OAK RIDGE National Laboratory

Autonomous Controls for Nuclear Thermal Propulsion

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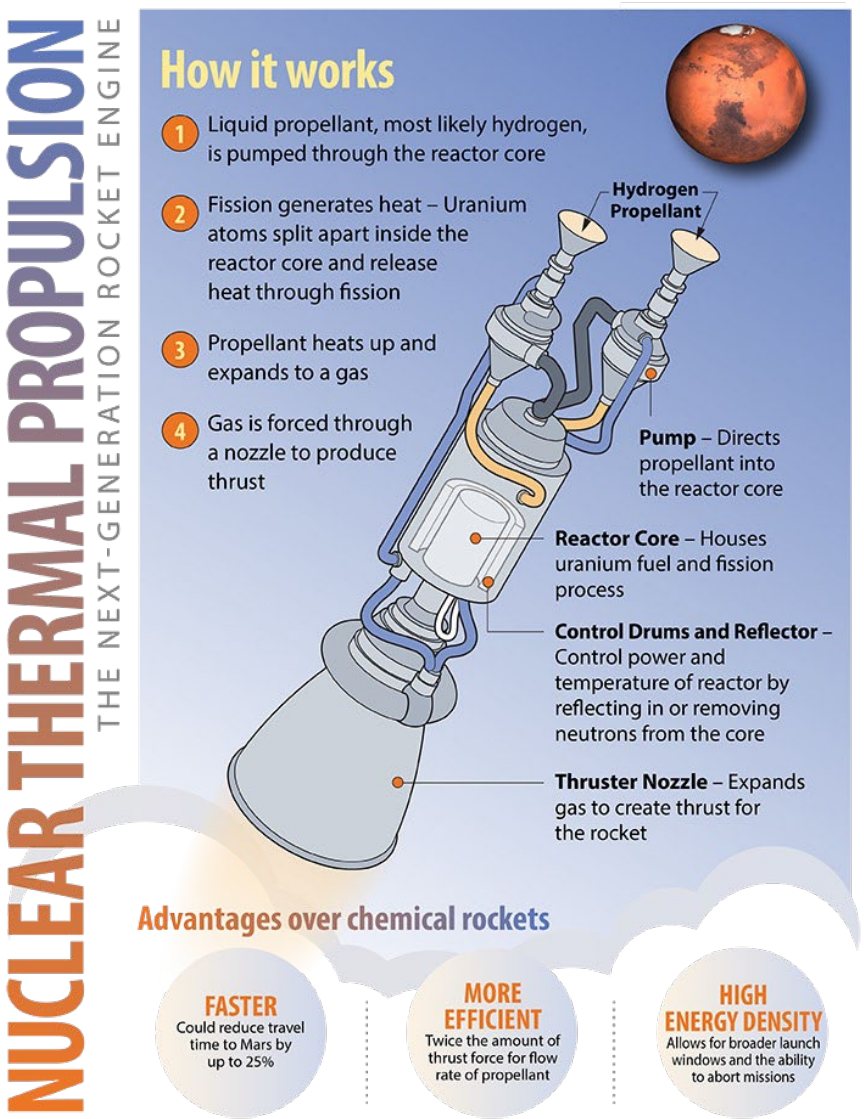
U.S. DEPARTMENT OF ENERGY

What is Nuclear Thermal Propulsion

- NTP provide high thrust and double the propellant efficiency of chemical rockets, making it a viable option for crewed missions to Mars (3 months instead of 6 months)
- Goal: manned Mars mission late 2030-2040's

