S-CO_2 Brayton Loop Transient Modeling

The 4th International Symposium on Supercritical CO_2 Power Cycles

September 9 & 10, 2014

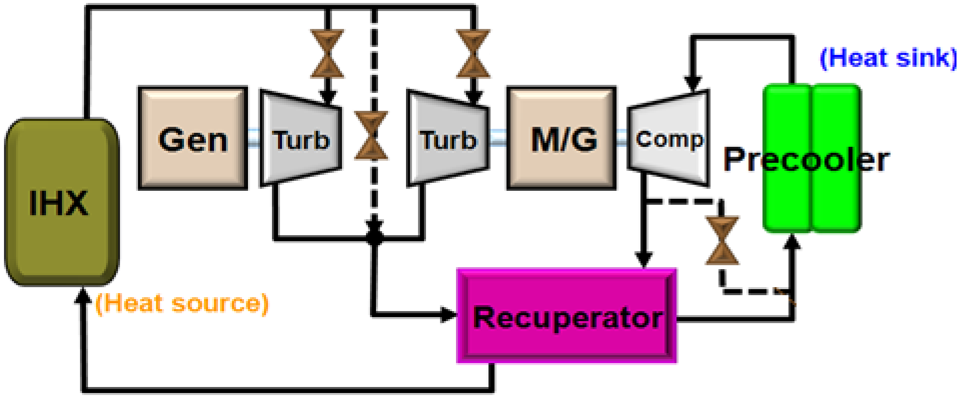
BMPC
BECHTEL MARINE PROPULSION CORPORATION

Outline

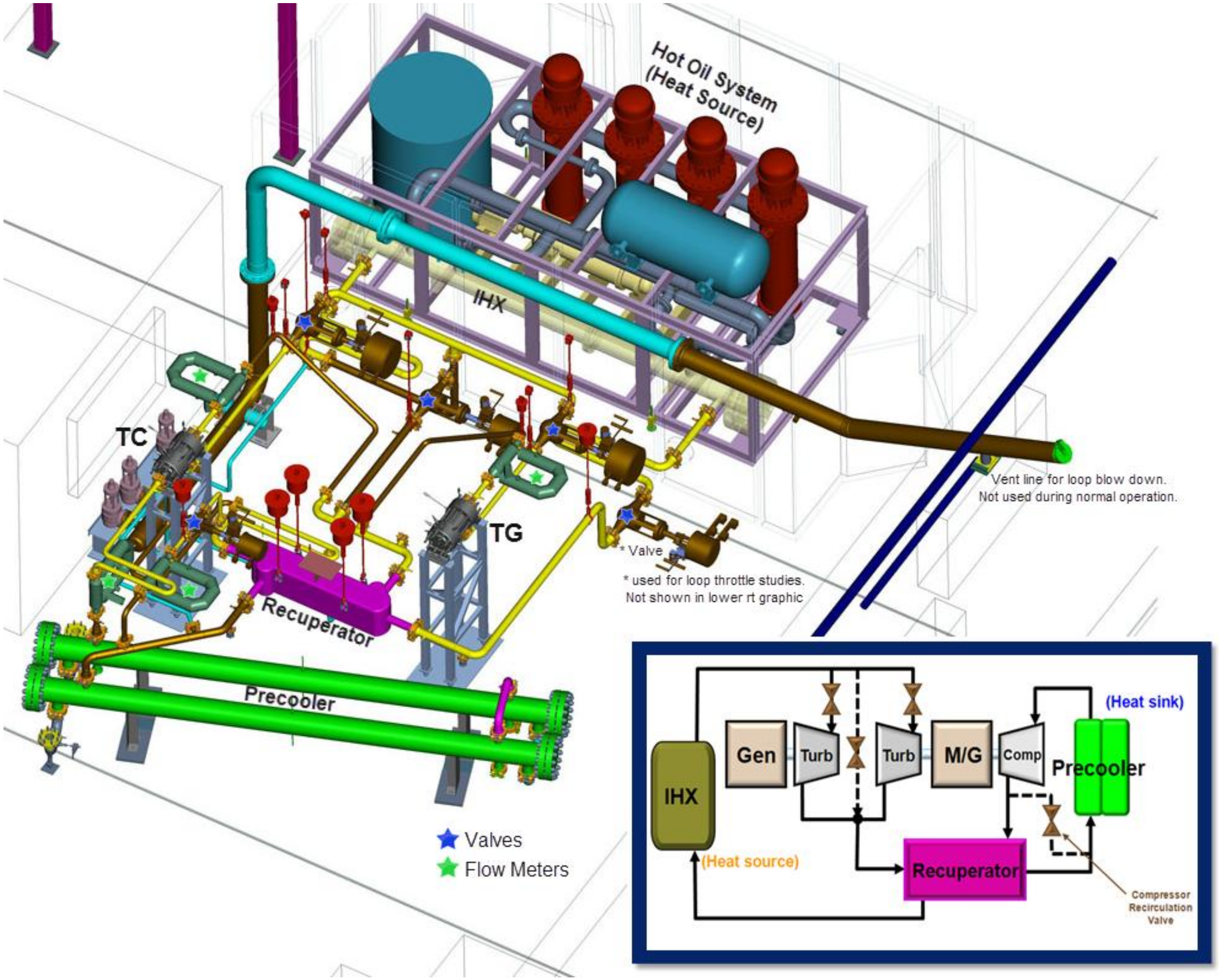
- Background
- Model Results and Comparisons with Test Data
  - Steady State Heat Balance
  - Transient
    - Turbomachinery Start-up
    - Power Transients
- Next Steps/Model Updates
  - NIST REFPROP/FIT
  - Test data
- Summary

