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Scoping Analysis of Nuclear Rocket Reactor Cores Using Ceramic Fuel Plates

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Changing the World's Energy Future

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Content

1. Introduction, Background

Nuclear thermal propulsion (NTP) engines use a nuclear reactor to heat up hydrogen to high temperatures. Thrust is generated as the hydrogen is ejected at high velocity through a nozzle. NTP has the potential of reducing travel times for deep space missions, such as to Mars. The United States studied NTP early in the space age [Corliss, 1971] and the National Aeronautics and Space Administration (NASA) is currently revisiting the potential of the technology to enable its missions [Mitchell, 2019 and Ballard, 2019]. Important objectives for NTP reactor designers are to obtain practical configurations with:

(1) the highest possible power output per unit reactor volume for low weight
(2) the highest possible coolant passage surface area per unit volume for high heat transfer (i.e. high S/V)
(3) the highest possible propellant exit temperature for high specific impulse

NTP Schematics are shown in Figure 1a and 1b below.

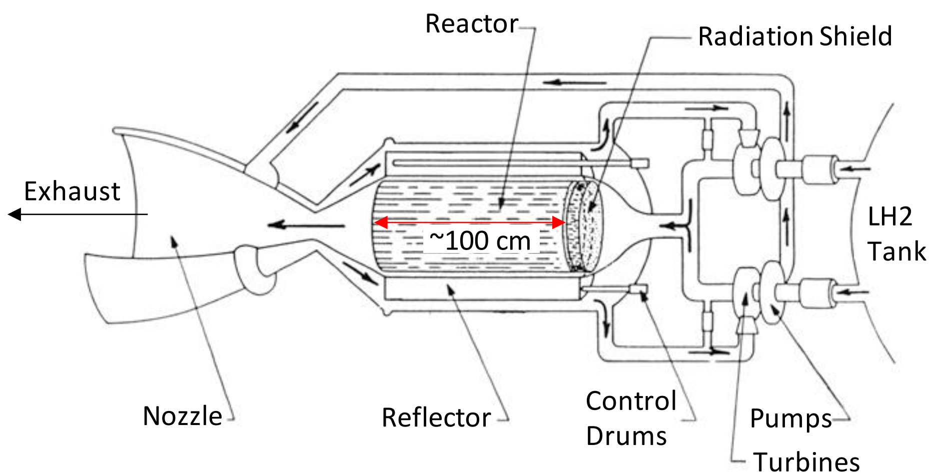

Figure 1a. Schematic of a nuclear thermal propulsion engine using liquid hydrogen [Borowski, 2009]

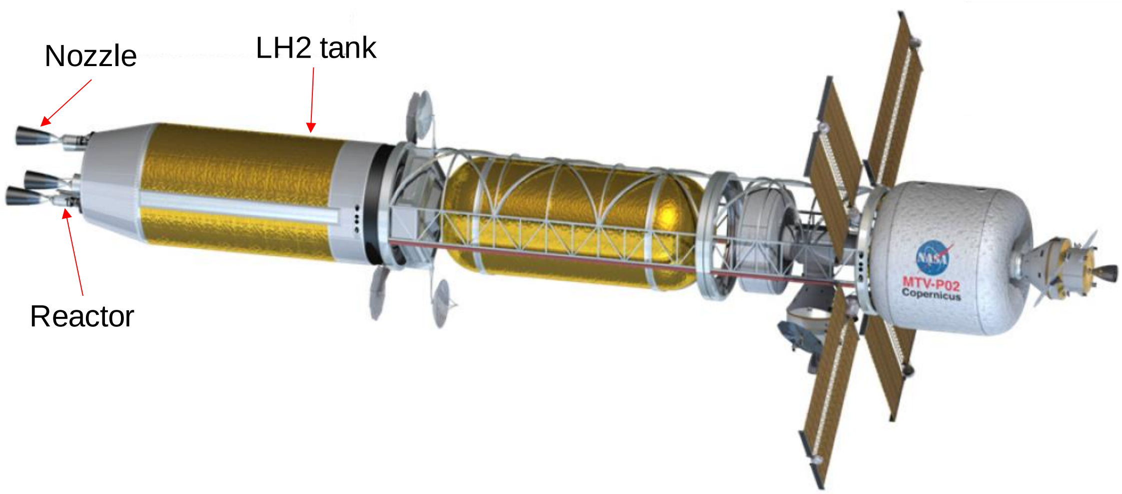

Figure 1b. Illustration of a rocket using 3 nuclear thermal propulsion engines [Borowski, 2014]

2. Past Rover/NERVA fuel element designs

The reactors considered during the Rover/NERVA program [Robbins, 1991 and Walton, 1991] all used highly enriched uranium (HEU) containing about 93% of uranium-235. This high level of uranium enrichment allowed the reactor designers to design reactors that are as small as practical for the target power levels. The fuel assemblies were designed such as to maximize heat transfer area in the core, hence maximizing the core power density (W/cm^3).

During the Pewee series of tests, peak core power densities of 5,200 W/cm^3 and hydrogen outlet temperature of 2550 K were obtained using a graphite composite fuel [Koenig, 1986] characterized by a surface-to-volume ratio of 7.1 cm^{-1}. This fuel was made up of a graphite matrix with up to 35% by volume of a (U,Zr)C solid solution corresponding to a uranium loading of up to about 0.6 g/cm^3.

Other fuel forms were also considered such as the tungsten (W) uranium oxide (UO2) cermets [Tucker, 2019] ANL-200 and GE-711 [Stewart, 2015 and Burkes, 2007] proposed by, respectively, Argonne National Laboratory and General Electric and characterized by surface-to-volume ratios of 6.2 cm^{-1} and 8.1 cm^{-1}. Fuel loadings of up to 60% UO2 by volume in the metal matrix were assumed for both GE and ANL engine designs corresponding to uranium density of up to about 5.5 g/cm^3. The remaining 40% of the volume contains W and a stabilizer such as Gd_2O_3 (respectively about 35% W and 5% Gd_2O_3). Since the H2 flow area represents about 20% of the assembly cross-sectional area, the average volume fractions in the active part of the core are approximately (at most) 48% for UO2, (at least) 32% for W and stabilizer and 20% for H2. Hence, the average U density in the cermet assembly is, at most, about 4.4 g/cm^3.

All these fuels used the same hexagonal geometry (Figure 2) with coolant holes directly located in the fuel matrix in order to ensure appropriate heat removal.

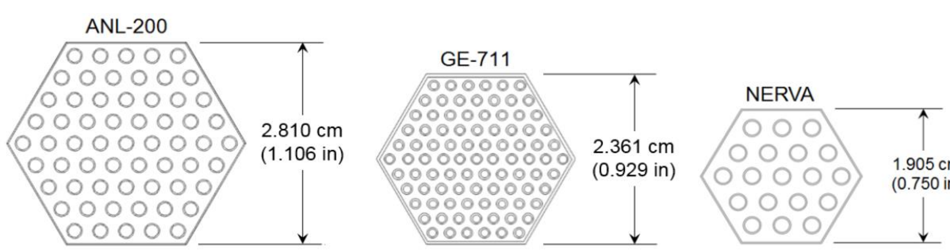

Figure 2. Schematics of fuel assembly designs used during the Rover/NERVA program.
Number and diameters of the H2 channels in fuel assemblies are, respectively, 61 and 1.702 mm for ANL-200; 91 and 1.118 mm for GE-711; 19 and 2.565 mm for NERVA [Fittje, 2015]

3. Objective of the present study

The Fuel Development Design Independent Review Team advising NASA's NTP program made several recommendations in 2019 (see slide 12 in [Ballard, 2019]) including (1) pursuing the development of a W/Mo/UN cermet fuel using a Spark Plasma Sintering (SPS) technique and (2) not pursuing graphite composite fuel development (former reference Rover/NERVA fuel). In a meeting of the Technology, Innovation & Engineering Committee of the NASA Advisory Council that took place in April 2019, it was also mentioned that this cermet fuel was probably at least a decade from Technology Readiness Level (TRL) 6 (see page 11 in [TI&E, 2019]).

In this context, the present study explores alternative fuel options that may be characterized by a higher TRL and, consequently, may present lower technical, cost and schedule risks. These alternative options are based on the use of ceramic fuel plates (uranium oxide, nitride or carbide) sandwiched between two refractory metal plates (tungsten or molybdenum) serving the role of cladding. Ultimately, the fuel element design is a compromise between fabricability, corrosion resistance, and strength at high temperature to ensure structural integrity under design loads.

The engines considered here should be able to generate at least 12,500 lbs of thrust with a specific impulse of 900 seconds while using uranium containing no more than 19.75% of uranium-235. Translating these engine performance requirements into reactor operating conditions requires systems analyses that are beyond the scope of the present study. However, previous results presented for example in [Borowski, 2012], [Emrich, 2016] and [Belair, 2013] indicate that, depending on the nozzle design, H2 core average outlet temperatures comprised between about 2650 K and 2850 K are necessary to obtain a specific impulse of 900 seconds. Hence, as a first approximation, the present study considers an H2 core average outlet temperature, $T_{H2,out}$, of 2750 K. Besides, engine thrust ($\mathbb{T}$), specific impulse (I_{sp}) and H2 mass flow rate ($\dot{m}_{H2}$) are related to each other through the following expression:

$$\mathbb{T} = \dot{m}_{H2} \times I_{sp}$$

This implies that the H2 mass flow rate is equal to 12,500 ÷ 900 = 13.89 lbs/sec. The H2 mass flow rate is in turn related to reactor operating conditions (power and temperatures) through the standard expression:

$$P = \dot{m}_{H2} \times C_{p,H2} \times (T_{H2,out} - T_{H2,in})$$

Consequently, assuming $T_{H2,out}$ = 2750 K and $T_{H2,in}$ = 350 K, a mass flow rate of 13.89 lbs/sec corresponds to a core power of about 250 MW.

4. Proposed alternative straight plate designs

4.1. Fuel Assembly Geometry

The fuel assemblies considered here have square cross-sections (Figure 3a). Their outside dimensions are arbitrarily fixed at 8×8 cm. Fuel plates may be separated by spacers (Figure 3b) and are enclosed in 1-mm thick ducts. The number of spacers will be determined such as to minimize the probability of plate deformation leading to flow restrictions. The impact of several geometric parameters on fuel, coolant (hydrogen) and structure volume fractions as well as surface-to-volume ratios are examined because they directly impact core nuclear and thermal hydraulics performances.

- cladding thickness (0.25 mm and 0.50 mm)
- fuel meat thickness (0.5 mm to 10 mm)
- hydrogen flow passage between fuel plates (0.5 mm, 0.75 mm and 1 mm)
- number of fuel plate per assembly (7 to 49)

Unless otherwise specified, fuel active height was fixed at 80 cm. Larger or smaller values are possible.

