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S-CO_2 Brayton Loop Transient Modeling

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Kevin D. Rahner received a B.S. in physics from University at Albany, SUNY and an M.S. degree in electrical engineering from Binghamton University, SUNY. In 2002 he joined the Knolls Atomic Power Laboratory, Niskayuna NY (operated by Bechtel Marine Propulsion Corporation for the U.S. Government). His development and work efforts have covered a wide range of engineering disciplines including electrical performance modeling and radiative heat transfer modeling of thermophotovoltaic (TPV) systems. Since 2007 he has been actively involved in transient modeling S-CO_2 Brayton cycles.

Abstracts

The Integrated System Test (IST) is a complete 100 kWe supercritical carbon dioxide (S-CO_2) Brayton system constructed and operated to validate design and control strategies. A full plant TRACE (TRAC/RELAP Advanced Computational Engine) model is the primary tool for thermal-hydraulic and control system design of this test facility. The model has been used to specify control strategy, control device characteristics and test procedures for safe and effective operation. While the model suggests which control methods are most effective, actual operation is needed to validate the predictions and gain valuable experience during nominal, off-nominal and faulted conditions. By qualifying the code and model using IST data the best design features and control methods will be applied to future applications. IST control strategy focuses on maintaining a constant compressor surge margin. At a constant surge margin high compressor efficiency and resilience to planned and unplanned transients is provided. Constant surge margin is achieved by matching compressor speed to system power output and matching system flow resistance to compressor speed. Changes in compressor speed and system resistance are best accomplished using a compressor recirculation (or recycle) valve, potentially in combination with turbine throttle valves. A compressor motor is available for startup, initial loop heatup, and special test purposes only.
Testing to date has confirmed the effectiveness of the overall IST control strategy and shown the TRACE model to be a highly effective tool for design and operation of an S-CO_2 closed Brayton power loop.

The Integrated System Test (IST) is a complete 100 kWe supercritical carbon dioxide (S-CO_2) Brayton system constructed and operated to validate design and control strategies. The IST turbomachinery was designed and manufactured by Barber-Nichols Inc (BNI). Predicted turbomachinery performance maps were also provided by BNI that relates mass flow, turbine/compressor speed, with enthalpy rise/drop. These performance maps are incorporated into a TRACE transient model used for thermal-hydraulic and control system design.
Recent testing performed over a wide range of operating conditions provides the opportunity for comparing predicted turbomachinery performance with data at off-nominal conditions. Because operational S-CO_2 power cycles are relatively new, there is limited data for empirically derived loss models and design tools to have been validated for use with operating turbomachinery near the working fluid critical point. The operation of radial inflow turbines and radial compressor at off-design conditions necessitate the use of “corrected” conditions to interrogate the performance maps. The pressure losses and need to correct for variations in inlet fluid conditions add to the uncertainty of predicted turbomachinery performance. IST test data will be compared to performance predictions to assess turbomachinery performance maps.

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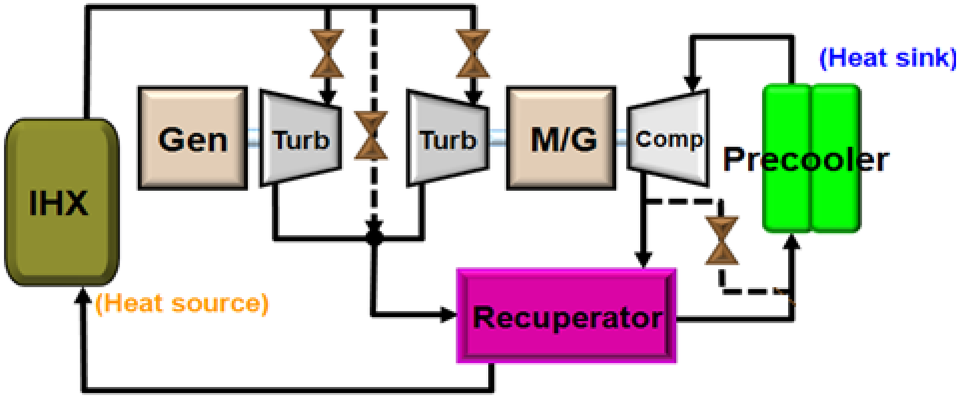
BECHTEL MARINE PROPULSION CORPORATION

Outline

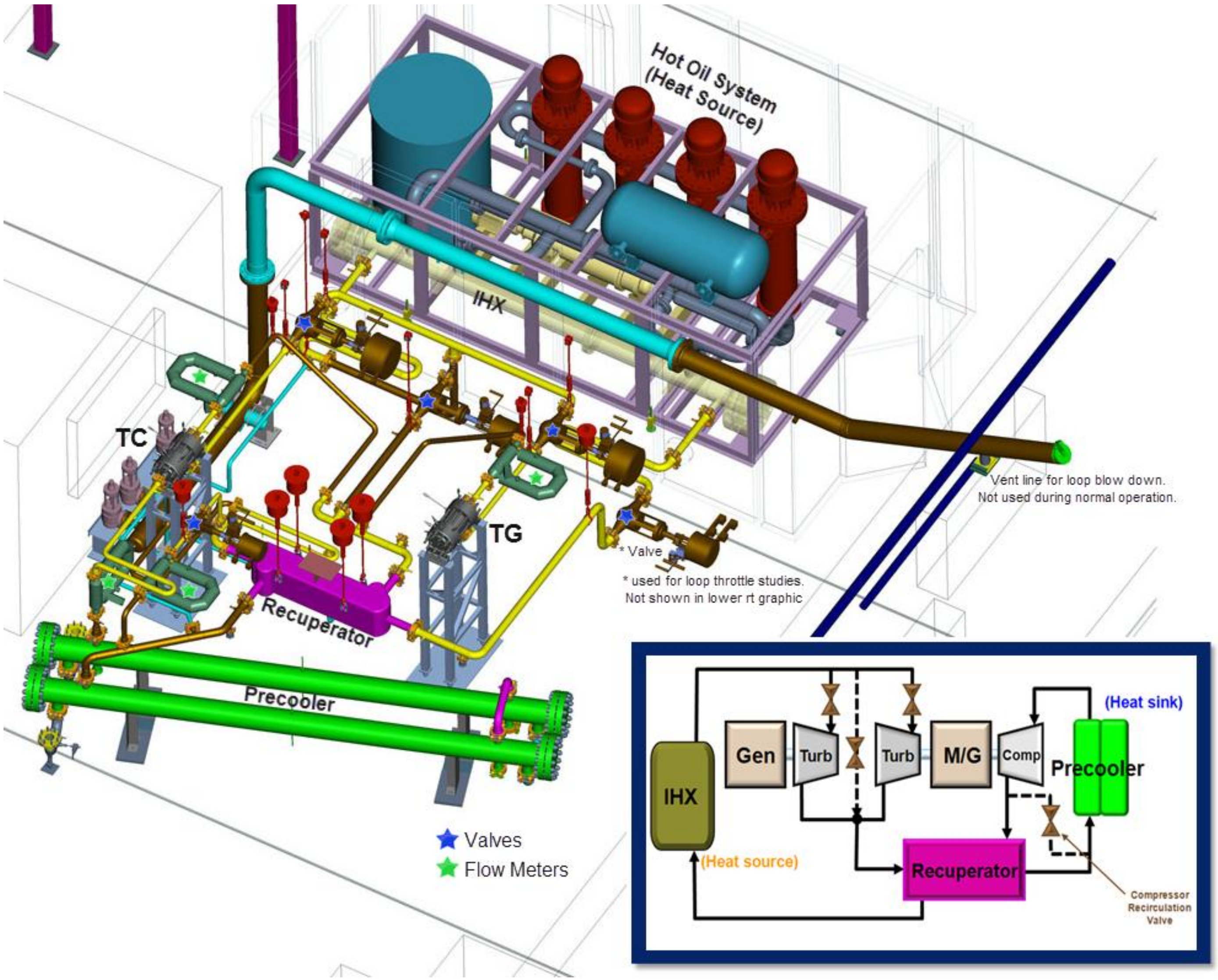
- Background
- Model Results and Comparisons with Test Data
  - Steady State Heat Balance
  - Transient
    - Turbomachinery Start-up
    - Power Transients
- Next Steps/Model Updates
  - NIST REFPROP/FIT
  - Test data
- Summary