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



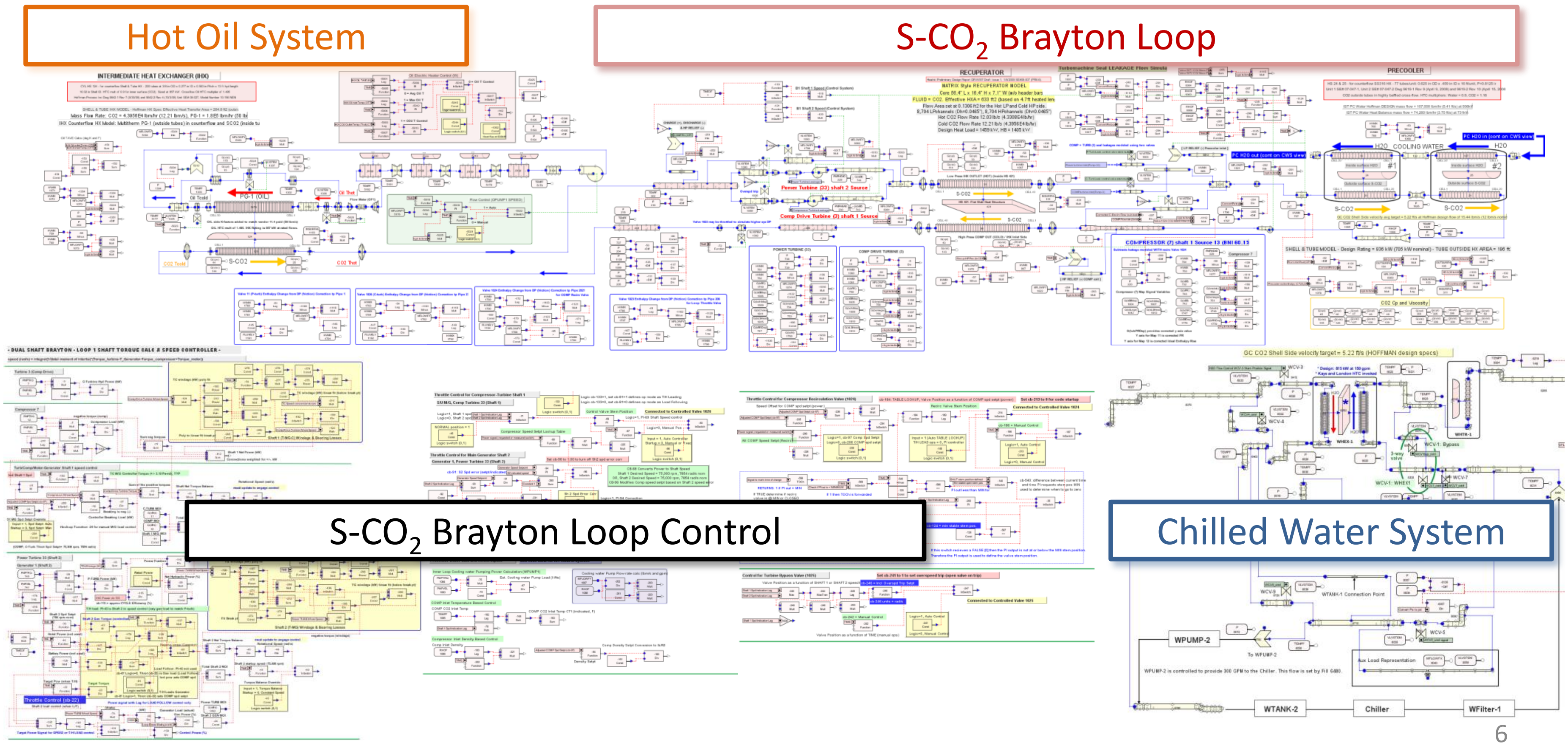
Background: Integrated Systems Test



Background: Integrated Systems Test

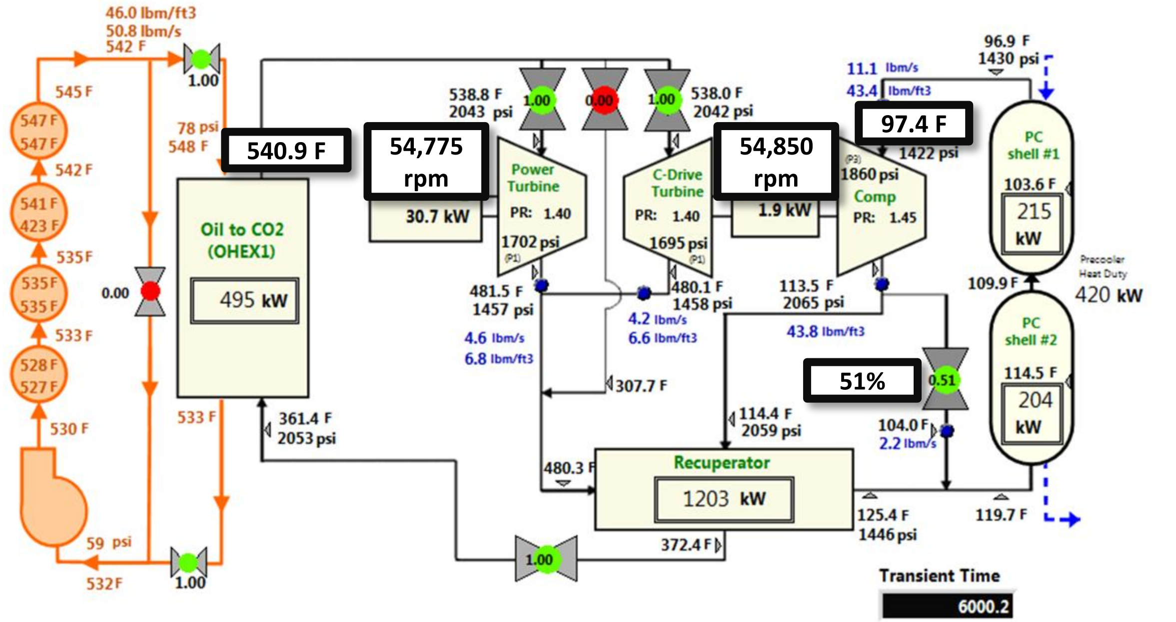
Background: IST Transient Model

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

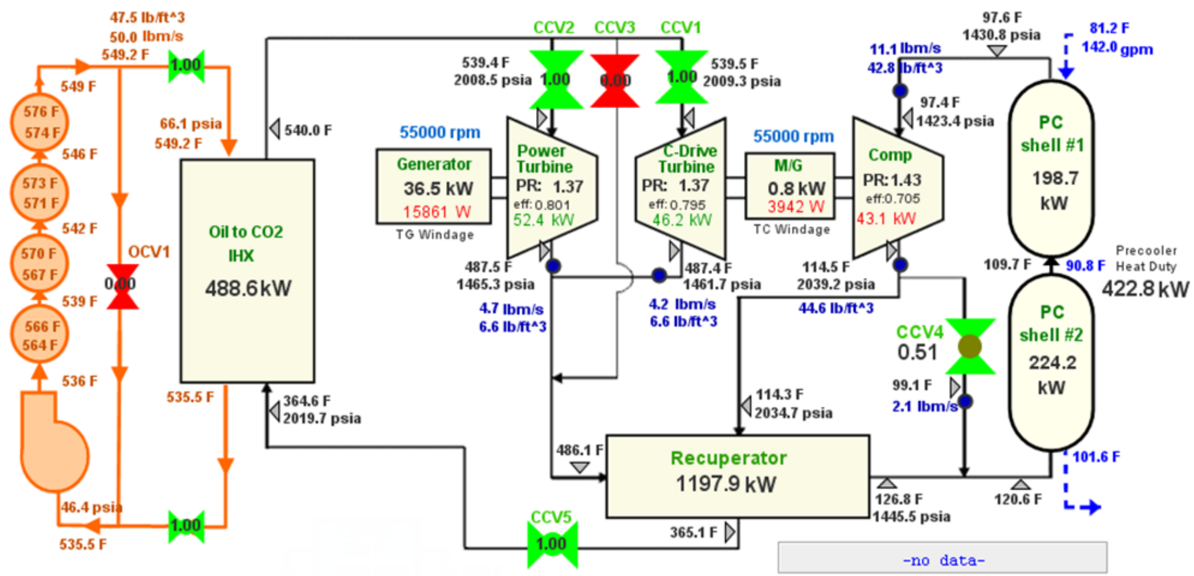


Steady State Comparison: Updated Model

Test



Model



Steady State Comparison: Updated Model

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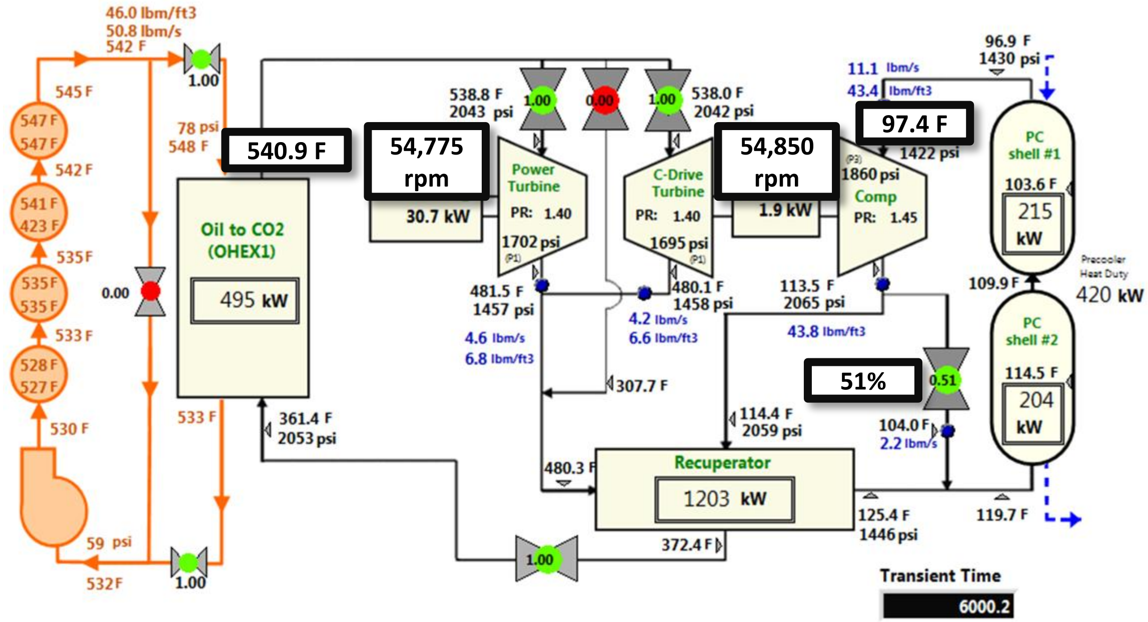


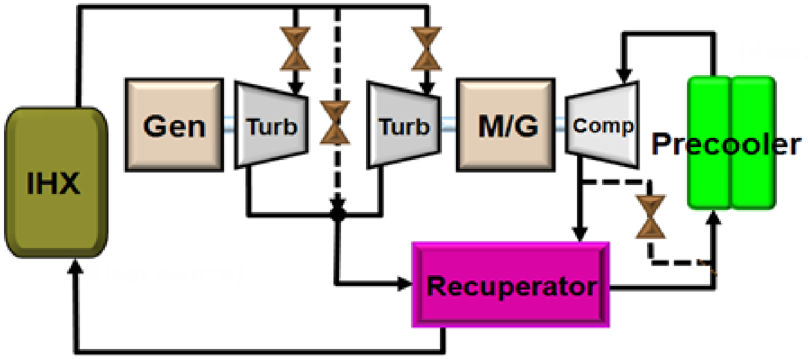
Parameter	Test	Pretest TRACE Model	TRACE Model With adjusted compressor map