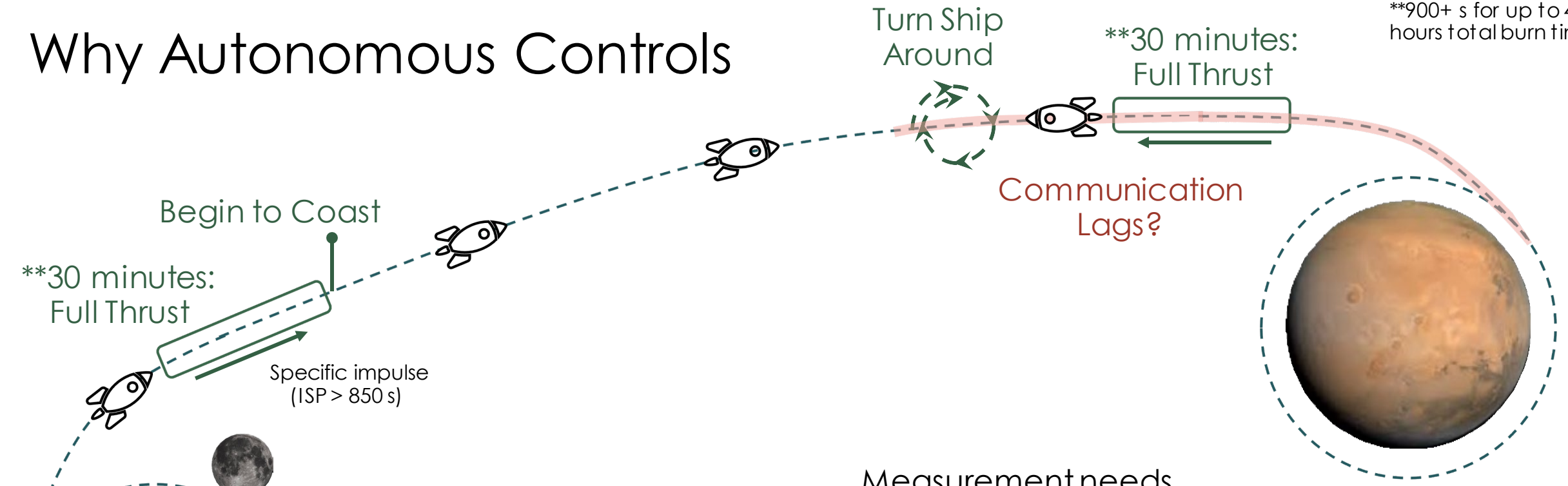


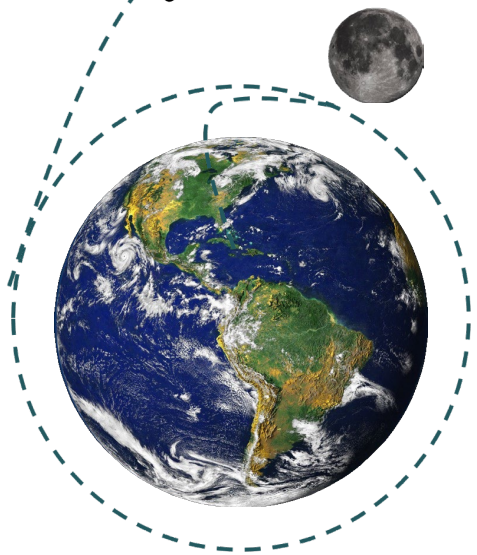
- **NASA**'s Marshall Space Flight Center; Glenn Research Center and Stennis Space Center
- **Universities:** Massachusetts Institute of Technology; University of Alabama Huntsville,
- **Industry:** Aerojet Rocketdyne, BWX Technologies, UltraSafe Nuclear Corporation, the Aerospace Corporation, Analytical Mechanics Associates, and Geocent
- **National Labs:** Oak Ridge National Laboratory, Idaho National Laboratory, and Los Alamos National Laboratory

https://www.nasa.gov/mission_pages/tdm/nuclear-thermal-propulsion/index.html
https://www.energy.gov/ne/articles/6-things-you-should-know-about-nuclear-thermal-propulsion