Background

- Integrated Systems Test (IST)
  - Characteristics
    - Recuperated Closed Cycle Brayton
    - Rated power 100kWe
    - Power and Compressor Turbines in Parallel
    - Constant Speed Turbine Generator
    - Generated power $\propto$Compressor Speed
    - Fixed inventory
  - Purpose
    - Operational experience
    - Demonstrate system control
    - Validate transient model



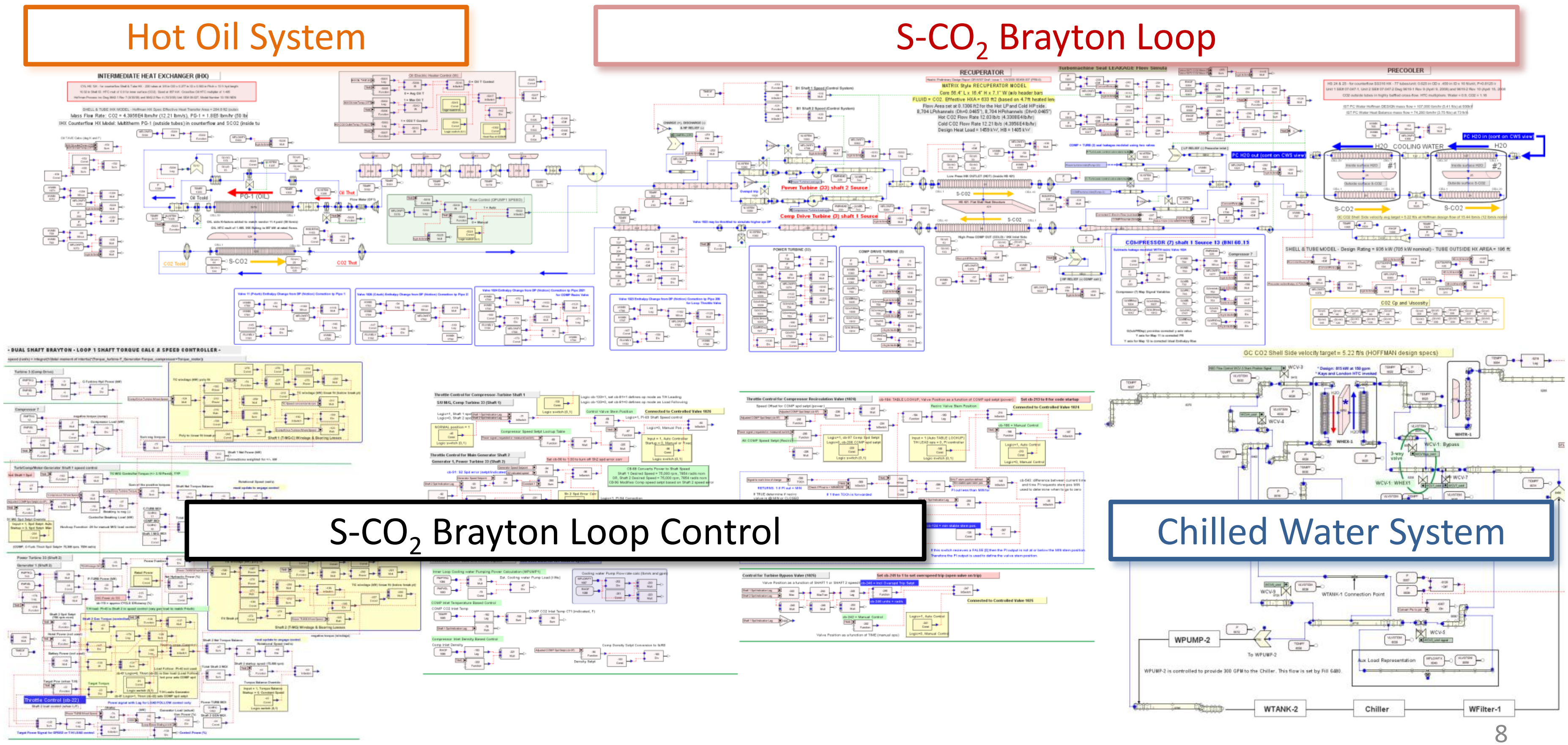
Background: Integrated Systems Test



Background: Integrated Systems Test

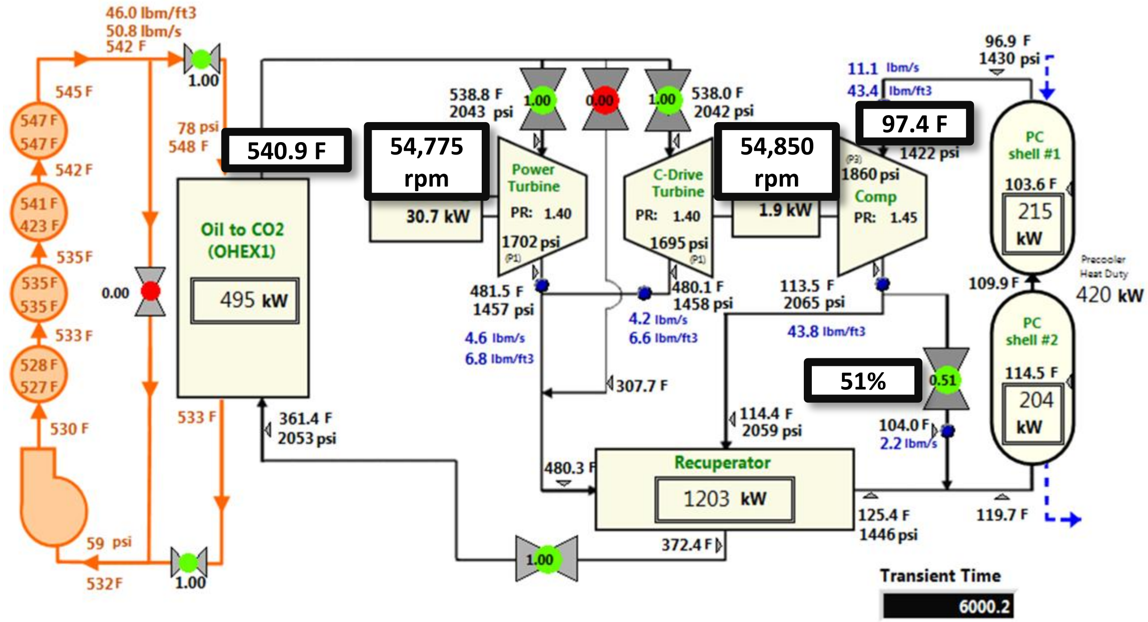
Background: IST Transient Model

- IST Transient Model
  - Built using TRACE and SNAP GUI
  - Heat Source to Heat Sink
  - Developed compressible fluid modeling methods
  - Developed control systems

