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Accident-Tolerant Control Drums Applied to Nuclear Thermal Propulsion

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1. Introduction

The development of Low Enriched Uranium Nuclear Thermal Propulsion (LEU-NTP) has recently become the focus of considerable private (Aerojet Rocketdyne, USNC), academic (KAIST, CSNR), and national (DOE, NASA) research and development. These research efforts center around enabling the implementation of LEU fuel in NTP systems. In doing so, the cost and development timelines for NTP will be reduced sufficiently to be an enabling technology for human Mars missions. Research is currently centered on demonstrating equivalent performance between HEU and LEU systems [1], resolving key hurdles for LEU systems [2][3], fuel development, and identifying a successful development path.

One of the large hurdles for the implementation of LEU-NTP is maintaining the reactor subcritical during a full water submersion accident. The accident occurs in the case of a mission abort when the system is first sent into orbit. When the ground to orbit rocket is forced to abort in mid-flight, the reactor will most likely land in a large body of water, resulting in the reactor becoming fully submerged in room temperature water. The resulting effect is a large reactivity insertion as the reactor is suddenly surrounded by an infinite water reflector and is filled by a water moderator. The reduced leakage along with the enhanced moderation of an already thermal spectrum reactor render the reactor prompt critical. Consequently, this is a situation that has to be avoided.

A recently proposed solution for compact space-power reactors has shown significant promise in mitigating this accident. This innovation involves enhancing the reactivity swing of the control drums. Originally proposed by Dr. Hyun Chul Lee et al. [4], the rotating drums are enhanced by including a section of fuel and impinging on the active core region. This combination along with the pre-existing poison plate on the opposite side serve to significantly enhance the total worth of the drum. This is illustrated in Fig 1 for more clarity. In addition to the significant worth of the drums, the system also promises to keep the reactor subcritical in case the drums are either lost or malfunction.

The present work seeks to apply the simple, yet elegant innovation of Dr. Lee to LEU-NTP systems. This application has a set of additional difficulties that make its implementation more than a matter of simply applying it to an existing LEU-NTP core design. These added difficulties include the presence of a heterogeneous active core region, extreme core temperatures, and the need to minimize the power generated in the control drum.

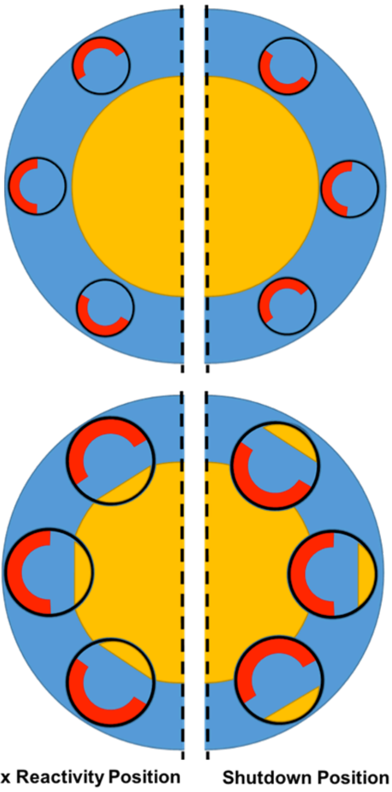

Fig. 1. Traditional control drum configuration (top) and modified control drum configuration (bottom) with fuel (orange), absorber plate (red), and reflector (blue).

In this work, the accident tolerant control drum system is examined in terms of its applicability to LEU-NTP and its neutronic characteristics are studied and characterized. A series of alternative configurations are proposed and evaluated as applied to the SULEU core. The neutronic calculations were done using the Serpent 2 Monte Carlo code [5] along with the ENDF/B-VII.0 [6] cross-section library.

2. Original Accident-Tolerant Control Drum

The original accident tolerant control drum was quite simple in design and how it was implemented. It took the control drum and increased its radius such that it encroached on the active core region. The portion of the drum which intersected the active core radius was then replaced with the solid fuel matrix and a small poison plate was implemented at the opposite side of the drum. This is clearly shown in Fig 2.

