Dynamic Analysis of a Closed-Loop Brayton Cycle Coupled to a Nuclear Reactor

Larry McCann
Integrated Plant Analysis Development
Bechtel Bettis Inc.

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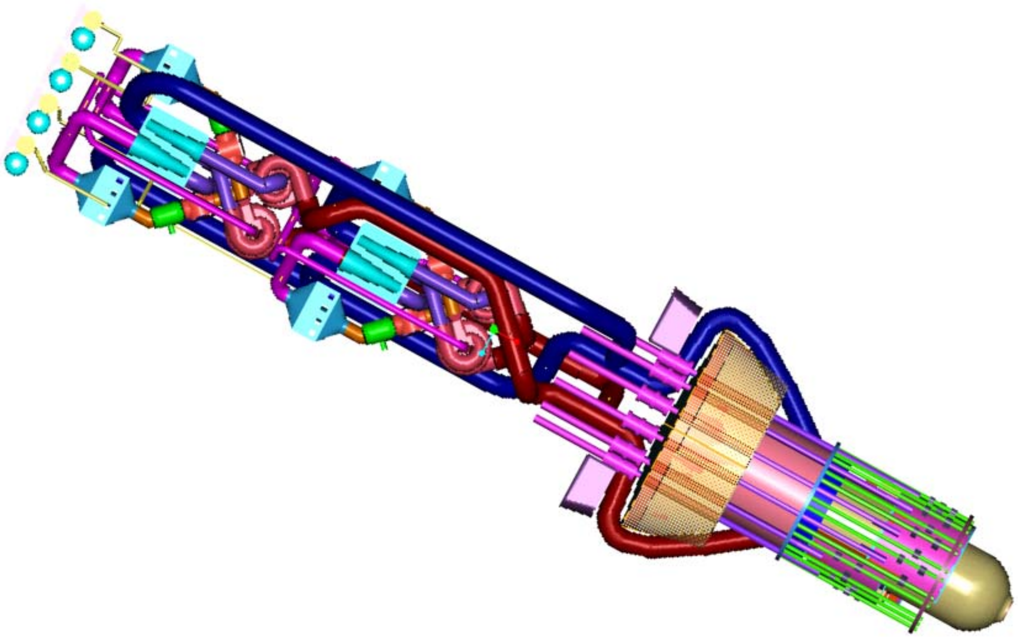
Introduction

- NRPCT started work on design of a nuclear reactor for the NASA Jupiter Icy Moons Orbiter (JIMO).
- The JIMO mission would have required 100 – 300 kW_e to propel the spacecraft to the outer planets, orbit the moons, and perform scientific investigations from lunar orbit.
- A gas-cooled fast reactor (GFR) directly connected to one or more closed-loop Brayton cycles was chosen as the best candidate to meet the mission requirements based on current technology.
- A RELAP5-3D model of the reactor and closed-loop Brayton cycle has been developed and used to perform dynamic analysis of the JIMO reactor plant.
- The RELAP5-3D computer code is used at Bechtel and widely in the commercial nuclear industry for dynamic analysis of nuclear reactor plants.
- The Idaho National Laboratory (INL) made changes to the RELAP5-3D code so it could be used to model the closed-loop Brayton cycle.
- The remainder of this presentation discusses the code changes, input model development, and results.

Spacecraft Reactor Plant Overview

- Gas coolant is 22% Xenon, 78% helium by mole fraction
- To maximize system efficiency (~23%) reactor outlet temperature is 1150K
- There are 4 Brayton loops installed in parallel with 2 required for 100% power.