Details of the geometry are presented in Appendix A. The fuel volume fractions in the fuel assemblies are between 20% and 80% depending on the combination of the parameters mentioned above. For the same H2 flow area, higher fuel volume fractions appear reachable with the plate geometry than with the cermet (section 2). For example, the 22-plate assembly design “22-2.3-0.25-0.75” (Table A.5) has volume fractions of H2, fuel and W of, respectively, 20%, 61% and 19% compared to 20%, 48% and 32% for the cermet (section 2). While this is not particularly relevant when HEU is used because uranium enrichment can be adjusted as necessary, it becomes very important when LEU is used because of criticality constraint.

The surface-to-volume ratios are comprised between about 2 and 12 depending on the combination of the parameters mentioned above. The surface-to-volume ratio increases with the number of plates which is beneficial to increase power density. However, the fuel volume fraction also decreases as the number of plates increases meaning that the neutron balance must be adjusted to maintain criticality. This can be done by (1) increasing fissile enrichment, or (2) using a better fissile isotope (e.g. uranium-233 instead of uranium-235) or (3) decreasing neutron leakage from the core. The latter effect can be obtained by increasing active core volume (adding fuel assemblies) and/or reflector thickness. Another way to compensate for the decreased fuel volume fraction is to introduce neutron moderation in the core in the form of zirconium hydride blocks (section 4.3).

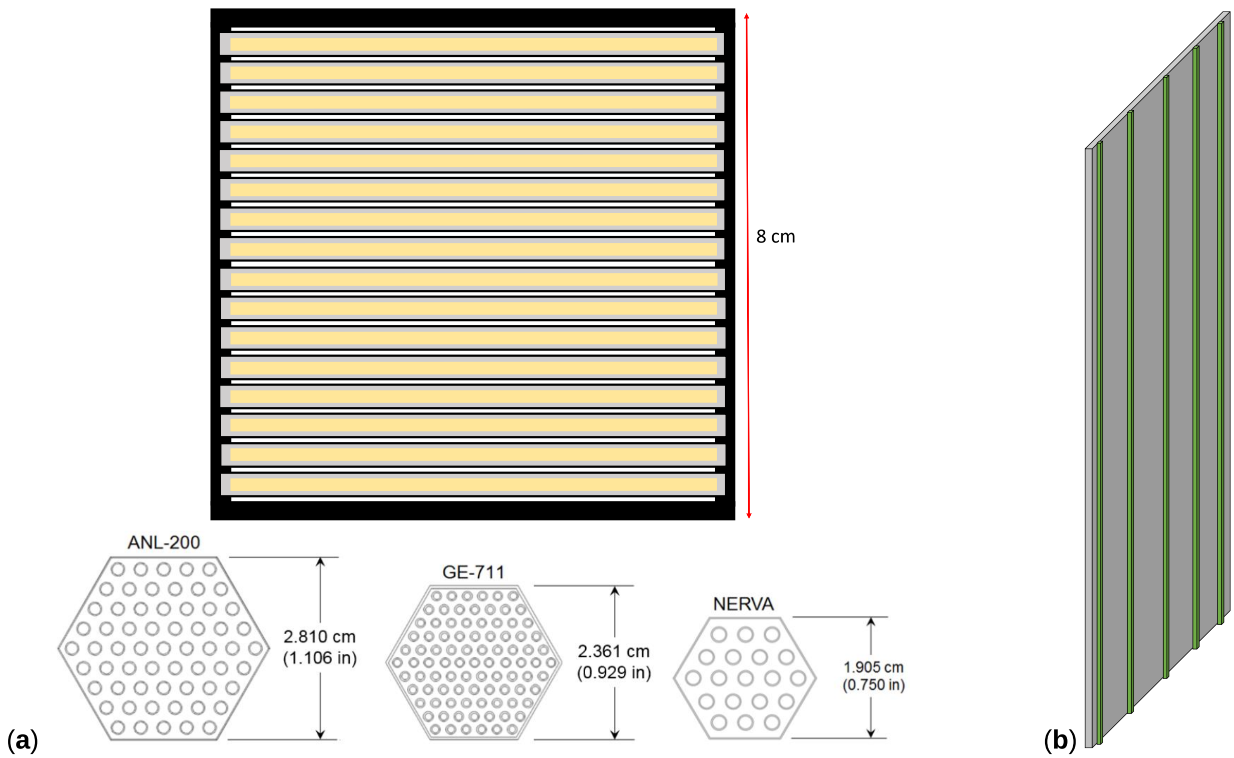

Figure 3. Schematic of a square 16-plate assembly compared with the Rover/NERVA fuel assembly designs (a) - Elements are shown to relative scale. Schematic of a fuel plate showing 5 spacers (b).

Similar fuel volume fractions and surface-to-volume ratios can be obtained with the plate geometry and the cermet geometry (Figures 2 and 3). For example, the fuel and W volume fractions in the 31-plate assembly design "31-1.3-0.25-0.75" (Table A.5) are, respectively, 47.2%, 24.4% compared to 48% and 32% for the cermet. Because it has a very similar fuel volume fraction but significantly lower W volume fraction, this 31-plate assembly design using UO2 fuel would have a better neutron economy that the W/UO2 cermet. Furthermore, this assembly has a surface-to-volume ratio of 7.6 cm^{-1}, i.e. comparable to the cermet's (~6-8 cm^{-1}).

Because of its higher density, a fuel assembly using uranium nitride (section 4.2) could provide the same U density as the W/UO2 cermet with a lower fuel volume fraction, i.e. about 35%. Hence, for example, the 40-plate assembly design "40-0.7-0.25-0.75" (Table A.5) with its fuel and W volume fractions of, respectively, 33.7% and 29.7% would be neutronically similar to the cermet fuel. Furthermore, this assembly has a surface-to-volume ratio of 9.7 cm^{-1}, i.e. larger than the cermet's (6 to 8 cm^{-1}), hence, allowing in principle even higher power density.

4.2. Fuel Assembly Materials

Three ceramic (solid solution) fuels are considered: uranium nitride (UN), uranium carbide (UC) and uranium oxide (UO2). Maximum UN, UC and UO2 allowable centerline temperatures assumed in the analyses are, respectively, 3100 K, 2700 K and 3100 K corresponding to their melting temperature. Depending on what proves more practical, fuel meat could be produced as a single monolithic plate (Figure 4a) or as several smaller plates put together (Figure 4b and c). The latter options would also be beneficial by allowing to adjust fissile loading within a given fuel plate in order to manage potential power peaking.

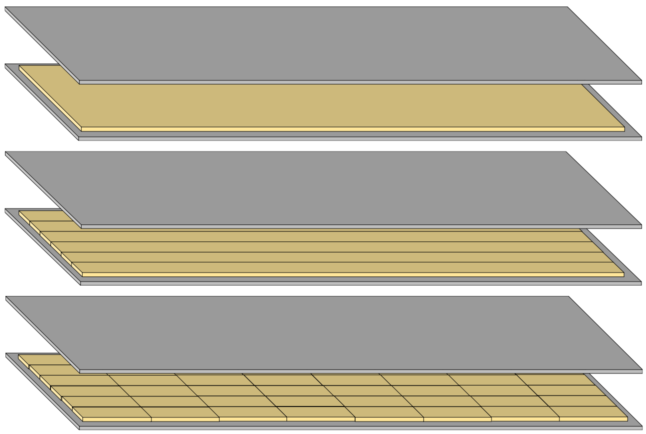

Figure 4. Schematic of potential fuel configurations (shown in yellow, cladding shown in gray) showing a fuel monolithic plate option (a) and two smaller fuel plate options (b and c)

Three refractory structural materials are considered for cladding and assembly ducts: natural molybdenum (Mo), natural tungsten (W) and enriched tungsten (W184). Structural materials used for fuel support and in-core structure must demonstrate compatibility with fuel, resistance to fuel interactions resulting from operation, compatibility with the hydrogen propulsion media and capability to keep the fuel contained during operation. Alloys such as Mo30W (30 wt% W) are also commercially available and may also be used.

In order to keep hydrogen from reacting with the fuel, cladding thicknesses of at least 0.2 mm for W or 0.4 mm for Mo are necessary [Rao, 2019]. Analyses were performed assuming 0.25 mm and 0.50 mm. Maximum Mo and W allowable temperatures assumed in the analyses are, respectively, 2320 K and 3000 K corresponding to about 80% of their melting temperatures (resp. about 2900 K and 3700 K). **These values have an important impact on engine performance and should be confirmed** by appropriate subject matter experts. The melting temperature of the Mo30W alloy is about 100 K higher than that of Mo, i.e. 3000 K [Naidu, 1984], and, consequently, could operate at slightly higher temperature than Mo. Indeed, assuming the same 80% melting temperature limit, Mo30W could operate at up to 2400 K.

W is necessary only close to the outlet where the H2 temperature is too high for Mo. Hence, in principle, and in order to improve the neutron economy, fuel assemblies could use Mo for cladding and duct material from the inlet down to an axial elevation z such that $T_{Mo}(z)$ = 2320 K (assumed maximum allowable Mo operating temperature) and then use W down to the outlet.

4.3. Moderator Material

The use of zirconium hydride blocks in the core has been considered (Figure 5b). Indeed, zirconium hydride has been shown by many researchers to minimize critical mass when used in conjunction with LEU fuel (see for example [Poston, 2018a], [Gates, 2018], [Steward, 2019]) as long as the quantity of materials with large thermal neutron absorption is low enough. For W-based cermet fuel, the latter constraint requires to use enriched W184 or to alloy W with a less absorbing material such as Mo. Also, zirconium hydride must be thermally insulated and cooled separately from the fuel in order to maintain its temperature below about

650 K. This thermal insulation is crucial for all concepts using zirconium hydride. Indeed, zirconium hydride tends to decompose above about 650 K [Ma, 2015] and hydrogen to migrate to lower-temperature regions of the core from higher-temperature regions. This could significantly impact core reactivity and power distribution. In particular, it could bring the core subcritical and, subsequently, could make it difficult, or impossible, to go back critical.

4.4. Core configurations

The cores are made up of 8×8×80 cm fuel assemblies surrounded by a beryllium reflector containing rotating drums to control the reactivity. The number of fuel assemblies and of zirconium hydride blocks (if any) is adjusted to reach a critical configuration. Unless otherwise specified, radial and axial **Be reflector thickness = 20 cm**. The control drums located in the reflector provide enough negative reactivity to maintain the core safely subcritical at cold shutdown, i.e. when it is not operating. However, additional negative reactivity is necessary to guarantee that the core remains subcritical even if submerged following a hypothetical launch accident. One possibility to meet this requirement is to insert B4C blades (green lines in Figure 6a) between fuel assemblies during core loading. Once in space, the blades could be retracted either in the radial reflector or in the upper reflector depending on what is more practical. This approach would also provide two independent reactivity control mechanisms as required in the nuclear industry (NRC GDC 26).