Compressor Mass Flow (lbm/s) [kg/s]	11.1 [5.0]	10.1 [4.6]	11.1 [5.0]
Compressor PR	1.45	1.37	1.43
Compressor Exit Temperature (F) [K]	113.5 [318.3]	113.2 [318.1]	114.5 [318.8]

IST Startup

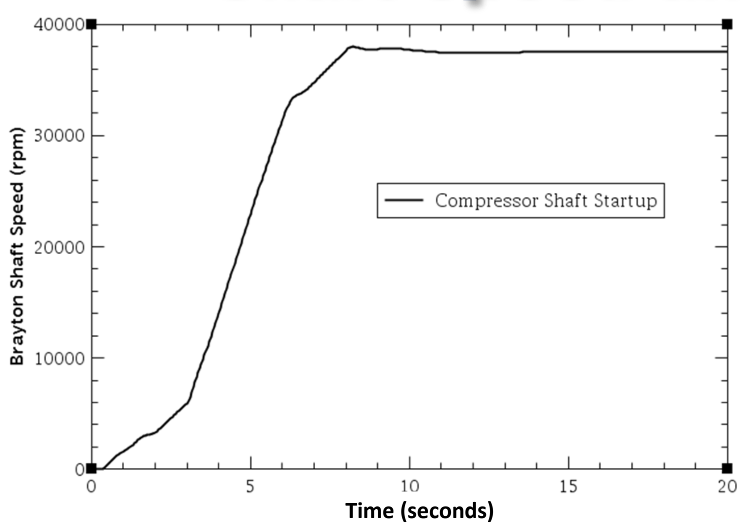
- Phenomenon considered during turbomachinery startup
  - Compressor surge
  - Reverse Turbine Flow
  - Gas Foil Bearing Lift-off

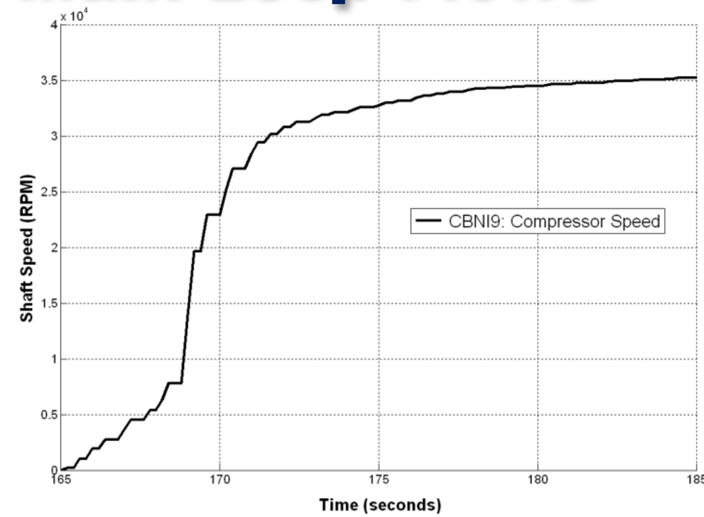
Target Conditions for IST Turbomachinery Startup

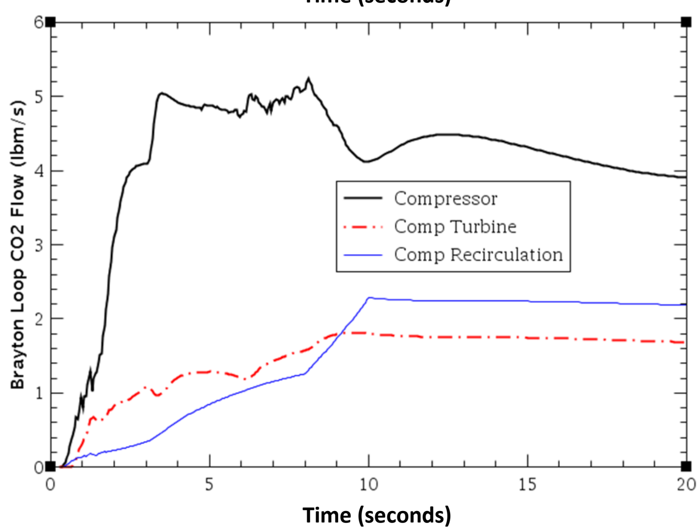
Parameter	Target Value
Turbine inlet temperatures	165˚F (Z = 0.7)
Compressor inlet temperature	100˚F
Compressor inlet pressure	1230 psia
Turbine bypass valve	Shut
Compressor recirculation valve	83% open