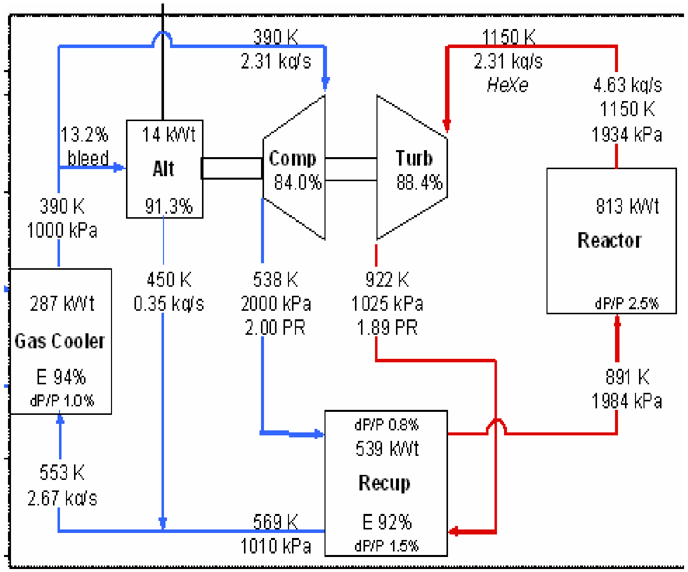


RELAP5-3D Code Improvements

- The INL was contracted to make the necessary code improvements so RELAP5-3D could be used for dynamic analysis of the JIMO concept:
  – Properties for the desired helium-xenon mixture were added to the code.
  – A compressor component was developed and included in the code.
- Bechtel Bettis enhanced the turbine model
  – The appropriate turbine performance maps can now be explicitly represented.
  – The enhanced turbine model has been provided to INL for their inclusion in a future version of RELAP5-3D.

RELAP5-3D input model of the JIMO Reactor Plant

- The reactor model is similar to other RELAP5-3D reactor models.
- There are two closed-loop Brayton systems operating in parallel.
- A turbine and compressor share the same shaft with the alternator which generates the electric power for the spacecraft.
- There are also a recuperator and a gas cooler in each Brayton loop.
- The gas cooler transfers excess energy to the heat rejection system.
- Jacob Crittenden will present a separate discussion of his novel solution to modeling compact heat exchangers.
- The bleed path was not included in this pre-decisional model.



Turbine and Compressor Performance

- NASA Glenn Research Center (GRC) provided generic compressor and turbine performance maps for use in the dynamic analysis.
  - The RELAP5-3D code changes made it possible to use the maps directly.
  - GRC also provided their method for determining off-design conditions.
  - For transients that operate far from the design condition, it was necessary to extrapolate the maps for the transient calculations. If JIMO were pursued, performance maps would be required for a wider range of mass flow rates and shaft speeds.
- In RELAP5-3D, the shaft speed is calculated by balancing the torques of the compressor, turbine, and alternator plus any additional losses.
- Shaft speed is controlled by a control system which transfers load to or from a parasitic load resistor (PLR). The control system operates fast enough that the nuclear reactor is unaffected by it.

Steady State Results

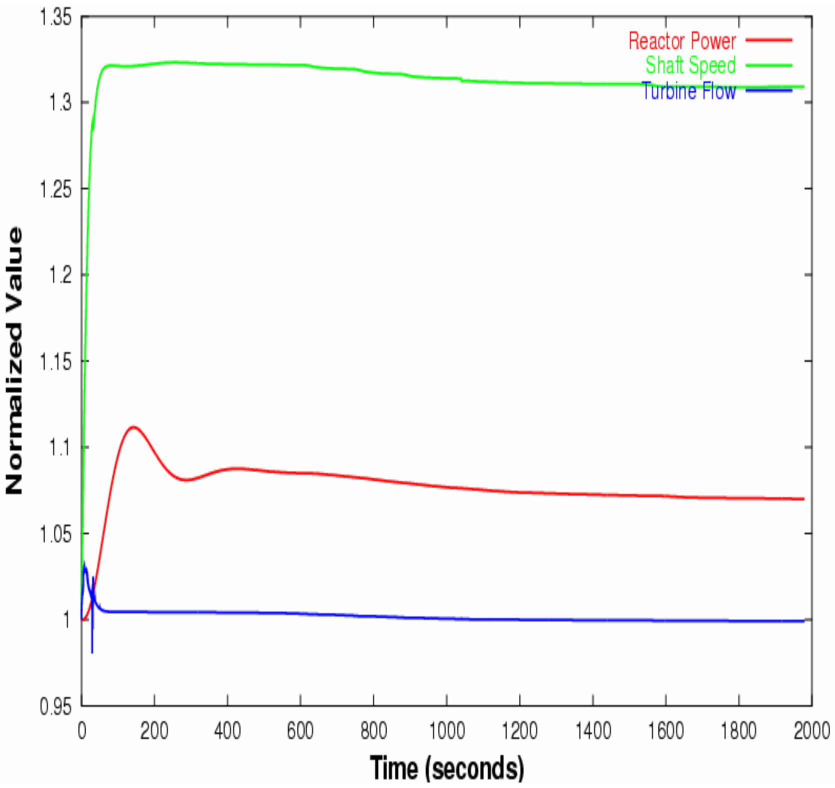
Location	Design Point Heat Balance		RELAP5-3D	
	Temperature (K)	Pressure (kPa)	Temperature (K)	Pressure (kPa)
Turbine Inlet	1150	1934	1149	1933
Turbine Exit	922	1025	927	1051
Recuperator Low Pressure Side Exit	569	1010	553	1036
Gas Cooler Exit	390	1000	380	1026
Compressor Exit	538	2000	526	2003
Recuperator High Pressure Side Exit	891	1984	892	1987