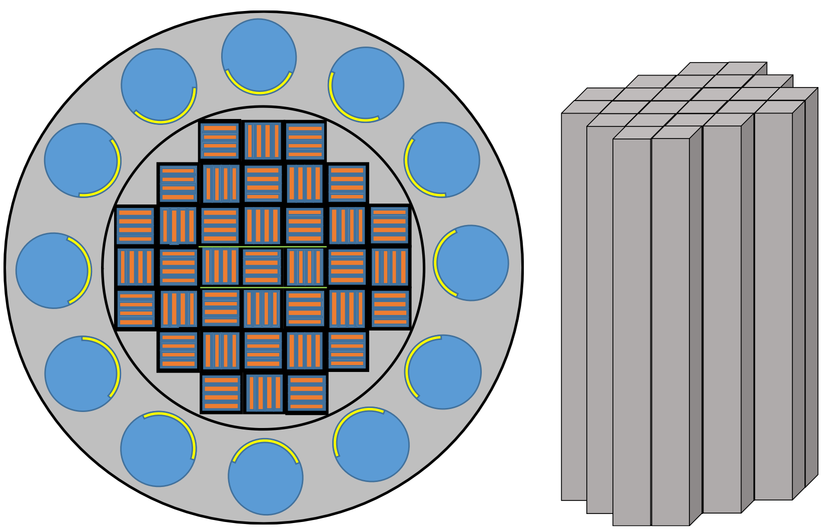

Figure 5a. Example of core radial (left) and fuel assembly axial (right) configurations.

The green lines represent in-core B4C blades guaranteeing the core is subcritical even if submerged.

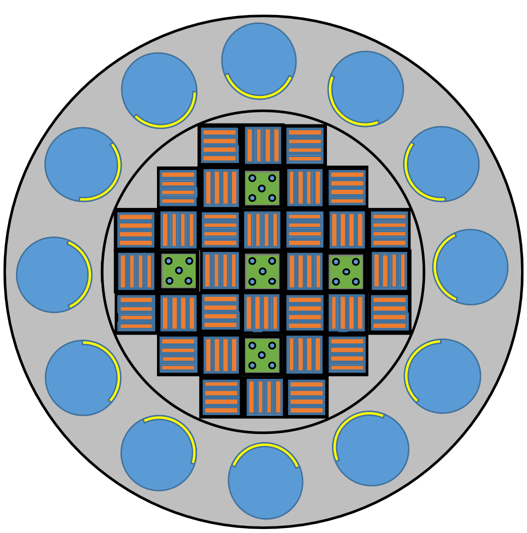

Figure 5b. Example of core radial configurations showing 5 moderator blocks (green). Each moderator block is shown with 5 coolant channels

4.5. Heat removal

The design of a nuclear reactor core is affected by parameters that operate in interrelated ways. For example, the degree of fuel subdivision, i.e. plate thickness, has a strong effect on the core power density obtainable since it determines the ratio of fuel volume to fuel-element surface area available for heat removal. Similarly, the hydrogen cross-sectional area through the core has a marked effect on the heat-removal-system circulation specifications. Consideration must also be given to the core pressure drop, heat-transfer coefficient, etc., which, of course, are sensitive to the hydrogen velocity and, in turn, to the cross-sectional area.

For these reasons numerous fuel assembly geometries (section 4.1) and materials (sections 4.2 and 4.3) were considered in order to cover a wide range of design space. A heat removal scoping analysis was performed in order to:

(1) Estimate the maximum fuel assembly power acceptable given an assumed set of design requirements:

- Maximum Mo and W allowable temperatures are, respectively, 2320 K and 3000 K corresponding to about 80% of their melting temperatures.
- Maximum UN, UC and UO2 allowable centerline temperatures assumed in the analyses are, respectively, 3100 K, 2700 K and 3100 K corresponding to their melting temperature.
- H2 velocity at core outlet should not exceed 1000 m/s corresponding to Mach numbers of about 0.26-0.30 for the range of H2 outlet temperature and pressure under consideration (respectively 2100 K to 2750 K and 3 MPa to 5 MPa)

(2) Estimate overall core dimensions and masses for a 250 MW output

Detailed results and methodology are presented in Appendix B, C and D. From a pure heat removal point of view, i.e. assuming criticality can be adjusted as necessary with appropriate means (e.g. section 4.1), the following conclusions can be drawn:

- Increasing the number of fuel plates per assembly allows increasing core power density in the fuel assemblies. For example, increasing the number of fuel plates per assembly from 16 to 31 about doubles the power density.
- Everything else being held constant, decreasing the hydrogen outlet temperature allows increasing the maximum allowable plate power. For example, lowering the outlet temperature by 200 K, from 2750 K to 2550 K, allows increasing the maximum W-clad UN plate power by between about 30% to 60% depending on the axial power distribution (see Table B.1a and B.1b).
- Because of the above, the H2 outlet temperature could in principle be higher in peripheral fuel assemblies than in central fuel assemblies. More detailed thermal hydraulic will be necessary to confirm this aspect.
- In all the cases analyzed, the peak fuel and cladding temperatures are always located at the outlet or very close to the outlet (see Figures B.4 to B.6)
- Axial power distributions that are depressed at the core outlet are beneficial to increase maximum allowable plate power. For example, for the W-clad UN cores with a 2750 K H2 outlet temperature, a 33% difference in power density was observed between the axial distributions shown in Figure B.2a and B.2b (see Table B.1a and B.1b). The effect is more limited at lower H2 outlet temperature, i.e. about 10% for a 2550 K outlet temperature. Both axial power distributions are symmetrical about the core mid-plane. Their peak-to-average are, respectively, 1.17 and 1.33.
- The last two observations suggest that it may be beneficial to have thinner fuel meat toward the outlet. If practical, one way to do this could be to insert a thin piece of W in the fuel platelets located toward the outlet (Figure 6).

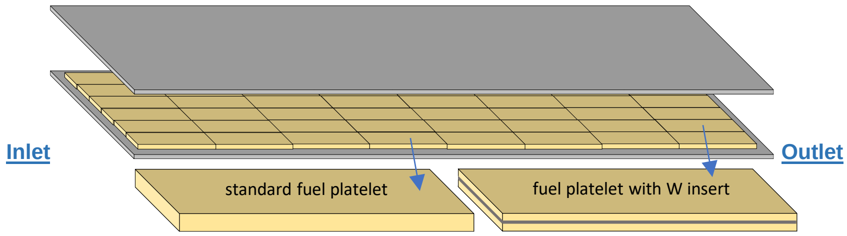

Figure 6. Illustration of a fuel plate with standard fuel platelets and fuel platelets containing W inserts closer to the outlet in order to minimize peak fuel temperature

- For the same plate thickness and outlet temperature, maximum allowable UO2 plate power is significantly lower than that allowable with UN because of lower thermal conductivity. The higher the outlet temperature the larger the difference between the two fuels (see Table B.1a and B.3).
- Because of its lower melting temperature, the use of UC fuel requires lowering the H2 outlet temperature at no more than about 2350 K in order to maintain an acceptable maximum allowable plate power. At this temperature, the maximum allowable W-clad UC plate power is about a factor 1.5 to 2 less than that obtainable with W-clad UN (see Table B.1 and B.2).
- The use of Mo cladding limits the H2 outlet temperature at no more than about 2100 K in order to maintain an acceptable maximum allowable plate power. For these cases, the Mo temperature is the limiting factor and the maximum allowable Mo-clad UN and Mo-clad UC plate powers are the same (see Table B.4). The same is also true for Mo-clad UO2 if the UO2 fuel meat thickness is less than 2 mm (see Table B.5).
- Fuel assembly peak power densities in excess of 5000 W/cm^3 appear feasible with the right combination of design parameters: UN fuel, W cladding, 30-35 fuel plates, hydrogen outlet temperature of no more than 2550 K.
- Because of the large heat fluxes (several 100's of W/cm^2) generated by the fuel plates, minimizing the fuel-cladding contact thermal resistance will be of utmost importance in order to minimize temperature gradients and consequently maximize the maximum allowable plate power. For example, the comparison of Tables B.1a and B.8 shows that there is a 20% to 30% difference in the maximum allowable W-clad UN plate power obtained with and without a 25-micron helium gap (see description of the thermal model in Appendix B).
- Overall core mass (including a 20-cm radial and axial beryllium reflector) as low as 1.0 mT appears possible if (1) hydrogen outlet temperature is limited to no more than 2550 K and (2) no moderator is present in the core, but would require about 200 kg of HEU fuel (see for example Table B14a). Increasing hydrogen outlet temperature to 2750 K requires more fuel assemblies and a total mass of about 1.5 mT (about 300 kg of HEU).
- With LEU fuel, core mass of 3.0-3.5 mT (including a 20-cm radial and axial beryllium reflector) is necessary if (1) hydrogen outlet temperature is limited to no more than 2550 K and (2) no moderator is present in the core. Increasing hydrogen outlet temperature to 2750 K requires more fuel assemblies and a total mass of 3.5-4.0 mT.

4.6. Neutronics

MCNP models have been developed in order to calculate the number of fuel assemblies necessary to be critical with the different combinations of fuel, structural materials, number of fuel plate per assembly and number of ZrH blocks (if any). Unless otherwise specified, radial and axial Be reflector thickness is equal to 20 cm. More details are presented in Appendix E.

4.6.1 Impact of enrichment and outlet temperature

Using W for cladding (0.25-mm) and duct material as well as UN fuel, the impacts of enrichment and outlet temperature on core characteristics were estimated and results are shown in Table 1. To estimate the impact of enrichment on the core performance, the sensitivity of criticality to both U and W vectors are investigated. The use of highly enriched uranium fuel can reduce the total reactor mass by ~70% compared to that of cores use the LEU fuel. A 20% difference in total reactor mass when using the enriched W (higher content of ^{184}W than the 30.6 wt% of natural W) as structural material. Total reactor mass increases more than 15% when increasing the H_2 outlet temperature from 2550 K to 2750 K.

A useful point of reference is provided in Table 3 of [Fittje, 2015] where the reference 266 MW HEU fast spectrum cermet core requires 0.24 mT of U235. The 250 MW HEU plate cores, in comparison, require between 0.15 mT and 0.21 mT of U235 depending on the H2 outlet temperature.

An important conclusion can be drawn from Table 1. Unlike with W-based cermet cores, the use of fuel plates makes it possible to design a LEU fast spectrum core with natural W. The reason is that the average W volume fraction in a fuel plate assembly is much lower than that in a cermet fuel element, respectively about 15% and 30%.