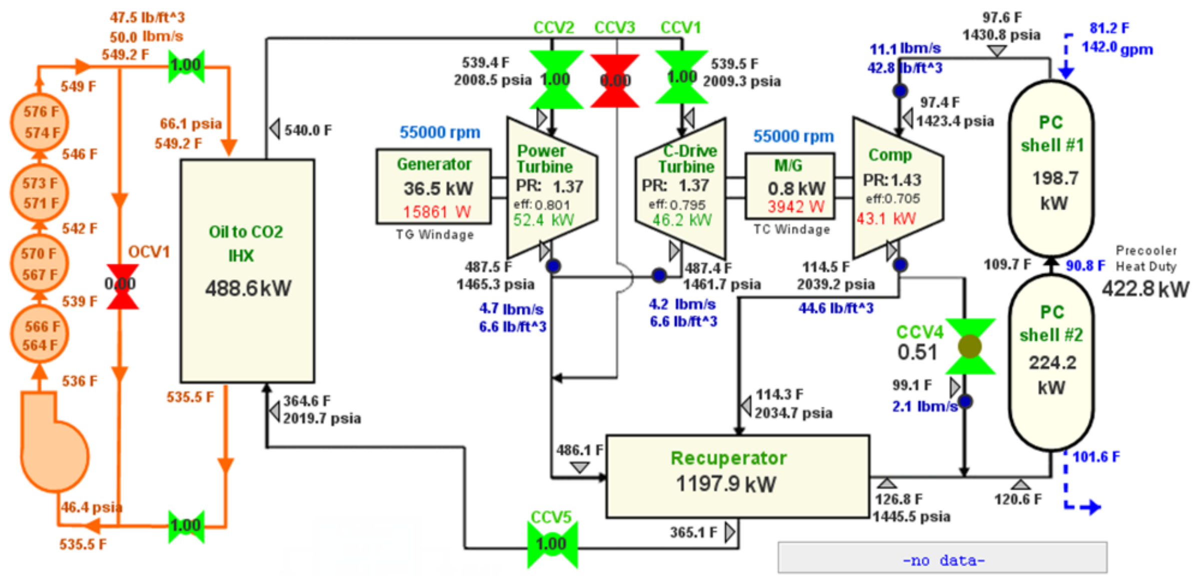


Steady State Comparison: Updated Model

Test

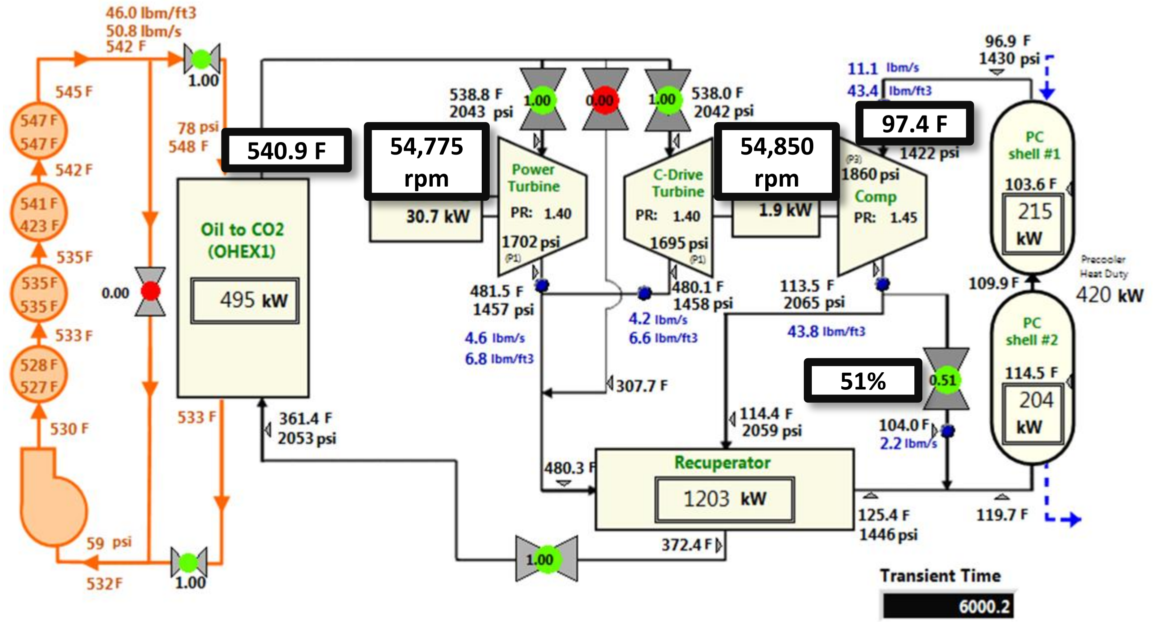


Model



Steady State Comparison: Updated Model

Test



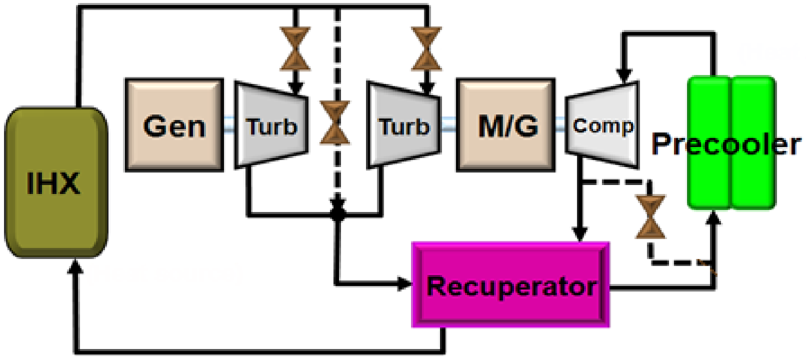
Parameter	Test	Pretest TRACE Model	TRACE Model With adjusted compressor map
Compressor Mass Flow (lbm/s) [kg/s]	11.1 [5.0]	10.1 [4.6]	11.1 [5.0]
Compressor PR	1.45	1.37	1.43
Compressor Exit Temperature (F) [K]	113.5 [318.3]	113.2 [318.1]	114.5 [318.8]

IST Startup

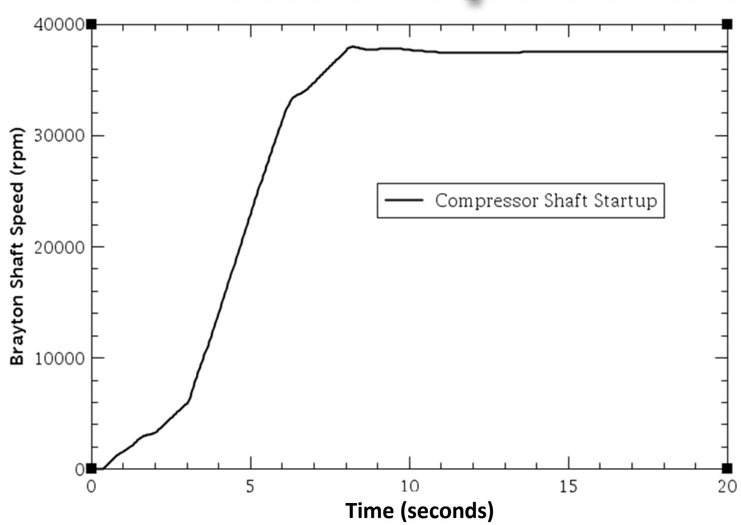
- Phenomenon considered during turbomachinery startup
  - Compressor surge
  - Reverse Turbine Flow
  - Gas Foil Bearing Lift-off

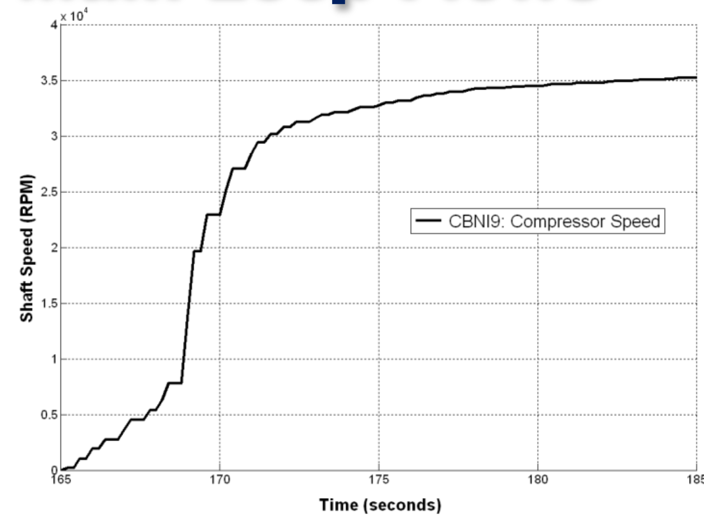
Target Conditions for IST Turbomachinery Startup

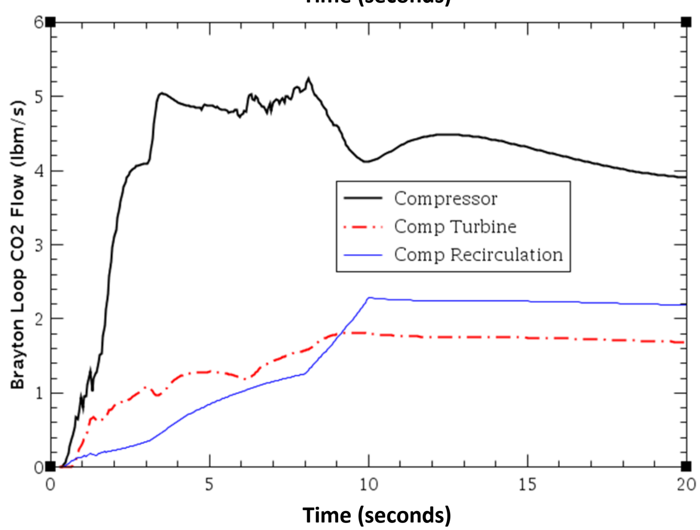
Parameter	Target Value
Turbine inlet temperatures	165˚F (Z = 0.7)
Compressor inlet temperature	100˚F
Compressor inlet pressure	1230 psia
Turbine bypass valve	Shut
Compressor recirculation valve	83% open