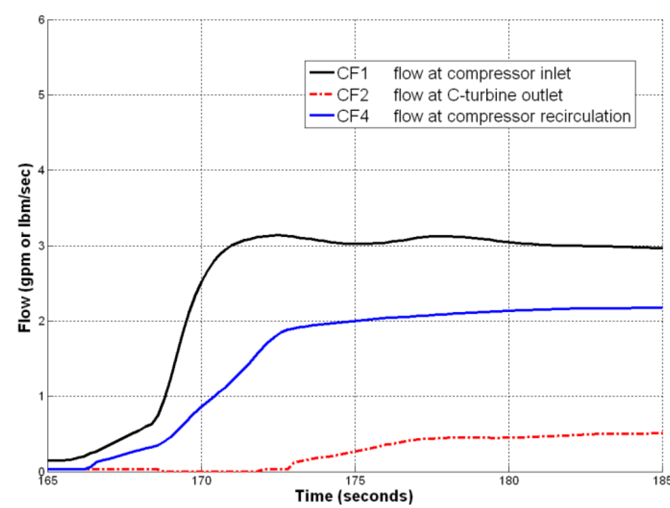


IST Startup: Comparison between Model (left) and Test data (right) for Compressor Startup – Shaft Speed and Main Loop Flows





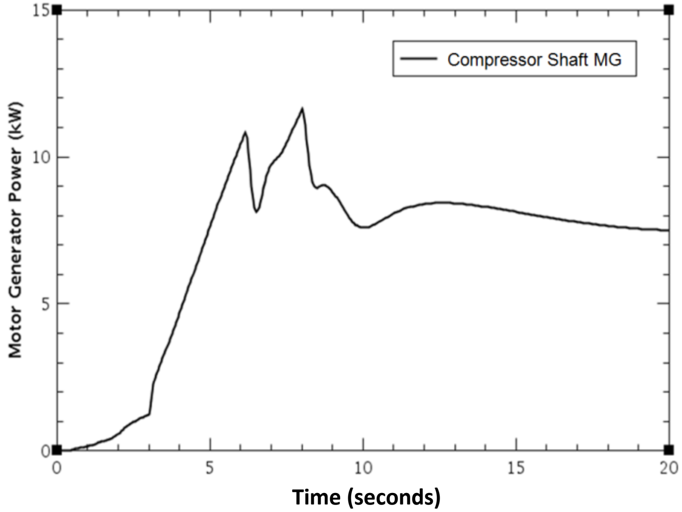


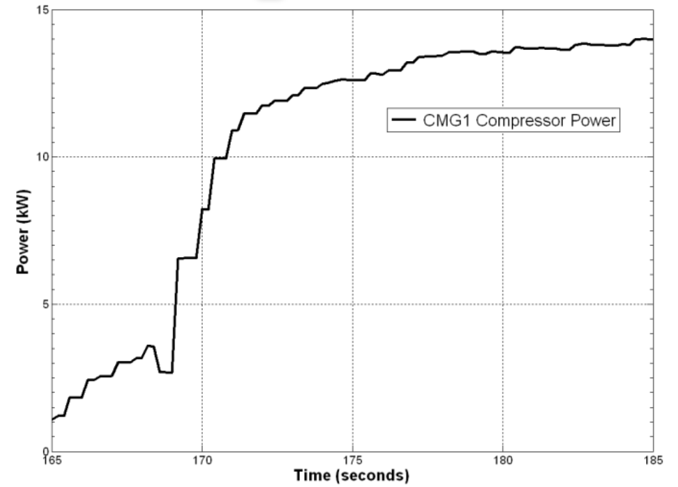


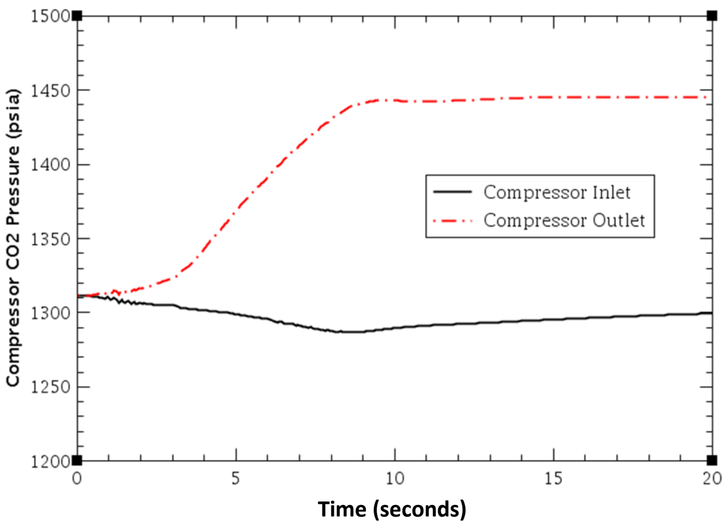
Model

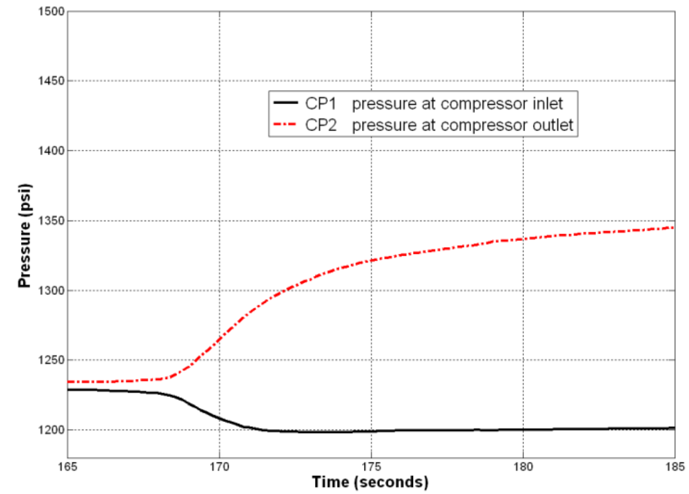
Test

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





