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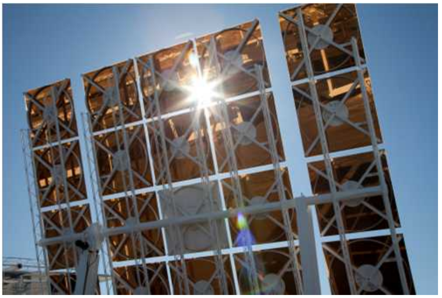

A Particle/sCO2 Heat Exchanger Testbed and Reference Cycle Cost Analysis

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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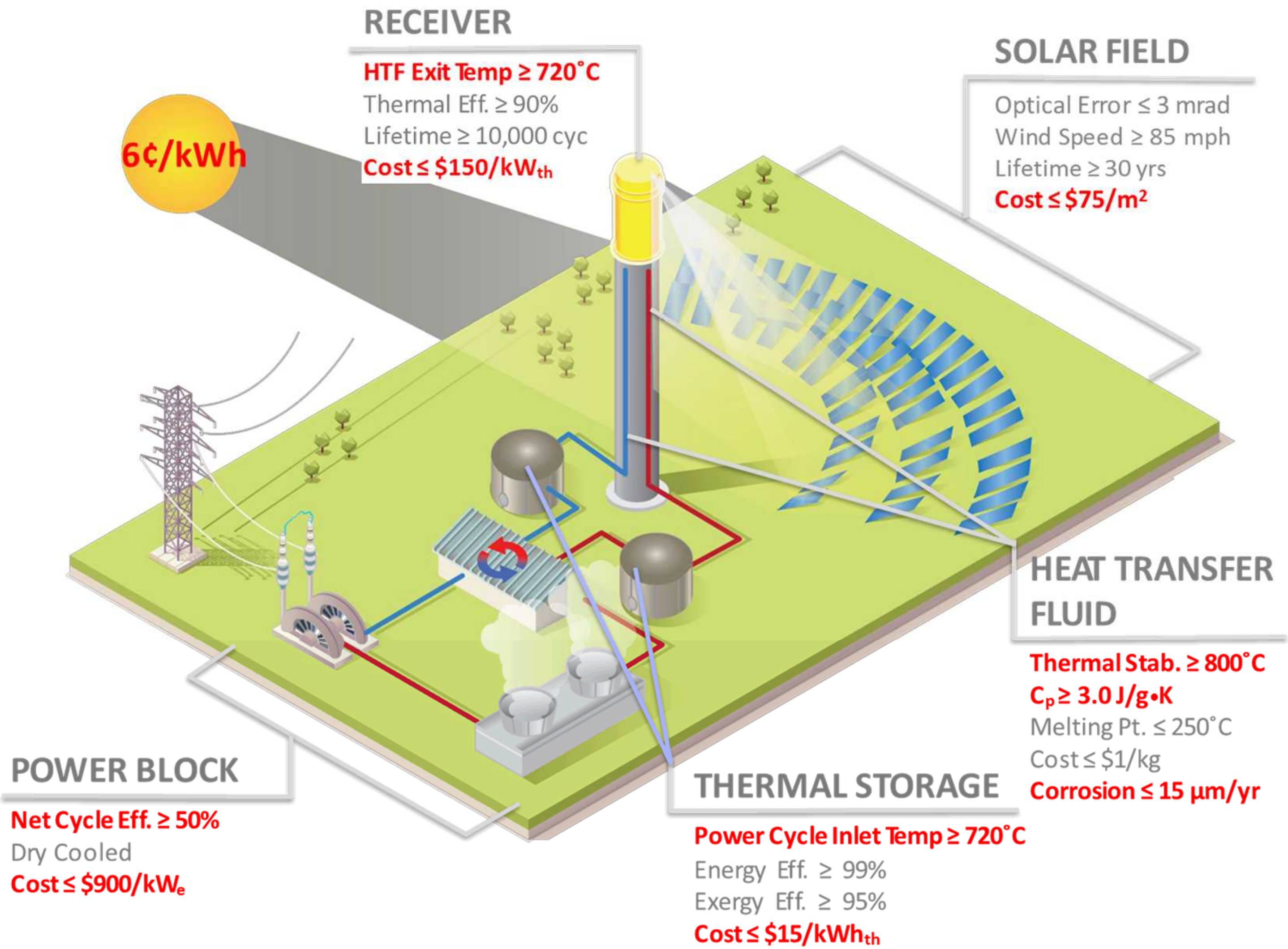
Overview

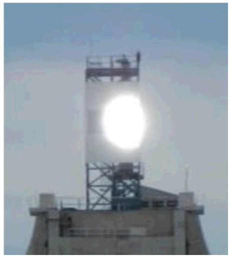
- Background and Objectives
- Particle/sCO2 Heat Exchanger Testbed
- Reference Cycle Cost Analysis
- Conclusions

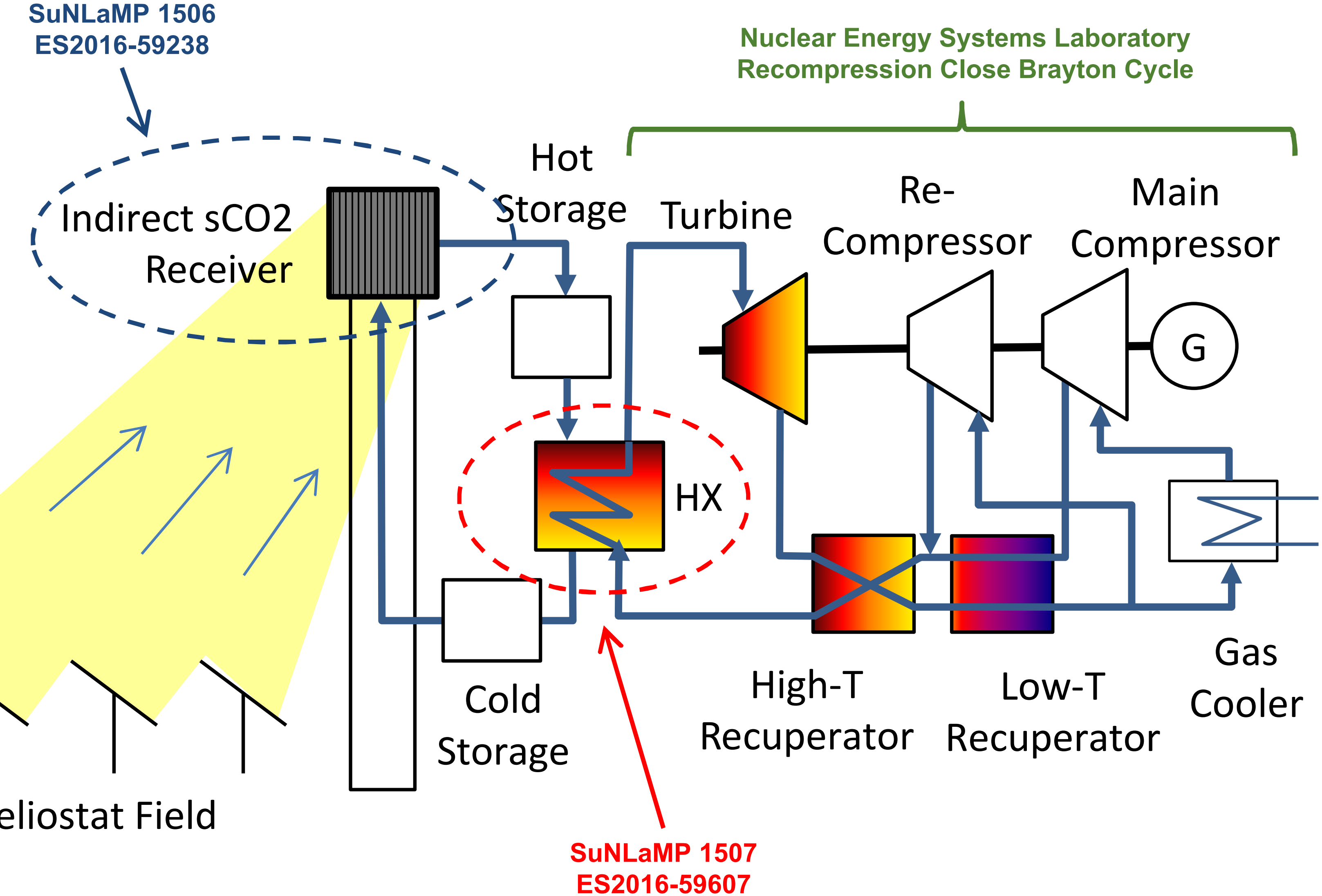
SunShot CSP Tower Targets



M. Bauer, R. Vijaykumar, M. Lausten, J. Stekli, "Pathways to Cost Competitive Concentrated Solar Power Incorporating Supercritical Carbon Dioxide Power Cycles," presented at the 5th International Symposium on Supercritical CO2 Power Cycles,San Antonio, TX, 2016.