Loss of Electrical Load from One of Two Alternators

- This transient causes the shaft speed in the affected loop to increase.
  - The back torque on the shaft from the alternator is suddenly lost.
  - For this transient to occur, it is assumed that loss of electrical load and loss of the PLR occur simultaneously.
  - A new higher shaft speed is reached based mostly on the alternator and compressor torques.
  - The temperature at the compressor inlet increases requiring more torque to turn the compressor, while the temperature at the turbine inlet is fairly constant, balancing the torques at a higher shaft speed.
- Significant interpolation of the compressor performance maps is required for this transient. More detailed maps would be desirable if the design effort were to continue.

Loss of Electrical Load from One of Two Alternators

- Shaft speed approaches the upper limit of performance data (1.4).
- Reactor power increase causes the core hot spot temperature to increase about 50K.
- Results are driven by performance maps, so these would need to be refined to further the design.



Start-up Transient

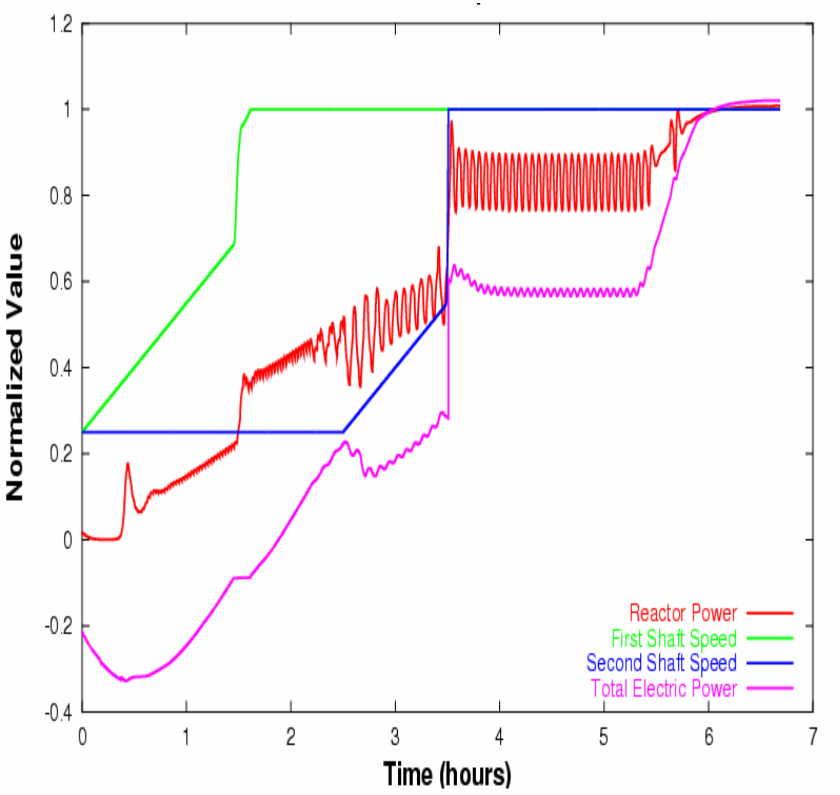
- This is highly assumption dependent. The assumed initial conditions are:
  - Initially the heat rejection system (HRS) loops and the gas loops are all at 400K.
  - The reactor has previously been taken critical and power increased to 1%.
  - During startup the HRS removes heat at a reduced rate. When the CBC are at operating temperature and shaft speed, the HRS heat removal rate is increased to normal.
  - Both turbines are initially motored at 25% of design shaft speed to preclude bearing damage using energy from solar collectors and/or batteries.