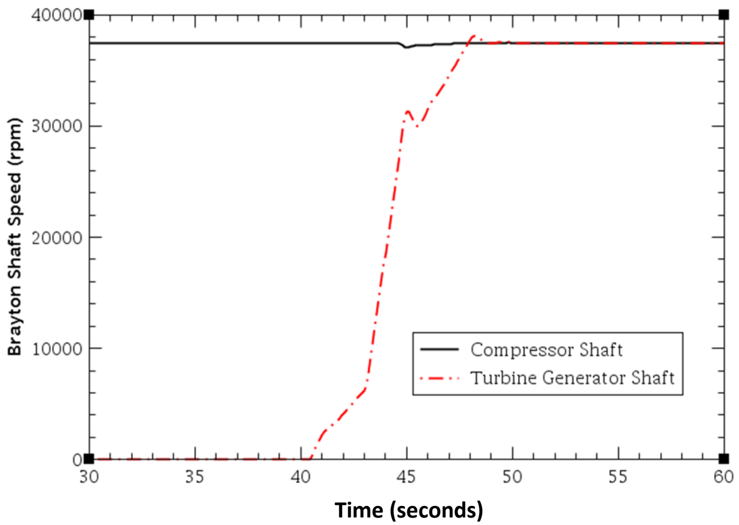


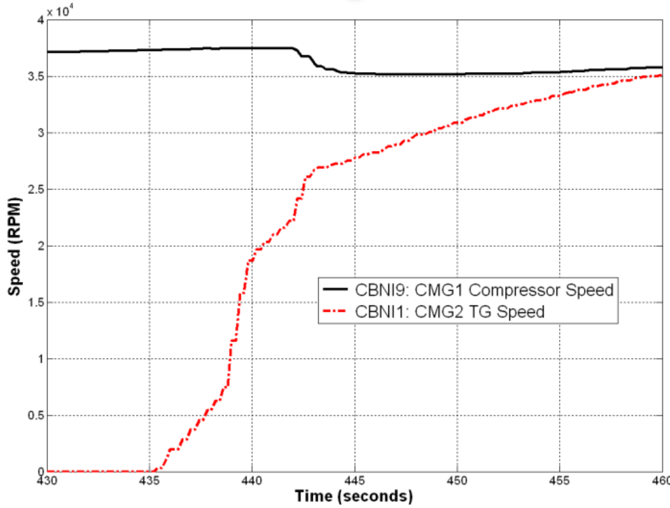


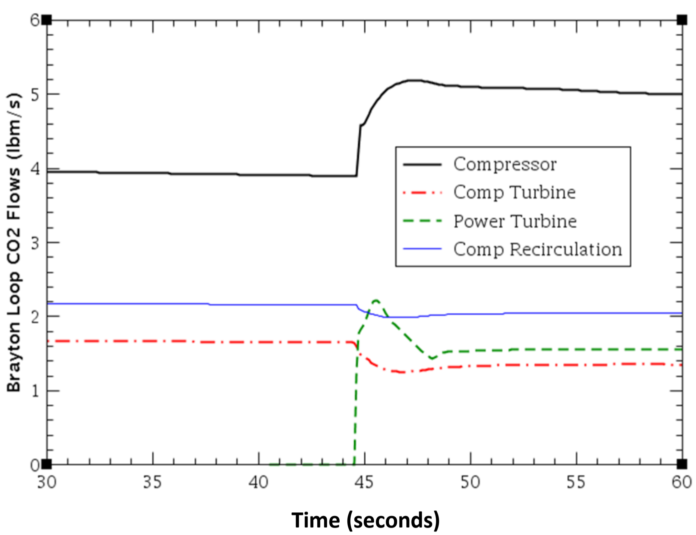
Model

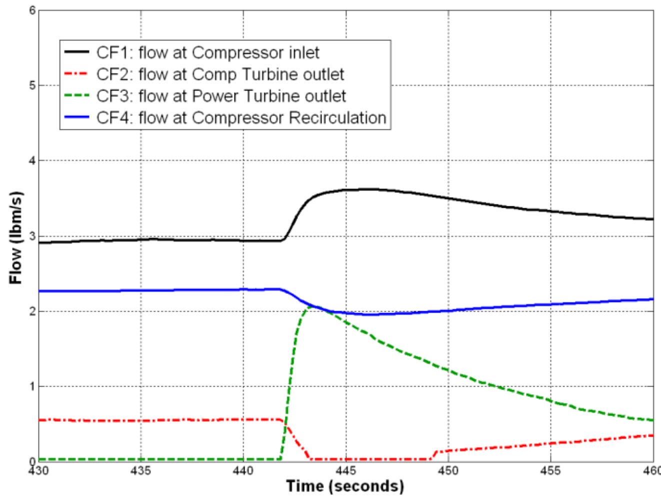
Test

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









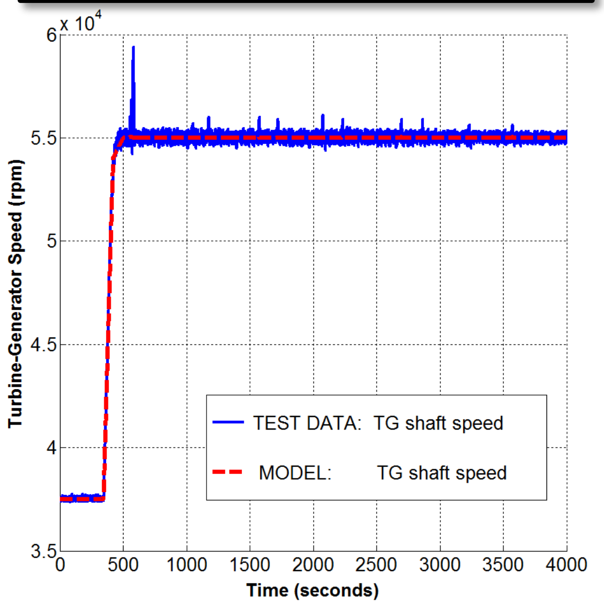
Model

Test

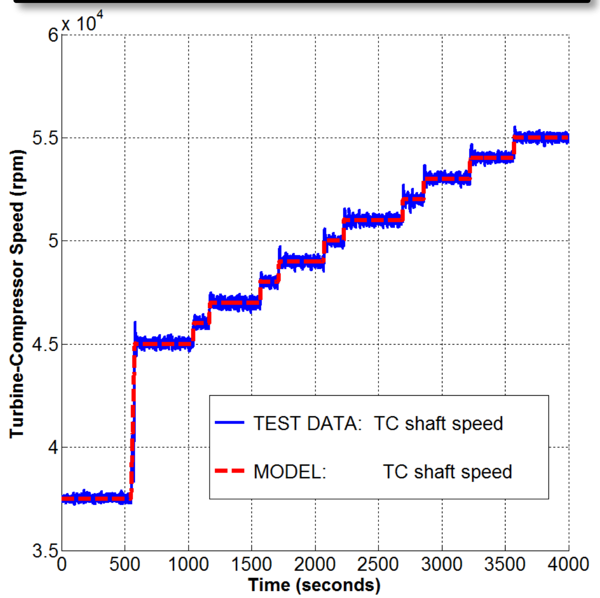
Power Increase Transient