Integration with Sandia Capabilities





sCO2 Cycle Cost & Performance

	SCBC		RCBC	CCBC	CBI
Net Power (MWe)	100	100	100	133	100
Efficiency (%)	16	46	46	28	51
ΔT_{HTR}(C)	540	172	170	518	159
T_{max}(C)	700	700	700	600	700
P_{max}(MPa)	20	20	20	27.6	15
P_{min}(MPa)	6.4	8.0	7.3	8.5	2.6
$T_{comp,min}$(C)	55	55	55	37	35
Heater ($/kWe)	381	212	322	281*	292
Recuperation ($/kWe)	0.00	243	244	122*	259
Cooling ($/kWe)	545	85	154	574*	350
Compression ($/kWe)	423	230	147	80*	74
Expansion ($/kWe)	136	128	135	138*	120
Total ($/kWe)	1,485	898	1,002	914*	1,095

SCBC=Simple Closed Brayton Cycle
RCBC=Recompression Closed Brayton Cycle
CCBC=Cascaded Closed Brayton Cycle
CBI=Combination Bifurcation with Intercooler

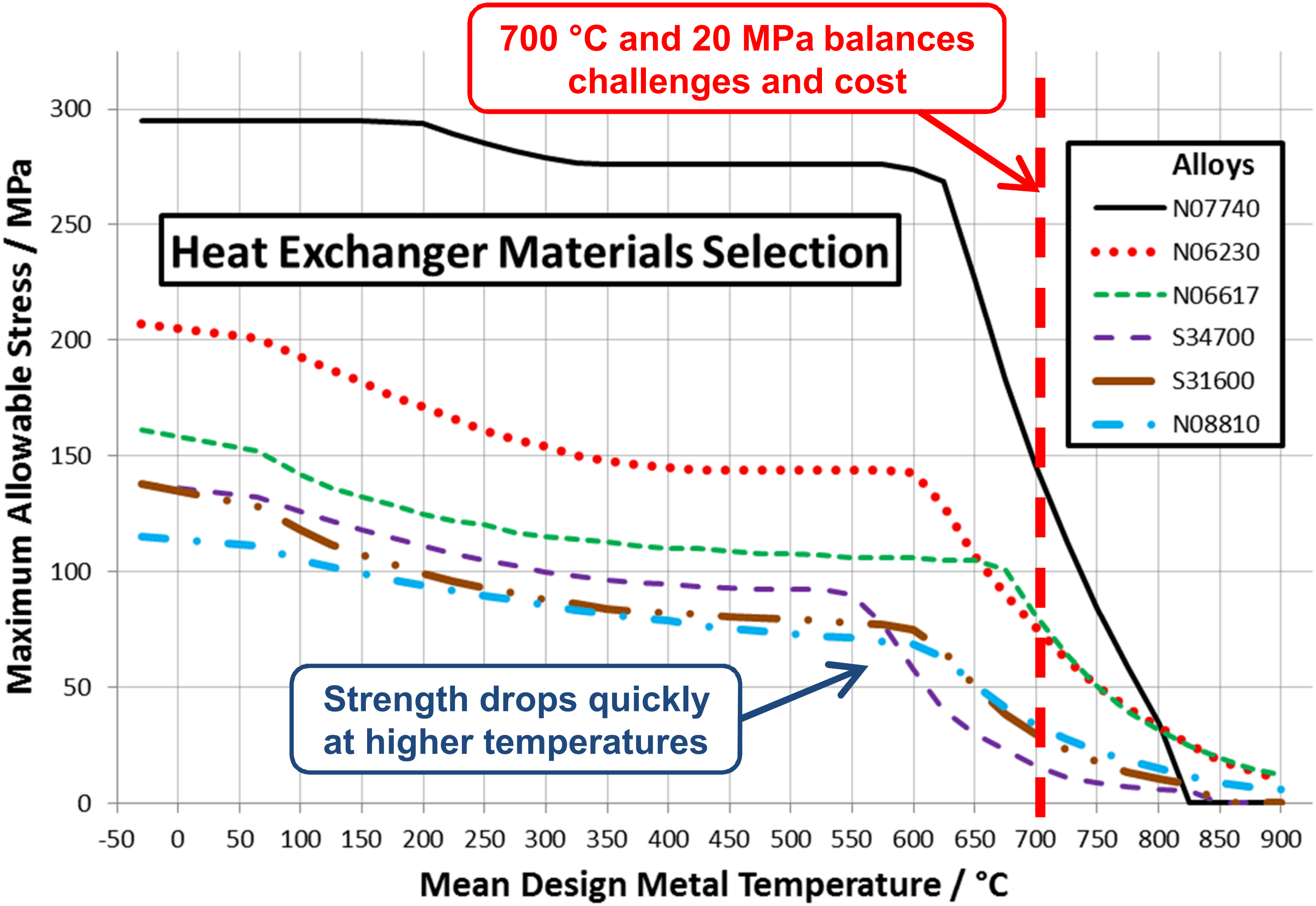
*Corrected from C. K. Ho, M. D. Carlson, P. Garg, and P. Kumar, "Cost and Performance Tradeoffs of Alternative Solar-Driven S-CO2 Brayton Cycle Configurations," in Proceedings of the ASME 2015 Power and Energy Conversion Conference, San Diego, California, 2015, pp. 1–10.

sCO2 Cycle Layout Options

Application	Size / MWe	Temp / ℃	Pressure / MPa
Nuclear	10-300	350-700	20-35
Fossil (Indirect)	300-600	550-900	15-35
Fossil (Direct)	300-600	1100-1500	35
Solar	10-100	500-1000	20-35
Shipboard	<10-10	200-300	15-25
Waste Heat	1-10	<230-650	15-35
Geothermal	1-50	100-300	15

Adapted from R. Dennis, "DOE Initiative on SCO2 Power Cycles (STEP) -Heat Exchangers: A Performance and Cost Challenge -," presented at the EPRI-NETL Workshop on Heat Exchangers for SCO2 Power Cycles, San Diego, CA, 2015

Materials Challenges



ASME Boiler and Pressure Vessel Code, "Section II, Part D - Properties (Metric)." The American Society of Mechanical Engineers, 2007.

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Preliminary Design Requirements

8	**PERFORMANCE OF ONE UNIT**					
9			**HOT SIDE**		**COLD SIDE**	
10	STREAM NAME		PARTICLES		SCO2	
15	FLUID FLOW RATE (TOTAL)	kg/s	0.41		0.53	
21	TEMPERATURE (IN/OUT)	°C	775	570.	550.	700.
22	DENSITY (VAP/FLUID)	kg/m^3	Per Note 3	Per Note 3	124	103
23	VISCOSITY (VAP/FLUID)	µPa-s	Per Note 4	Per Note 4	37.4	41.6
24	MOLECULAR WEIGHT (VAP/FLUID)	kg/kmol	N.A.	N.A.	44	44
25	SPECIFIC HEAT (VAP/FLUID)	kJ/kg-K	1.210 (Per Note 5)	1.140 (Per Note 5)	1.240	1.270
26	THERMAL CONDUCTIVITY (VAP/FLUID)	W/m-K	Per Note 4	Per Note 4	0.06258	0.07207
28	PRESSURE (IN)	MPa	0.101		20.0	
30	PRESSURE DROP (ALLOW./CALC.)	kPa	Per Note 6	Per Note 6	200	200
31	FOULING RESISTANCE (MIN.)	m^2-K/W	0.0 (nil)		0.000176	
32	HEAT EXCHANGED	100	kW	MTD (corrected)	STA	°C
33	TRANSFER RATE, SERVICE	STA	W/m^2-K	CLEAN	STA	W/m^2-K

34	**CONSTRUCTION OF ONE MODULE**						SKETCH OF NOZZLE ORIENTATION
35			**HOT SIDE**		**COLD SIDE**		
36	DESIGN/TEST PRESSURE	kPa	STA	STA	24000	STA	
37	DESIGN TEMP (MIN/MAX)	°C	0.00	800.	0.00	800.	
39	CORROSION ALLOWANCE	mm	0.0 (nil)		0.0 (nil)		
40	CONNECTION SIZE AND RATING	IN	STA	STA	STA	STA	
41		OUT	STA	STA	STA	STA	
42	MATERIAL OF CONSTRUCTION		Per Note 7		Per Note 7		
43	INSULATION		Per Note 8		Per Note 8		

44 NOTES:

45 1. NOMENCLATURE: STA = Supplier to advise; N.A. = Not Applicable

46 2. Design must satisfy ASME Boiler and Pressure Code VIII Division 1 (latest)

47 3. ~2000 kg/m^3; See CARBO Accucast ID50 properties provided in Ho et al. 2015 (PowerEnergy2015-49421, pre-published)

48 4. Cliff Ho (SNL) and Zhiwen Ma (NREL) to advise on effective transport properties for particle flows depending on flow characteristics

49 5. Latest measurements suggest $0.365(T)^{0.18}$ for temperatures between 50 and 1100 °C

