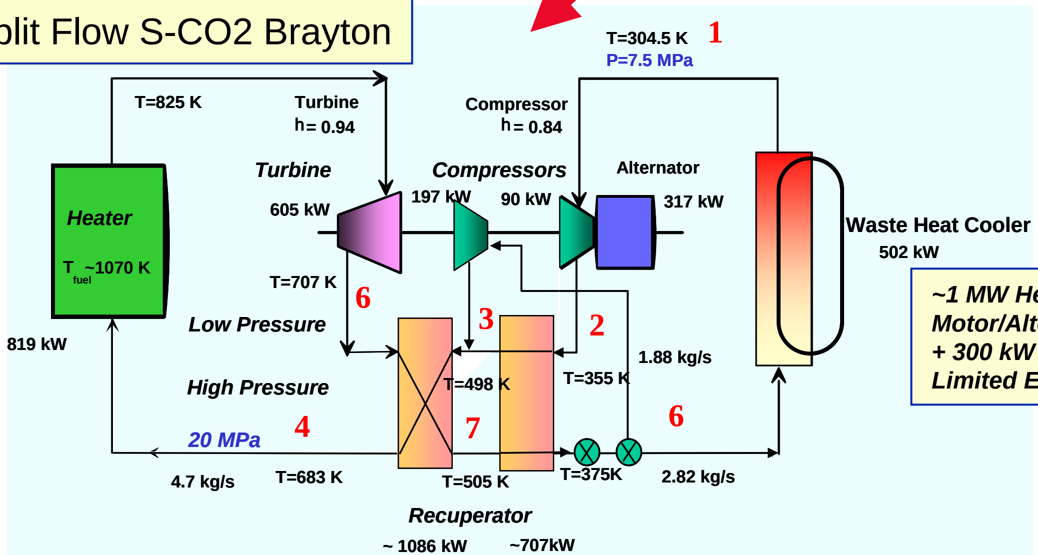
***No Heater & ~40 kWe Motor***

Phase 2 – Non-recuperated Brayton Split flow



***Up to 1 MW Heater & ~40 kWe Motor/Alternator Produces Electricity***

Phase 3 – Split Flow S-CO2 Brayton



***~1 MW Heater & ~40 kWe Motor/Alternator + 300 kW Dynamometer Produces Limited Electricity***

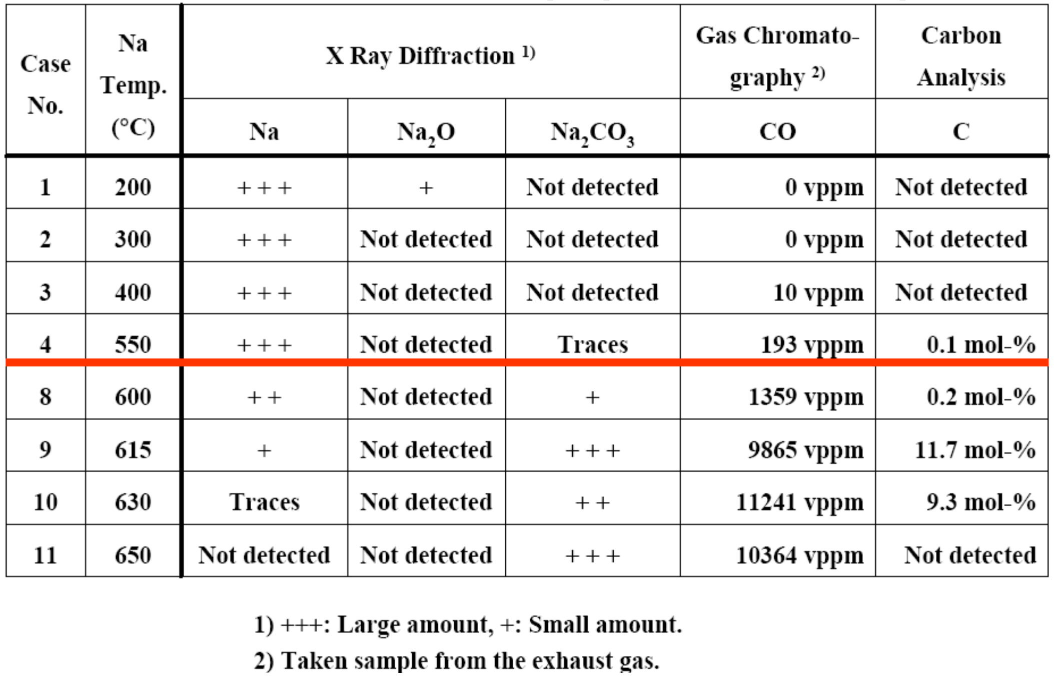
# Gen IV Energy Conversion

## S-CO2 Interactions

- *CO2 reaction with Na at higher temperatures*
- *Japanese observed slow reactions below ~ 550 C, increasing reaction rates above 550 C*
- *Korean data (CO2 bubbled into Na Column) suggest some reaction below ~ 550 C*

- *Expected interaction mode in PCHE – small cracks – form oxides or carbonates – could lead to plugging if not removed, E release not primary concern.*
- *Does not appear to be major issue for current Na outlet temperatures – but need to confirm*
- *Significantly less of a concern than water – Na reaction*