Table 1. Impact of enrichment and H2 outlet temperature for W-clad (0.25-mm) cores using UN fuel

Outlet temp., K	2550			2750		
^{235}U enrich., wt%	18.3	85.2	19.8	18.8	71.7	19.6
^{184}W enrich, wt%	30.6	30.6	66.0	30.6	30.6	93.0
# FA for 250 MW (see Table B.14a)	42	9	32	50	15	40
# plates per FA	13	43	16	16	43	19
U mass, mT	2.1	0.18	1.5	2.3	0.29	1.7
U235 mass, mT	0.38	0.15	0.30	0.43	0.21	0.33
Radial Be reflector outer diameter, cm	106	74	97	111	82	104
Total mass, mT	3.5	1.0	2.7	4.0	1.3	3.2

4.6.2 Impact of fuel materials and outlet temperature

Using Mo for cladding (0.5-mm) and duct material, the impacts of fuel materials and outlet temperature on core characteristics were estimated and the results are presented in Table 2. Total reactor mass obtainable with UN and UC fuel are significantly lower than those obtainable with UO_2 fuel and a marginal benefit in ^{235}U mass is observed when using UC fuel compared to UN fuel. Total reactor mass is very sensitive to outlet temperature, which increases by 40% for UN and UC fuels and 10% for UO_2 fuel when the temperature increases from 2100K to 2200K.

Table 2. Impact of fuel type and H2 outlet temperature for Mo-clad (0.5-mm) FA.

Outlet temp., K	2100			2200		
Fuel material	UN	UC	UO_2	UN	UC	UO_2
# FA for 250 MW (see Table B.11c and d)	48	48	85	71	71	93
# plates per FA	13	13	13	16	16	13
^{235}U enrich., wt%	18.1	17.3	19.0	19.2	17.7	18.7
U mass, mT	2.1	1.9	3.7	2.8	2.6	4.1
U235 mass, mT	0.38	0.33	0.70	0.54	0.46	0.77
Radial Be reflector outer diameter, cm	110	110	133	124	124	142
Total mass, mT	4.0	3.8	6.7	5.6	5.4	7.4

4.6.3 Impact of zirconium hydride moderating blocks and reflector thickness

The impact of zirconium hydride on critical mass is limited when natural W is used (Table 3) because the moderation enhances not only the absorption in fuel but also the absorption in W. In cases using enriched W, the critical mass decreases significantly with the presence of zirconium hydride due to the reduced absorption in W. Furthermore, the comparison of Table 3a and 3b indicates that reflector thickness has only a limited impact on critical mass.

On the other hand, Table 4 shows that when Mo (natural) is used, the presence of zirconium hydride significantly decreases critical mass. The total reactor masses obtainable with zirconium hydride are also significantly lower than those obtainable with non-moderated cases.

Table 3a. Impact of zirconium hydride blocks in W-clad UN cores – Fixed Be radial reflector thickness (20 cm) – 16 fuel plates per FA – H2 outlet temperature = 2600 K – Core power = 250 MW

^{184}W enrich, wt%	30.6 (natural)			93.0		
# of FA/ Mod. Block	37/0	37/8	37/32	37/0	37/8	37/32
^{235}U enrich., wt%	20.3	19.9	20.6	18.4	14.1	8.6
Active core diameter (cm)	61.0	68.8	82.4	61.0	68.8	82.4
Be radial reflector thickness (cm)	20.0	20.0	20.0	20.0	20.0	20.0
Radial Be reflector outer diameter (cm)	101.0	108.8	122.4	101.0	108.8	122.4
k-eff nominal, CD out, hot temp.	1.020	1.020	1.020	1.020	1.020	1.020
U mass, mT	1.7	1.7	1.7	1.7	1.7	1.7
U235 mass, mT	0.35	0.34	0.35	0.31	0.24	0.15
Total mass, mT	3.1	3.3	4.3	3.1	3.3	4.3

Table 3b. Impact of zirconium hydride blocks in W-clad UN cores – Variable Be radial reflector thickness and fixed Be radial reflector outer diameter (122.4 cm) – 16 fuel plates per FA – H2 outlet temperature = 2600 K – Core power = 250 MW

^{184}W enrich, wt%	30.6 (natural)			93.0		
# of FA/ Mod. block	37/0	37/8	37/32	37/0	37/8	37/32
^{235}U enrich., wt%	18.4	18.7	20.6	16.5	12.8	8.6
Active core diameter (cm)	61.0	68.8	82.4	61.0	68.8	82.4
Be radial reflector thickness (cm)	30.7	26.8	20.0	30.7	26.8	20.0
Radial Be reflector outer diameter (cm)	122.4	122.4	122.4	122.4	122.4	122.4
k-effective	1.020	1.020	1.020	1.020	1.020	1.020
U mass, mT	1.7	1.7	1.7	1.7	1.7	1.7
U235 mass, mT	0.31	0.32	0.35	0.28	0.22	0.15
Total mass, mT	3.6	3.7	4.3	3.6	3.7	4.3

Table 4. Impact of zirconium hydride blocks in Mo-clad UN cores – Core power = 250 MW

Outlet temp., K	2100		2200	
# of FA/Mod. Block (see Table B.11c)	48/0	22/23	71/0	36/21
# fuel plates per FA	13	28	16	31
^{235}U enrich., wt%	18.1	18.9	19.2	19.5
U mass, mT	2.1	0.51	2.8	0.69
U235 mass, mT	0.38	0.10	0.54	0.13
Active core diameter (cm)	70	68	84	76
Be radial reflector thickness (cm)	20	20	20	20
Radial Be reflector outer diameter (cm)	110	108	124	116
Total mass, mT	4.0	2.6	5.6	3.3

4.6.4 Reactor Dynamics and Control Parameters

A few reactor dynamic and control parameters were investigated using a core model with 41 13-plate FAs (Figure 7). Two 40×0.5×28 cm B_4C (90% enriched ^{10}B) control blades are loaded between fuel assemblies to ensure the core is subcritical when flooded. The nominal k-effective (nominal hot temperature, drums out, blades out) is 1.02 and the flooded k-effective (300 K isothermal, drums in, blades in) is 0.97. For comparison, the same flooded k-effective of 0.97 is obtained in the LEU cermet core presented in [Poston, 2018b] by inserting about 2700 gadolinium wires in the coolant channels.

The temperature defect via cross sections is about 800 pcm compared to about 3500 pcm in the LEU cermet core presented in [Poston, 2018b]. The hydrogen worth is only about 10 pcm, which is the difference in k-effective between the no hydrogen (void) operating state versus the full steady-state inventory. For comparison, the hydrogen worth is about 900 pcm in the LEU cermet core presented in [Poston, 2018b]. As described in [Poston, 2018b], the low hydrogen reactivity worth and small temperature defect would be beneficial in reactor startup.

The power distribution of this core is also be estimated by using the tally functions of MCNP. The assembly power peaking factor is 1.2 and the peak plate power is 0.9 MW, i.e. about 1.9 times the power of the average plate. By employing the enrichment zoning strategy, the plate power peaking is reduced to 0.60 MW, which is below the thermal design limit of 0.62 MW obtained from simplified thermal calculations presented in Appendix B (see Table B.14a, assembly "13-4.7-0.25-0.75", T-H2-out = 2550 K).

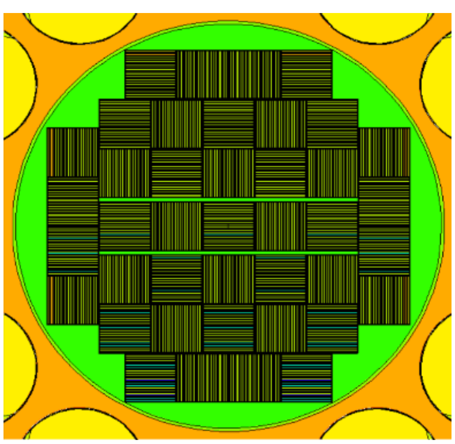

Figure 7. Radial core layout of a 41-FA core configuration with control blades (MCNP model)

4.7. Flow induced vibrations

The primary sources of flow induced vibrations are from vortices shedding from bluff bodies and boundary layer separation in turbulent flows. If the rate that these flow phenomena are occurring coincides with the natural frequencies of the structural components (i.e. fuel plates) the vibrations will quickly amplify (resonance) and may cause failure of the structural components. Due to the size and complex nature of the entire reactor core, one fuel element (comprised of 16 fuel plates) was analyzed in the finite element analysis (FEA) code, Abaqus and the CFD code, Star-CCM+. The Abaqus model was used to calculate the natural frequencies and mode shapes of the fuel element. The Star-CCM+ model was used to model the hydrogen coolant flow to assess the rate that vortices will shed from the trailing edges of the fuel plates.

The fundamental natural frequency (first mode) of the fuel element was calculated to be 7618 Hz. The natural frequency of the next four mode shapes were nearly equal to the frequency of the first mode. This is likely due to the length and high aspect ratio of the fuel plates. The vortex shedding frequency was calculated to be 22,322 Hz or about three times the natural frequencies of the fuel element. This indicates that it is unlikely that vortex shedding will cause resonance in the first five modes of the fuel plates. The RANS based turbulence model that was utilized in this analysis can tend to overly dissipate turbulent vortices therefore a future and more detailed analyses should consider using a Large Eddy Simulation to model the turbulent flow more accurately. Additionally, a more accurate assessment of the natural frequencies of the fuel element could be obtained by using temperature dependent material properties with realistic temperature distributions throughout the fuel element. These temperature distributions could be obtained from a conjugate heat transfer model. However, with the large margin between the vortex shedding and natural frequencies calculated in this preliminary analysis it is unlikely adding these additional features to the models will dramatically alter the overall conclusions of this analysis.

More details are presented in Appendix E.

5. Proposed alternative curved plate designs

In case curved fuel plates proved more practical from a mechanical standpoint some additional analyses were performed with this geometry.

5.1. Fuel Assembly Geometry

The fuel assemblies considered here have cylindrical cross-sections (Figure 8). The outside diameter is arbitrarily fixed at 10.1 cm. The impact of several geometric parameters on fuel, coolant (hydrogen) and structure volume fractions as well as surface-to-volume ratios are examined because they directly impact core nuclear and thermal hydraulics performances.

- cladding thickness (0.25 mm for W and 0.50 mm for Mo)
- fuel meat thickness (0.8 mm to 3 mm)
- number of fuel plates per assembly (8 to 16)

Unless otherwise specified, fuel active height was fixed at 80 cm. Larger or smaller values are possible.

Hydrogen flow passage between fuel plates is the same in all configurations and equal to 0.75 mm. Details of the geometry are presented in Appendix F. The fuel volume fractions in the fuel assemblies analyzed are between 38% and 65% depending on the combination of the parameters mentioned above. The surface-to-volume ratios are comprised between about 4.3 and 8.6. The surface-to-volume ratio increases with the number of plates which is beneficial to increase power density. However, the fuel volume fraction also decreases as the number of plates increases meaning that either uranium enrichment must be increased or that more fuel assemblies are necessary to reach a critical configuration. Another way to compensate for the decreased fuel volume fraction is to introduce neutron moderation in the core in the form of zirconium hydride blocks in the center of each assembly (Figure 8).