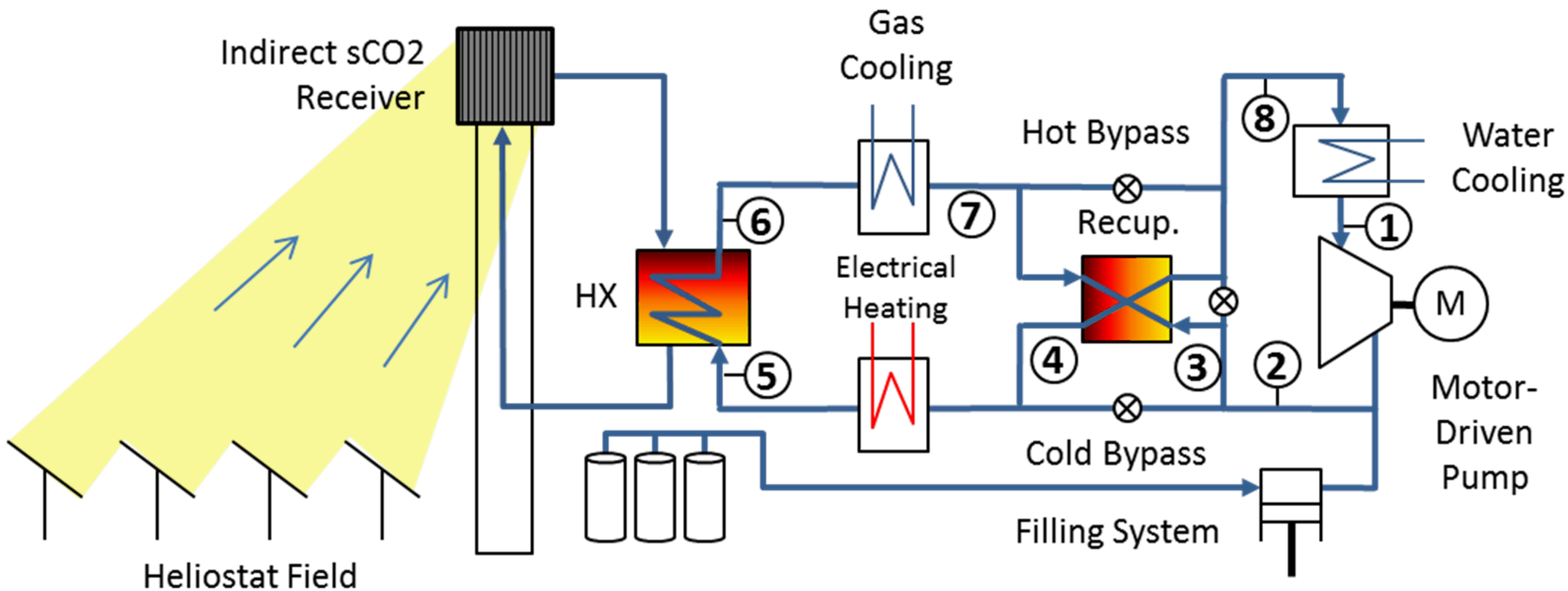
50 6. Must allow for gravity-driven flow of particles through the unit or include a flow system in the unit design

51 7. Material must be stainless steel or nickel alloy (i.e. UNS#s S31600/S31603, S34700, N08810, N06617, N06625, N06230, N07740)

52 8. Insulation to be provided to maintain 90% thermal efficiency (<10% or 10 kW of heat loss) with potential for 99% at a 100 MW scale

***Key elements of the preliminary heat exchanger design requirements**

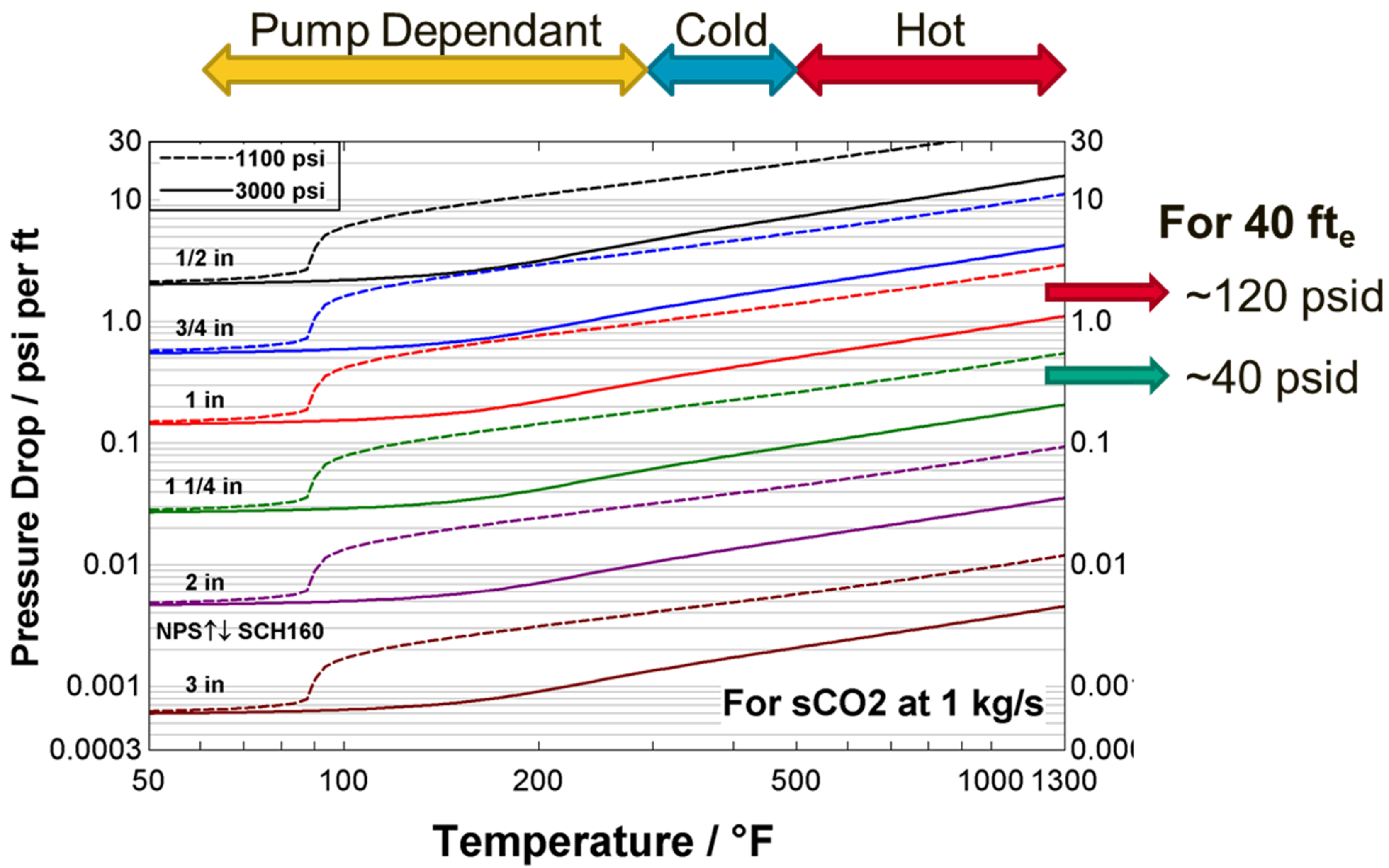
Purpose of the sCO2 Flow System



Provide the particle/sCO2 heat exchanger a supply of carbon dioxide at:

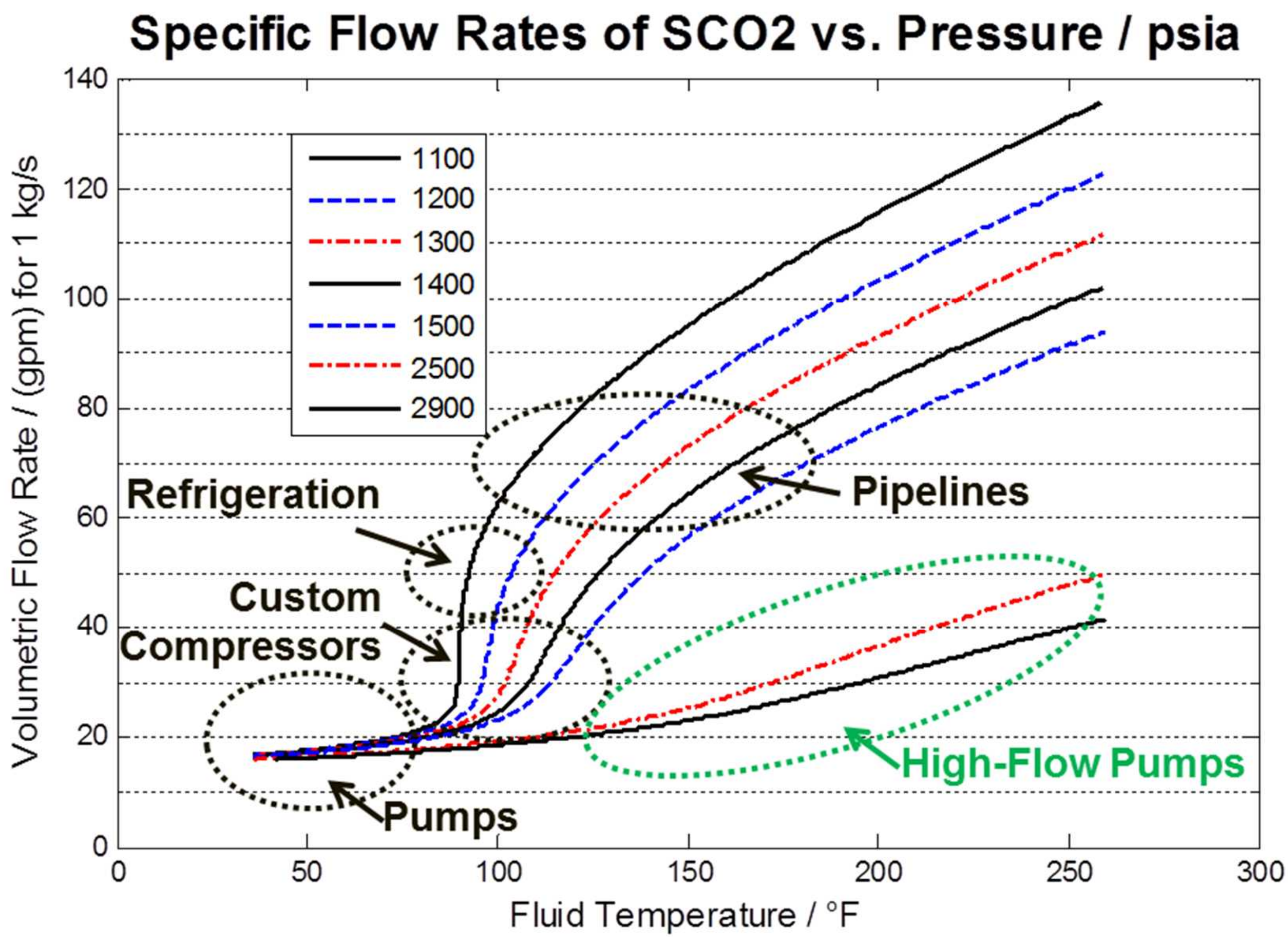
Mass Flow / kg/s	T / °C	P / MPa
0.75	550.	20.0

