the Energy to Lead

# Steady State and Transient Modeling for the 10 MWe $SCO_2$ Test Facility Program

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# Agenda

- $SCO_2$ Test Facility Program Overview
- Steady State Modeling
  - Modeling Assumptions
  - Optimization Parameters
  - Initial Results
  - Impact of Results
- Transient Modeling
- Conclusion

# $SCO_2$ Test Facility Program

- Funded by DOE NETL
- 6 year program started in October 2016
- Design, construct, and build test facility in San Antonio, Texas
  - 700°C or higher turbine inlet temperature
  - 10 MWe net RCBC configuration
  - Simple Cycle configuration also to be tested
- Objectives
  - Demonstrate operability of SCO2 cycle
  - Verify performance of components
  - Show potential for producing lower COE
  - Demonstrate potential and pathway for thermodynamic η > 50% in commercial applications

# Steady State Modeling: Overview

- Steady State Modeling
  - Provides input for technical specifications for each equipment
  - Component sizing and optimization based on a 10 MWe RCBC configuration with 715°C turbine inlet temperature
- 3 modeling tools used
  - Ensures accuracy and repeatability of results

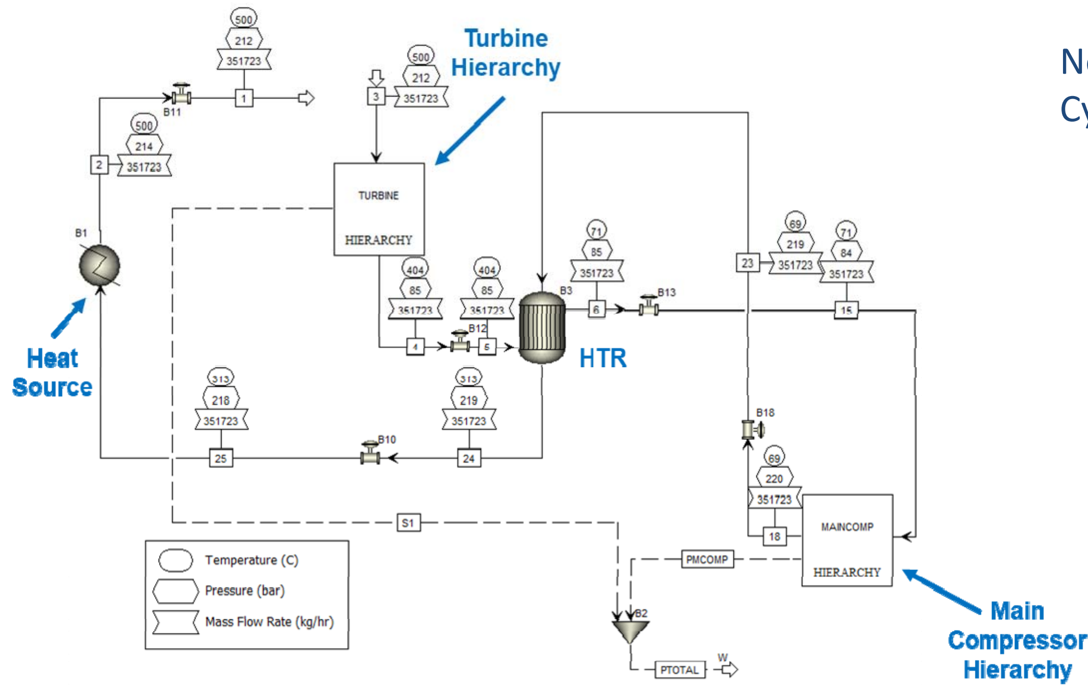
| Organization | Steady State Modeling Tool |
|---|---|
| Gas Technology Institute | Aspen Plus |
| General Electric Global Research | Aspen Hysys |
| Southwest Research Institute | Numerical Propulsion System Simulation (NPSS) |

# Steady State Modeling: Assumptions

- Thermodynamic property method: REFPROP
- Turbomachinery performance maps provided by GE
- Recuperator parameters:
  - 5°C approach temperature
  - 0.7 bar pressure drop per side
- Heat source pressure drop was 4 bar
- Initial piping pressure drops based on past GTI layout of a commercial scale plant