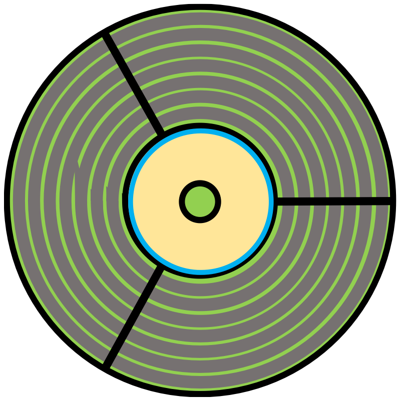

Figure 8. Schematic of a fuel assembly showing 3 sectors each containing 7 fuel plates (gray). The central region may contain moderating materials (yellow) and a thermal insulator (blue). Hydrogen is shown in green. Cladding material = W. Inner and outer tubes = Mo

5.2. Fuel Assembly Materials

Same as Section 4.2. As mentioned in Section 4.2, W is necessary only close to the outlet where the H2 temperature is too high for Mo. Hence, in principle, and in order to improve the neutron economy, the fuel assemblies could use Mo for cladding and duct material from the inlet down to an axial elevation z such that $T_{Mo}(z)$ = 2320 K (assumed maximum allowable Mo operating temperature) and then use W down to the outlet.

5.3. Moderator Material

The use of solid casings made of beryllium, beryllium oxide, zirconium hydride and graphite was considered to hold the fuel assemblies in place (section 5.4). The use of moderating material inside fuel assemblies was also considered (Figure 8).

5.4. Core configurations

The cores are made up of 10-cm diameter cylindrical fuel assemblies surrounded by a beryllium reflector containing reactivity control drums (Figure 9a). The number of fuel assemblies is adjusted to reach a critical configuration. Unless otherwise specified, radial and axial **Be reflector thickness = 20 cm**. Different possibilities exist to assemble the fuel assemblies into a critical configuration.

The fuel assemblies could be positioned in holes drilled in a solid casing made up of beryllium, beryllium oxide or graphite for example. In that case, an important design variable is the fuel assembly pitch (Figure 9b) since it determines the moderator-to-fuel volume ratio which has a strong impact on the nuclear characteristics of the core. Increasing the fuel assembly pitch increases the neutron moderation and may lower the critical mass. However, the core diameter increases as well and, with it, the total mass of the system.

Another possibility is to use a few spacer grids at different axial locations (Figure 10) in order to maintain the fuel assemblies in place. In that case the space between fuel assemblies is essentially empty which is beneficial to minimize mass. As mentioned earlier, if necessary, some neutron moderation could still be provided by using moderating materials at the center of the fuel assemblies (Figure 8).

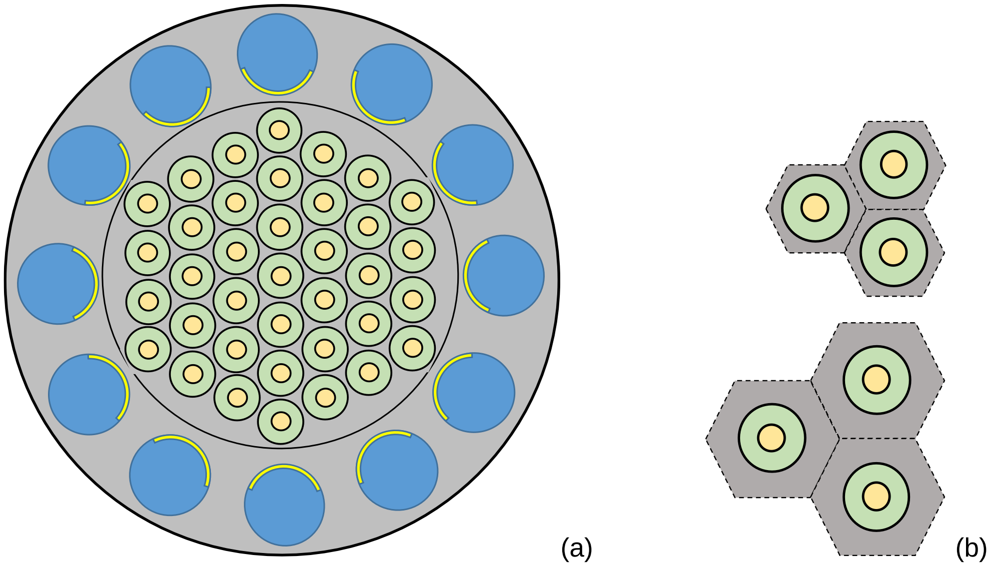

Figure 9. Illustration of a core radial configuration with 37 fuels assemblies positioned in a casing made up of either Be, BeO, graphite or zirconium hydride (a) and of two fuel assembly pitches (b)

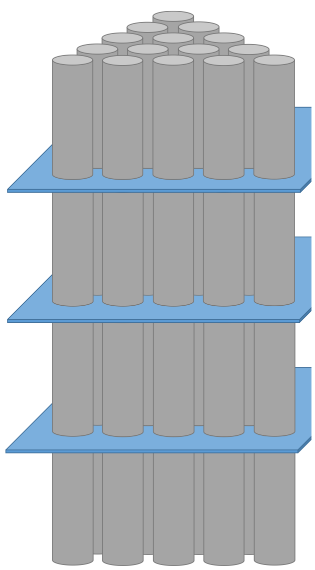

Figure 10. Illustration of an axial configuration showing 3 spacer grids holding 15 fuel assemblies in place

5.5. Heat removal

Unlike for straight plate geometry, simple heat transfer equations are not readily available for curved geometry. Hence, the estimation of the maximum allowable assembly power is based on the results obtained with straight plates that are presented in Appendix B. The main results are presented in Table 5 and the methodology is presented in Appendix H

Table 5. Maximum allowable assembly power (MW) as a function of H2 outlet temperature for the 4 curved-plate designs using UN fuel and either Mo or W cladding

FA Identifier	A	B	C	D
plate #	8	8	12	16
Cladding thickness (mm) / material	0.5 / Mo	0.25 / W	0.25 / W	0.25 / W
Fuel thickness (mm) / material	2.50 / UN	3.00 / UN	1.58 / UN	0.09 / UN
T-H2-out = 2750 K	-	8.86	14.8	20.8
T-H2-out = 2550 K	-	13.9	23.2	32.6
T-H2-out = 2100 K	11.0	-	-	-

5.6. Neutronics

This section presents a few results concerning core configurations using Be, BeO, graphite or ZrH1.6 casings in the active part of the core. Table 6a and 6b presents a few core configurations using different fuel assembly designs and H2 outlet temperatures. For each combination {assembly design – H2 outlet temperature} corresponds a minimum number of fuel assemblies necessary to generate a given power while satisfying the assumed material temperature limits (see Section 4.2). Once the number of fuel assemblies is known, the fuel assembly pitch is calculated so that k-eff = 1.02 (Figure 11).

Figure 11 shows the evolution of core k-effectives as a function of fuel assembly pitch and for different casing materials. It shows that the use of graphite as casing material would not bring enough moderation to obtain a critical configuration whereas ZrH1.6 would provide the most compact cores.

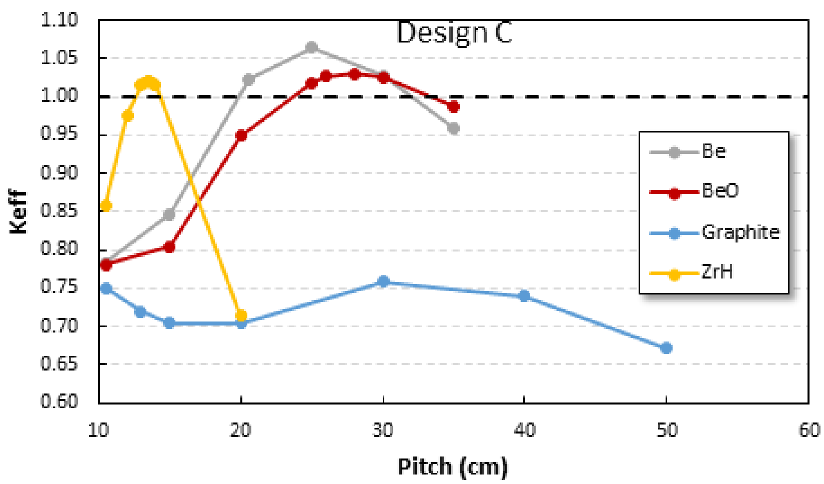

Figure 11. Core k-effectives as a function of fuel assembly pitch and for different casing materials. (Natural W cladding)

Table 6a shows that 250 MW Be-moderated core configurations using LEU and natural W appear feasible with only about 150 kg of U235 and a total core mass (including radial and axial reflector) of about 3.7 mT. If enriched W is available, the U235 mass necessary would be only about 60 kg and the total core mass about 2.7 mT. The use of enriched W would also allow increasing the core power up to 460 MW with 110 kg of U235 and a total mass of 3.2 mT. These core configurations do <u>not</u> use zirconium hydride.

Table 6a. Examples of 245 to 460 MW core configurations using cylindrical fuel assemblies in Be casings

FA Identifier (see Appendix F)	B	C	D	D	D
# plate per FA	8	12	16	16	16
# FA	37	19	19	10	19
Core power (MW)	250	250	290	245	460
U enrichment (wt%)	19.75	19.75	19.75	19.75	19.75
H2 outlet temperature (K)	2750	2650	2750	2550	2550
FA pitch (cm) assuming natural or enriched W cladding	15.9	20.6 / 16.7	* / 18.3	* / 19.5	* / 18.3
U / U235 mass (mT)	1.8 / 0.36	0.74 / 0.15	0.54 / 0.11	0.29 / 0.06	0.54 / 0.11
Total mass (mT) assuming natural or enriched W cladding (incl. reflector)	5.2	3.7 / 3.0	* / 3.2	* / 2.7	* / 3.2

* subcritical when natural W is used in conjunction with LEU

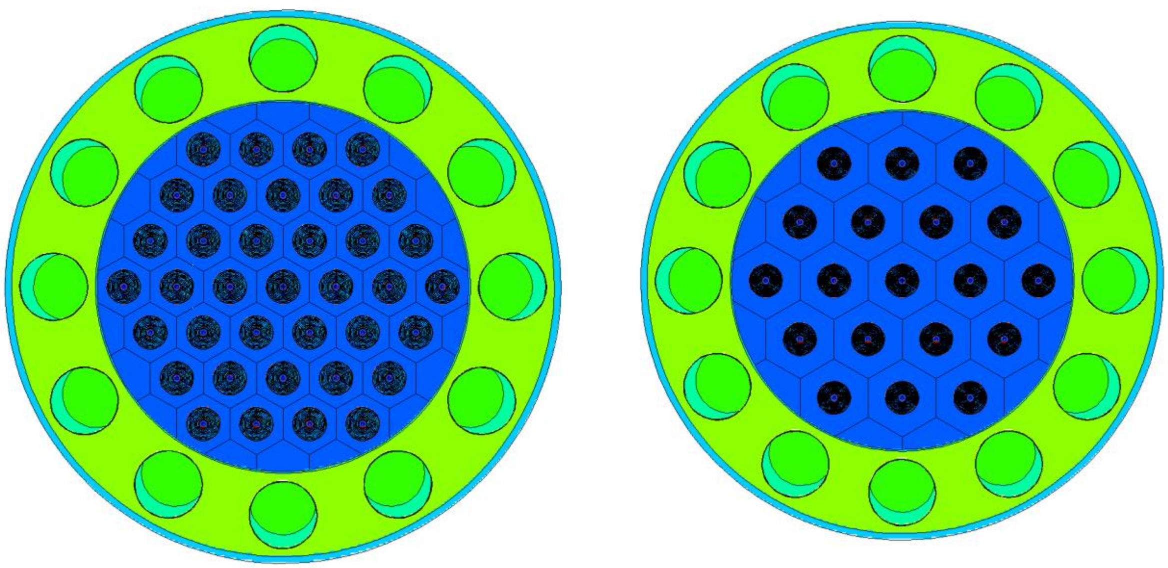

Figure 12. Radial core layout of 37- and 19-FA core configurations (MCNP models)

Table 6b shows the impact of the casing material on total core mass using fuel assembly C with natural W cladding. The use of a zirconium hydride casing would provide the most compact configuration and a total mass of 3.1 mT. On the other hand, the use of BeO necessitates a larger pitch and a total mass of 5.8 mT.