sCO2 Flow System Piping Losses



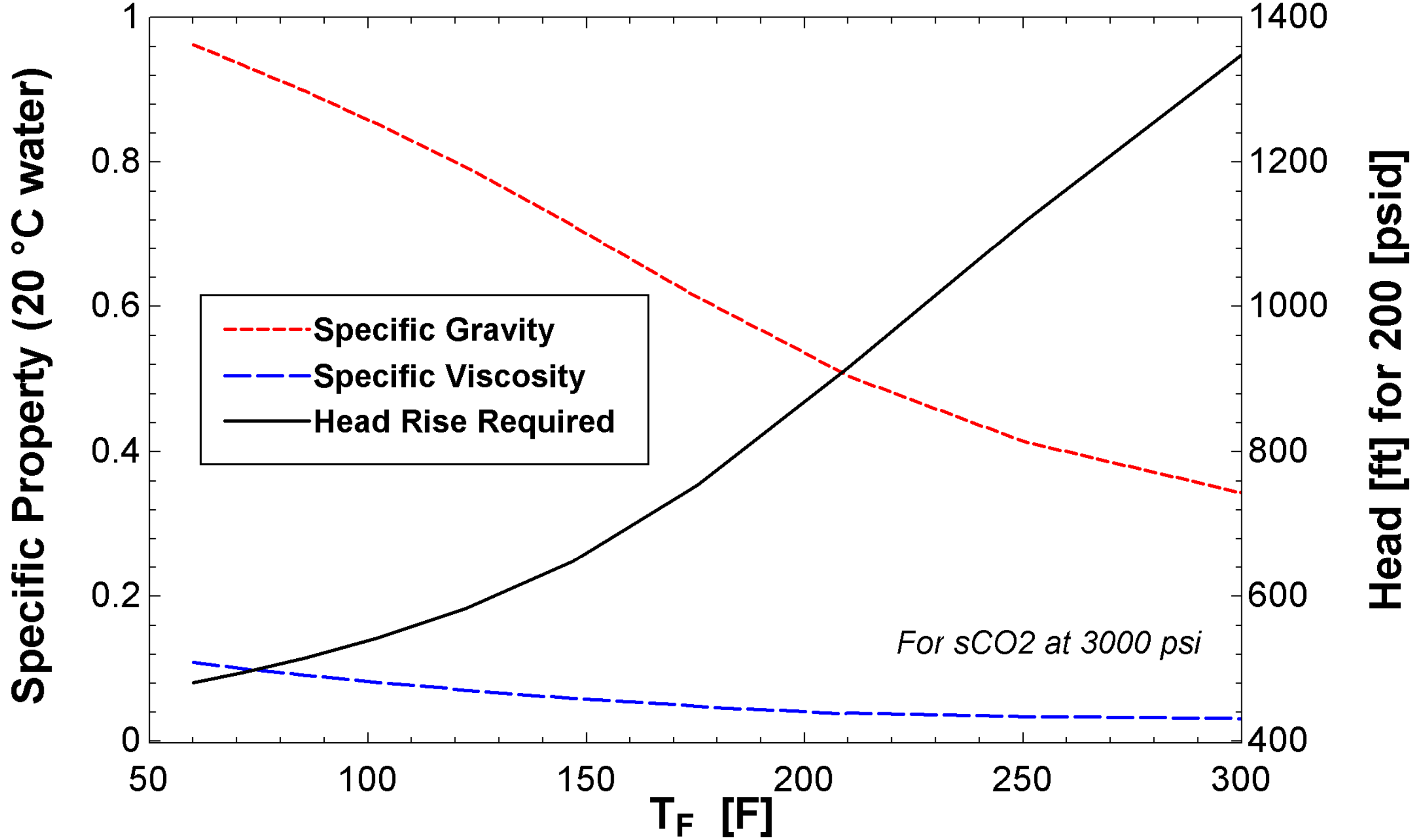
Total system pressure drop approximately 200 psid including 1% per component.

Pump Volumetric Flow Rate



Pump Head Rise Considerations

Head rise increasing significantly as specific gravity (density) reduces



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Reference Cycle Cost Analysis

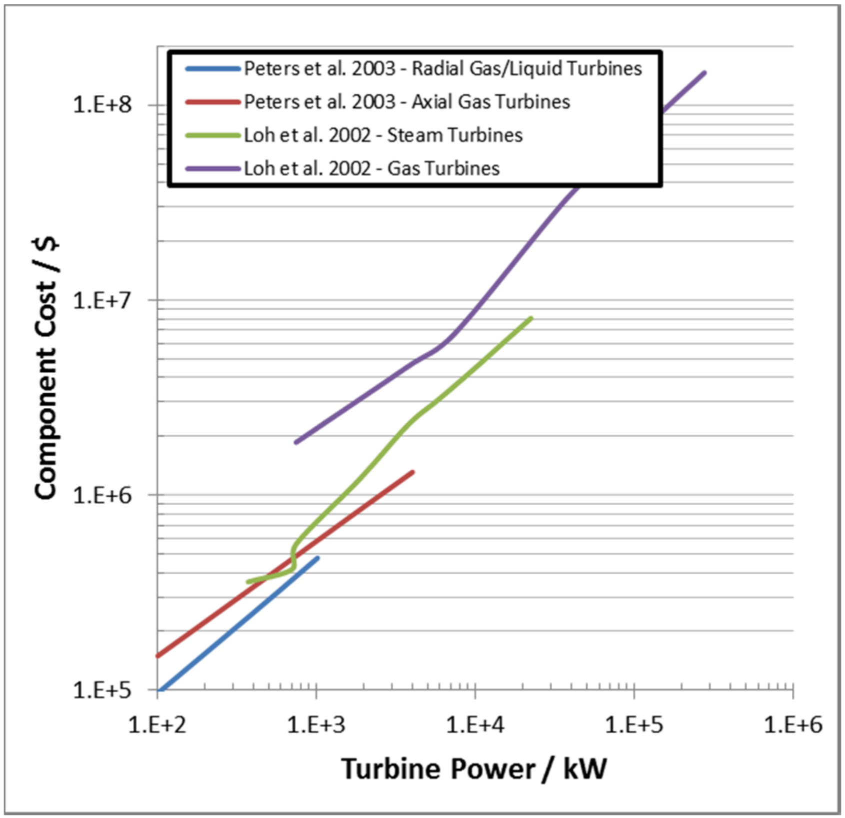
- **Purpose**
  - Develop a cost metric for the particle/sCO2 heat exchanger using the SunShot power block cost of 900 $/kWe

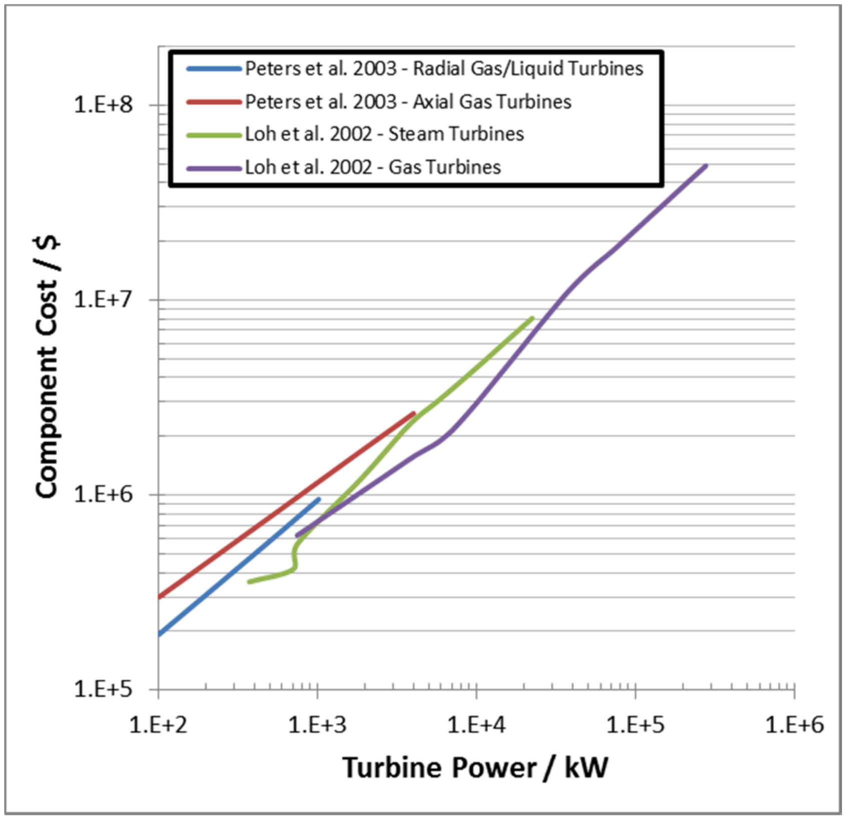
- **Approach**
  1. Collect literature-based cost models for the major components
  2. Collect sCO2 Brayton cycle layout options, including CSP-optimized

     For 1 and 2 see C. K. Ho, M. D. Carlson, P. Garg, and P. Kumar, "Cost and Performance Tradeoffs of Alternative Solar-Driven S-CO2 Brayton Cycle Configurations," in Proceedings of the ASME 2015 Power and Energy Conversion Conference, San Diego, California, 2015, pp. 1–10.
  3. Fit cost model trends to available and obtained vendor estimates
  4. Approximate the uncertainty in cost model estimates
  5. Develop a confidence range for the particle/sCO2 Hxer cost