- *ABR program – constructing a small facility to investigate plugging issue (ANL)*
- *ABR will investigate Na CO2 interactions,*
- *Gen IV focus on cycle development*

**Sodium-CO2 reaction (Japanese results)**

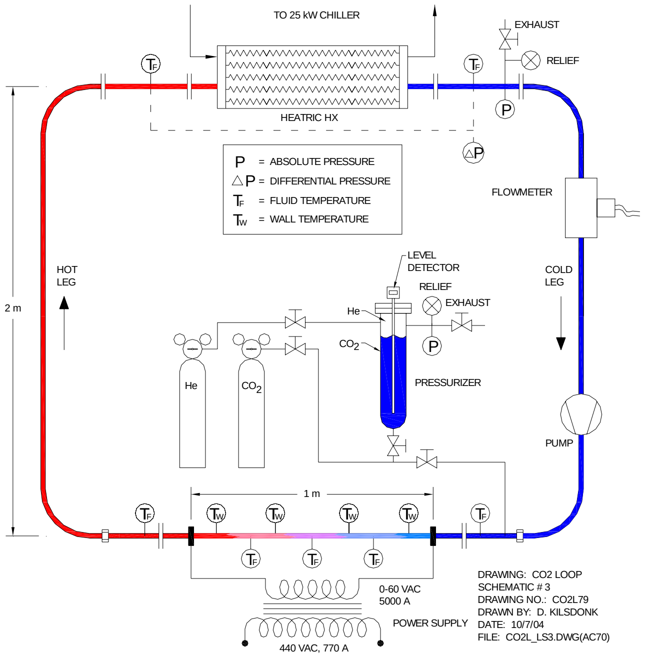


| Case No. | Na Temp. (°C) | X Ray Diffraction [1] | | | Gas Chromatography [2] | Carbon Analysis |
|---|---|---|---|---|---|---|
| | | Na | $Na_2O$ | $Na_2CO_3$ | CO | C |
| 1 | 200 | + + + | + | Not detected | 0 vppm | Not detected |
| 2 | 300 | + + + | Not detected | Not detected | 0 vppm | Not detected |
| 3 | 400 | + + + | Not detected | Not detected | 10 vppm | Not detected |
| 4 | 550 | + + + | Not detected | Traces | 193 vppm | 0.1 mol-% |
| 8 | 600 | + + | Not detected | + | 1359 vppm | 0.2 mol-% |
| 9 | 615 | + | Not detected | + + + | 9865 vppm | 11.7 mol-% |
| 10 | 630 | Traces | Not detected | + + | 11241 vppm | 9.3 mol-% |
| 11 | 650 | Not detected | Not detected | + + + | 10364 vppm | Not detected |