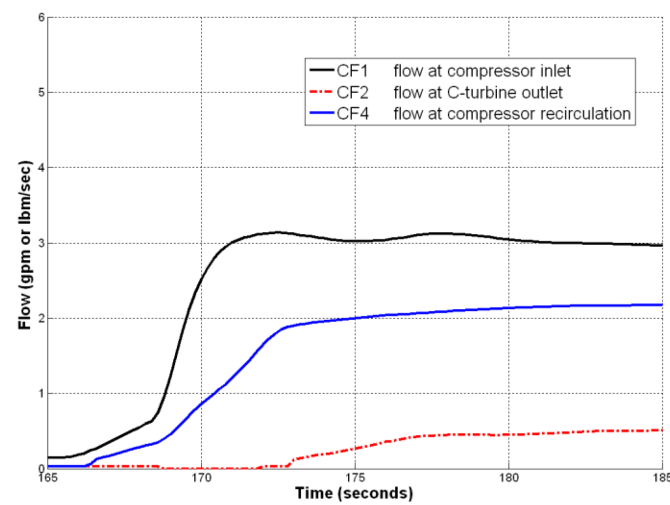


IST Startup: Comparison between Model (left) and Test data (right) for Compressor Startup – Shaft Speed and Main Loop Flows





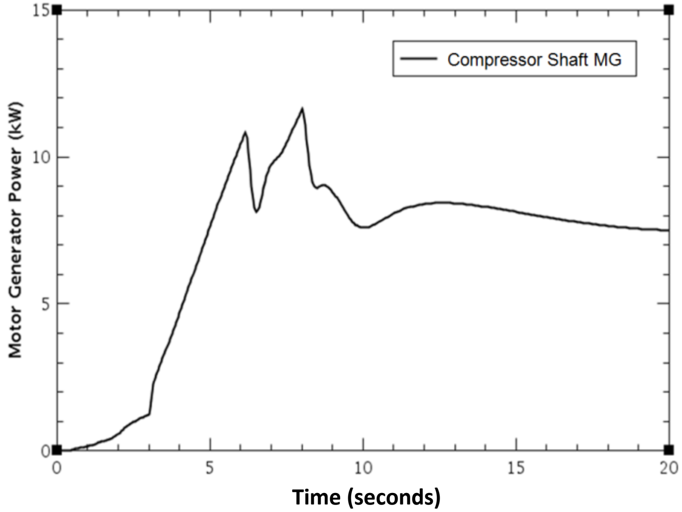


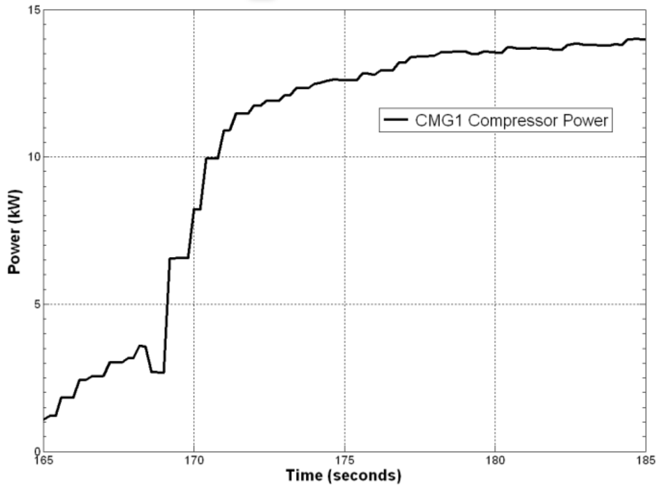


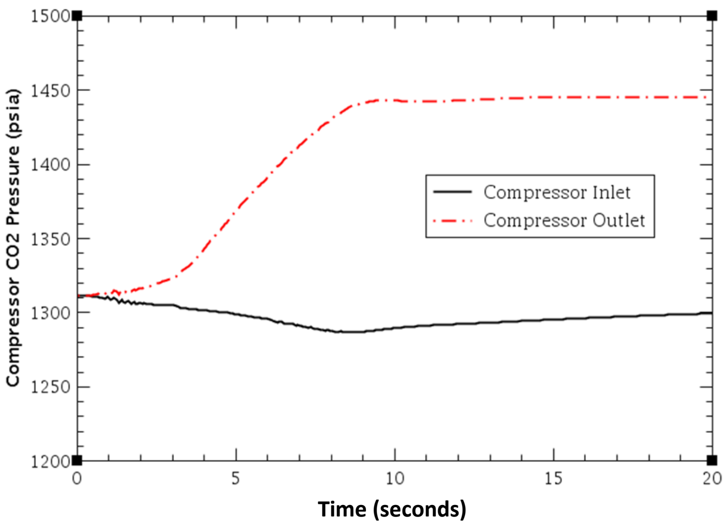
Model

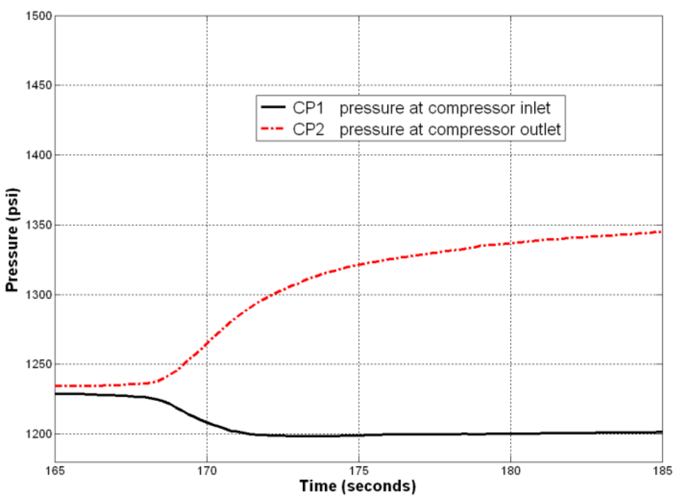
Test

<u>IST Startup</u>: Comparison between Model and Test for Turbine Compressor Startup – Shaft Motor Generator Powers and CO_2 Pressures