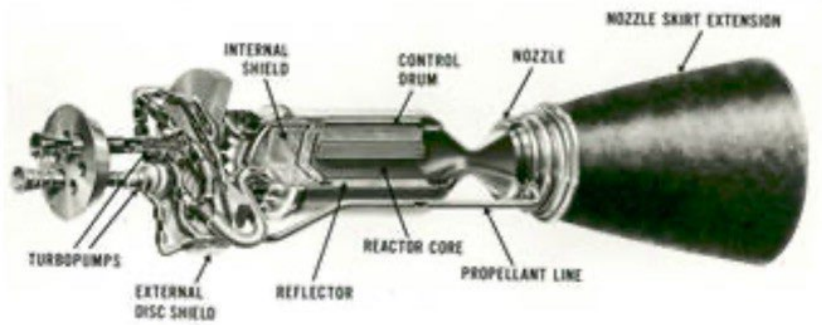
Why Autonomous Controls

**900+ s for up to 4 hours total burn time





Not to scale



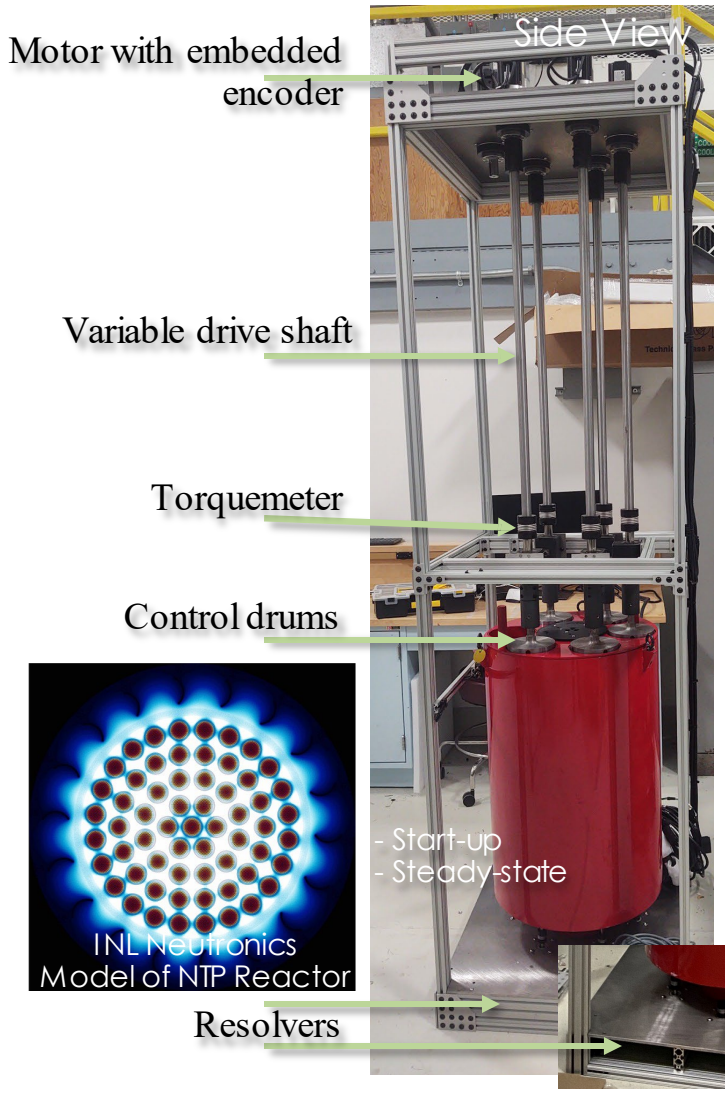
Measurement needs

- Control drums: position, speed, motor status; couplings status
- Flow loop: pressure, flow rate, temperatures
- Turbo Machinery: temperature, input or output status; performance efficiency

- Very Harsh conditions:
- (HALEU) Flux: 10^{14} n/cm^2-s
- Temperature: ~2400 °C (~2600 K; ~4800 °R)
- 2-phase loop: Cryo H_2

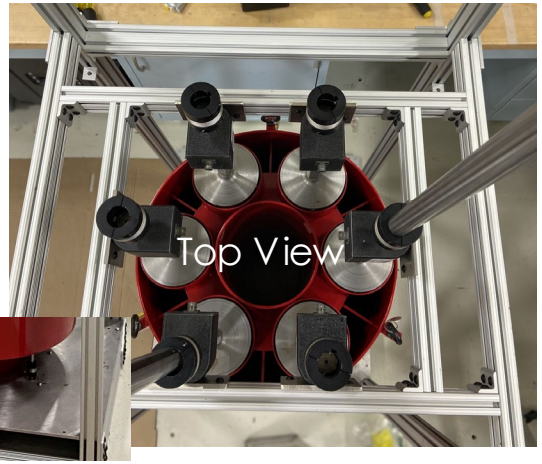
Non-Nuclear I&C testbed – "Mock-Reactor"