- 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

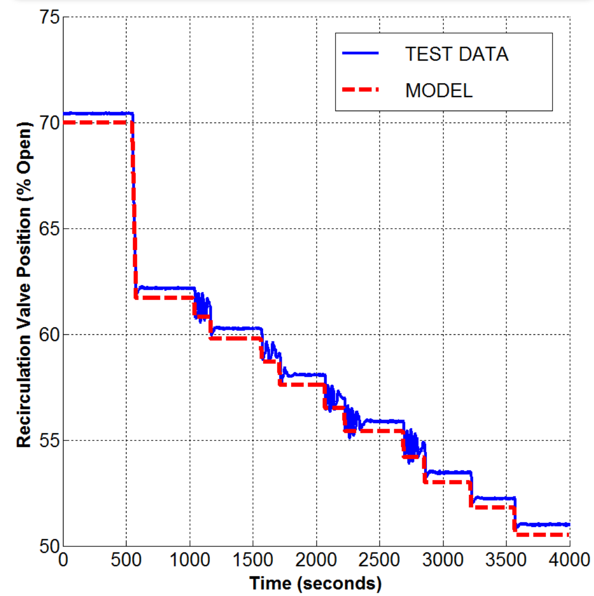
Turbine-Generator Speed



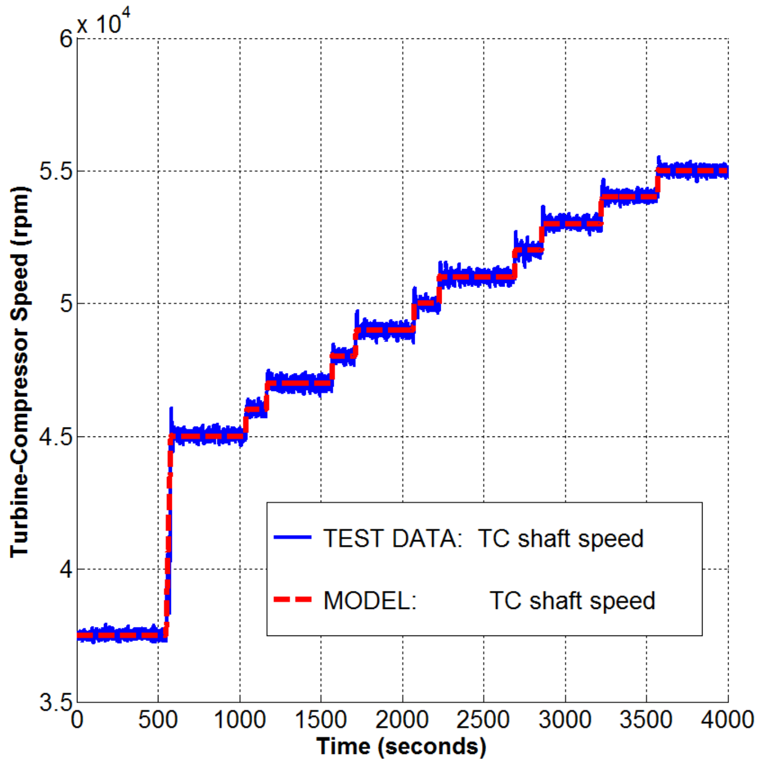
Turbine-Compressor Speed

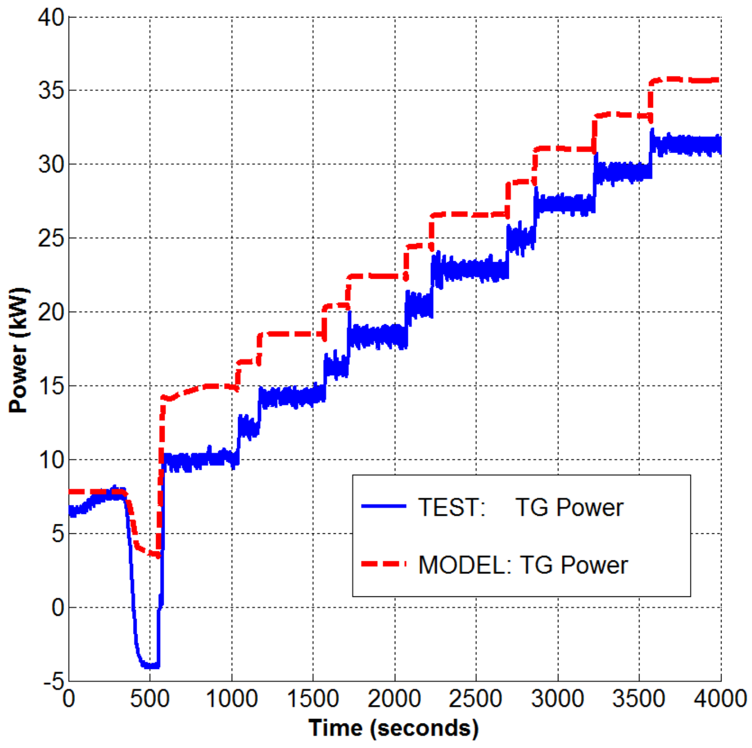


Recirculation Valve Position

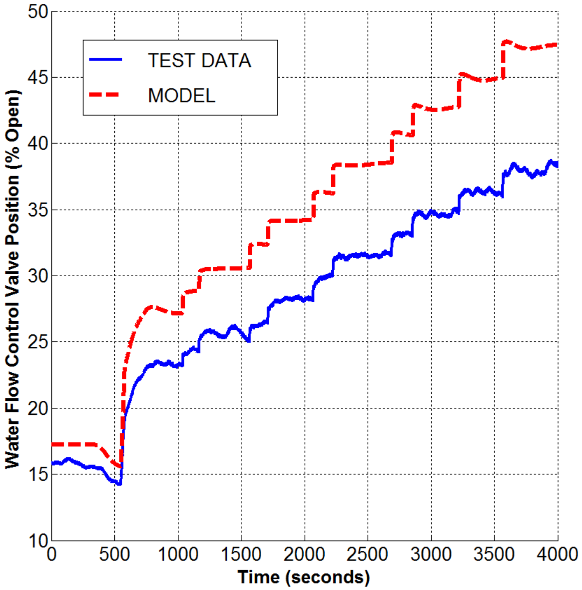


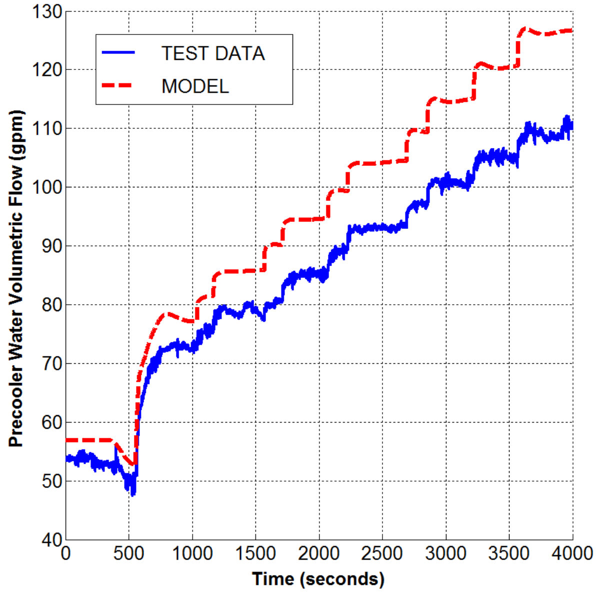
Power Increase Transient: Turbine Generator Power