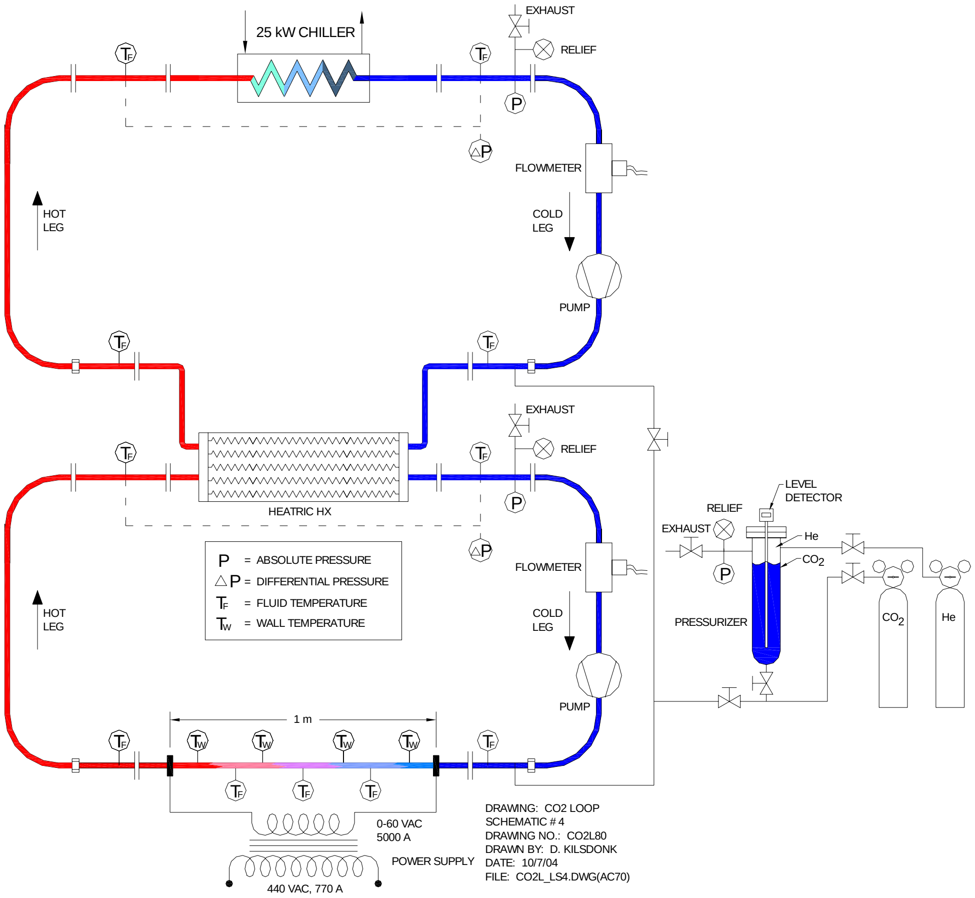
1) +++: Large amount, +: Small amount.
2) Taken sample from the exhaust gas.