- Test bed will be used to validate **control algorithms / control mechanisms**; demonstrate **instrument performance**; develop / demonstrate **dynamic system models;** demonstration **fault condition** responses
- Over instrumented for instrumentation qualification
- Parts selected based on Nerva/Rover program and guidance from BWXT
- Reactor model drives heating element or LED = reactor power



Mission:
Developing a testbed to experimentally test and trial sensors, control elements and control algorithms is essential in reducing the risk, enhancing the safety, reliability, and optimization of a nuclear thermal propulsion (NTP) rocket engine

Designed to be reconfigurable:
- Control drums / rods/ sleeves
- Drive shaft length
- Independent / Ganged motor drive
- Flow rate
- System Pressure (within limitation of flow loop machinery)
- Temperature – up to 2400 C
- Future: Cryo / H_2



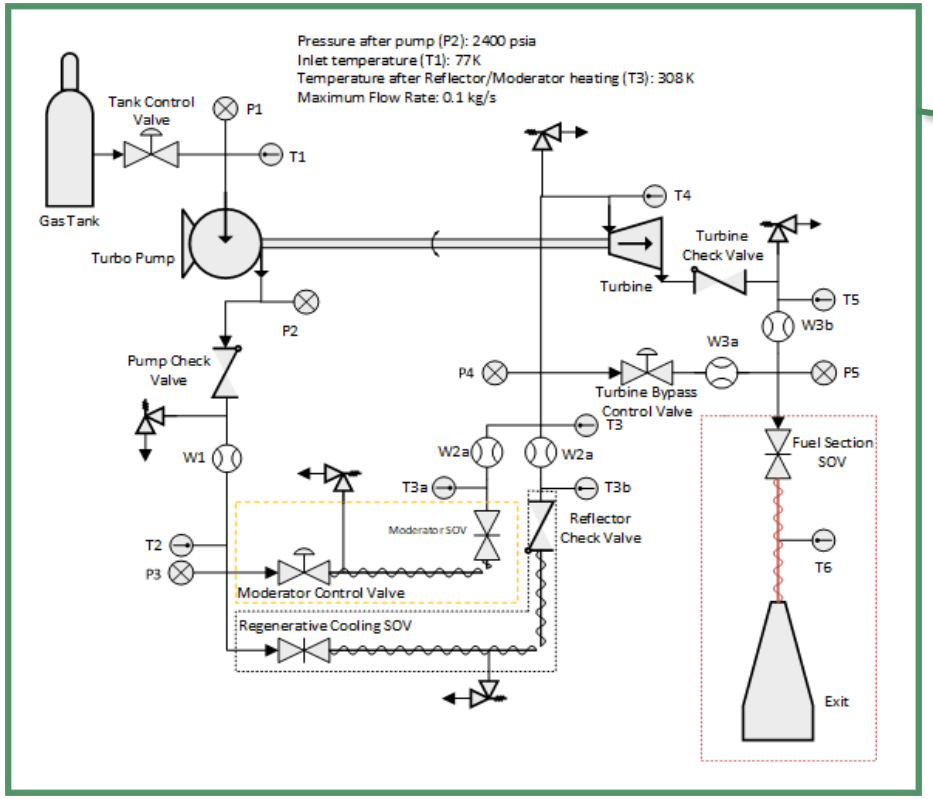
Control 1: Reactivity

Drums

Control 2: Loop – Valves

Fuel inlet valve
Mass Flow Valve
Turbine valve

Flow Loop Design



- Tightly coupled with drum hardware
- Demonstrates a 2-phase loop
- Based on AJRD design