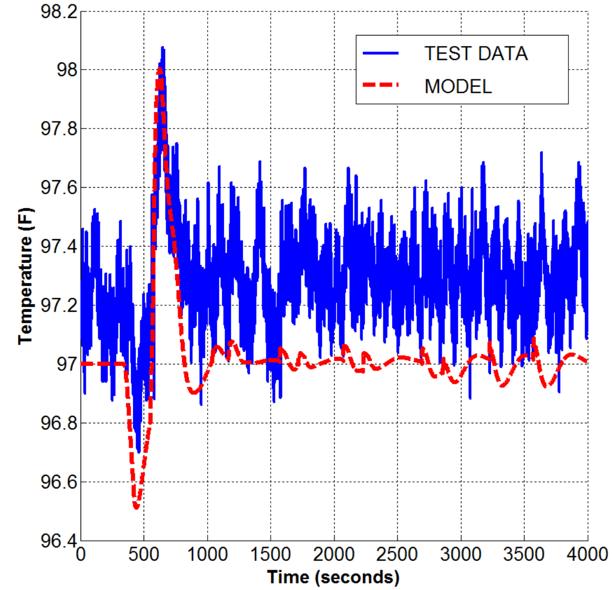


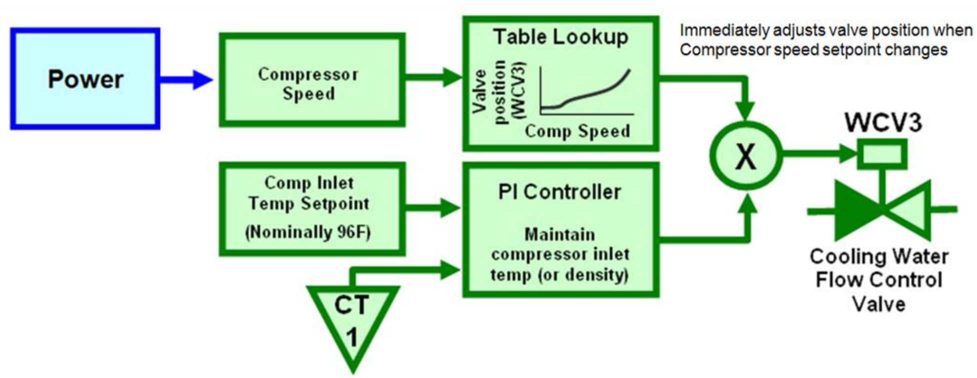


Power Increase Transient: Cooling Water Control Valve Position, Flow Rate and Compressor Inlet Temperature



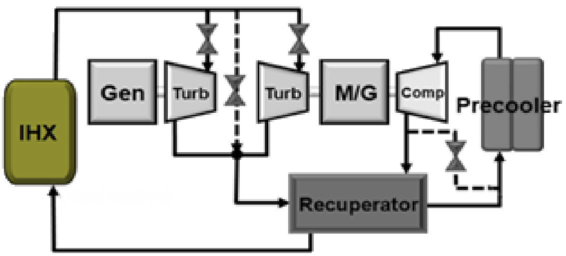


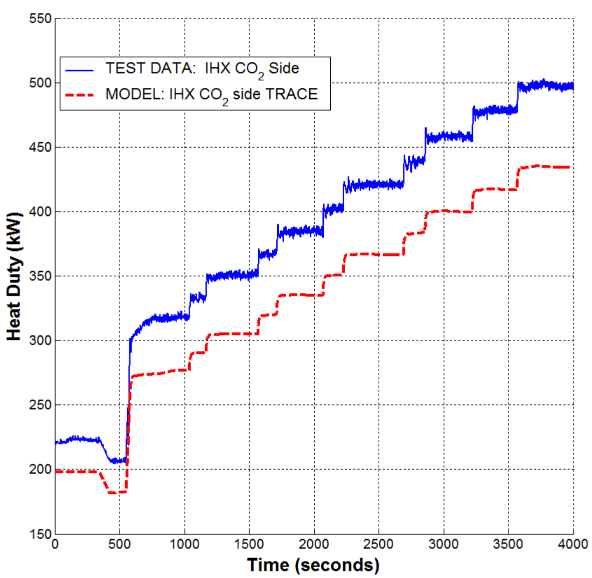




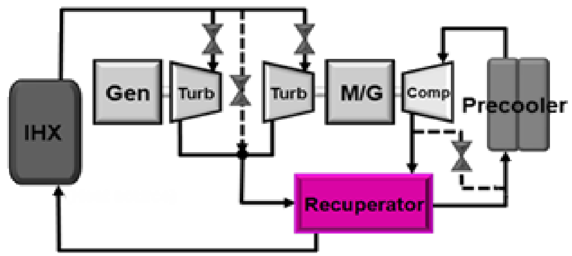
Power Increase Transient:
Heat Exchanger Heat Duties

