**Dynamic Modeling of Nuclear Thermal Propulsion Systems Under Drum Fault Conditions**

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## INTRODUCTION

As part of the effort to enable interplanetary travel, Oak Ridge National Laboratory (ORNL) has been supporting studies of the instrumentation and control (I&C) systems for nuclear thermal propulsion (NTP) engine concepts. NTP engines utilize nuclear fission reactions to heat hydrogen, which expands through a nozzle and provides thrust. The development and progress made by ORNL has been documented over the past several years [1][2][3]. This work is in collaboration with various governmental and private entities, who have complementary NTP models focusing on various aspects of the mission.

ORNL's NTP model is constructed within the Dymola integrated development environment (IDE) of the Modelica programming language; it utilizes the ORNL-developed TRANSFORM library package of nuclear and thermal hydraulic components. The NTP model is well developed and designed to accommodate the dynamically changing specifications provided by the US National Aeronautics and Space Administration (NASA). A simplified version of the NTP model can be seen in Fig. 1.

The components within the model are provided primarily by the ORNL-developed TRANSFORM library [4] to increase the accuracy of component behavior and to interface with the ExternalMedia package and take advantage of the CoolProp parahydrogen thermophysical properties routines. However, the Modelica Standard Library (MSL) was also used for some more generic components of the system.

Increased capabilities have been implemented in the Modelica model to investigate the system response to various upset conditions (i.e., fault modes). To prepare I&C systems for safe travel, these transient conditions must be modeled and understood. Identification of difficult dynamics prior to physical testing is an opportunity to significantly reduce the cost of the overall project. Previous work has covered some initial valve and turbomachinery failure mode effects on the system performance [5]. The focus of this work deals specifically with failures occurring in the control drums used to control the nuclear reactions in the core. This work represents a great

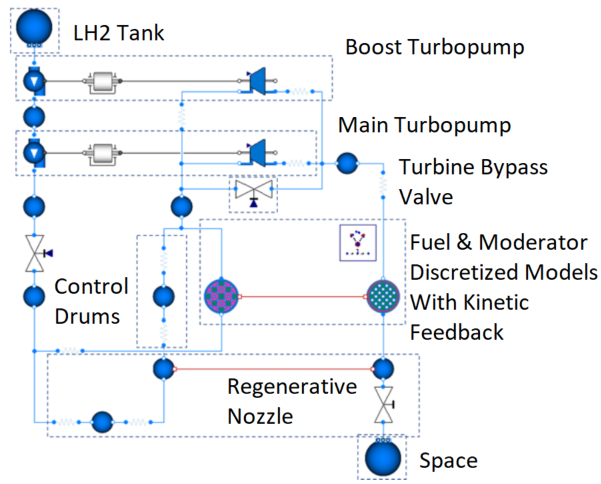


Fig. 1. Basic flow arrangement for the ORNL NTP model. Blue lines indicate fluid connections, and red lines represent heat transfer connections.

opportunity to compare our model response to that of our collaborator's more detailed models of the nucleonics response of the core. Such models pave the way for deploying digital twins that can be used for predicting system performance or forecasting maintenance and component failure. Going forward, failures within other components will be considered and studied with the aim of capturing a broad spectrum of potential impacts. Also, the link will be made between computational models and physical components to support the development of digital twins.

## MODEL DESCRIPTION

The liquid hydrogen (LH2) is stored in cryogenic tanks before entering the propulsion system. It is brought out of the tanks via a low-pressure 'boost' turbopump before entering the main turbopump. It then cools the outside of the regenerative nozzle or the control drum/reflector system, turning the LH2 to a gaseous form. The gas either passes through one of the two turbines (which power the pumps), or it bypasses via the turbine bypass valve (TBP). It then re-conjoins to cool the core and pass through a regenerative nozzle before providing thrust to the rocket.

System control is provided by the control drums and turbine bypass valve (TBV). The drums control the reactor power and, thus, the temperature of the hydrogen expelling out of the nozzle. The expelled hydrogen pressure and flow rate is controlled by the TBV. If this system was not in place, hydrogen

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would have to pass through the turbines, pulling out more LH2 from the tank, making it impossible to thrust down. Opening up the TBV allows for the turbines to slow down. Hydrogen temperature and pressure are measured directly before the regenerative nozzle. Failure of either of these components could result in catastrophic effects to a mission. It is imperative to understand how the system would respond to these failures.

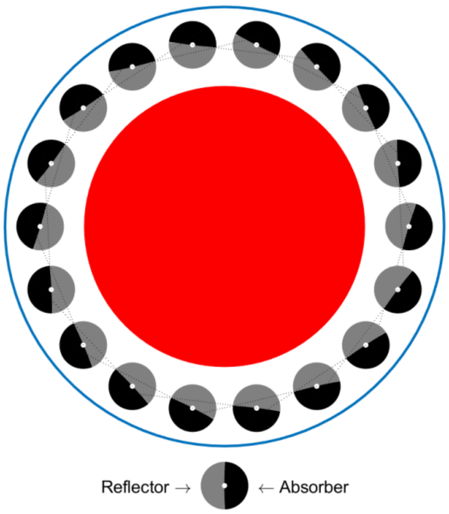


Fig. 2. Example control drum arrangement[2].