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NASA

LSU Health NEW ORLEANS

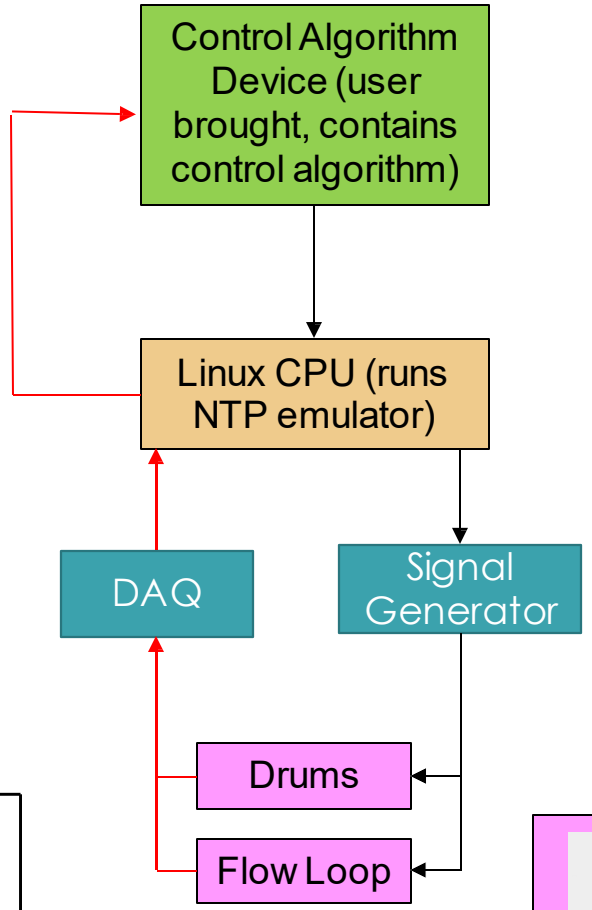
BWXT
BWX Technologies, Inc.