Start-up Transient

- The transient assumptions are:
  - Increase gas temperature and the shaft speed of one of the two turbines simultaneously at a rate that results in the desired reactor outlet temperature and shaft speed on one turbine in 2.5 hours (Note that a much slower transient would be more likely to be used, but the trends should be similar).
  - After the first turbine is at operating speed, start increasing the second turbine at a rate to reach operating speed in 2.5 hours.
  - Once a turbine reaches self-sustaining (turbine torque exceeds compressor torque) shaft speed is allowed to increase until operating speed is reached.
  - After the temperature and shaft speed are at operating conditions at about 5 hours, bring the HRS loops up to full flow.

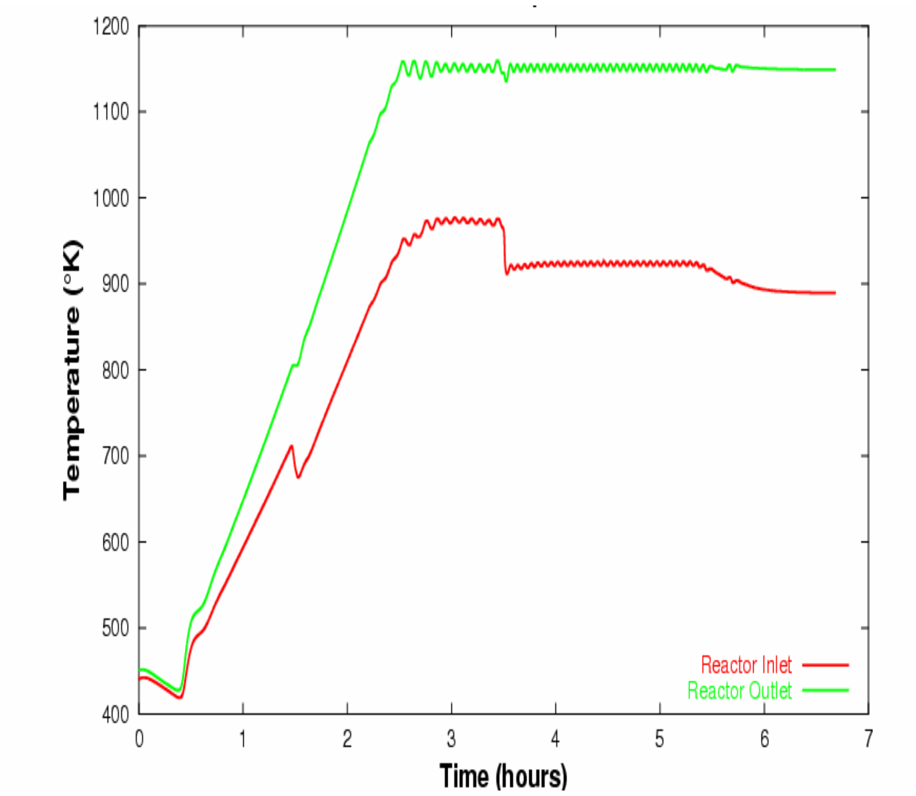
Start-up Transient

- Even at high rates of heat-up and shaft speed increase, the reactor power does not exceed 100%.
- The first turbine is self-sustaining at about 67% and the second at about 56%, because the inlet temperature to the second turbine is hotter.
- Negative electric power indicates power is required to motor the turbines before reaching self-sustaining.



Start-up Transient

- The heat-up is accomplished by moving the sliders as follows:
  - Move the sliders a short time then hold position.
  - Repeat the above steps as necessary to match the heat-up goal.
  - Reactor outlet temperature is compared to the heat-up goal.
  - This can result in some oscillations, since the times are pre-determined. A method with reduced oscillations could be developed.



Summary

- Models predict stable operation and self-correcting response to component failures.
- RELAP5-3D can be used to represent a GFR directly connected to a parallel pair of closed-loop Brayton systems.
- Steady state results are consistent with a steady state heat balance for the reactor plant.
- Turbine and compressor performance maps beyond the normal range of operations are required to represent some extreme transients.
- Transient response seems reasonable for the transients analyzed.
- Validation of the RELAP5-3D input modeling procedure is required against test data or a validated transient analysis code.
- It is judged that RELAP5-3D could have been successfully validated for transient analysis of this JIMO reactor plant.