A useful point of reference is provided in [Fittje, 2015] where the reference HEU NERVA derived engines (graphite dispersion fuel using zirconium hydride to improve neutron moderation) require between about 30 and 40 kg of U235 for core power between about 160 MW and 560 MW. [Poston, 2018a] also describes a 543 MW LEU cermet core using zirconium hydride as well as enriched W184 and containing about 70 kg of U235.

Furthermore, results obtained so far indicate that fast spectrum core configurations using only spacer grids to maintain the fuel assemblies in place (i.e. no moderating casing materials) require U enrichment higher than 19.75% to reach a critical configuration in a reasonable volume.

Table 6b. Examples of 250 MW core configurations using cylindrical fuel assemblies in Be, BeO and ZrH1.6 casings – Natural W cladding

Casing material	Be	BeO	ZrH1.6
FA Identifier (see Appendix F)	C	C	C
# plate per FA	12	12	12
# FA	19	19	19
Core power (MW)	250	250	250
U enrichment (wt%)	19.75	19.75	19.75
H2 outlet temperature (K)	2650	2650	2650
FA pitch (cm)	20.6	26.0	13.5
U / U235 mass (mT)	0.74 / 0.15	0.74 / 0.15	0.74 / 0.15
Casing mass (mT)	0.96	2.6	0.88
Be axial and radial reflector mass (mT)	1.8	2.3	1.2
Total mass including reflector (mT)	3.7	5.8	3.1

6. Conclusions

The Fuel Development Design Independent Review Team advising NASA's NTP program recently recommended to pursue the development of a W/Mo/UN cermet fuel. In a meeting of the Technology, Innovation & Engineering Committee of the NASA Advisory Council, it was also mentioned that this cermet fuel was probably at least a decade from Technology Readiness Level (TRL) 6. In this context, the present study explores alternative options that may be characterized by a higher TRL and, consequently, may present lower technical, cost and schedule risks. These alternative options are based on the use of ceramic fuel plates (uranium oxide, nitride or carbide) sandwiched between two refractory metal plates serving the role of cladding (tungsten or molybdenum).

The engines considered here should be able to generate at least 12,500 lbs of thrust with a specific impulse of 900 seconds while using uranium containing no more than 19.75% of uranium-235, i.e. LEU. This translates into a core power and hydrogen outlet temperature of about, respectively, 250 MW and 2750 K. The table below presents a few examples of representative performances obtained with fuel plate core configurations together with those of fast and moderated W/UO2 cermet concepts presented in [Fittje, 2015] and [Poston, 2018a].

A few important conclusions are:

- The combination of uranium nitride fuel and tungsten cladding provides the best LEU core performances, i.e. smallest core mass and highest hydrogen outlet temperature. With HEU fuel, uranium oxide and nitride reach similar performances.

- The use of fuel plates makes it possible to design LEU fast spectrum cores with natural W. About 1.7 mT of uranium nitride containing 350 kg of uranium-235 are necessary. Total core mass is 3.2 mT for 250 MW. Hydrogen outlet temperature is at least 2600 K.

- Access to enriched tungsten would bring about only limited benefits for the LEU fast spectrum cores compared to natural tungsten, i.e. about 40 kg less uranium-235 and 300 kg less on the total core mass.

- With HEU fuel, total fast spectrum core mass is as low as 1.0 to 1.6 mT. Between about 150 and 230 kg of uranium-235 are necessary. As mentioned above, uranium nitride and oxide reach similar performances.

- The use of fuel plates makes it possible to design LEU thermal spectrum cores with natural W. About 740 kg of uranium nitride containing 150 kg of uranium-235 are necessary. Total core mass is between 3.1 and 3.7 mT for 250 MW depending on the moderator used (respectively, zirconium hydride and beryllium). Hydrogen outlet temperature is at least 2650 K.

- Compared to natural tungsten, access to enriched tungsten could save up to 90 kg of uranium-235 and up to 1 mT on the total core mass of LEU thermal spectrum cores.

- Preliminary flow induced vibration analyses indicate that it is unlikely that the H2 flow could excite fuel plate natural frequencies.

Finally, it must be underscored that these evaluations are preliminary, and that more detailed analyses are necessary to confirm the level of performance and of practicality of nuclear rocket reactor cores using ceramic fuel plates.

Uranium Classification	Structural Material	T-H2-outlet (K)	Mass U/U-235 (mT)	Core+Reflector mass (mT)	Power (MW)
UN FUEL – FAST SYSTEM (SECTION 4)					
LEU	Natural Mo	2100	2.1 / 0.38	4.0	250
	Natural W	2600	1.7 / 0.35	3.2	250
	Enriched W	2600	1.7 / 0.31	2.9	250
HEU	Natural W	2750	0.29 / 0.21	1.3	250
		2550	0.29 / 0.21	1.3	415
		2550	0.18 / 0.15	1.0	250
UO2 FUEL – FAST SYSTEM (SECTION 4)					
LEU	Natural Mo	2100	3.7 / 0.70	6.7	250
HEU	Natural W	2750	0.28 / 0.23	1.6	250
UN FUEL – MODERATED SYSTEM – BERYLLIUM CASING – NO ZRH (SECTION 5)					
LEU	Natural W	2650	0.74 / 0.15	3.7	250
	Enriched W	2750	0.54 / 0.11	3.2	290
		2550	0.54 / 0.11	3.2	460
		2550	0.29 / 0.06	2.7	245
UN FUEL – MODERATED SYSTEM – ZRH CASING (SECTION 5)					
LEU	Natural W	2650	0.74 / 0.15	3.1	250
CERMET [Fittje, 2015] – FAST SYSTEM – 34%WNAT-60%UO2-6% Gd2O3					
HEU	-	~ 2750	0.26 / 0.24	1.4	266
CERMET [Poston, 2018a] – MODERATED SYSTEM – 34% W184-60%UO2-6%Gd2O3 – ZRH MOD.					
LEU	-	2670	0.36 / 0.07	3.5 (with shield)	543

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Appendices

Appendix A. Fuel assembly geometrical descriptions – Straight plates

Appendix B. Heat removal scoping analyses for straight plate designs

Appendix C. Fuel thermal conductivities

Appendix D. Hydrogen heat transfer coefficient

Appendix E. Neutronics – Straight plate designs

Appendix F. Flow induced vibrations – Straight plate designs

Appendix G. Fuel assembly geometrical descriptions – Curved plates

Appendix H. Heat removal for curved plate designs

Appendix I. Neutronics – Curved plate designs

Appendix A. Fuel assembly geometrical descriptions – Straight plates

Table A.1. Fuel assemblies characterized by a 0.5 mm cladding thickness and a 1 mm H2 flow gap – Number of plates varies between 7 and 31 – FA Identifier = number of fuel plates–fuel meat thickness–clad thickness–H2 gap thickness

FA identifier	7-9.1-0.5-1	10-5.8-0.5-1	13-4.0-0.5-1	16-2.8-0.5-1	19-2.1-0.5-1	22-1.5-0.5-1	25-1.1-0.5-1	28-0.7-0.5-1	31-0.5-0.5-1
duct out (cm)	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00
t-duct (cm)	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
duct in (cm)	7.80	7.80	7.80	7.80	7.80	7.80	7.80	7.80	7.80
t-fuel (cm)	0.9143	0.5800	0.4000	0.2875	0.2105	0.1545	0.1120	0.0786	0.0516
t-clad (cm)	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
t-plate (cm)	1.0143	0.6800	0.5000	0.3875	0.3105	0.2545	0.2120	0.1786	0.1516
t-H2 (cm)	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100
t-lattice (cm)	1.1143	0.7800	0.6000	0.4875	0.4105	0.3545	0.3120	0.2786	0.2516
plate #	7	10	13	16	19	22	25	28	31
H2 %	8.53%	12.19%	15.84%	19.50%	23.16%	26.81%	30.47%	34.13%	37.78%
Fuel %	77.00%	69.78%	62.56%	55.34%	48.13%	40.91%	33.69%	26.47%	19.25%
Struct %	14.47%	18.03%	21.59%	25.16%	28.72%	32.28%	35.84%	39.41%	42.97%
H2 flow area (cm^2)	5.46	7.8	10.14	12.48	14.82	17.16	19.5	21.84	24.18
Fuel S/V (cm^{-1})	1.71	2.44	3.17	3.90	4.63	5.36	6.09	6.83	7.56

Table A.2. Fuel assemblies characterized by a 0.5 mm cladding thickness and a 0.75 mm H2 flow gap – Number of plates varies between 7 and 34 – FA Identifier = number of fuel plates–fuel meat thickness–clad thickness–H2 gap thickness

FA identifier	7-9.4-0.5-0.75	10-6.0-0.5-0.75	13-4.2-0.5-0.75	16-3.1-0.5-0.75	19-2.3-0.5-0.75	22-1.8-0.5-0.75	25-1.4-0.5-0.75	28-1.0-0.5-0.75	31-0.8-0.5-0.75	34-0.5-0.5-0.75
duct out (cm)	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00
t-duct (cm)	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
duct in (cm)	7.80	7.80	7.80	7.80	7.80	7.80	7.80	7.80	7.80	7.80
t-fuel (cm)	0.9393	0.6050	0.4250	0.3125	0.2355	0.1795	0.1370	0.1036	0.0766	0.0544
t-clad (cm)	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
t-plate (cm)	1.0393	0.7050	0.5250	0.4125	0.3355	0.2795	0.2370	0.2036	0.1766	0.1544
t-H2 (cm)	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075
t-lattice (cm)	1.1143	0.7800	0.6000	0.4875	0.4105	0.3545	0.3120	0.2786	0.2516	0.2294
plate #	7	10	13	16	19	22	25	28	31	34
H2 %	6.40%	9.14%	11.88%	14.63%	17.37%	20.11%	22.85%	25.59%	28.34%	31.08%
Fuel %	79.11%	72.79%	66.47%	60.16%	53.84%	47.52%	41.21%	34.89%	28.57%	22.26%
Struct %	14.50%	18.07%	21.64%	25.22%	28.79%	32.37%	35.94%	39.52%	43.09%	46.66%
H2 flow area (cm^2)	4.095	5.85	7.605	9.36	11.115	12.87	14.625	16.38	18.135	19.89
Fuel S/V (cm^{-1})	1.71	2.44	3.17	3.90	4.63	5.36	6.09	6.83	7.56	8.29