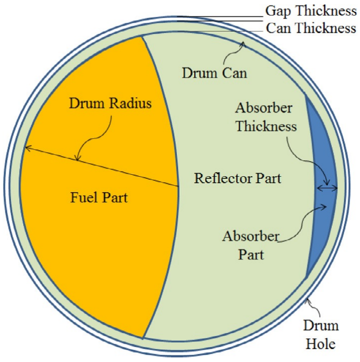

Fig. 2. Details of the original accident tolerant control drum [4].

This simple configuration was possible for two reasons. First of all, the drum was originally applied to a reactor that had a radially homogenous active core. This enabled the implementation of the drums with an equivalent reactivity to the design without the accident tolerant drums. Second is that the core was a low power core, designed to operate at 5 kW thermal. This means that even when the drums are fully inserted into the core and it is operating at full power, the drums can be cooled by the heat-pipes in the active core region without additional cooling systems.

3. Reference LEU-NTP Core: SULEU

The reference core to which the accident tolerant control drums have been applied is the SULEU [7] core, a pre-existing reference core design developed by USNC. The core is capable of providing 155 kN of thrust with a specific impulse of 897.7 seconds with an LEU graphite composite fuel. The core is structured around heritage NERVA/ROVER designs and was developed using SPOC/SPACE [8], a code originally developed by NASA Marshall and CSNR for rapid NTP core design and development. The operating characteristics of the core are summarized in Table 1 while Figures 3 and 4 detail the radial and axial geometries of the core. Further details on the core can be found in reference [7].

Table I: Key Performance and System Parameters [7]

<table>
<tr><th colspan="4">Key Performance Parameters</th></tr>
<tr><td colspan="3">Nominal Isp (150:1 Nozzle)</td><td>897.9</td></tr>
<tr><td colspan="3">Nominal Thrust (kN)</td><td>155.7 (35k lbf)</td></tr>
<tr><td colspan="3">Whole Reactor Power(MW)</td><td>768.9</td></tr>
<tr><td colspan="3">Fuel Temperature Max (K)</td><td>2850</td></tr>
<tr><th colspan="4">Engine System Interface Information</th></tr>
<tr><td>Interface Point</td><td>Flow Rate (kg/s)</td><td>Pressure (MPa)</td><td>Temp. (K)</td></tr>
<tr><td>Core inlet</td><td>17.68</td><td>8.0</td><td>300.0</td></tr>
<tr><td>Core outlet</td><td>17.68</td><td>5.0</td><td>2712.8</td></tr>
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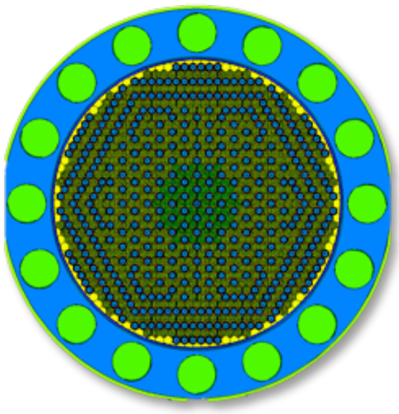

Fig. 3. SULEU radial geometry [7]

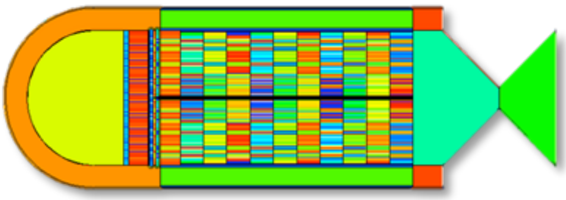

Fig. 4. SULEU axial geometry [7]

4. Accident- Tolerant Drum in NTP

The implementation of the new drum system into an NTP core is complicated by two factors. First of all, the power produced is significantly higher than in the low power space reactor the drums were originally developed for. Second, the core is radially highly heterogeneous. In rotating the drums in and out of the core they need to be able to remove not only fuel but moderator as well. These key complications require the drums to have a different configuration. In the present study, the drums were modified in terms of four variables: control drum radius, fuel type, shape of the fuel, and fraction of the drum consisting of fuel. The range studied for these variables is given in Table 2.