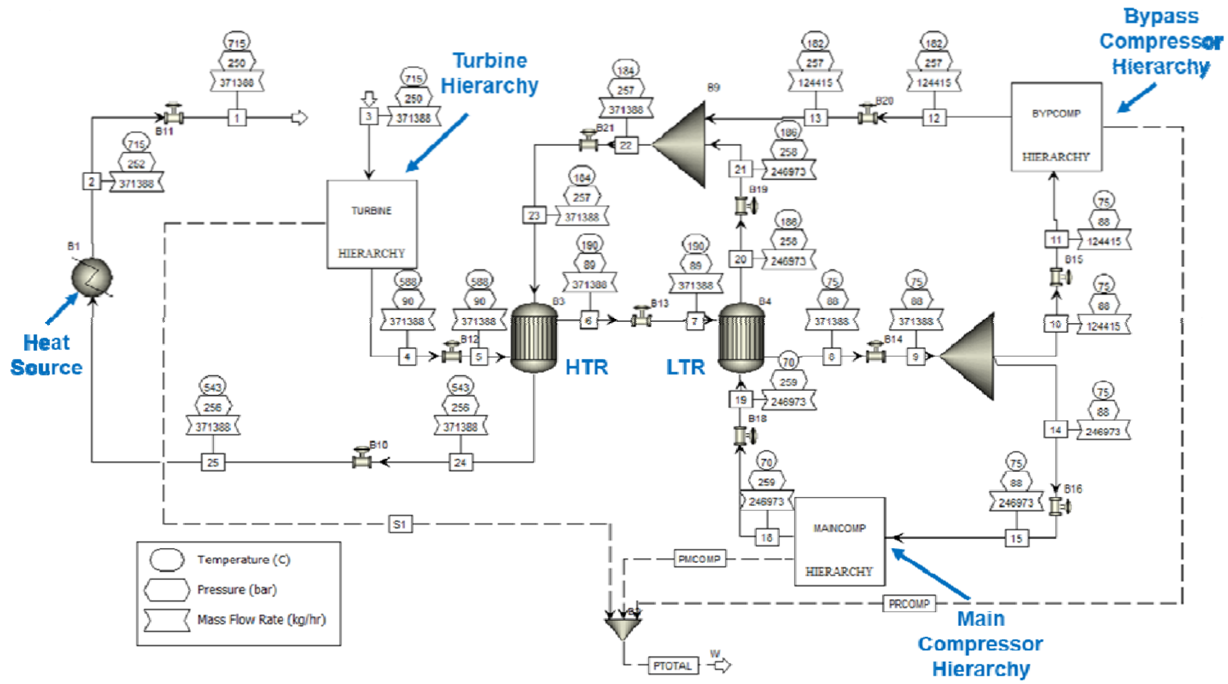
# Steady State Modeling: Aspen Models

Net Plant Power = 6.5 MWe
Cycle η = 30.8%




Simple Cycle Pilot Plant Aspen Plus Model

# Steady State Modeling: Aspen Models




Net Plant Power = 10.4 MWe

Cycle η = 46.2%

RCBC Pilot Plant Aspen Plus Model

# Steady State Modeling: Optimization Parameters

- 3 elements to achieving high cycle efficiency for a given net power output
  - Maximizing turbine power production
  - Minimizing compressor power
  - Minimizing heat input into the system

| Parameter | Simple Cycle | Recompression Cycle |
|---|---|---|
| Turbine Inlet Temperature | X | X |
| Turbine Inlet Pressure | X | X |
| Turbine Pressure Ratio (Exit Pressure) | X | X |
| Compressor Inlet Guide Vane (IGV) Setting | X | X |
| Flow Split between Compressors | | X |

# Steady State Modeling: Maximizing turbine power production

- Turbine power dependent upon:
  - Inlet and outlet conditions
  - Mass flow rate
  - Turbine efficiency
- Turbine exit pressure needs to be high enough to ensure two phase flow does not occur at main compressor inlet
- 15% margin on the critical pressure applied in these initial models

# Steady State Modeling: Minimizing Compressor Power

- Compressor power dependent upon:
  - Inlet and outlet conditions
  - Mass flow rate
  - Compressor efficiency
- Inlet guide vane (IGV) settings can be adjusted to vary compressor ratios and efficiencies
- Complicating factor for RCBC configuration is flow split between compressors, which affects efficiency

# Steady State Modeling: Minimizing Heat Input

- 2 factors
- 1st factor: minimize mass flow rate through heater
  - Dependent upon turbine flow function
- 2nd factor: Achieve highest cold stream outlet temperature from high temperature recuperator (HTR)
  - Minimize approach temperature in recuperators
  - 5°C chosen