Table A.3. Fuel assemblies characterized by a 0.5 mm cladding thickness and a 0.5 mm H2 flow gap – Number of plates varies between 7 and 37 – FA Identifier = number of fuel plates–fuel meat thickness–clad thickness–H2 gap thickness

FA identifier	7-9.6-0.5-0.5	10-6.3-0.5-0.5	13-4.5-0.5-0.5	16-3.4-0.5-0.5	19-2.6-0.5-0.5	22-2.0-0.5-0.5	25-1.6-0.5-075	28-1.3-0.5-0.5	31-1.0-0.5-0.5	34-0.8-0.5-0.5	37-0.6-0.5-0.5
duct out (cm)	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00
t-duct (cm)	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
duct in (cm)	7.80	7.80	7.80	7.80	7.80	7.80	7.80	7.80	7.80	7.80	7.80
t-fuel (cm)	0.9643	0.6300	0.4500	0.3375	0.2605	0.2045	0.1620	0.1286	0.1016	0.0794	0.0608
t-clad (cm)	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
t-plate (cm)	1.0643	0.7300	0.5500	0.4375	0.3605	0.3045	0.2620	0.2286	0.2016	0.1794	0.1608
t-H2 (cm)	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050
t-lattice (cm)	1.1143	0.7800	0.6000	0.4875	0.4105	0.3545	0.3120	0.2786	0.2516	0.2294	0.2108
plate #	7	10	13	16	19	22	25	28	31	34	37
H2 %	4.27%	6.09%	7.92%	9.75%	11.58%	13.41%	15.23%	17.06%	18.89%	20.72%	22.55%
Fuel %	81.21%	75.80%	70.38%	64.97%	59.55%	54.14%	48.73%	43.31%	37.90%	32.48%	27.07%
Struct %	14.52%	18.11%	21.70%	25.28%	28.87%	32.45%	36.04%	39.62%	43.21%	46.80%	50.38%
H2 flow area (cm^2)	2.73	3.9	5.07	6.24	7.41	8.58	9.75	10.92	12.09	13.26	14.43
Fuel S/V (cm^{-1})	1.71	2.44	3.17	3.90	4.63	5.36	6.09	6.83	7.56	8.29	9.02

Table A.4. Fuel assemblies characterized by a 0.25 mm cladding thickness and a 1 mm H2 flow gap – Number of plates varies between 7 and 37 – FA Identifier = number of fuel plates–fuel meat thickness–clad thickness–H2 gap thickness

FA identifier	7-9.6-0.25-1	10-6.3-0.25-1	13-4.5-0.25-1	16-3.4-0.25-1	19-2.6-0.25-1	22-2.0-0.25-1	25-1.6-0.25-1	28-1.3-0.25-1	31-1.0-0.25-1	34-0.8-0.25-1	37-0.6-0.25-1
duct out (cm)	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00
t-duct (cm)	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
duct in (cm)	7.80	7.80	7.80	7.80	7.80	7.80	7.80	7.80	7.80	7.80	7.80
t-fuel (cm)	0.9643	0.6300	0.4500	0.3375	0.2605	0.2045	0.1620	0.1286	0.1016	0.0794	0.0608
t-clad (cm)	0.025	0.025	0.025	0.025	0.025	0.025	0.025	0.025	0.025	0.025	0.025
t-plate (cm)	1.0143	0.6800	0.5000	0.3875	0.3105	0.2545	0.2120	0.1786	0.1516	0.1294	0.1108
t-H2 (cm)	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100
t-lattice (cm)	1.1143	0.7800	0.6000	0.4875	0.4105	0.3545	0.3120	0.2786	0.2516	0.2294	0.2108
plate #	7	10	13	16	19	22	25	28	31	34	37
H2 %	8.53%	12.19%	15.84%	19.50%	23.16%	26.81%	30.47%	34.13%	37.78%	41.44%	45.09%
Fuel %	81.21%	75.80%	70.38%	64.97%	59.55%	54.14%	48.73%	43.31%	37.90%	32.48%	27.07%
Struct %	10.26%	12.02%	13.77%	15.53%	17.29%	19.05%	20.80%	22.56%	24.32%	26.08%	27.84%
H2 flow area (cm^2)	5.46	7.8	10.14	12.48	14.82	17.16	19.5	21.84	24.18	26.52	28.86
Fuel S/V (cm^{-1})	1.71	2.44	3.17	3.90	4.63	5.36	6.09	6.83	7.56	8.29	9.02

Table A.5. Fuel assemblies characterized by a 0.25 mm cladding thickness and a 0.75 mm H2 flow gap – Number of plates varies between 7 and 43 – FA Identifier = number of fuel plates–fuel meat thickness–clad thickness–H2 gap thickness

FA identifier	7-9.9-0.25-0.75	10-6.6-0.25-0.75	13-4.7-0.25-0.75	16-3.6-0.25-0.75	19-2.9-0.25-0.75	22-2.3-0.25-0.75	25-1.9-0.25-0.75	28-1.5-0.25-0.75	31-1.3-0.25-0.75	34-1.0-0.25-0.75	37-0.9-0.25-0.75	40-0.7-0.25-0.75	43-0.6-0.25-0.75
duct out (cm)	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00
t-duct (cm)	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
duct in (cm)	7.80	7.80	7.80	7.80	7.80	7.80	7.80	7.80	7.80	7.80	7.80	7.80	7.80
t-fuel (cm)	0.9893	0.6550	0.4750	0.3625	0.2855	0.2295	0.1870	0.1536	0.1266	0.1044	0.0858	0.0700	0.0564
t-clad (cm)	0.025	0.025	0.025	0.025	0.025	0.025	0.025	0.025	0.025	0.025	0.025	0.025	0.025
t-plate (cm)	1.0393	0.7050	0.5250	0.4125	0.3355	0.2795	0.2370	0.2036	0.1766	0.1544	0.1358	0.1200	0.1064
t-H2 (cm)	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075
t-lattice (cm)	1.1143	0.7800	0.6000	0.4875	0.4105	0.3545	0.3120	0.2786	0.2516	0.2294	0.2108	0.1950	0.1814
plate #	7	10	13	16	19	22	25	28	31	34	37	40	43
H2 %	6.40%	9.14%	11.88%	14.63%	17.37%	20.11%	22.85%	25.59%	28.34%	31.08%	33.82%	36.56%	39.30%
Fuel %	83.32%	78.80%	74.29%	69.78%	65.27%	60.76%	56.25%	51.73%	47.22%	42.71%	38.20%	33.69%	29.18%
Struct %	10.29%	12.05%	13.82%	15.59%	17.36%	19.13%	20.90%	22.67%	24.44%	26.21%	27.98%	29.75%	31.52%
H2 flow area (cm^2)	4.10	5.85	7.61	9.36	11.12	12.87	14.63	16.38	18.14	19.89	21.65	23.40	25.16
Fuel S/V (cm^{-1})	1.71	2.44	3.17	3.90	4.63	5.36	6.09	6.83	7.56	8.29	9.02	9.75	10.48

Table A.6. Fuel assemblies characterized by a 0.25 mm cladding thickness and a 0.5 mm H2 flow gap – Number of plates varies between 7 and 49 – FA Identifier = number of fuel plates–fuel meat thickness–clad thickness–H2 gap thickness

FA identifier	7-10-0.25-0.5	10-6.8-0.25-0.5	13-5.0-0.25-0.5	16-3.9-0.25-0.5	19-3.1-0.25-0.5	22-2.5-0.25-0.5	25-2.1-0.25-0.5	28-1.8-0.25-0.5	31-1.5-0.25-0.5	34-1.3-0.25-0.5	37-1.1-0.25-0.5	40-0.9-0.25-0.5	43-0.8-0.25-0.5	46-0.7-0.25-0.5	49-0.6-0.25-0.5
duct out (cm)	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00
t-duct (cm)	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
duct in (cm)	7.80	7.80	7.80	7.80	7.80	7.80	7.80	7.80	7.80	7.80	7.80	7.80	7.80	7.80	7.80
t-fuel (cm)	1.0143	0.6800	0.5000	0.3875	0.3105	0.2545	0.2120	0.1786	0.1516	0.1294	0.1108	0.0950	0.0814	0.0696	0.0592
t-clad (cm)	0.025	0.025	0.025	0.025	0.025	0.025	0.025	0.025	0.025	0.025	0.025	0.025	0.025	0.025	0.025
t-plate (cm)	1.0643	0.7300	0.5500	0.4375	0.3605	0.3045	0.2620	0.2286	0.2016	0.1794	0.1608	0.1450	0.1314	0.1196	0.1092
t-H2 (cm)	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050
t-lattice (cm)	1.1143	0.7800	0.6000	0.4875	0.4105	0.3545	0.3120	0.2786	0.2516	0.2294	0.2108	0.1950	0.1814	0.1696	0.1592
plate #	7	10	13	16	19	22	25	28	31	34	37	40	43	46	49
H2 %	4.27%	6.09%	7.92%	9.75%	11.58%	13.41%	15.23%	17.06%	18.89%	20.72%	22.55%	24.38%	26.20%	28.03%	29.86%
Fuel %	85.42%	81.81%	78.20%	74.59%	70.98%	67.37%	63.77%	60.16%	56.55%	52.94%	49.33%	45.72%	42.11%	38.50%	34.89%
Struct %	10.31%	12.09%	13.88%	15.66%	17.44%	19.22%	21.00%	22.78%	24.56%	26.34%	28.12%	29.91%	31.69%	33.47%	35.25%
H2 flow area (cm^2)	2.73	3.90	5.07	6.24	7.41	8.58	9.75	10.92	12.09	13.26	14.43	15.60	16.77	17.94	19.11
Fuel S/V (cm^{-1})	1.71	2.44	3.17	3.90	4.63	5.36	6.09	6.83	7.56	8.29	9.02	9.75	10.48	11.21	11.94

Appendix B. Heat removal scoping analyses for straight plate designs

The objective of the heat removal scoping analyses is to estimate the maximum fuel assembly power acceptable given an assumed set of design requirements:

- Maximum Mo and W allowable temperatures are, respectively, 2320 K and 3000 K corresponding to about 80% of their melting temperatures.
- Maximum UN, UC and UO2 allowable centerline temperatures assumed in the analyses are, respectively, 3100 K, 2700 K and 3100 K corresponding to their melting temperature.
- Fuel active width / height = 7.8 cm / 80 cm

The approach consists in calculating the maximum plate power allowable as a function of fuel meat thickness for each fuel type, cladding thickness, hydrogen outlet temperature and power distribution using the set of equations presented below for a symmetrically cooled plate (analytical solutions for asymmetrically cooled plates can be found for example in [Reilly, 1966]). The plate linear power, P_{lin}, is adjusted together with the hydrogen mass flow, $\dot{m}_{H2}$, until an assumed thermal limit is reached (fuel or cladding temperature) while maintaining the hydrogen outlet temperature at the desired value, i.e. 2750 K or less depending on the case.