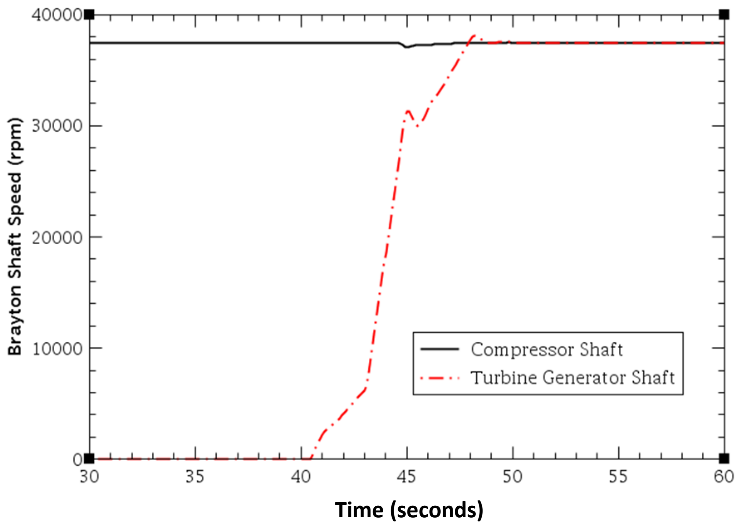


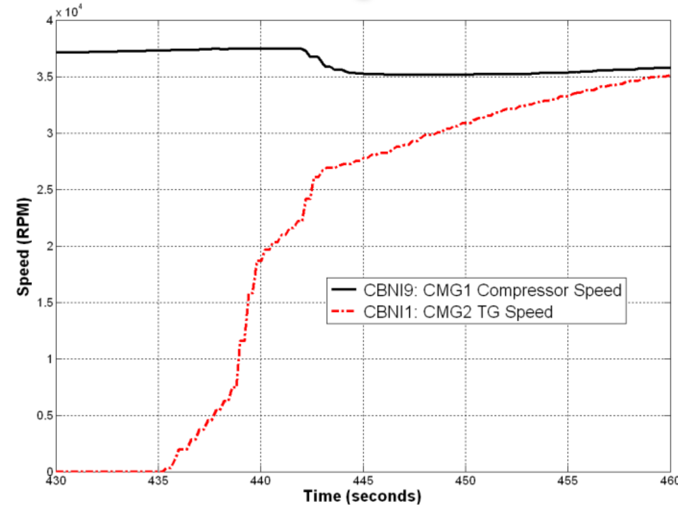


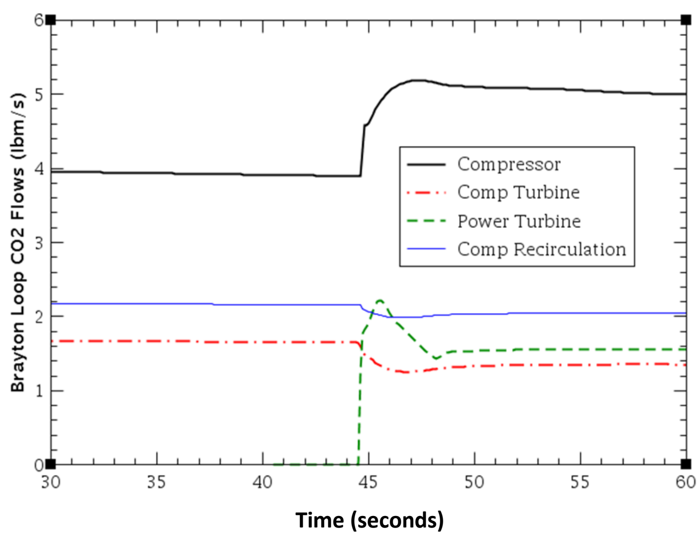
Model

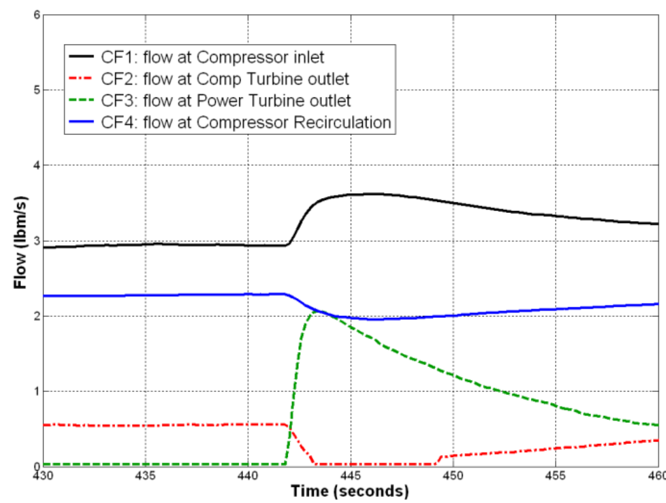
Test

IST Startup: Comparison between Model and Test for Turbine Generator Startup – Shaft Speed and Main Loop Flows









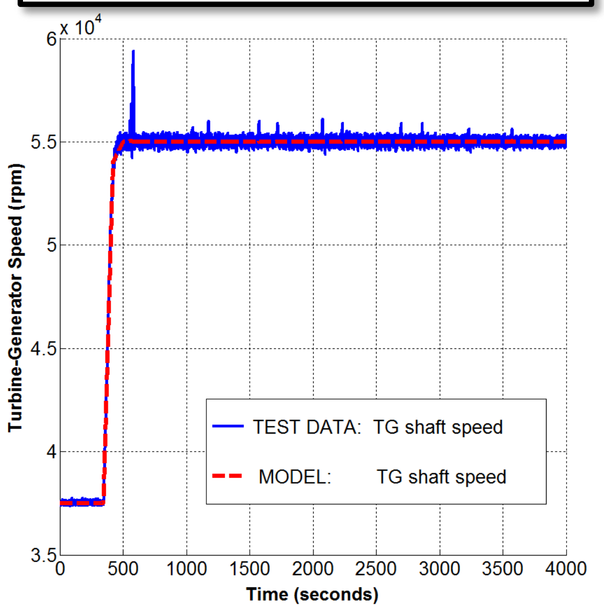
Model

Test

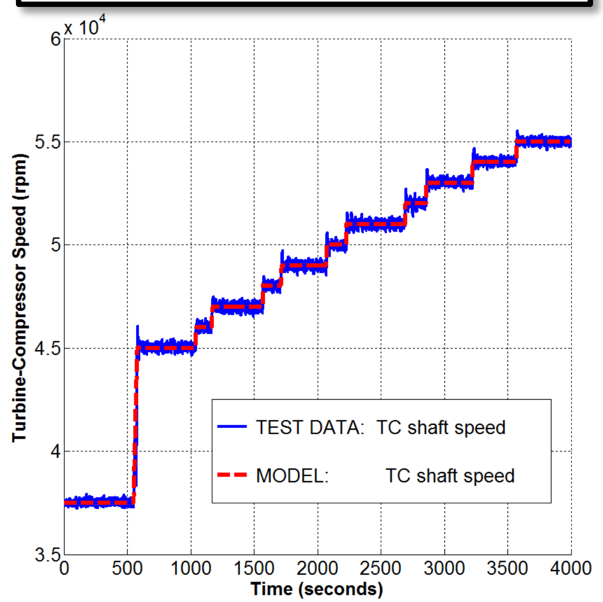
Power Increase Transient

- Initial Conditions: Hot Idle (540°F/37,500 rpm)
- TG speed increased
- TC speed increased in steps
- Compressor recirculation valve decreased in steps
- Water flow automatically controlled to maintain compressor inlet T