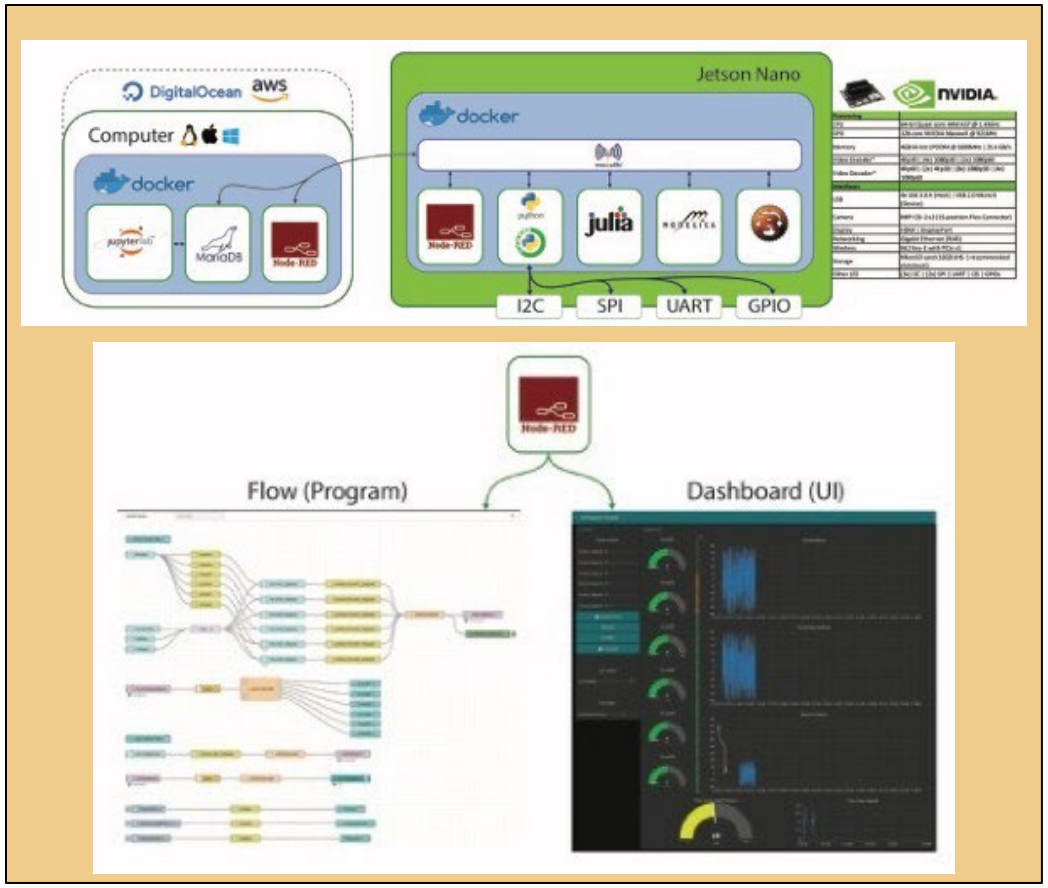
THE UNIVERSITY OF TENNESSEE KNOXVILLE

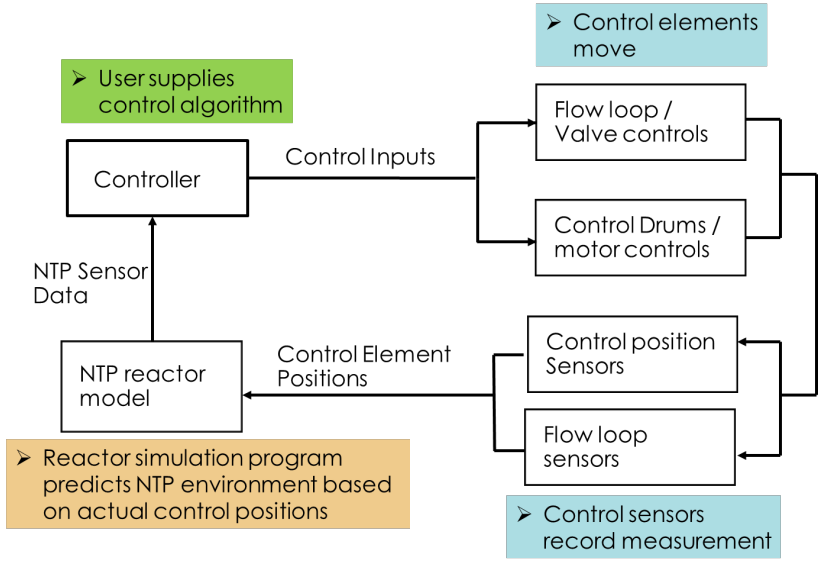
AEROJET ROCKETDYNE

Digital Architecture

- Low-Cost ($ versus $$$ NI)
- Customizable (scales easily/fast)
- Python coding platform
- User interfaces with the system through Jetson Nano
- Plug-n-play architecture
- Fault conditions defined by AJRD/ORNL randomly test autonomous control response