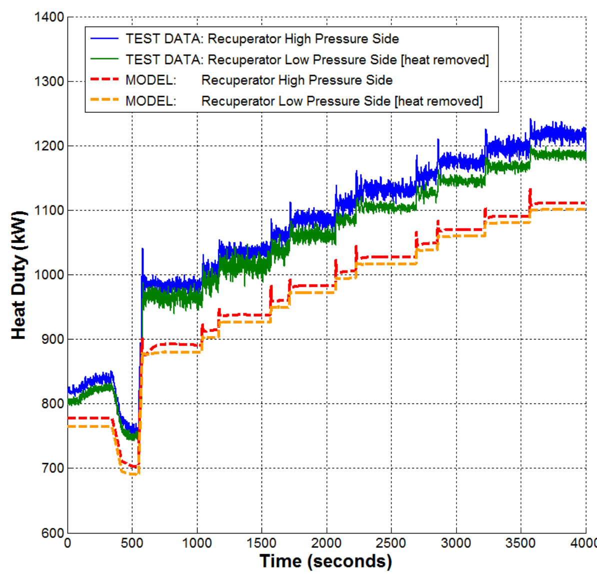
Intermediate Hx



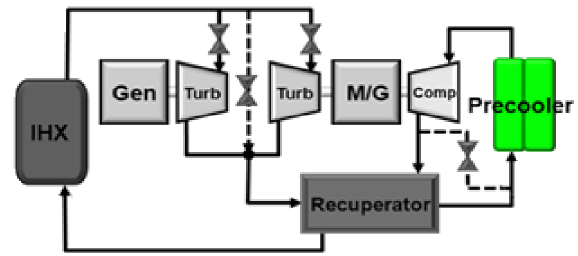


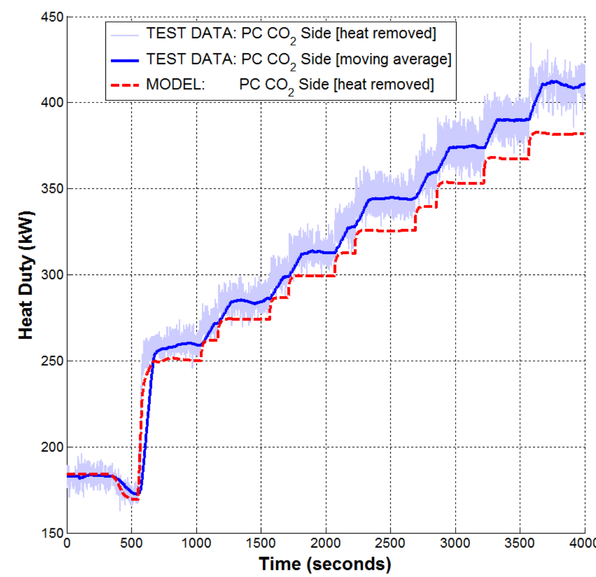
Recuperator



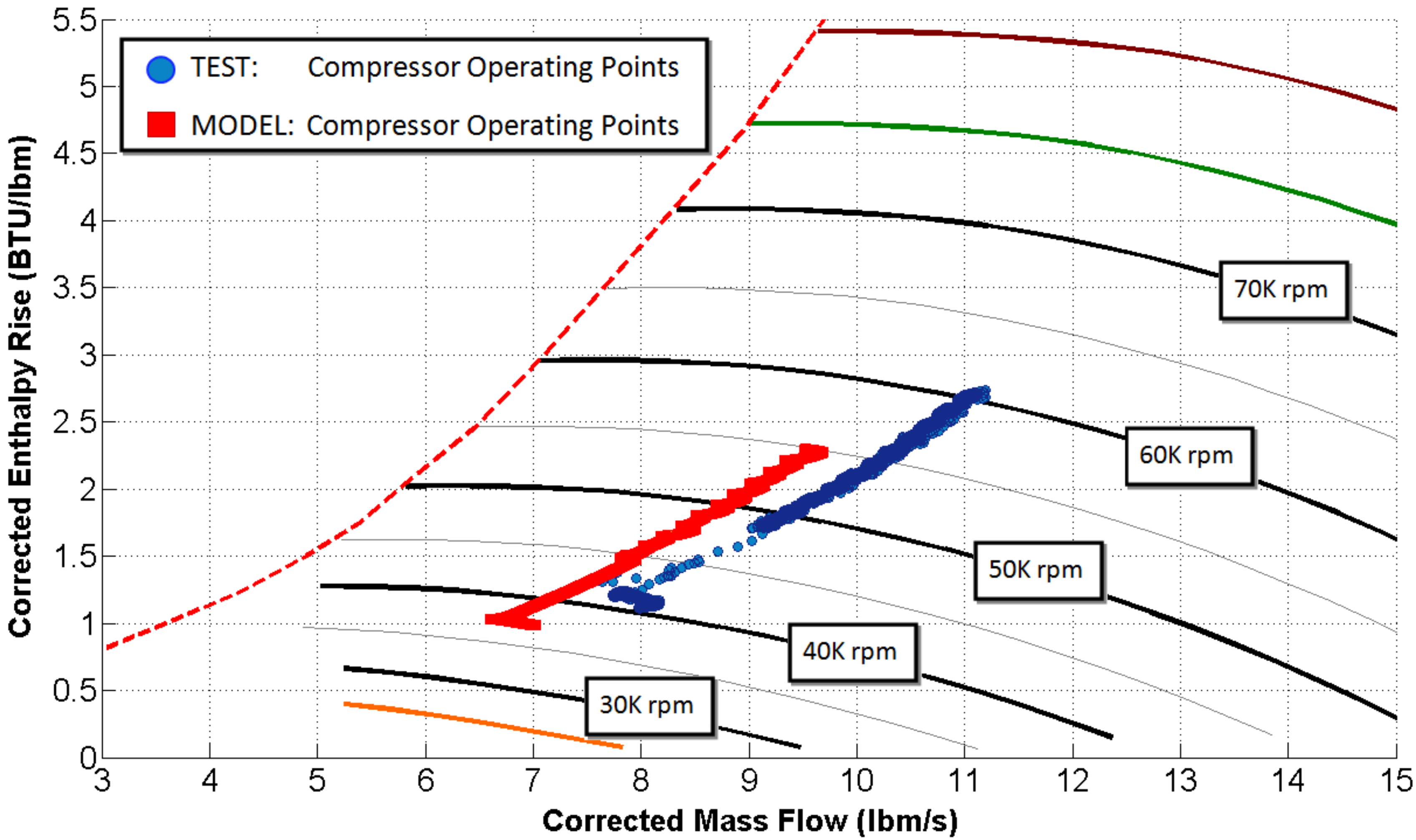


Precooler





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)

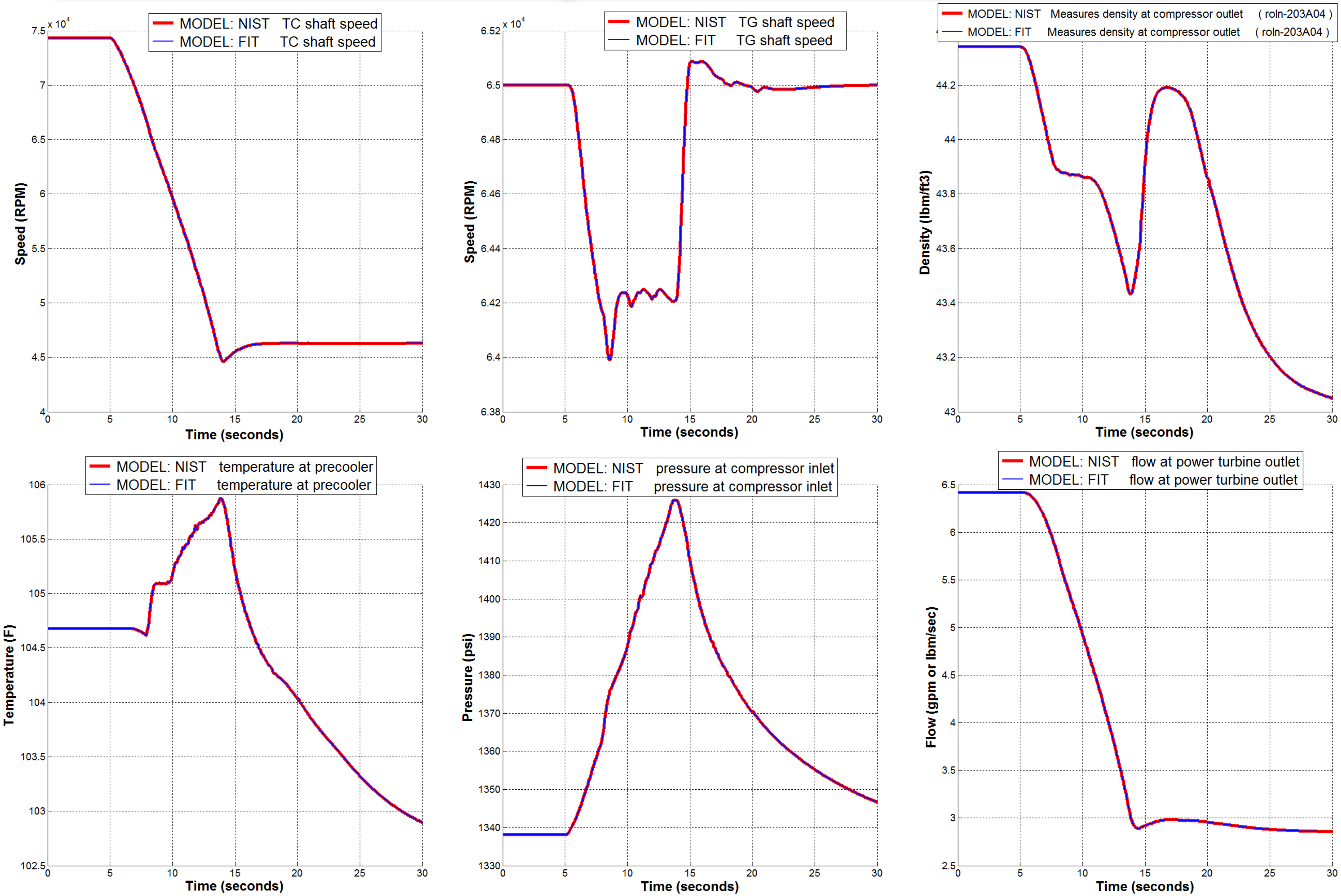
- Up until now: *Model Time << CPU time*
  - *Root cause - largest contributor was fluid property calls*
- *Now: Model Time ≈ CPU time*
  - *Change is the replacement of NIST property calculations with commercial package (FIT) [Northland Numerics]*

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