# Steady State Modeling: Initial Results

- 7 cases were modeled

| Model Names | Cycle Configuration | Load % | Net Power Level (MWe) | Turbine Inlet Temperature | Turbine Inlet Pressure | Cooler Exit Temperature | Cycle Efficiency |
|---|---|---|---|---|---|---|---|
| 033 | Simple | Min | 3.6 | 500°C | 170 bar | 35°C | 26.0% |
| 036 | Simple | Max | 6.5 | 500°C | 212 bar | 35°C | 30.8% |
| 051 | Recompression | 100% | 10.4 | 715°C | 250 bar | 35°C | 46.2% |
| 052 | Recompression | 100% | 7.9 | 715°C | 259 bar | 50°C | 42.1% |
| 053 | Recompression | 100% | 13.6 | 715°C | 250 bar | 20°C | 45.2% |
| 054 | Recompression | 40% | 4.0 | 715°C | 170 bar | 35°C | 39.1% |
| 055 | Recompression | 100% | 7.7 | 500°C | 250 bar | 35°C | 36.6% |

# Steady State Modeling: Agreement Among 3 Models

- Results of the 3 models show good agreement for baseline case
- Differences less than 2% generally
- LTR heat duty difference is larger due to different pressure drop and approach temperature assumptions

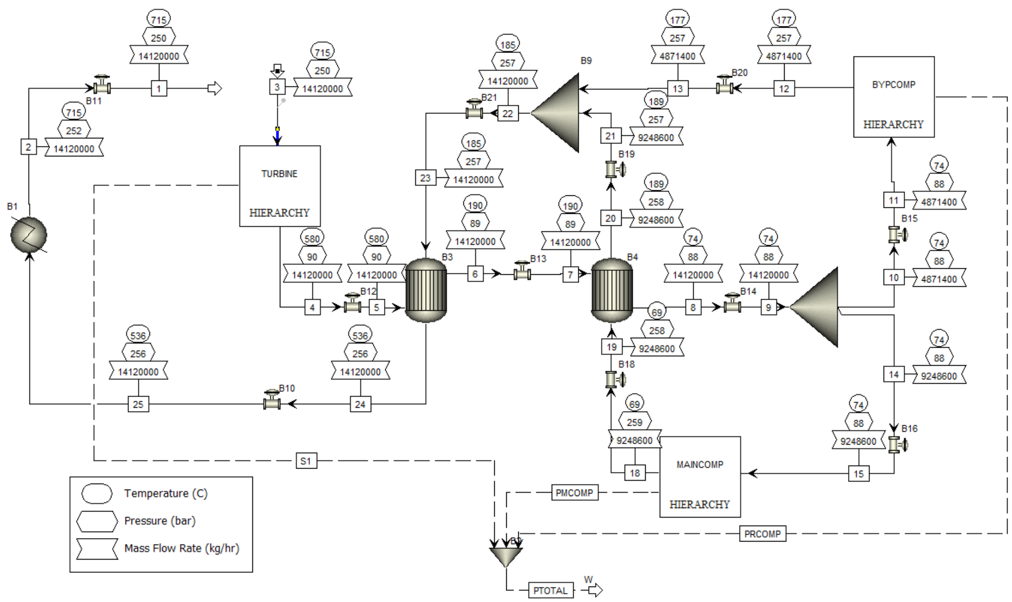
| Parameter | Unit | Aspen Plus | Aspen Hysys | NPSS | Largest Delta |
|---|---|---|---|---|---|
| Net Electric Power | MWe | 10.4 | 10.3 | 10.3 | 0.96% |
| Cycle Efficiency | % | 46.2 | 45.7 | 45.8 | 1.1% |
| Turbine Power | MWe | 15.6 | 15.6 | 15.6 | 0.06% |
| Main Comp Power | MWe | 2.15 | 2.15 | 2.16 | 0.47% |
| Bypass Comp Power | MWe | 2.68 | 2.67 | 2.65 | 1.1% |
| Optimized Flow Split to Main Comp | % | 66.5 | 66.7 | 66.8 | 0.45% |
| HTR Heat Duty | MWth | 48.0 | 48.3 | 48.1 | 0.48% |
| LTR Heat Duty | MWth | 15.4 | 14.8 | 14.7 | 4.5% |
| Heater Heat Duty | MWth | 22.5 | 22.5 | 22.6 | 0.44% |

# Steady State Modeling: Agreement Among 3 Models

| Parameter | Unit | Aspen Plus | Aspen Hysys | NPSS | | Largest Delta |
|---|---|---|---|---|---|---|
| Net Electric Power | MWe | 4.0 | 4.0 | 3.9 | | 2.5% |
| Cycle Efficiency | % | 39.1 | 39.5 | 39.7 | | 1.4% |
| Turbine Power | MWe | 7.75 | 7.47 | 7.49 | | 3.9% |
| Main Comp Power | MWe | 1.54 | 1.50 | 1.56 | | 4.0% |
| Bypass Comp Power | MWe | 2.06 | 1.77 | 1.85 | | 14% |
| Optimized Flow Split to Main Comp | % | 61.0 | 64.0 | 63.0 | | 4.9% |
| HTR Heat Duty | MWth | 31.2 | 30.6 | 32.95 | | 7.7% |
| LTR Heat Duty | MWth | 8.28 | 9.13 | 7.32 | | 20% |
| Heater Heat Duty | MWth | 10.3 | 10.2 | 9.9 | | 3.9% |