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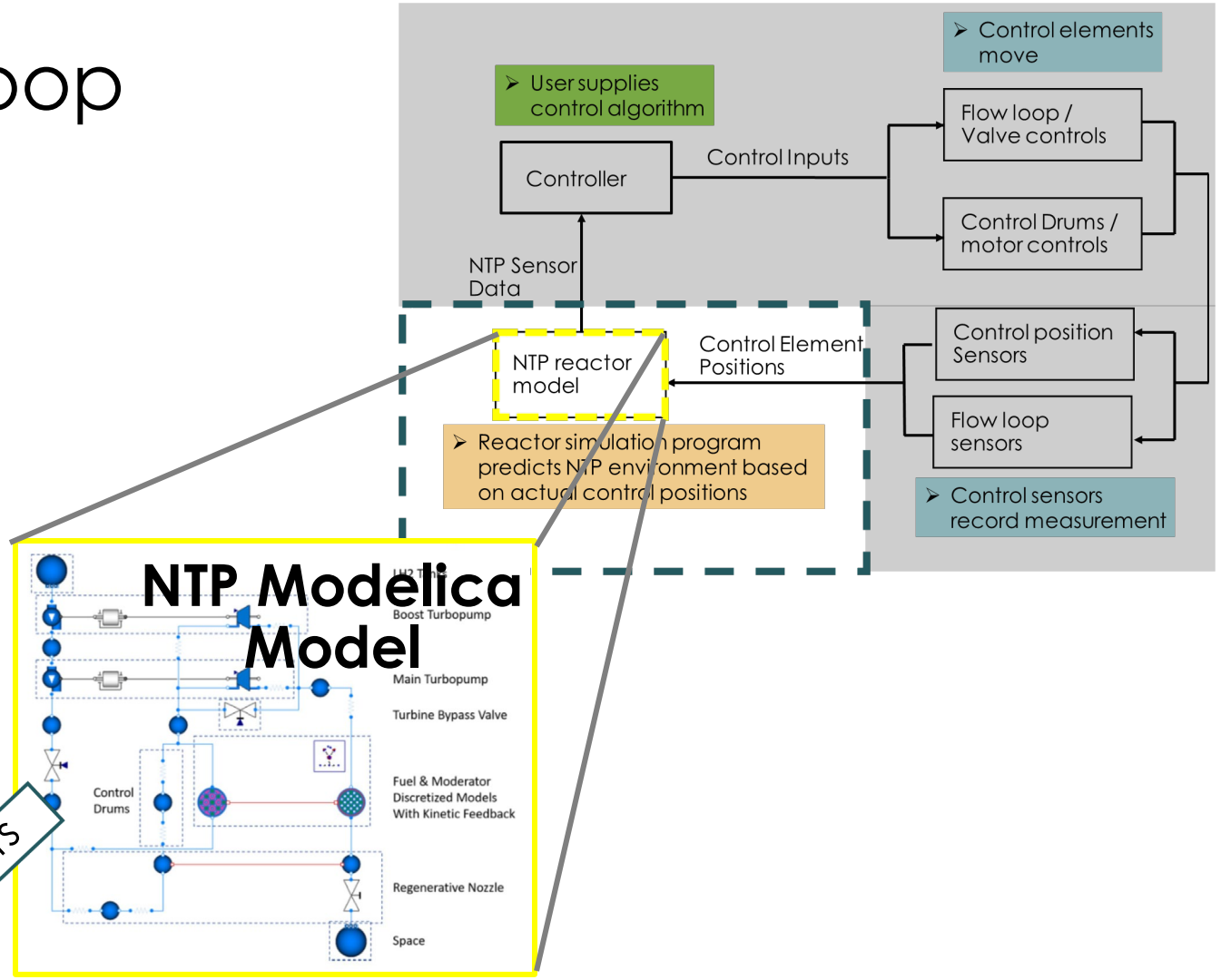
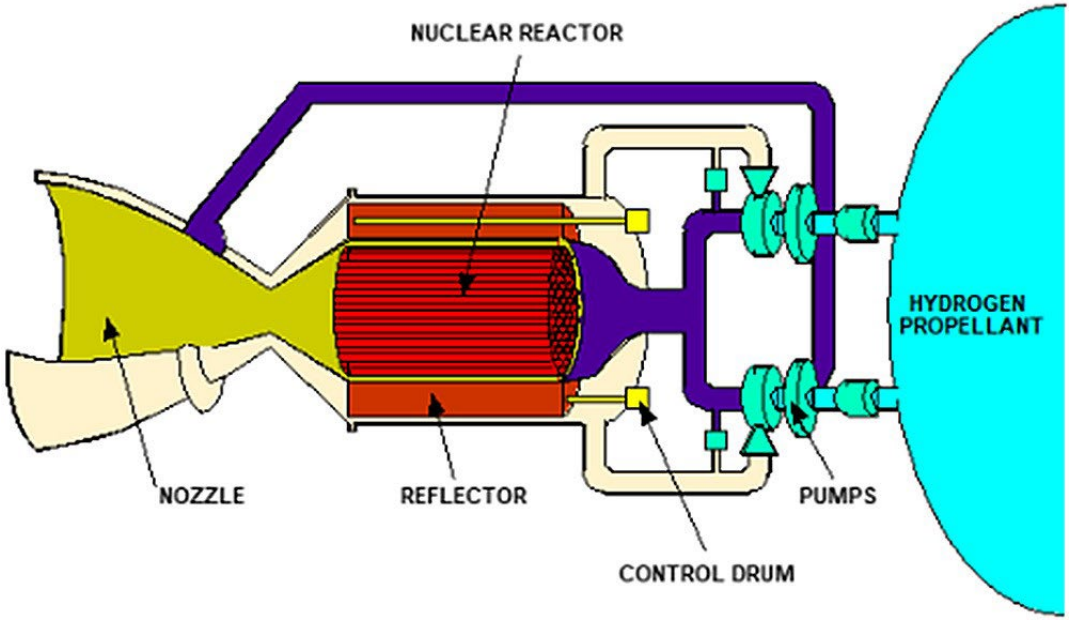
FMU for Hardware in the Loop

- A dynamic system model is used as surrogate for the nuclear aspects of the NTP system
- The Functional Mock-Up (FMU) standard packages the simulation with numerical solvers in a convenient black box surrogate model
- The FMU can be run as real-time simulation in the hardware loop and provide calculated responses based on the first principles model