Control drums are used to provide control over the nuclear reactor used in the NTP design. Fig. 2 shows an example formation of the reactor core (in red) would be surrounded by the drums. These drums have an absorptive material on one side, and a reflective material on the other side. By rotating the drums toward the reflective material, more neutrons scatter back into the core area and potentially cause a fission reaction. The nuclear chain reaction can be slowed down by increasing the absorptive material facing the reactor core.

Due to computational limits and run time constraints, the neutronics within the model are simplified to point kinetics equations (PKEs) rather than using a more accurate Monte Carlo simulation. This is an oversimplification that has two primary consequences. The first effect is that the dynamics of startup and shutdown are not well defined. This leads to unreliable values for the first few seconds of the simulation. Secondly, there is no spatial dependence because the reactor is modeled as a point. This becomes more important when considering the failure of a single control drum. Future work could consist of modeling the reactor in a Monte Carlo program such as the Monte Carlo N-Particle Transport Code (MCNP) or SCALE. This would provide insight into the startup dynamics as well as the spatial effects when control drums are in non-uniform positions.

The external reactivity provided by the individual drums is summed to be entered as a single value to be provided to the PKEs. Previously, the reactivity of the drums came from single combined reactivity; however, this has been subdivided algebraically to six different drums that individually sum to the same reactivity as that of the original model. For now this work is only focused on first-order impacts due to a lack of more completely developed NTP reactor designs.

## CONTROL DRUM FAULT MODELS & RESULTS

The fault mode modeling and effects are described in this section. The first scenario is one or multiple stuck drums, and the second fault is due to resolver errors, both positive and negative.

### Stuck Drums

By subdividing the reactivity insertion into multiple drums, we can approximate the system response to drums at various angles. During idealistic nominal operation, all of the drums would be at the same angle relative to the reactor core. One or multiple drums could get caught at a certain angle during an operational transient time or while in steady-state operation. A mechanical failure during a transient could lead to a stuck drum, which could have drastic consequences for the mission. However, at a constant full thrust (steady state), there is little drum movement and thus conceivably lesser consequences for the mission. It is possible that the control drums remain stuck at a certain position when movement has ceased, such as in a “freeze in” condition. Practically, this fault could be avoided by continuously moving the drums around the desired position in small increments, and this would likely occur as the controller for the control drum attempts to achieve the setpoint temperature value exactly.

To demonstrate a probable “sticking” time, the drums will lose their ability to move and respond at the moment as the rocket reaches full thrust. In this work, six control drums were modeled to match up with the mock reactor demonstration facility being constructed at ORNL [6]. Simulations were performed to evaluate the I&C response caused by the failure of 0 to 3 control drums.

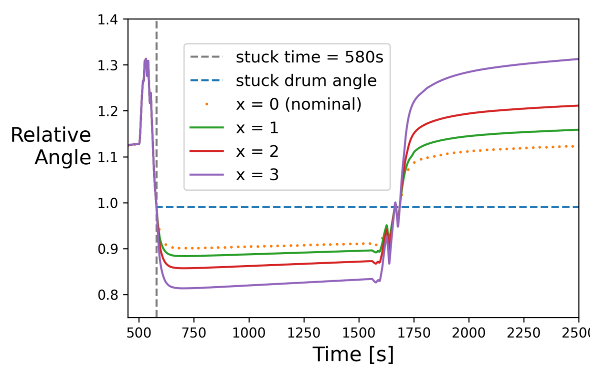


Fig. 3. Controller response for x number of stuck drums. Failure occurs at the gray vertical line at 580 s; the healthy response is indicated by the dotted orange line; the stuck angle is represented by the dashed blue line.

Fig. 3 shows the various control drum angles during healthy and faulted simulations. This time section of the graph shows when the rocket is reaching full thrust (~600 s), leveling off to the constant full thrust (~600–1500 s), then transitioning to a new angle to achieve a lower thrust (~1550–2500 s)).

The non-faulted simulation is shown by the 'x = 0' orange dotted line. For the faulted simulations, either 1, 2, or 3 of the 6 control drums gets stuck at time 580 s (marked by the vertical gray dashed line) and at the same angle every time. The drum's controller is attempting to achieve a temperature setpoint following the nuclear reactor. Because the stuck drums are unable to help, it accounts for this deficit by compensating with the healthy drums. The distance from the nominal drum position increases with the number of stuck drums.

Due to the use of PKEs, the spatial effects of the control drums on the neutronics are not present. This becomes problematic when considering uneven drum positions. It is not possible to determine how much of an oversimplification this is without studying the reactor via Monte Carlo simulation. Hypothetically, it would be worse if all three stuck drums were on one side, for example; this may result is a very uneven temperature and flux distribution within the reactor core, which could lead to catastrophic structural failure.