Fit Cost Models to Vendor Data

Cost models are collapsed to approximately trend with vendor data.
****Proprietary vendor data not shown****

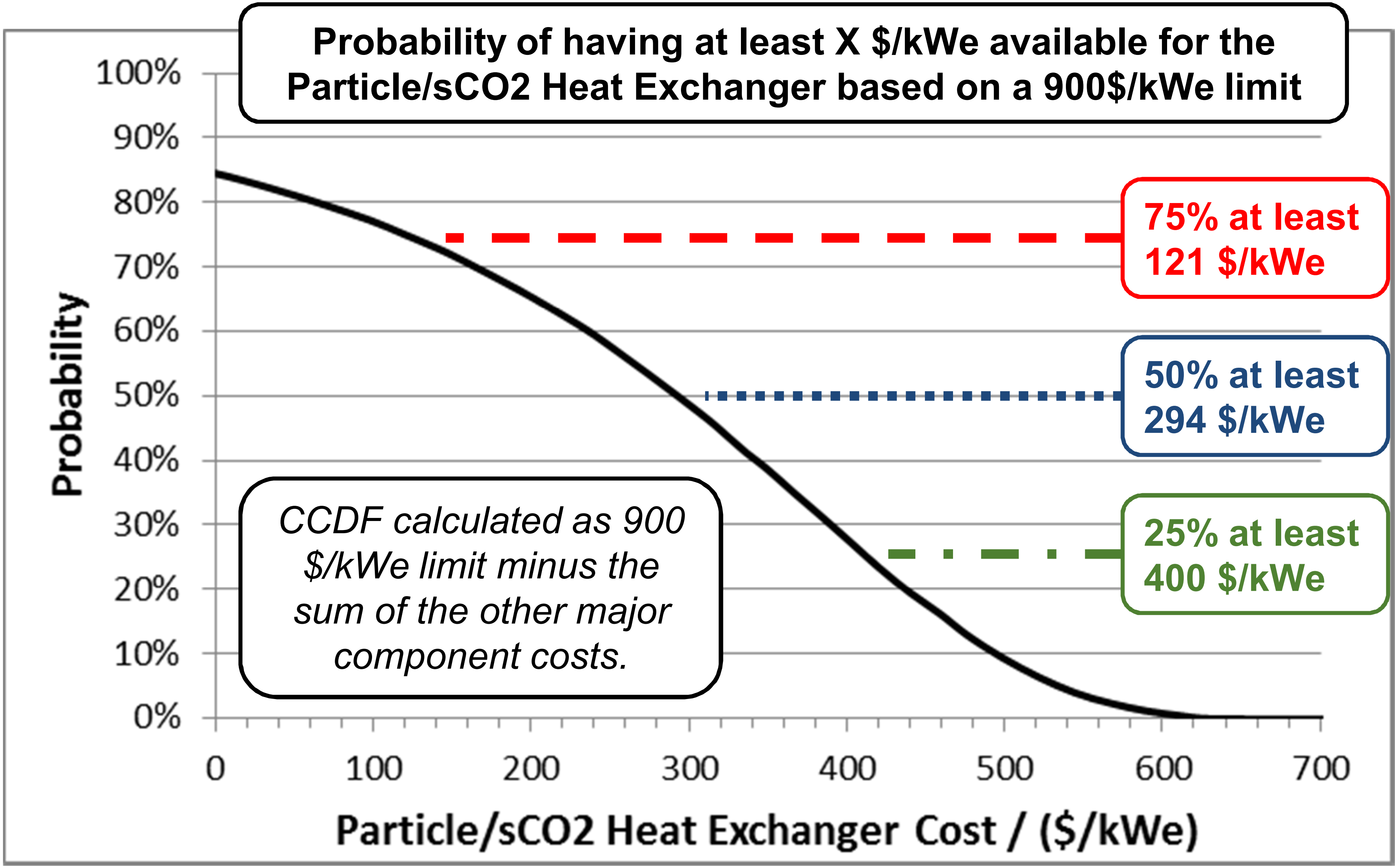




Cost Confidence with Minimal Data

- Approaches to cycle cost estimation
  - Use specific literature cost models or vendor estimates
    - X Assigning uncertainty to specific data is somewhat arbitrary
  - Weighted average of available cost data (Ho et al. 2015)
    - X Propagated uncertainty still relies on assigned uncertainty data
  - Bayesian analysis of component cost data (SuNLaMP)
    - ➢ Only assumes the functional form and fit parameter distributions
- Assumption of the hierarchical Bayesian approach
  - Component cost will follow a log-normal distribution
  - Cost vs. size functional form (i.e. power-law, $Cost = \alpha_0 Capacity^{\alpha_1}$)
  - Fitting parameters are normally-distributed
  - Prior precision is described by a gamma distribution
  - See P. R. Garvey, S. A. Book, and R. P. Covert, *Probability methods for cost uncertainty analysis: a systems engineering perspective*. 2016.

Heat Exchanger Cost Confidence



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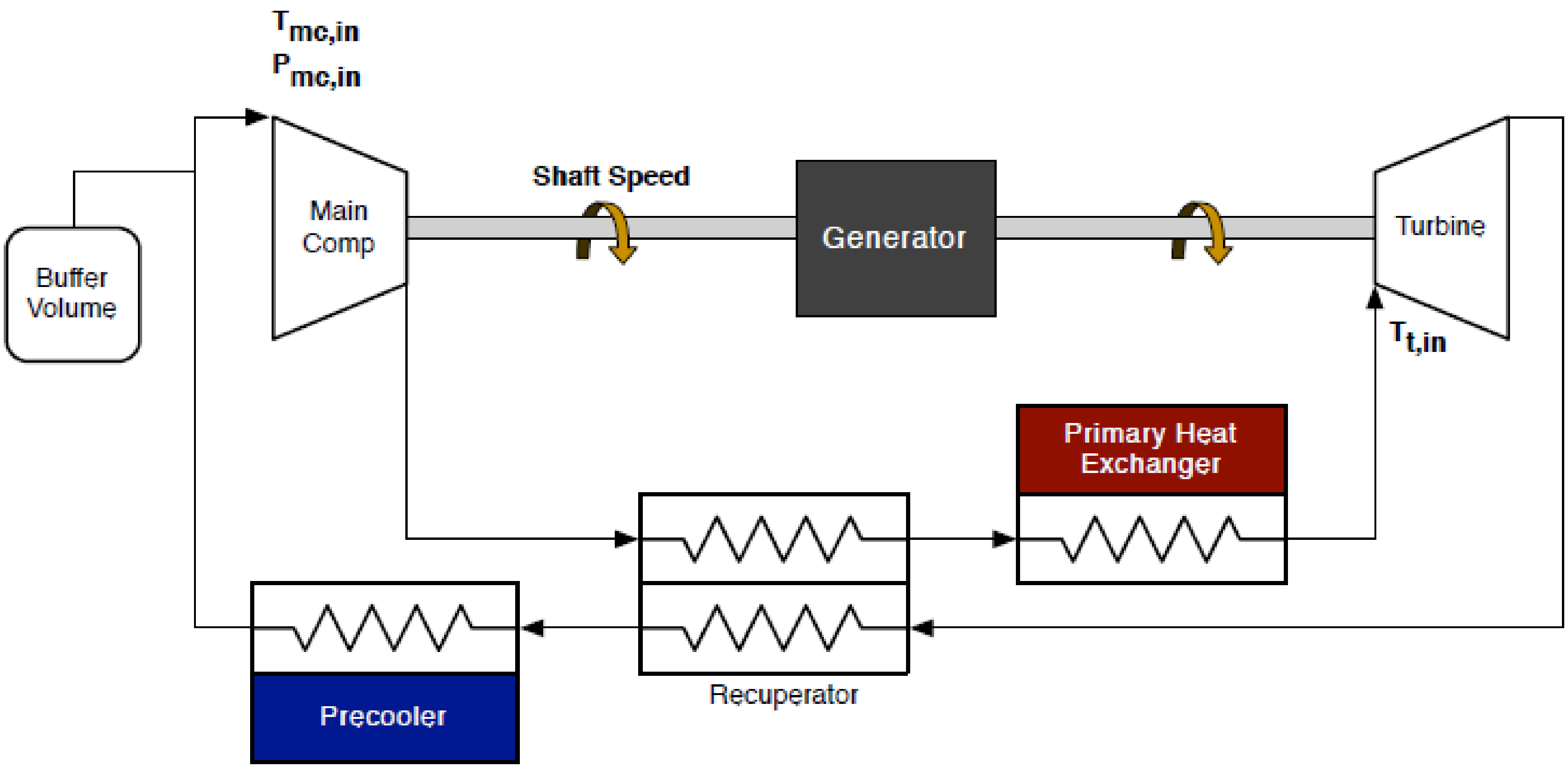
Conclusions