# ANL S-CO2 Heat Transfer Loop

## $CO_2$ / $H_2O$ Heat Exchanger

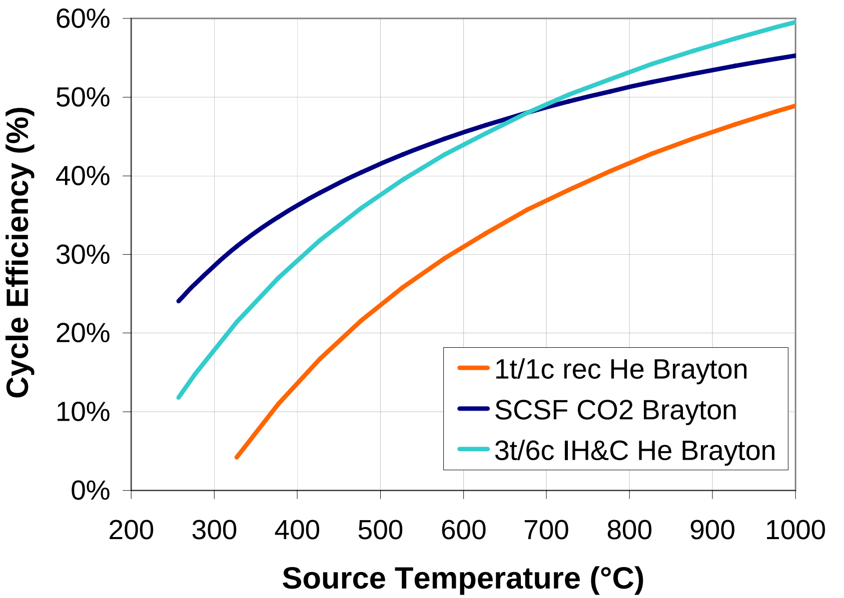


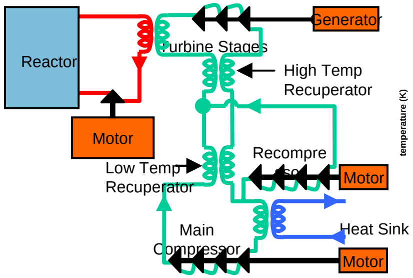
## $CO_2$ / CO2 Heat Exchanger Design



# *Gen IV Energy Conversion Objectives: Optimize performance and cost effectiveness of Gen IV reactors*

## *Brayton Cycle Options for Gen IV Reactors*





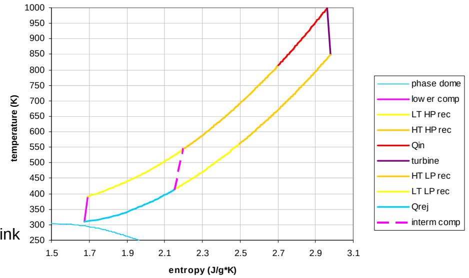
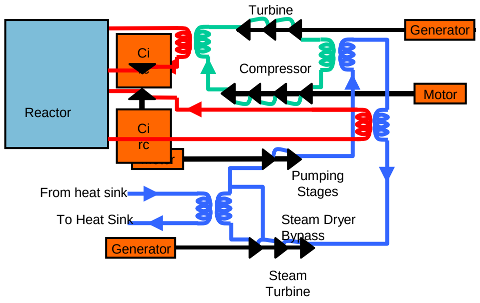


**Figure 13: T-s diagram for split flow recuperated Brayton cycle using $CO_2$ beween 7.5 and 22.5 MPa with 29% of the flow diverted by the intermediate compressor (eff=49%)**

**Split Flow S-CO2 Brayton Cycle**



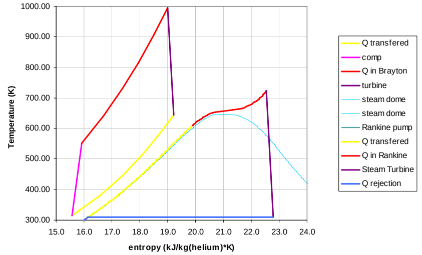
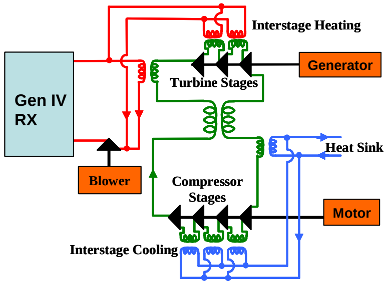
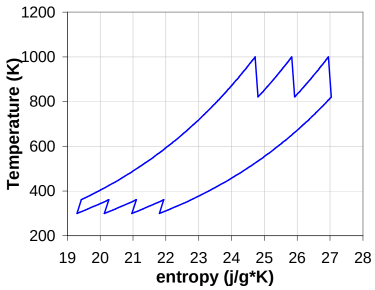


**Figure 11: T-s plot for simple Brayton cycle using Helium flow at 6.9 and 23 MPa with SC steam bottoming cycle with mass flow ratio of 1.241 water/helium (eff=48%)**

**Rankine Bottoming Cycle**





**Multi Reheat - Interstage cooled Brayton Cycle**