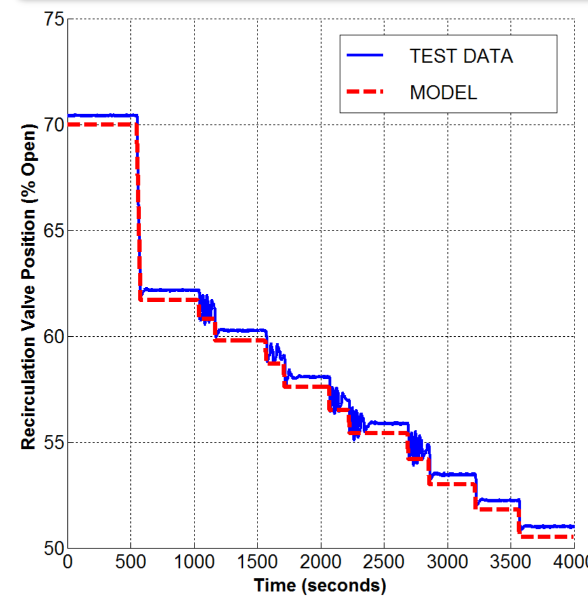
Turbine-Generator Speed



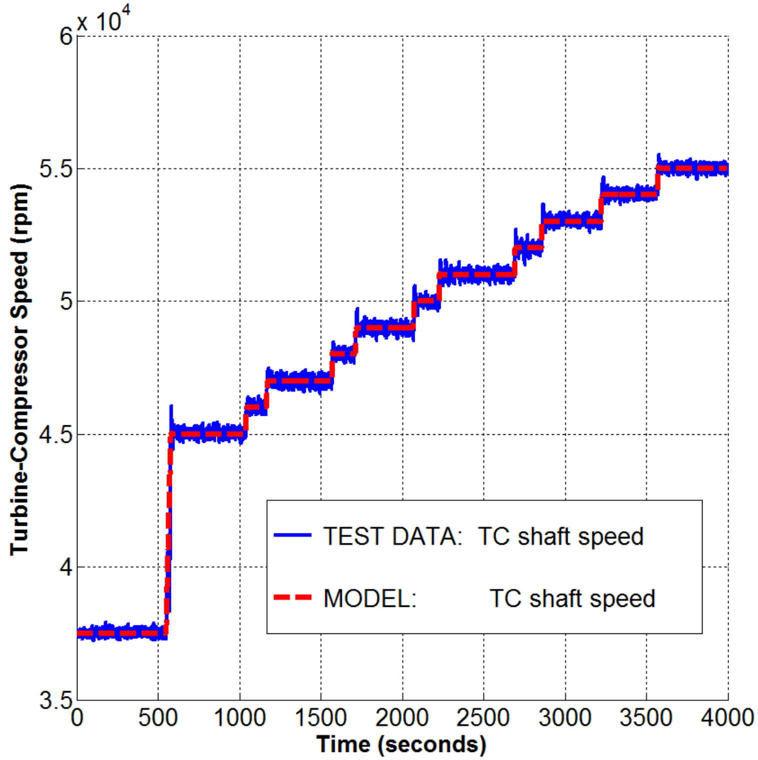
Turbine-Compressor Speed

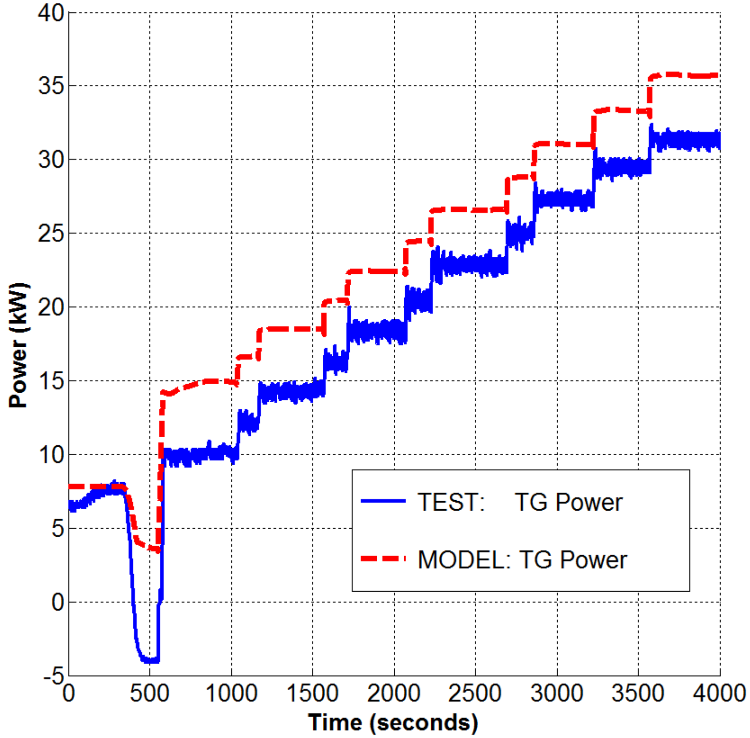


Recirculation Valve Position

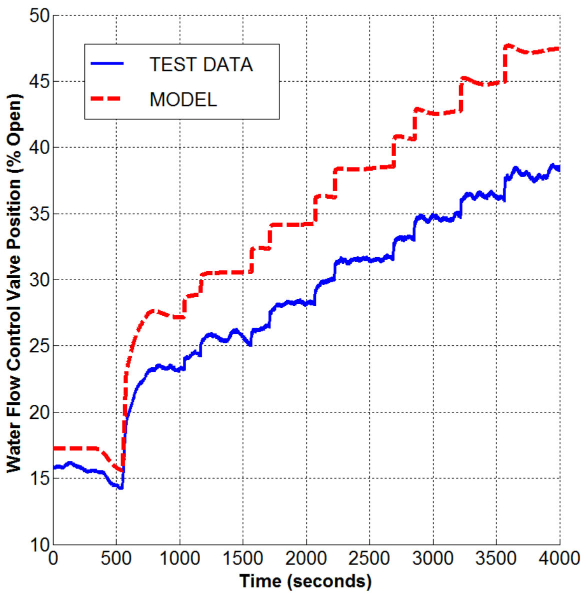


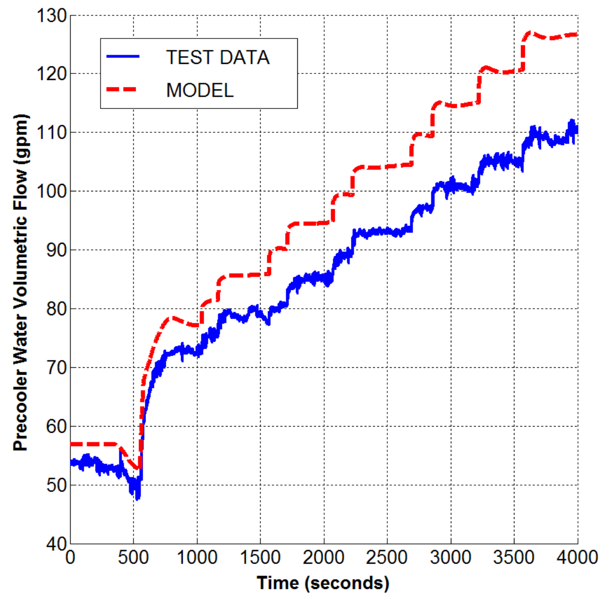
Power Increase Transient: Turbine Generator Power

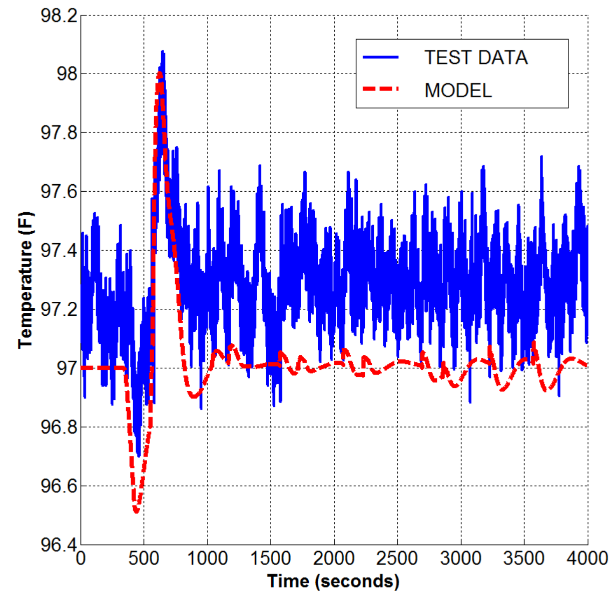


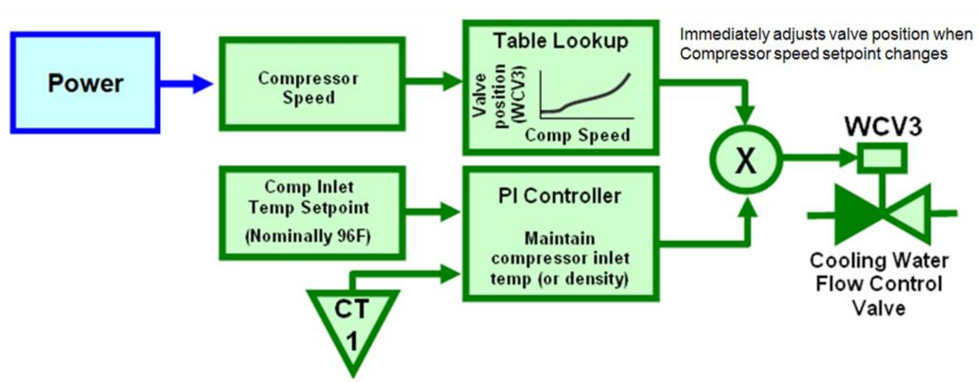


Power Increase Transient: Cooling Water Control Valve Position, Flow Rate and Compressor Inlet Temperature