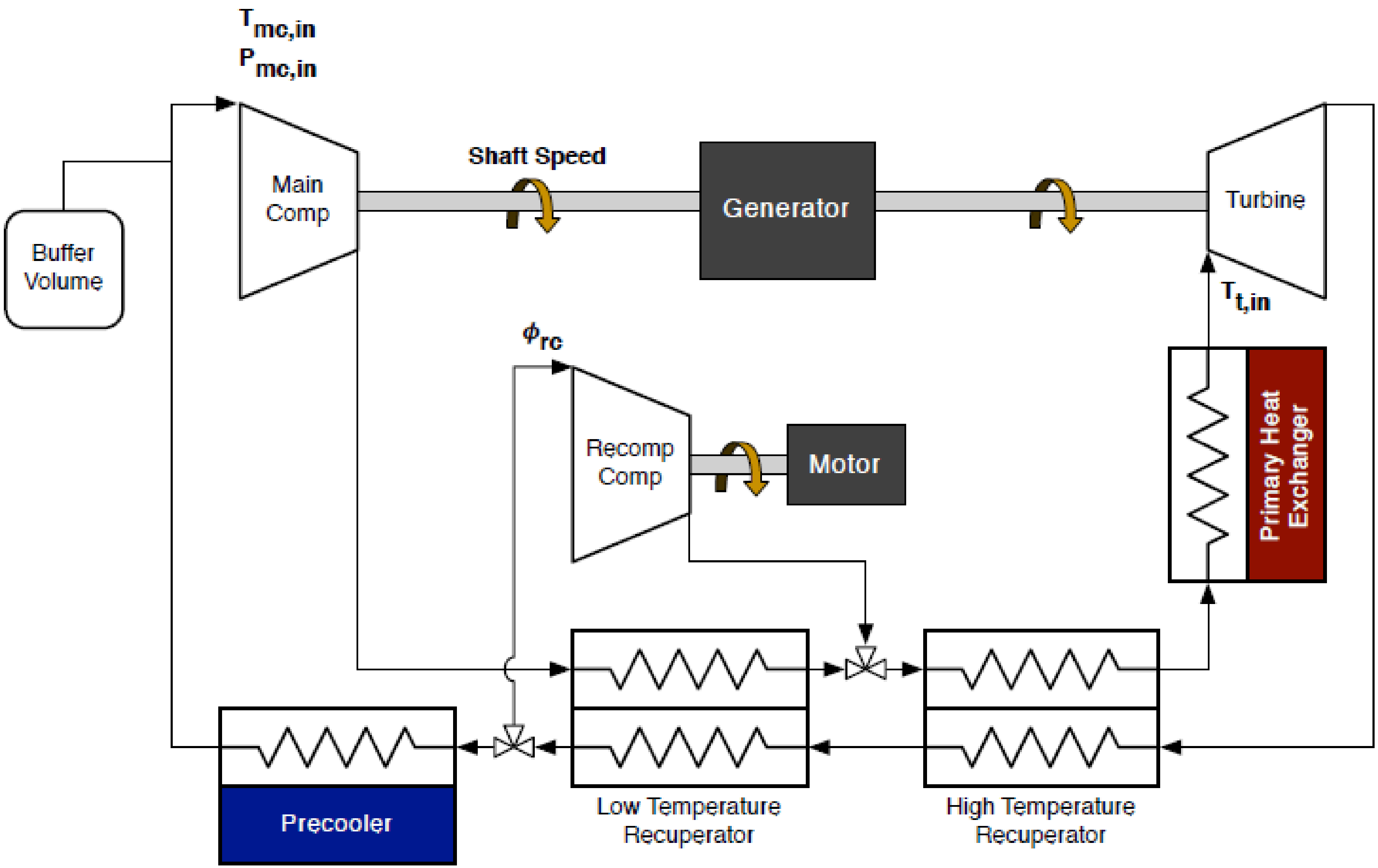
- The particle/sCO2 heat exchanger test bed is a last step in an integrated solarized sCO2 Brayton cycle demonstration
  - Sandia now has a falling particle receiver and RCBC equipment
  - Once tested, the SuNLaMP particle/sCO2 heat exchanger could couple the falling particle receiver and RCBC system
- Hierarchical Bayesian analysis of sCO2 Brayton cycle cost provides approximate confidence bounds with minimal data
  - Literature models exist for similar equipment but not for sCO2
  - Few vendor estimates or FOAK costs for sCO2 designs exist
- Next steps
  - Complete final design and procurement for the sCO2 support loop
  - Iterate power law fit parameter distributions in Bayesian analysis

Backup Slides

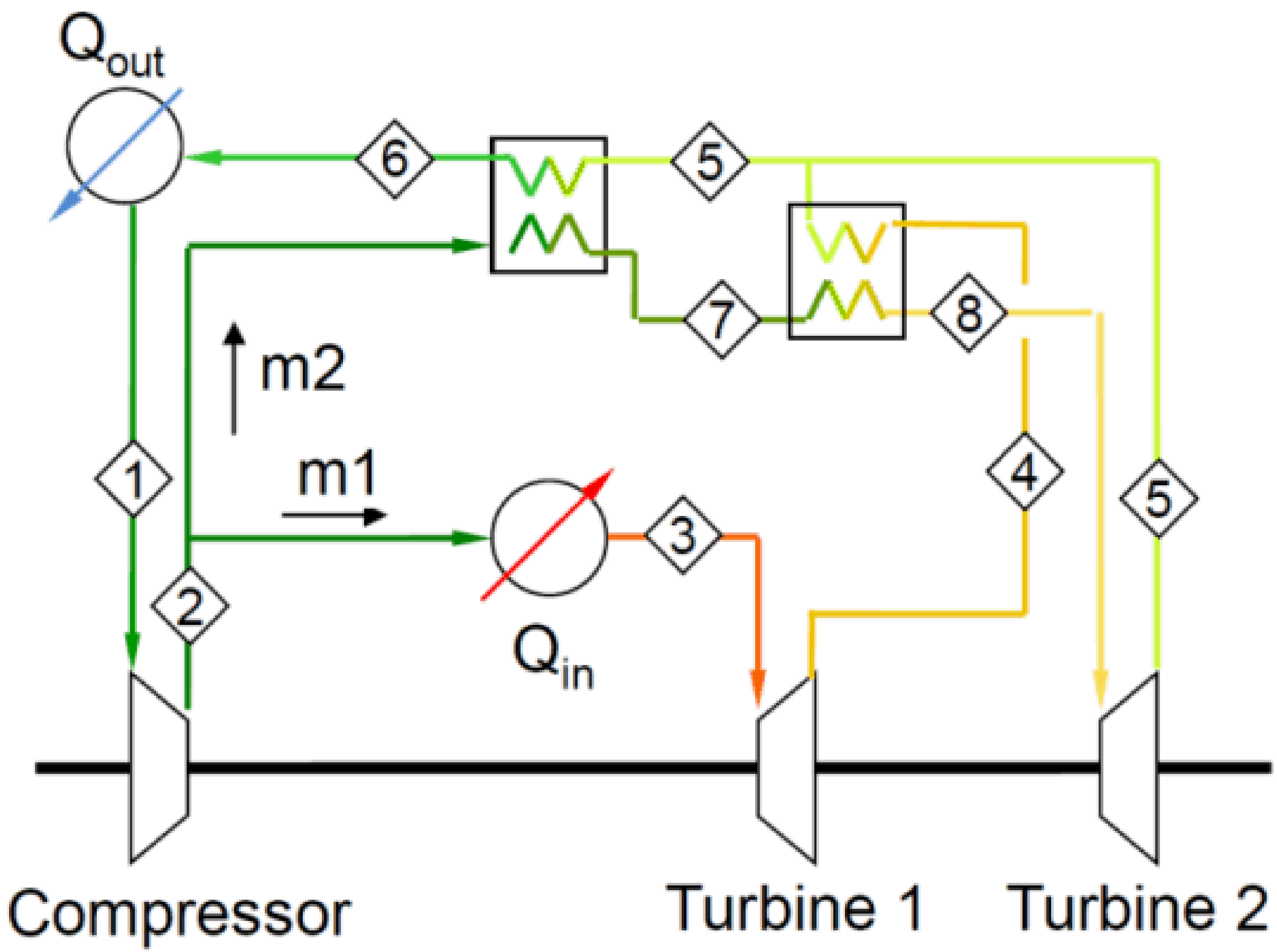
Simple Closed Brayton Cycle (SCBC)



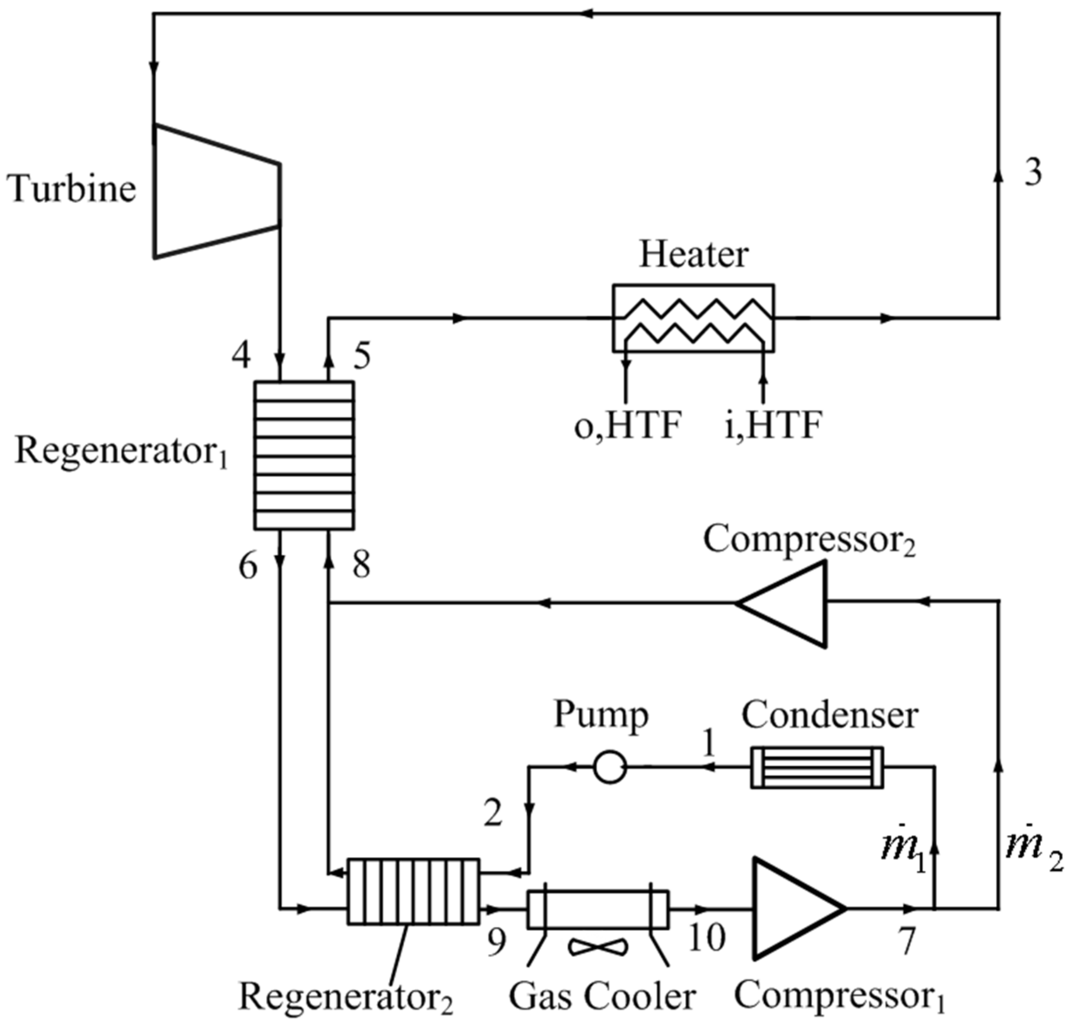
Recompression Closed Brayton Cycle (RCBC)