### Positive Resolver Error

The resolver is the piece of equipment that reads in the current individual angular position of the control drums. An error in the drum feedback could lead to a quick change in the measured position of the drums. This error would be either a positive or negative error in the angular measurement; see Fig. 4. A positive error, described first, would mean that the measured angle is higher than the actual drum angle. This would mean that although the drum controller is signaling for the desired angular position, the drum would be actuated to a smaller angular position, and much lower than desired resultant external reactivity would thus be inserted by that drum.

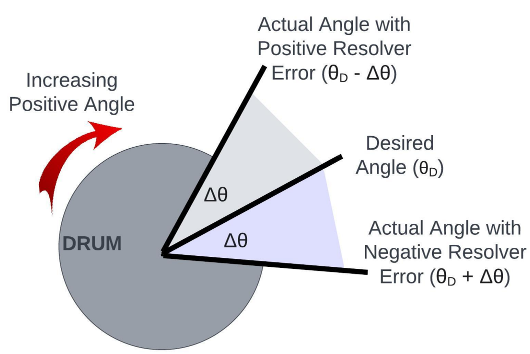


Fig. 4. Explanation of drum angle with positive and negative resolver error. Measured angle is larger than the desired angle for the positive offset and smaller for the negative offset. Therefore, the actual angle is smaller for the positive offset and larger for the negative offset.

The control response and effect on the rocket's propulsion are shown in Fig. 5. The light violet region is the time in which the resolver error occurs; the resolver fault causes the abrupt angle change in less than 1 s. Prior to the fault mode, the controller response (desired location) is directly matched by the drum's location. The resulting decrease in drum angle slows the nuclear reaction and decreases the temperature of the coolant; this is measured, and the controller increases the requested angle to return to the coolant temperature setpoint. Following the fault, the controller spikes the requested angle and finds a new equilibrium. At the new equilibrium, the difference between the actual drum location and controller response is the value of the resolver offset ($\Delta\theta$ in Fig. 4).

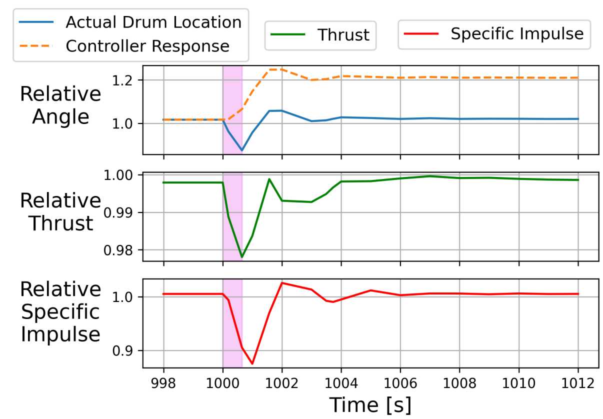


Fig. 5. System response to a positive resolver error.

Fig. 5 also shows the effect on the rocket, with the plots of the relative thrust and specific impulse. Both of these variables decrease and then return to their nominal value within a few seconds. This response is very similar to that recorded by this project's collaborators. A major distinction is that their model was numerically capable of a step in the resolver error, where ours needed to be a sharp increase. Comparing the model responses, the response we found with respect to thrust was almost equivalent to theirs. The response to the specific impulse was more drastic for our model; this could be due to differing control strategies for the TBV.

### Negative Resolver Error

A negative resolver error would mean that the measured angle is lower than the actual drum angle (Fig. 4). In action, although the drum controller would be signaling for the desired angular position, it would actuate the drum to a higher angular position; thus, a much higher than desired resultant external reactivity would be inserted by that drum.

Following the increased drum angle, the controller responds to the hot temperature of the coolant and quickly decreases the drum angle. The effect on the thrust is a quick spike, then a return to the nominal value. Specific impulse also spikes; however, it dips relatively far below the nominal value before returning back to the nominal value. These results are also consistent with the model of our collaborators, except for the effect seen in the specific impulse. In our model, the response on the TBP is more significant during the negative resolver case.

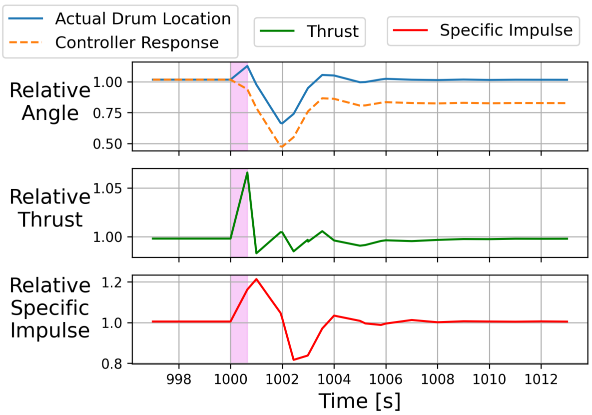


Fig. 6. System response to a negative resolver error.

## CONCLUSIONS

This work has demonstrated a new capability for investigation of control drum faults in an NTP system. The ability to observe individual drum's effects on the overall point kinetics equations allows for analyzing the response of other drums to offset the fault condition. These are important factors that figure into the design of the I&C systems as well as in the assessment of overall mission safety and success criteria. This work also will enable integration of the model into the mock reactor test bed at ORNL and advance the field of digital twin development.

## ACKNOWLEDGMENTS

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