Table 2: Parameters varied.

Parameter	Values
Control Drum Radius (cm)	4 - 10
Fuel Type	$UZrH_{1.6}$, U10Mo
Fuel Shape	Pad, Sector
Fuel Fraction (Inner radius, cm)	0 - 5

4.1 Fuel Selection

The fuel was selected based on two criteria. First, it had to have the ability to insert and remove significant reactivity. This is achieved by having a large fissile density and/or significant built-in moderation. Second, it has to be compatible with a hot hydrogen atmosphere. This is because the fuel and the drum will be cooled down with pressurized hydrogen. With these criteria, the first two compatible fuels are U10Mo and UZrH. Both of these are fuels that have been used in the past in research reactors and are well characterized and understood. As such, both can be implemented with well-known operating limits.

5. Results

The implementation of the drums has a set of consequently noticeable effects on the reactivity that enhance their worth. The first and most noticeable of these is the increase in the total worth of the drum. This is due to the removal of fuel and, in the case where the drum impinges on the active fuel region, the introduction of a poison plate into the core. The second is the increase in reactivity due to the additional fuel introduced. By adding a high fissile density fuel and, in the case of the UZrH fuel, a highly moderated fuel, there is a large neutron contribution coming directly from the drums. Consequently, a large fraction of the power in the core is then produced in the drums. This effect is clearly shown in Figures 5, 6 and 7. In Figure 5 the reactivity for the cold submerged shutdown (CSS) is given alongside the hot full power conditions (HFP) for the UZrH fuel for different drums of different radii. The same is given in for the U10Mo fuel in Figure 6. In Figure 7 is an example of the relative power and thermal flux for one of the cases. Here it can be clearly seen how, with the new fuel type, a large fraction of the core power is now deposited in the control drum.

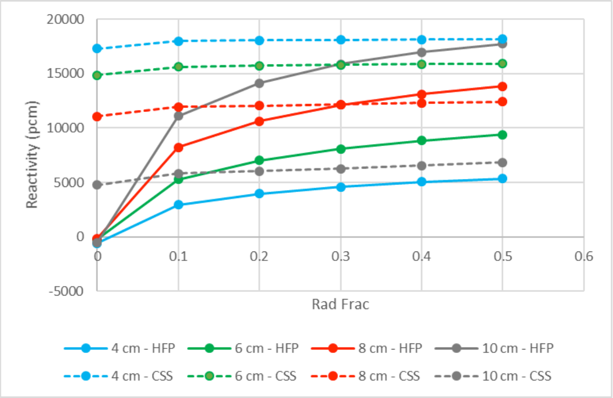

Fig. 5. Effect on HFP and CSS reactivity using UZrH fuel.

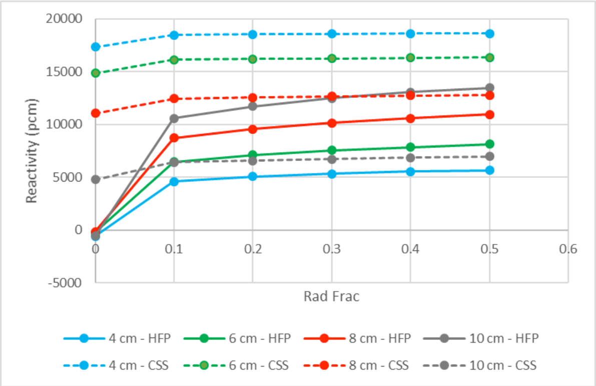

Fig. 6. Effect on HFP and CSS reactivity using U10Mo fuel.

