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LEU CERMET NTP DESIGN SPACE STUDIES

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Five studies were undertaken to explore the low enriched uranium nuclear thermal propulsion (LEU NTP) design space at the 25,000 lbf thrust class. This paper presents the progression of the five studies, outlines what was varied in each study, and covers key results. This work explored design points with and without isotopic enrichment of the cermet/cermetalloy matrix materials. A major finding was designs with a MoW matrix material and no isotopic purification can have appealing performance and meet criticality requirements. Other findings include: Clad thickness is a major performance driver for LEU NTP cermet systems, using TZM and Nb1Zr[a] as the tie-tube material instead of zircalloy results in a notable performance penalty, and UN-MoW cases are less sensitive to neutronic penalties than UO_2-MoW cases.

I. INTRODUCTION

Nuclear thermal propulsion with low enriched uranium (LEU NTP) is an appealing technology for a human Mars mission or a lunar tug. This paper presents design studies on a subset of LEU NTP technology that uses a cermet or cermatalloy fuel form. Cermet refers to a fuel form made of ceramic particles dispersed in a metal matrix. The name cermet is an amalgamation of ceramic and metal. Cermetalloy extends the amalgamation to include an alloy in the metal part of the ceramic; in this work referring to molybdenum tungsten.

The central innovation to this work is demonstrating that cermetalloy LEU NTP cores that use a matrix material of an existing commercial alloy[1] of 70% weight molybdenum and 30% weight tungsten (Mo30W) and no isotopic purification can have comparable performance to cermet LEU NTP cores with isotopically purified W-184.

II. Method

Combinatoric design studies were conducted using the SPACE analysis package. This approach is similar to other designs studies conducted using SPACE but the underlying process is restated here in brief[2]. Figure 1 outlines how design studies are created using SPACE.

The process relies on using a large number of SPACE inputs in a combinatoric manner where the parameters of interest are varied. Neutronic and thermal calculations are conducted to resolve key properties of the core from each set of SPACE inputs. A map of the design space is created at the end of the process of points that produce the desired thrust, have the same max fuel temperature, and meet criticality requirements.

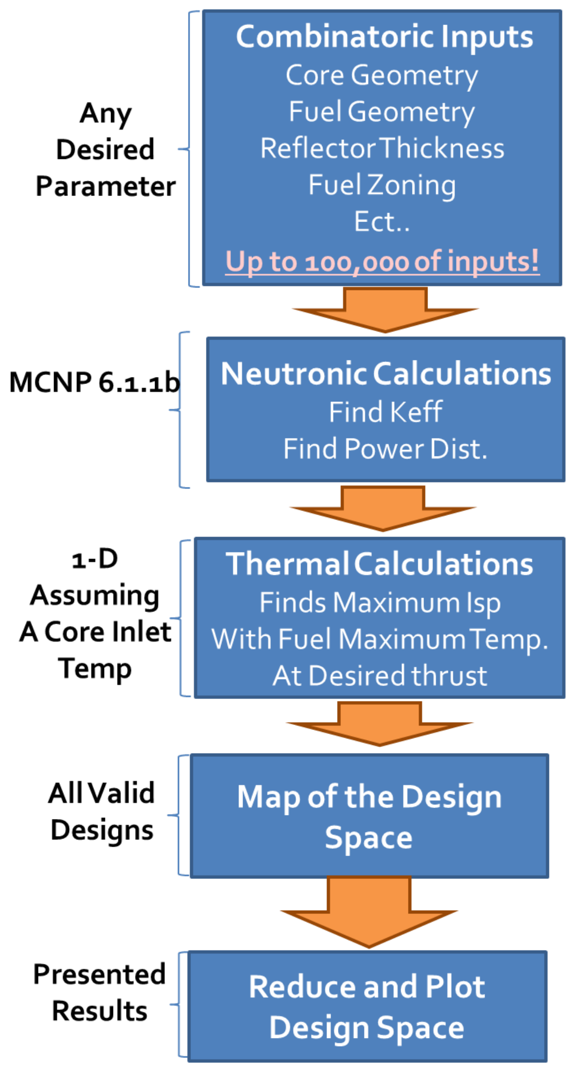

Fig. 1. An outline of the design study process

[a] The non-subscripted number in the formula means weight %, e.g., 1 wt% Zr in Nb