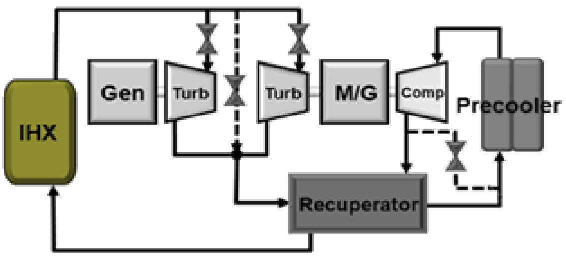


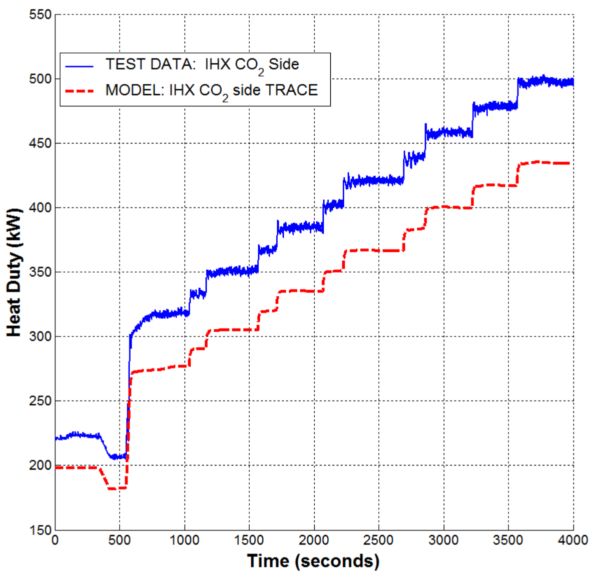




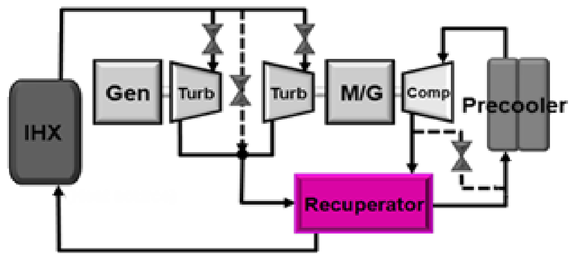
Power Increase Transient: Heat Exchanger Heat Duties

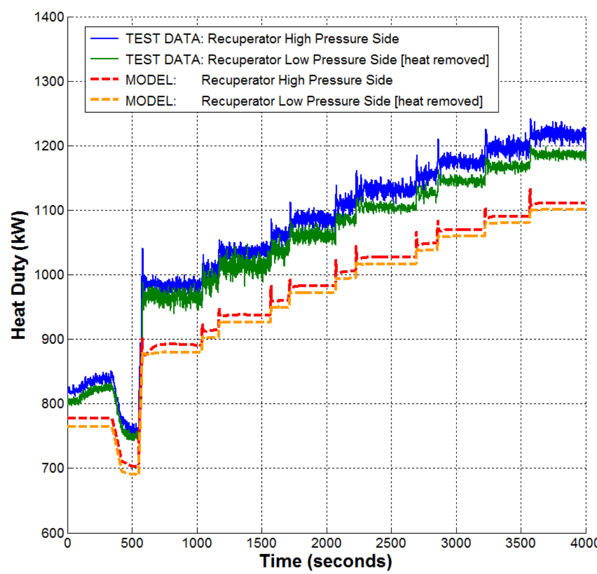
Intermediate Hx



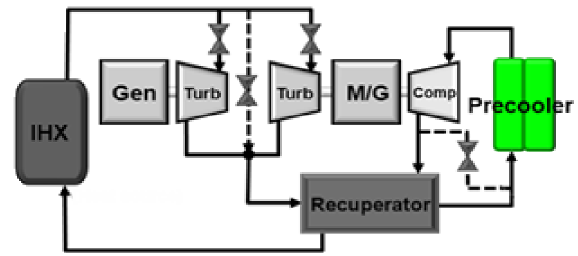


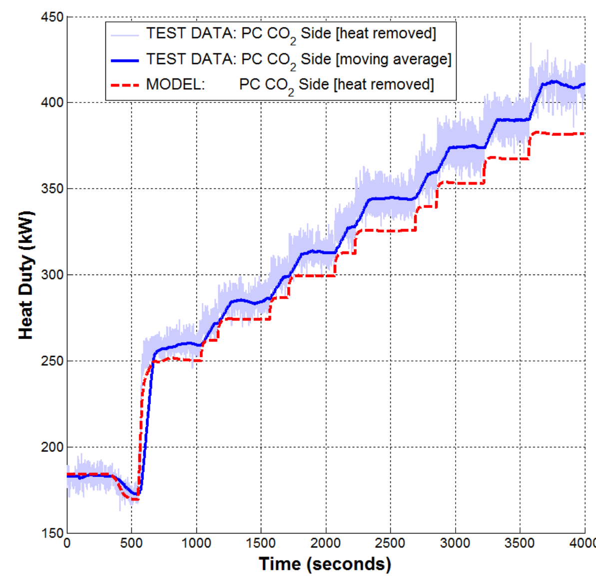
Recuperator



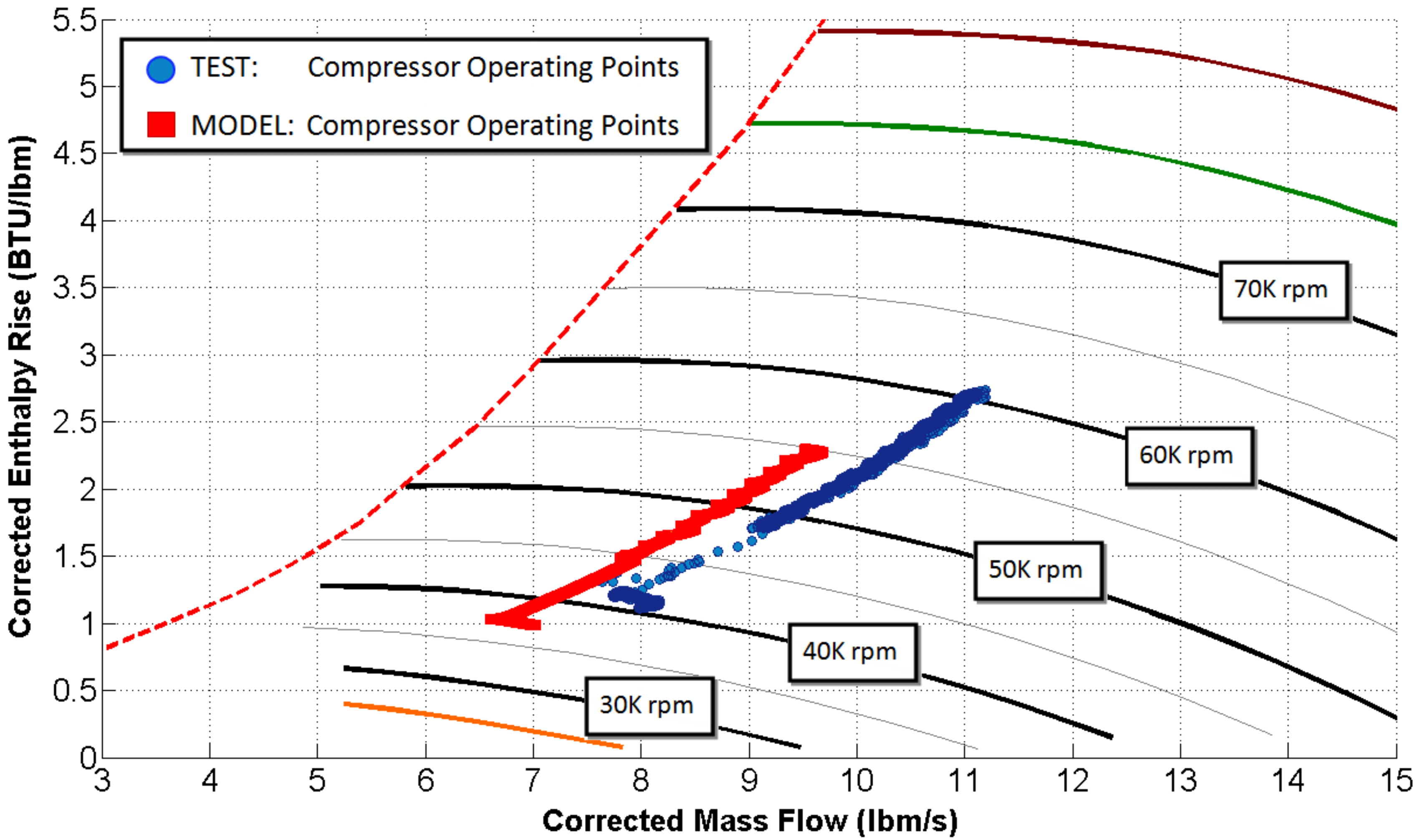


Precooler





Power Increase Transient: Comparison of Compressor Operation



Factors that Influence Runtime

- *CPU time* *(clock time)* is a function of
  - Computer Hardware (RAM speed, etc.)
  - Model Complexity
    - Component nodalization
    - Fluid property models and interrogation (PG-1®, Water, CO_2, etc.)
  - Transient Rate of Change
    - Heat up/Power Transients/Turbomachinery startup/etc.
  - *Model/Physical time*: time of actual transient (hour heat up)