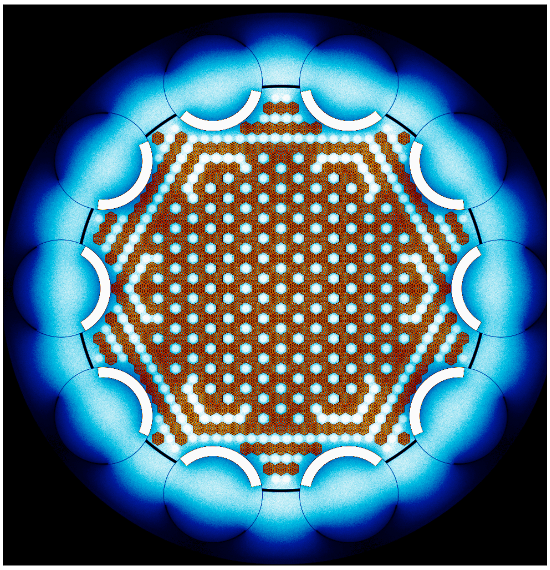

Fig. 7. Illustrative example of the effect on relative fission density in the core (red – white) and thermal flux (blue-white).

In the current study, the figure of merit was the difference between CSS and HFP. This figure determines how effective the drums are at preventing a criticality accident in case of a water submersion and still enable the core to operate at full power. This is shown for the two fuel types in Figures 8 and 9. Here, it becomes clear that the drums are effective reducing the effect of the full submersion, if not able to single-handedly maintain the reactor in a subcritical state during the accident.

Of interest is the clear trend of how the effectiveness of the drums is increased. The ability of the drums to effect the reactivity of reactor is directly related to their contribution to the neutron flux. The larger the neutron importance of the drums, the larger their worth. Consequently, the power generated in the drums is connected directly to the worth of the drums. This allows us to determine the maximum worth of the drums for a given reactor configuration if the coolant flow rate for the reflector region is known. In the case of SULEU, this is about 104 MWth with a hydrogen mass flow rate of 8.95 kg/s.

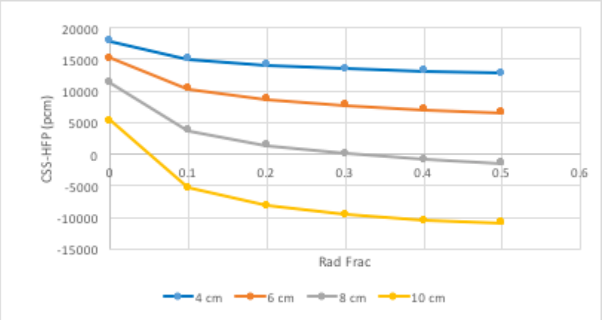

Fig. 8. CSS-HFP for UZrH fueled drums.

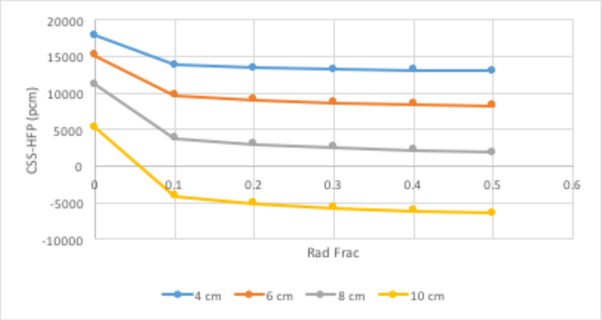

Fig. 9. CSS-HFP for U10Mo fueled drums.

6. Conclusions

The present study has shown that the accident tolerant control drum is able to ensure a subcritical state in the case of a full water submersion accident. However, it requires significant further development in order to be successfully implemented. The chief hurdle that needs to be addressed is the fission heat produced in the drums. In the current implementation, well over 100 MWth is generated in the drums, rendering it an unfeasible configuration.

Despite the power produced in the drums, the accident tolerant drums are still a promising technology. The drums have been shown to be able to maintain a subcritical core during a submersion accident. Consequently, future work will focus on refining the design space with the objective of minimizing the amount of heat produced in the drums.

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