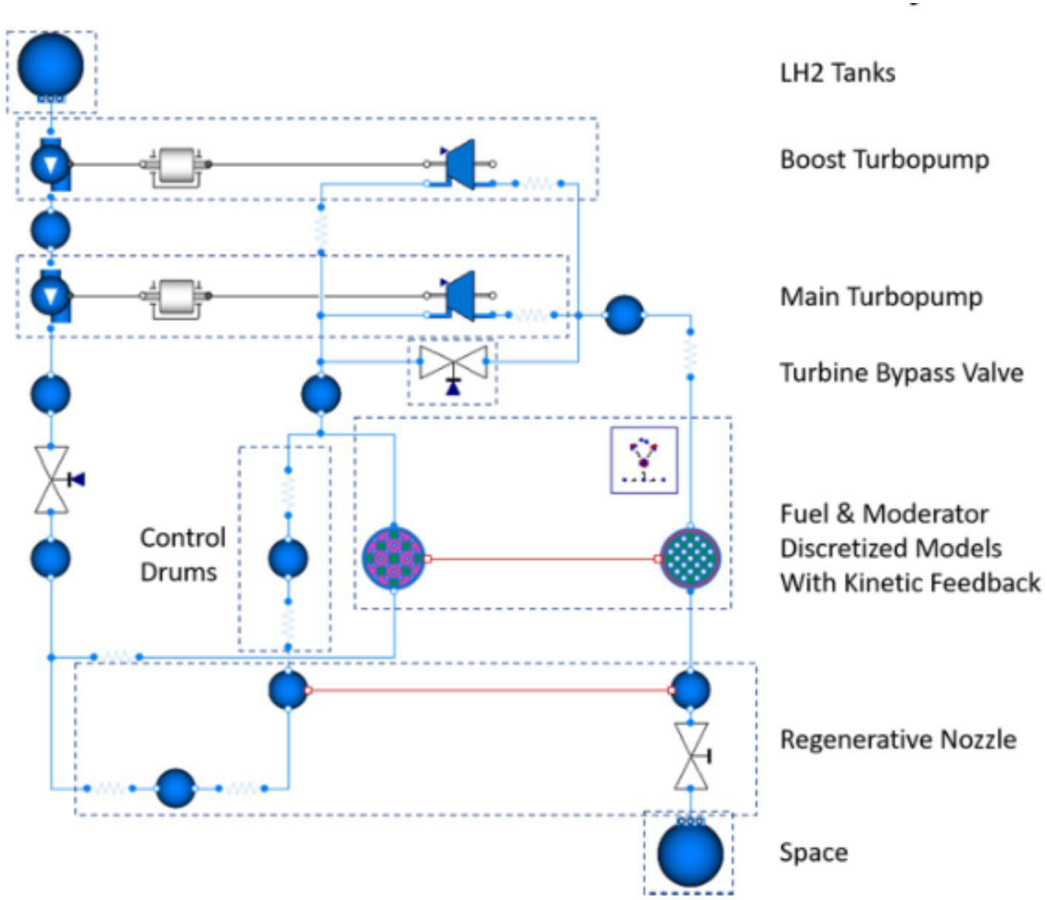
Dynamic System Modeling – Modelica: NTP



https://www1.grc.nasa.gov/research-and-engineering/nuclear-thermal-propulsion-systems/typical-components/

- 1-D flow
- 1-D flow, 2-D r-z solid fuel and moderator with appropriate lumped mass simplifications
- Turbomachines based on affinity laws used to scale from nominal values
- Compressible flow nozzle
- Pressure drop coefficients calculated from nominal flow rate and pressure drop
- Point kinetics with some 1-D reactivity weighting features
- Heat transfer calculated with appropriate correlations
- Fluid properties from CoolProp

Dynamic System Modeling – Modelica



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Conclusions

- Non-nuclear I&C testbed is operating at ORNL in support of advance controls demonstration and fault condition testing
  - Modular, reconfigurable, tightly-coupled hardware system
  - Open-source, user-friendly software platform (in-expensive hardware to interface with sensors), deployable at user site with web-based software to easy push/pull access
- Development of this system was successful thanks to the collaborations with NASA, Aerojet Rocketdyne, BWXT, and several universities


Questions?
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