A comprehensive list of assumptions and parameters that may be varied in each case study is beyond the scope of this paper. Parameters that were varied in these combinatoric design studies include core radius, core length, channel diameter, fuel to tie-tube ratio, clad thickness, material choices, number of channels in a fuel element, fuel geometry, reflector thickness, and others. Key assumptions and screening criteria used in the studies include:

- A traditional NERVA-type fuel and tie-tube configuration with similar flow paths through the core,
- A minimum K-eff value with sufficient excess reactivity to account for future increases in model fidelity,
- For thermal calculations, inlet hydrogen into the fuel region has a temperature of 300 K and a pressure of 8 MPa,
- A conservative channel-by-channel power peaking factor for the peak hot channel,
- A maximum fuel centerline temperature of ~2,800 K is used in average channel calculations for both MoW and W matrix materials and UO_2 and UN fuel material to provide >200K margin to fuel melt,
- A conservative maximum Mach number to prevent supersonic flow,
- An axial reflector made of BeO on the cold (entry) end of the reactor,
- A radial reflector made of Be, which includes geometry regions for control drums,
- Drums rotated to 60˚ from fully out in all cases for neutronic calculations.

II.A. Study Revisions

A total of five studies were conducted to explore the LEU NTP cermet/cermetalloy design space at the 25,000 lbf thrust class with a target I_{sp} of greater than 850 seconds. Each design study revision was changed to reflect program needs, incorporate subject matter input, and build upon what was learned in the previous iteration. An outline of what was changed between iterations is presented below:

- Case 1: Initial exploration of the 25,000 lbf thrust class UO_2-W cermet design space using many of the same assumptions as the SCCTE work[3]
- Case 2: Varied Re content in the matrix, tubing, and canning and W-184 content in the matrix
- Case 3: Removed the Re from the matrix material, varied tie-tube material
- Case 4: Explored UO_2 designs using MoW and W matrix material without isotopic purification
- Case 5: Explored UN designs using MoW and W matrix material without isotopic purification

III. Results

Figure 2 presents a comprehensive and minimally sorted collection of the results from the Rev. 3, Rev. 4, and Rev. 5 design studies. Each point is a product of neutronic and thermal calculations and represents a viable NTP core design, as determined by a Kkeff value greater than 1.04, a minimum thrust of 25,000 lbf, and a the same maximum fuel temperature.

Figure 2 represents the information produced at the "map of the design space" step in Fig. 1 and is provided to better explain the design study process. Additional sorting and filtering of the design space is provided in the proceeding sections.

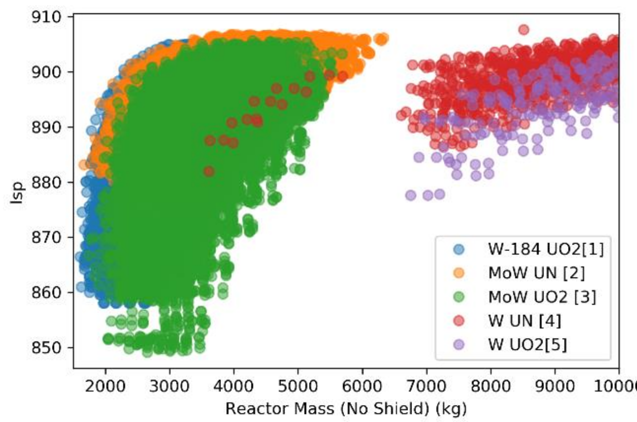

Fig. 2. The entire combined unsorted design space

III.A. Isotopic Purification Comparison

Pareto fronts of the ^{184}W-UO_2, W-UO_2, W-UN, MoW UO_2, and MoW-UN design spaces are presented in Figure 3. The W-UO_2, W-UN, MoW-UO_2, and MoW-UN data sets do not include isotopic purification of the matrix material. The source and matrix material used in each data sets is presented in Table I. It can be seen in Figure 3 that the MoW-UN cases show similar performance to the ^{184}W-UO_2 cases, and MoW-UO_2 cases are comparable but not optimal.