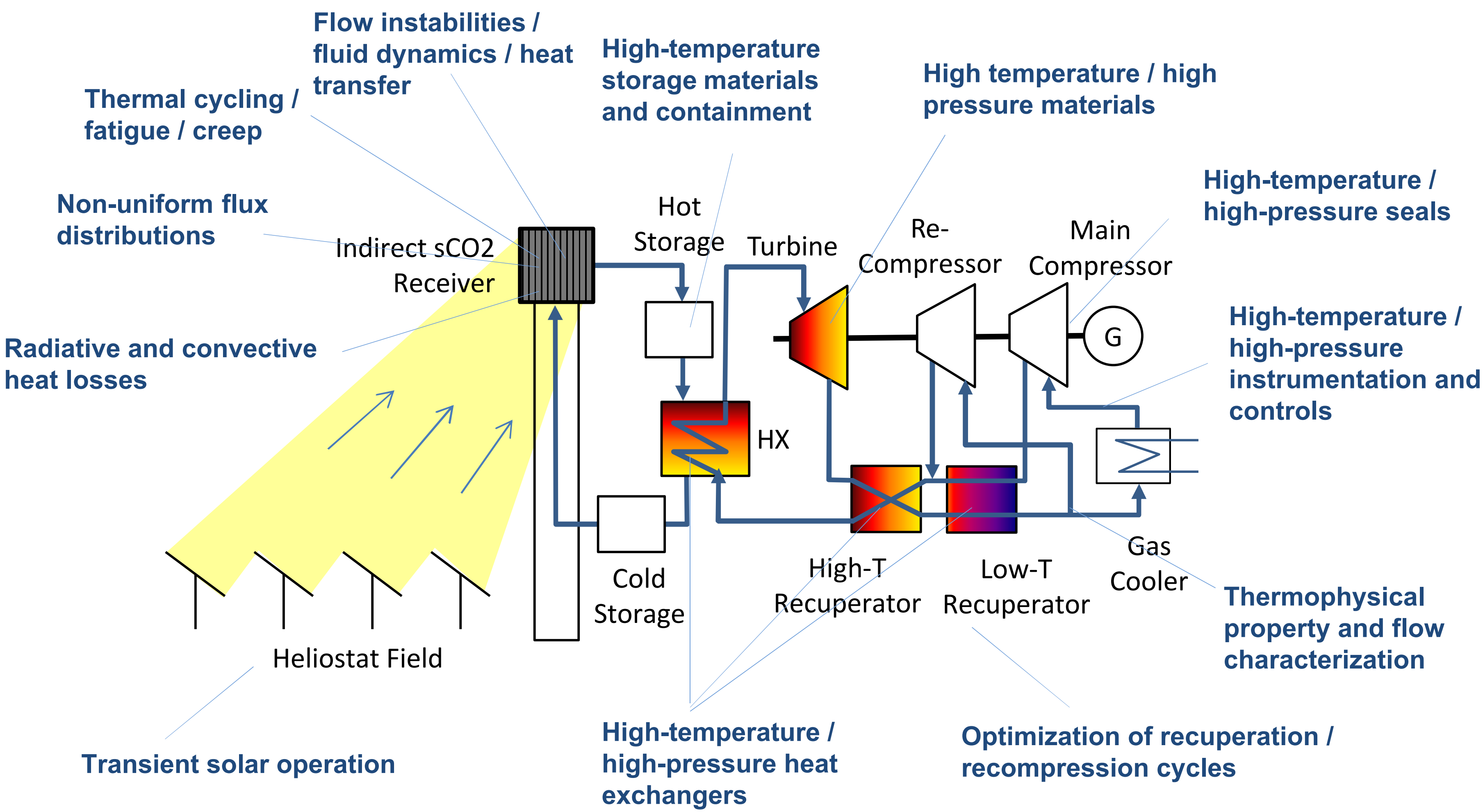
Cascaded Closed Brayton Cycle



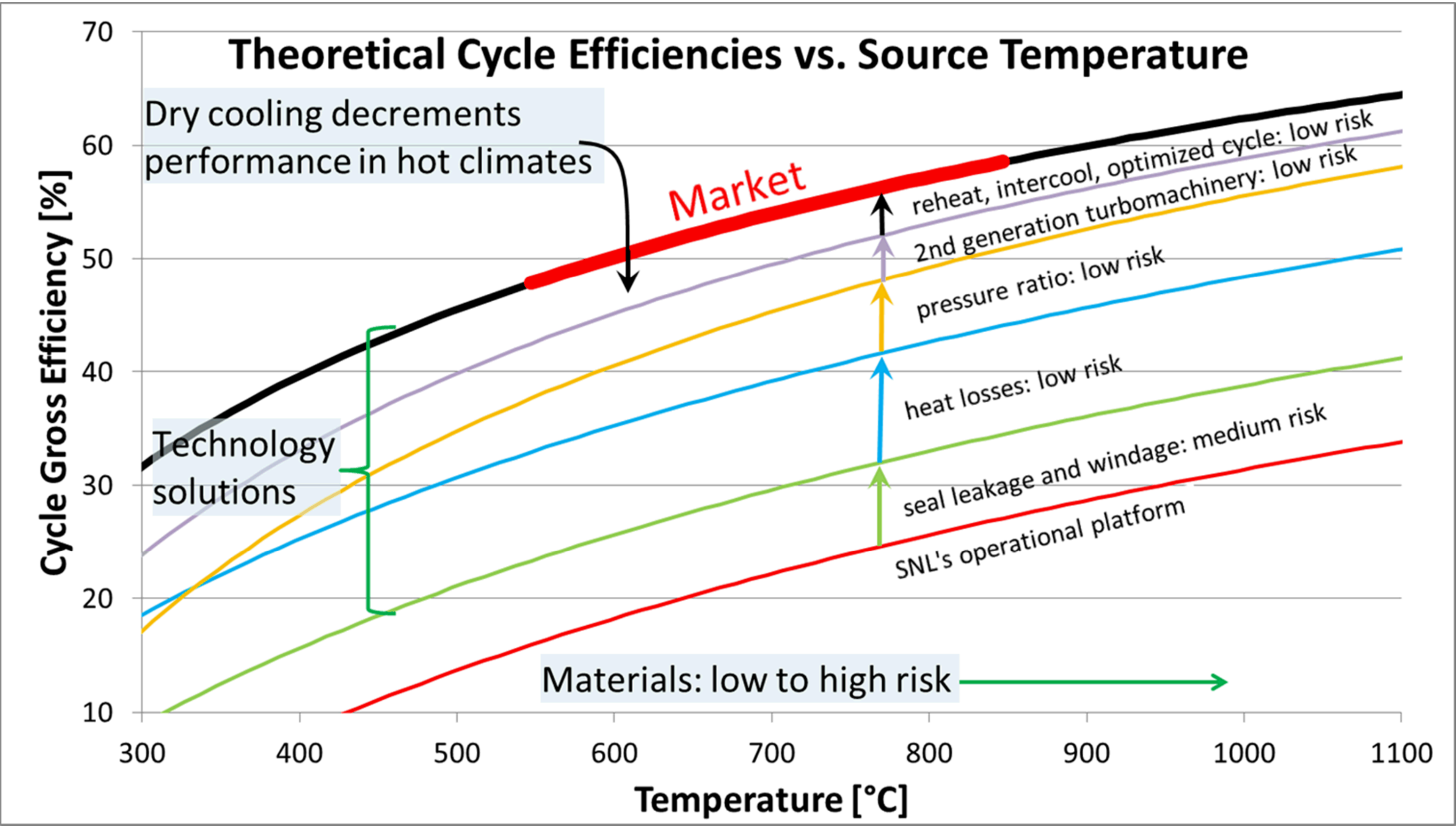
Combination Bifurcation with Intercooler (CBI)