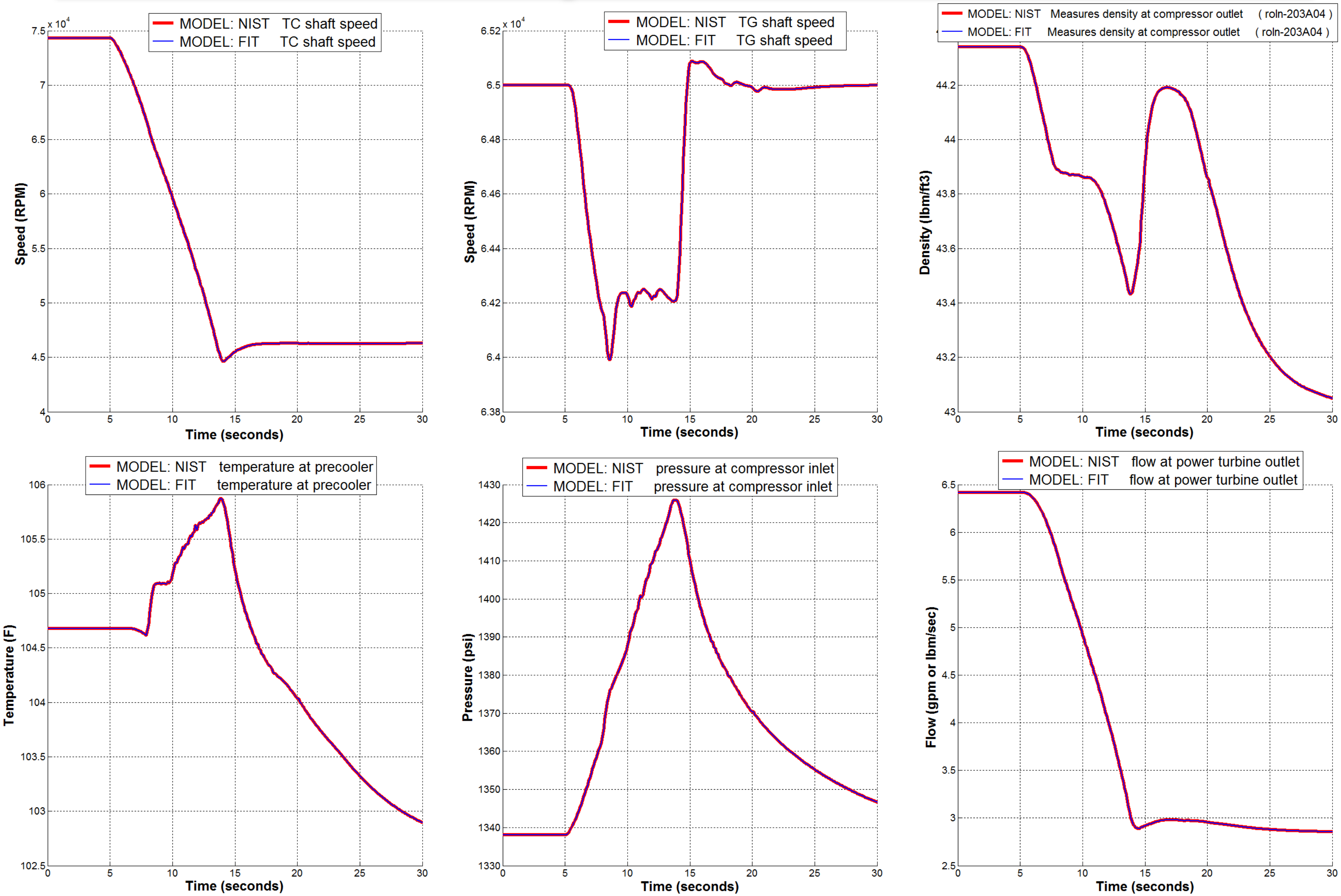
- Up until now: *Model Time << CPU time*
  - *Root cause - largest contributor was fluid property calls*
- *Now: Model Time ≈ CPU time*
  - *Change is the replacement of NIST property calculations with commercial package (FIT) [Northland Numerics]*

NIST/FIT Comparison: Benchmarking

- Suite of 15 transient runs
  - Range in duration from 50 to 4000 seconds (physical time)
  - Include entire range of operations
    - Cold (150°F) with both shafts off
    - Start up
    - Configuration of CWS
    - Heat up/Power Transients

Run Name	Run Id	Model Run Description	model time (seconds)	NIST CPU time (seconds)	NIST to Real Time	FIT CPU time (seconds)	FIT to Real Time
IST_v4p017_START_TG65K.med	*START*	Model startup at full power conditions. Thot = 570F.	50	495	**9.91**	63	**1.26**
Rs1ss_THL_TG65K	*Restart 1*	Reduce TG speed to 65krpm. CCV4 open from 0.00 to 0.06	400	3006	**7.51**	358	**0.90**
Rs2ss_Speed_TG65K	*Restart 2*	Control switches changed to transition from T/H LEAD to SPEED ctrl.	400	3444	**8.61**	397	**0.99**
Rs3DP_10pps_MG_TG65K	*Restart 3*	Down power. Recirculation valve open from 0.06 to 0.59.	400	4126	**10.32**	461	**1.15**
Rs4DP_HIdle_CD300_MG_TG65K	*Restart 4*	TC speed dropped to idle then Thot reduced from 570F to 300F.	3700	31300	**8.46**	3530	**0.95**
Rs5_CD150_MG_TG65K	*Restart 5*	Cool down from 300F to 150F with TC/TG idle.	3700	33377	**9.02**	3521	**0.95**
Rs6CWS_OL_Iloop_Cidle	*Restart 6*	Configure CWS to heating mode (isolate inner loop and start Pump1)	400	4777	**11.94**	510	**1.28**
Rs7S1S2SD_150F_CWS100F	*Restart 7*	TC and TG shut down from idle. Turbine inlet T = 150F.	200	2011	**10.05**	249	**1.24**
Rs8S1S2SU_150F	*Restart 8*	TC and TG start up from 0 rpm. Turbine inlet T = 150F.	120	1838	**15.31**	218	**1.82**
Rs9ILoopSD_150F	*Restart 9*	CWS inner loop pump ON to OFF. CWS to cooling config.	240	3044	**12.69**	353	**1.47**
Rs10_WCV3auto_Cidle	*Restart 10*	Transition to cold idle. Comp inlet temp 100F. WCV3 in auto.	1400	13694	**9.78**	1321	**0.94**
Rs11HU300F_1Hr_TG65Ktab	*Restart 11*	Brayton loop heated to 300F from cold idle.	4000	36197	**9.05**	3790	**0.95**
Rs12HU435F_1Hr_TG65Ktab	*Restart 12*	Brayton loop heated to 435F from 300F.	4000	34304	**8.58**	3786	**0.95**
Rs13HU540F_1Hr_TG65Ktab	*Restart 13*	Brayton loop heated to 540F from 435F.	4000	39875	**9.97**	3852	**0.96**
Rs14_TCTG55K_540F_TG65Ktab	*Restart 14*	Raise TC and TG speeds from idle to 55 krpm.	300	3080	**10.27**	299	**1.00**

Transient Comparisons: NIST vs. FIT



Summary

- TRACE has been demonstrated as an effective tool for S-CO_2 Brayton analysis
  - SNAP GUI/AptPlot enables
    - efficient model building
    - interpretation of results (animation views)
  - predicts loop steady state conditions
  - transient predictions support control system development and operation
  - minimizes risks (trial and error approach) during testing

- High fidelity transient modeling on a PC can approach real time execution by replacing NIST REFPROP with Northland Numerics FIT

- IST transient model still evolving: as-designed → as-built → as-tested
  - Update performance maps
  - Update windage correlation
  - Update component performance (e.g. valve C_{SUBV}, Hx's dP)

- Future: complete qualification of TRACE code for use as an effective tool for scale-up designs