The ^{184}W-UO_2, MoW-UO_2, and MoW-UN data sets all used comparable assumptions in terms of fuel loading, Re in the clad and clad thickness. It should be noted that the W UO_2 and W UN data sets use very technologically aggressive material compositions, with a high fuel loading and no Re in the clad like the other data sets. Even with these aggressive material compositions, the resulting reactor mass values are greater than what can likely be tolerated.

The ^{184}W-UO_2 core generally outperforms the MoW-UO_2 and MoW-UN cores, but the difference in performance is small. The difference in performance is primarily due to the fact that natural Mo has a cross section similar to that of W-184 and because MoW has a much lower density than pure W. It can be seen that, for high I_{sp} values, MoW-UN generally outperforms ^{184}W-UO_2, since the UN cores have more fuel and benefit from the lower density of MoW.

III.B. Specific Technical Trends

It is also possible to extract specific technical trends from the combinatoric design studies and identify central performance drivers. A few examples are provided in the following figures. Figure 4 shows the natural MoW-UO_2 design space sorted by propellant channel tubing and Element Canning Thickness. The data has clear striations, and shows a predictable trend where thinner canning and tubing produces better performance. In these figures, the reactor mass penalty for increasing canning and tubing thickness by 150 μm can be seen to be on the order of 500 kg around 900s of I_{sp}.

Figure 5 shows the same trend analysis as Figure 4, but for the UN design space. A notable difference between the UO2 and UN data sets is that the performance penalty for going to a thicker web is less than the performance penalty in the UO_2 data. This trend of UN-MoW NTP systems being able to overcome neutronically challenging design choices relative to equivalent UO_2-MoW systems is also observed in other design parameter variations, including those with lower fuel loadings, higher rhenium content, or greater k-eff margin requirements.

Figure 6 shows the impact of tie-tube material on performance in the W-184 data set from Rev 3. TZM and Nb1Zr are not strong neutron poisons, but absorb more neutrons than Zircaloy and cause a notable drop in

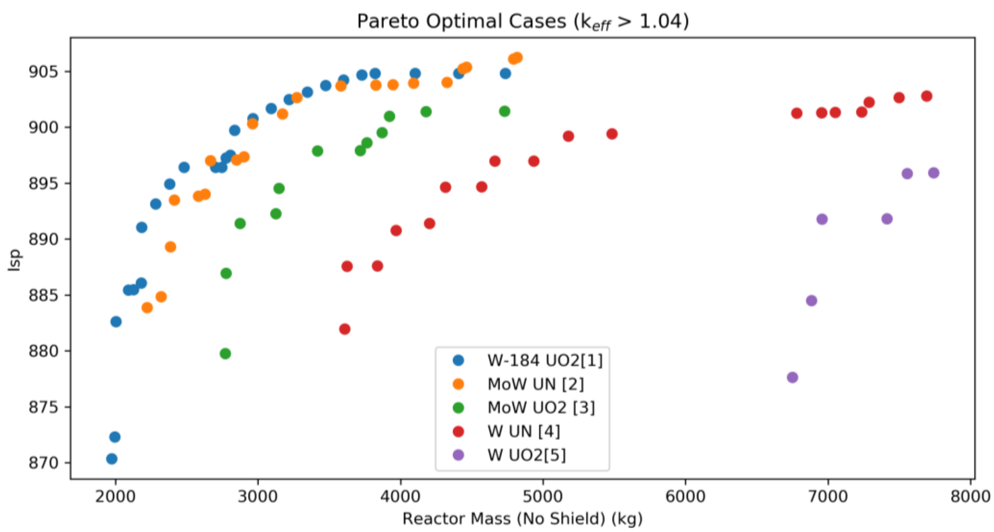

Fig. 3. Pareto fronts of cermet and cermetalloy design spaces

TABLE I. Key parameters of the data sets presented in figure 2

Data Set	Matrix Material (isotopic purification)	Data Source
W-184 UO2[1]	W (98 a% W184)	Case 3
MoW UN [2]	Mo-30W (Natural)	Case 4
MoW UO2 [3]	Mo-30W (Natural)	Case 4
W UN [4]	W (Natural)	Case 5
W UO2[5]	W (Natural)	Case 5

performance, as indicated by increased mass and lower I_{SP} values.