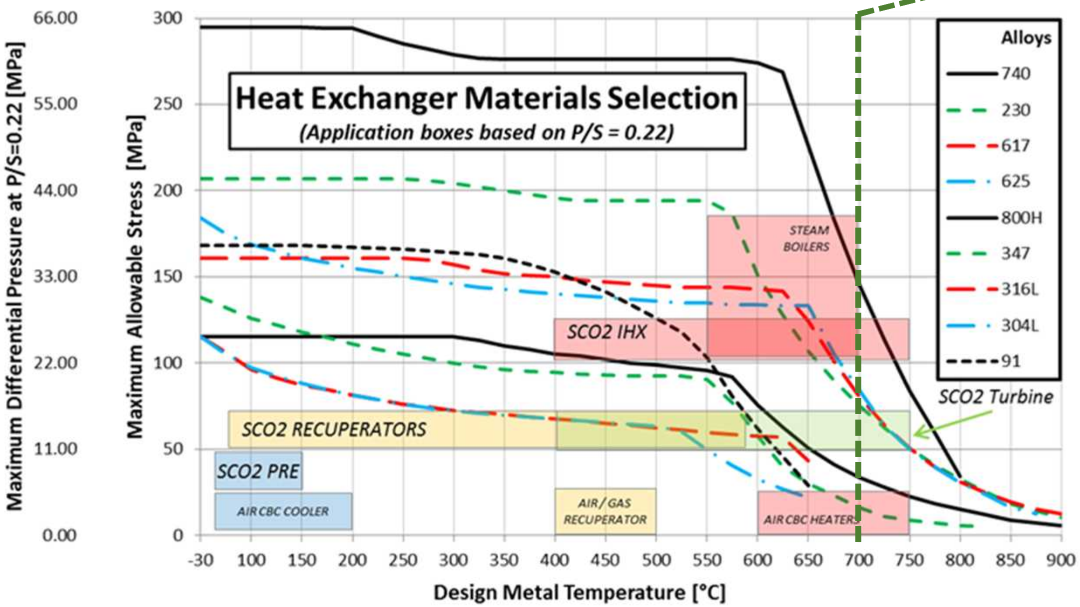
Technical Challenges

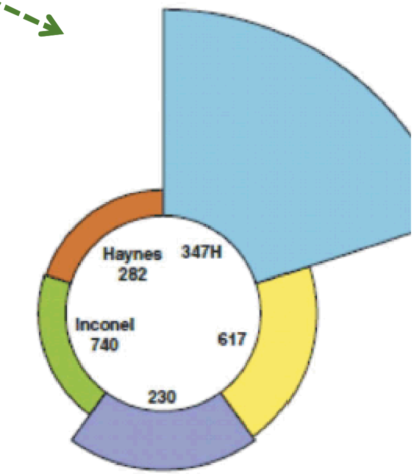


Path to High Efficiency

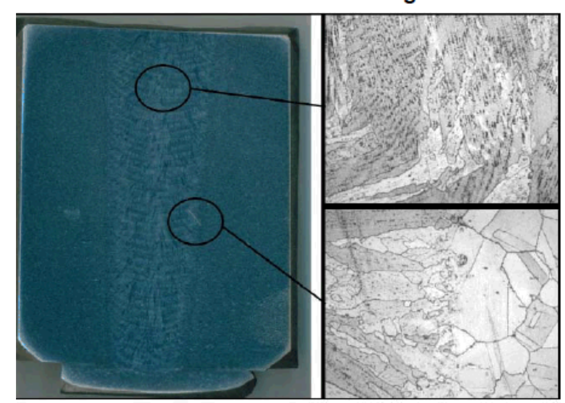


Materials are limited to <700C





Today: Repeatable 3" (75mm) thick Inconel 740 welds without cracking



- Advanced Ultrasupercritical (A-USC) research has advanced high temperature materials[1]
- Alloy 617 and 740 are leading candidates for such systems
  - 740 has recently been welded without cracking, more work is still needed to vet any materials issues[1]
- Little industrial experience exists and field testing is sparse.

1. *Shingledecker, Development of Advanced Materials for Advanced Ultrasupercritical (A-USC) Boiler Systems, 2014*
2. M. Carlson, "Options for SCO2 Brayton Cycle Heat Exchangers," presented at the The 4th International Symposium on Supercritical CO2 Power Cycles, Pittsburgh, PA, 2014.

Assumptions for Centrifugal Pumps

- At any particular value of pump capacity, there is a distribution for the cost of the pump.
  - ✓ Distribution is assumed to be lognormally distributed since cost can't be less than zero, but theoretically could be as high as anyone wants to charge.
  - ✓ Garvey, et al, state that lognormal distributions can model the production costs of goods well.
- The mean values of the distributions at each capacity level are related to each other via a power law model.

$$Cost = \alpha_0 * Capacity^{\alpha_1}$$

- α_0 α_1 and the standard deviation (σ) of the cost distributions are unknown.

Process

- Treat unknowns as random variables.
- Assign a prior distribution to each of the unknown variables.
- Use Bayes’ Theorem to update with the data.

Bayes' Theorem

$$P(\theta|y)P(y) = P(y|\theta)\pi(\theta)$$

$$P(\theta|y) = \frac{P(y|\theta)\pi(\theta)}{P(y)} = \frac{P(y|\theta)\pi(\theta)}{\int_{\text{all possible values of } \theta} P(y|\theta)\,d\theta}$$

$$P(\alpha_0,\alpha_1,\sigma|y) = \frac{P(y|\alpha_0,\alpha_1,\sigma)P(\alpha_0,\alpha_1,\sigma)}{P(y)}$$

$$= \frac{P(y|\alpha_0,\alpha_1,\sigma)P(\alpha_0,\alpha_1,\sigma)}{\int P(y|\alpha_0,\alpha_1,\sigma)\,d(\alpha_0,\alpha_1,\sigma)}$$

Using Monte Carlo simulation, the posterior distribution for the parameters can immediately be found. However, this involves sampling from a 3-dimensional distribution.

Instead, we can rewrite in such a way that we can sample from 3 one-dimensional distributions.

- θ represents a vector of unknowns (α_0, α_1, σ).
- Π represents the joint prior distribution for θ.
- y represents an observed data point (in our case, this would be a single cost/capacity observation for a centrifugal pump).
- P(y|θ) represents the assumed form of the distribution for data (lognormally distributed cost for a given mean and SD, which are determined by the triplet of (α_0, α_1, σ)).

Sampling Technique

$$P\left(\alpha_0^{t_1}\middle|\alpha_1^{t_0},\sigma^{t_0},y^{t_0}\right)=\frac{P\left(\alpha_1^{t_0},\sigma^{t_0},y^{t_0}\mid\alpha_0^{t_0}\right)P\left(\alpha_0^{t_0}\right)}{\int P\left(\alpha_1^{t_0},\sigma^{t_0},y^{t_0}\mid\alpha_0^{t_0}\right)d\alpha_0^{t_0}}$$

$$P\left(\alpha_1^{t_1}\middle|\alpha_0^{t_0},\sigma^{t_0},y^{t_0}\right)=\frac{P\left(\alpha_0^{t_0},\sigma^{t_0},y^{t_0}\mid\alpha_1^{t_0}\right)P\left(\alpha_1^{t_0}\right)}{\int P\left(\alpha_0^{t_0},\sigma^{t_0},y^{t_0}\mid\alpha_1^{t_0}\right)d\alpha_1^{t_0}}$$

$$P\left(\sigma^{t_1}\middle|\alpha_0^{t_0},\alpha_1^{t_0},y^{t_0}\right)=\frac{P\left(\alpha_0^{t_0},\alpha_1^{t_0},y^{t_0}\mid\sigma^{t_0}\right)P\left(\sigma^{t_0}\right)}{\int P\left(\alpha_0^{t_0},\alpha_1^{t_0},y^{t_0}\mid\sigma^{t_0}\right)d\sigma^{t_0}}$$

- This represents a single iteration of the MCMC process.
- The process is repeated thousands of time until the posterior distribution changes very little.
- At this point, it is assumed that the distribution has converged to a point that is very close to the stationary distribution.

Monte Carlo Simulation

- Monte Carlo – a numerical technique based on probability theory which is used for calculating the value of an integral
- Define: $I \equiv \int h(x)dx = \int \frac{h(x)}{\omega(x)}\omega(x)dx$
- Now, suppose $\omega(x)$ is a probability density function. Then, the integral, I, is the expected value of $\frac{h(x)}{\omega(x)}$ which, according to the Law of Large Numbers, can be approximated by

$$I \approx I_N \equiv \frac{1}{N}\sum_{t=0}^{N-1}\frac{h(x_t)}{\omega(x_t)}$$

- Note that the number of samples, N, required for a good approximation, can be reduced by choosing the appropriate function $\omega(x)$.

Markov Chains

- Markov Chain – A model of a system in which the state of a system (including all associated probabilities) at time t+dt depends only upon the state of the system at time t (i.e., times prior to the present do not influence the future).

$$\vec{P}(t_{i+1}) = T\vec{P}(t_i)$$

- In this expression, $\vec{P}(t)$ is a vector representing the probabilities of various states at time t and T is the transition matrix, which contains the probabilities of transitioning from state to state.

Markov Chains, cont.

- Stationary Distribution – The limiting distribution of a Markov process. A stationary distribution will exist if:
  - The transition matrix, T, is time homogeneous
  - It is possible to transition from any state to any other state, given enough time (this property is called irreducibility)
  - Given any current state, there is a finite expected time to return to that state (i.e., all states are positive recurrent)

Markov Chain Monte Carlo

- Markov Chain Monte Carlo is a technique by which an approximate distribution is sampled and successively updated until the distribution is deemed to be “close enough” to the desired stationary distribution.
- The stationary distribution is the desired state.
- For our system, a state is defined by a particular set of values for the five parameters of the release model and the data that we have.