- Off-design cases results show more disagreement
- Smaller difference in system level parameters, such as cycle efficiency or turbine power
- Larger difference in detail component performance, such as IGV setting
- Main reason for discrepancies is off-design assumptions for recuperator performance and minor flow rate differences

# Steady State Modeling: Impact of Results



| Parameter | 10 MWe Pilot Plant | Commercial Plant |
|---|---|---|
| Net Plant Capacity | 10 MWe | 450 MWe |
| Turbine PR | ~3 | Same as Pilot |
| Turbine Efficiency | 87.3% | 91% |
| Main Compressor PR | ~3 | Same as Pilot |
| Main Compressor Efficiency | 78.5% | 83% |
| Bypass Compressor PR | ~3 | Same as Pilot |
| Bypass Compressor Efficiency | 78.2% | 80.1% |
| Generator Efficiency | 97.6% | 99% |
| Gearbox Efficiency | 99.3% | N/A |
| System Pressure Drop | ~12 bar | Same as Pilot |
| Cycle Efficiency | 46.2% | 50.5% |

# Steady State Modeling: Impact of Results

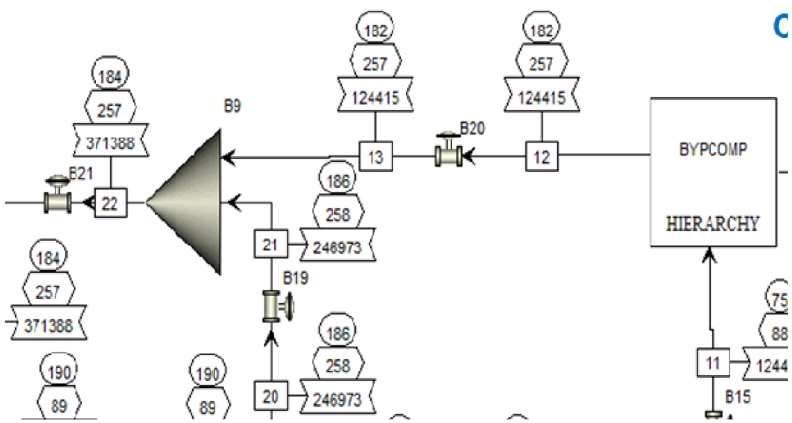
- Performance losses due to increased pressure drop

| | Pressure Drop (bar) |
|---|---|
| Initial piping + equipment pressure drop assumption | ~12 bar |
| Initial piping layout + equipment pressure drop | ~17 bar |

- 2 cases modeled to determine impact
  1. Maintain baseline compressor pressure ratios → decreasing turbine pressure ratio
     - Result: turbine pressure ratio dropped by 2.6%, cycle efficiency dropped by 0.9 points
  2. Maintain turbine pressure ratio → increasing compressor pressure ratios
     - Result: compressor pressure ratios increased by 3-4%, cycle efficiency dropped by 0.2 points
- More work needed, but initial results show maintaining turbine pressure ratio is better for maintaining a higher efficiency

# Steady State Modeling: Impact of Results

- Performance losses due to recuperator approach temperature
  - Increasing recuperator approach temperature → reduced cycle efficiencies
  - One exception: LTR approach temperature



# Transient Modeling: Overview

- Transient Modeling
  - Results will provide insight into operational analysis for the facility
- 2 modeling tools will be used
  - Ensures accuracy and repeatability of results

| Organization | Steady State Modeling Tool |
|---|---|
| Gas Technology Institute | Flownex |
| General Electric Global Research/Southwest Research Institute | Numerical Propulsion System Simulation (NPSS) |

# Transient Modeling: Next Steps

- Build/modify steady state models
- Benchmark these to Aspen Plus & Hysys models
- Develop and implement control system methodology
- Run analysis for various transient cases

# Conclusion

- Initial steady state analysis has been performed
  - 3 different steady state modeling tools: Aspen Plus, Aspen Hysys, NPSS
  - Initial results show good agreement among the models for overall performance
  - Steady state results have been incorporated into technical specifications for the components
  - Updates to steady state models in progress
- Transient modeling of the facility is in progress
  - 2 modeling tools will be used: Flownex and NPSS
  - Results will aid in the operational analysis for the facility

# Acknowledgement & Disclaimer


- Acknowledgement
  - This material is based upon work supported by the Department of Energy under Award Numbers DE-FE0028979.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# Thank you!

## Questions?

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