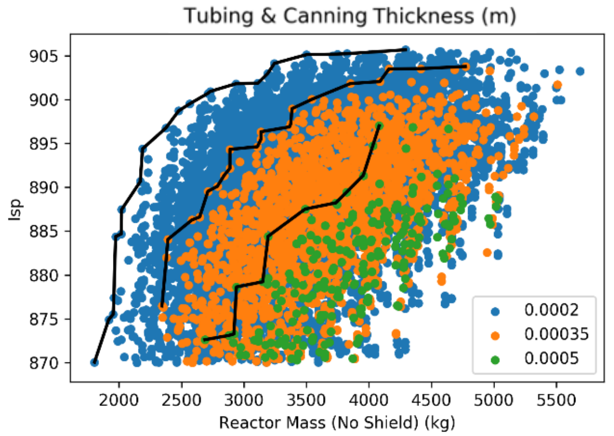

Fig. 4. The natural MoW UO_2 design space sorted by propellant channel (tubing and canning) thickness from Case

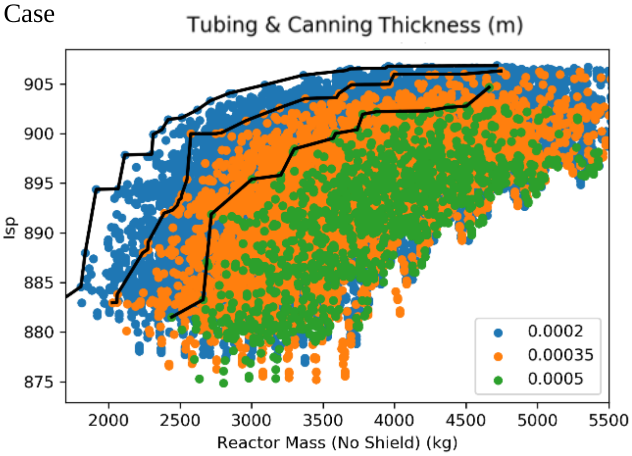

Fig. 5. The natural MoW UN design sorted by propellant channel (tubing and canning) thickness from Case. 5

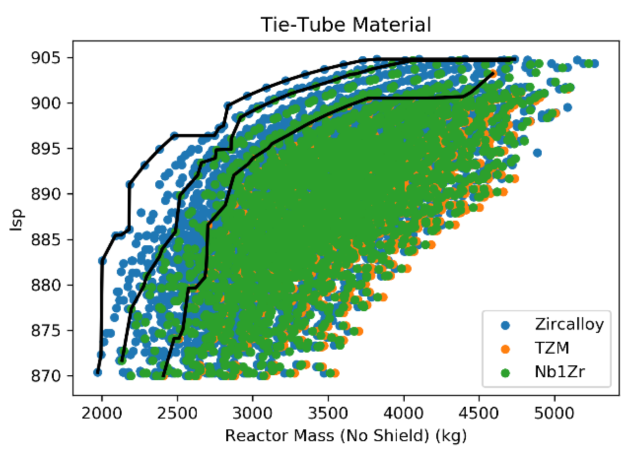

Fig. 6. The Isotopically Purified W-184 UO_2 Design Space Sorted by Tietube Material from Case 3.

IV. CONCLUSION

Combinatoric design studies were conducted using the SPACE analysis package to explore the LEU cermet / cermetalloy NTP design space. It was found that performance comparable to that of a W-184 cermet fuel could be achieved with MoW-UO_2 and MoW-UN without isotopic purification of the matrix material. Other examples of trends in the combinatoric design studies include the finding that clad thickness and tie-tube material are key drivers in performance. It was also found that the UN design space is less neutronically sensitive than the UO_2 design space.

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