Separate correlations giving maximum allowable peak plate power as a function of fuel meat thickness are then derived for each case (see Table B.1 to B.9). Maximum allowable peak assembly power is then obtained by multiplying the number of fuel plates in the assembly by the maximum allowable peak plate power. Once this is done, obtaining core size, fuel mass, etc… is a matter of simple algebra and is presented in Table B.10 to B.15.

In any given channel within a fuel assembly, the hydrogen bulk temperature, outside cladding temperature, inside cladding temperature and fuel centerline temperature at height z can be evaluated using the following expressions:

- Hydrogen bulk temperature $T_{H2,b}(z)$ is obtained from:

$$\int_{z_{in}}^{z} P_{lin}(z)dz = \int_{T_{H2,b,in}}^{T_{H2,b}(z)} \dot{m}_{H2} C_{p,H2} dT_{H2,b} \cong \dot{m}_{H2} C_{p,H2}(T_{H2,b}(z) - T_{H2,b,in})$$

In this simple thermal model used for scoping analyses, power in each plate is assumed independent of the x and y directions (Figure B.1). Three axial power distributions were considered, two symmetric (Figure B.2a and B.2b) and one asymmetric (Figure B.3).

- Outside cladding temperature $T_{co}(z)$ is obtained from:

$$h_{H2}\left(T_{co}(z) - T_{H2,b}(z)\right) = \frac{P_{lin}(z)}{2w_p} = q''(z)$$

(Plate width, w_p, assumed in these analyses is 7.8 cm)

- Inside cladding temperature $T_{ci}(z)$ is obtained from:

$$T_{ci}(z) - T_{co}(z) = q''(z)\frac{\delta_c}{k_c(z)} = \frac{P_{lin}(z)}{2w_p}\frac{\delta_c}{k_c(z)}$$

- Fuel surface temperature is obtained assuming that there is a 25-micron interface zone containing Helium between the cladding and the fuel surface characterized by thermal conductivity $k_{int}(z)$. This is somewhat arbitrary but allows accounting for a less than perfect fuel-cladding contact.

$$T_S(z) - T_{ci}(z) = q''(z)\frac{\delta_{int}}{k_{int}(z)} = \frac{P_{lin}(z)}{2w_p}\frac{\delta_{int}}{k_{int}(z)}$$

- Fuel centerline temperature $T_{CL}(z)$ is obtained from:

$$\int_{T_S(z)}^{T_{CL}(z)} k_f(T)dT = q'''(z)\frac{a^2}{2} = \frac{P_{lin}(z)}{2a \cdot w_f}\frac{a^2}{2} = \frac{P_{lin}(z)}{w_f}\frac{a}{4}$$

With "a" the half plate thickness (Figure B.1).

If k_f is constant

$$k_f[T_{CL}(z) - T_S(z)] = q'''(z)\frac{a^2}{2}$$

The following input data were assumed in order to perform the numerical calculations:

- p_{H2} = 4 MPa
- $C_{p,H2}$ = 16 kJ/kg-K
- $T_{H2,b,in}$ = 350 K
- $T_{H2,b,out}$ between 2100 K and 2750 K
- k_f = 0.25 W/cm-K for UN, 0.45 W/cm-K for UC and 0.025 W/cm-K for UO2 (see Appendix C)
- k_c = 0.75 W/cm-K
- k_{int} = k_{He} = 0.006 W/cm-K
- h_{H2} = 1.5 W/cm^2-K (this is a conservatively low value, see Appendix D)

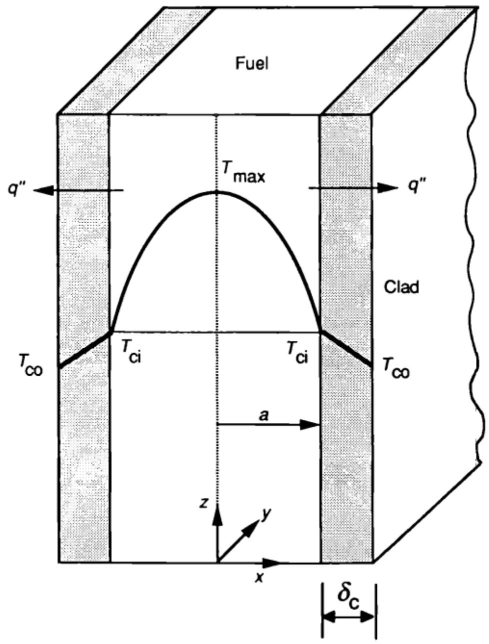

Figure B.1. Plate fuel element [Todreas, 1990]

References

H. J. Reilly, K. J. Baumeister, and S. Altomare, Heat Transfer Analysis of the Plum Brook Reactor, NASA Technical Note TN D-3552, 1966

Todreas, Kazimi, Thermal Hydraulic Fundamentals, Hemisphere Publishing, 1990

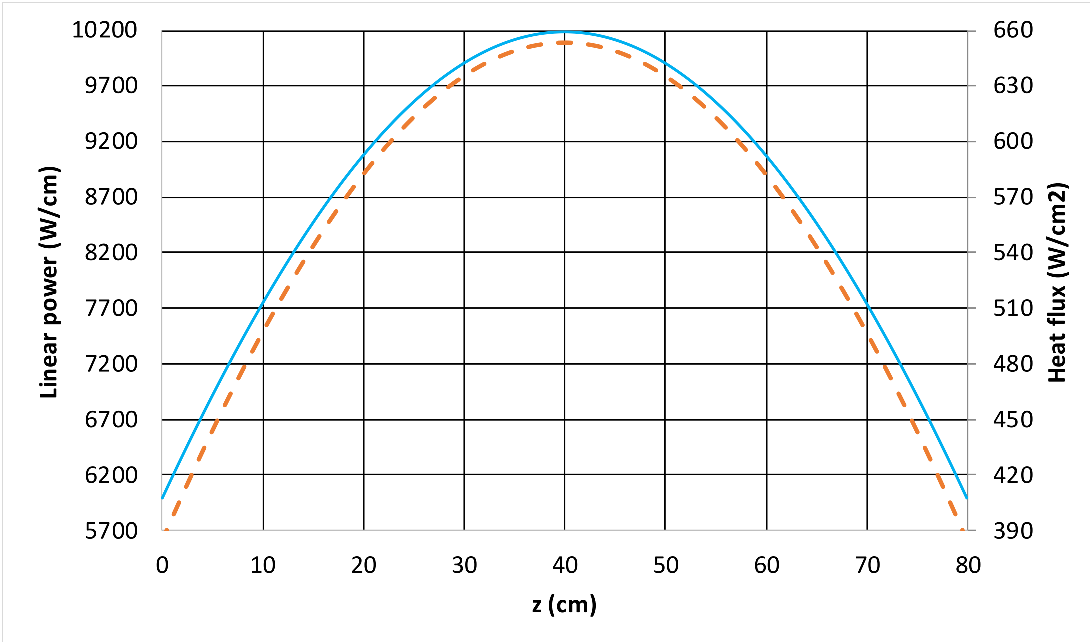

Figure B.2a. Axially symmetric power distribution [a] – peak-to-average = **1.17** – Solid blue = linear power ; dash orange = heat flux. In this example the total plate power is 700 kW and the linear power can be expressed as: $P_{lin}(z) = 1.2561 \cdot 10^{-4} \cdot z^4 - 2.0097 \cdot 10^{-2} \cdot z^3 - 1.6204 \cdot z^2 + 193.95 \cdot z + 5991.3$

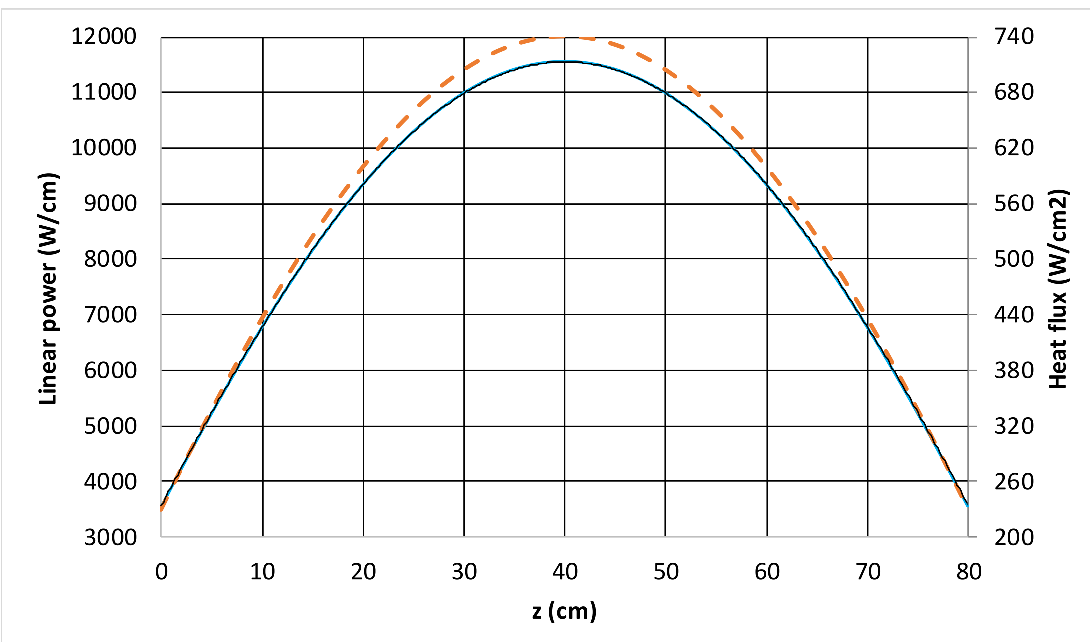

Figure B.2b. Axially symmetric power distribution [b] – peak-to-average = **1.33** – Solid blue = linear power ; dash orange = heat flux. In this example the total plate power is 700 kW and the linear power can be expressed as: $P_{lin}(z) = 4.3590 \cdot 10^{-4} \cdot z^4 - 6.9744 \cdot 10^{-2} \cdot z^3 - 1.4993 \cdot z^2 + 343.13 \cdot z + 3574.1$

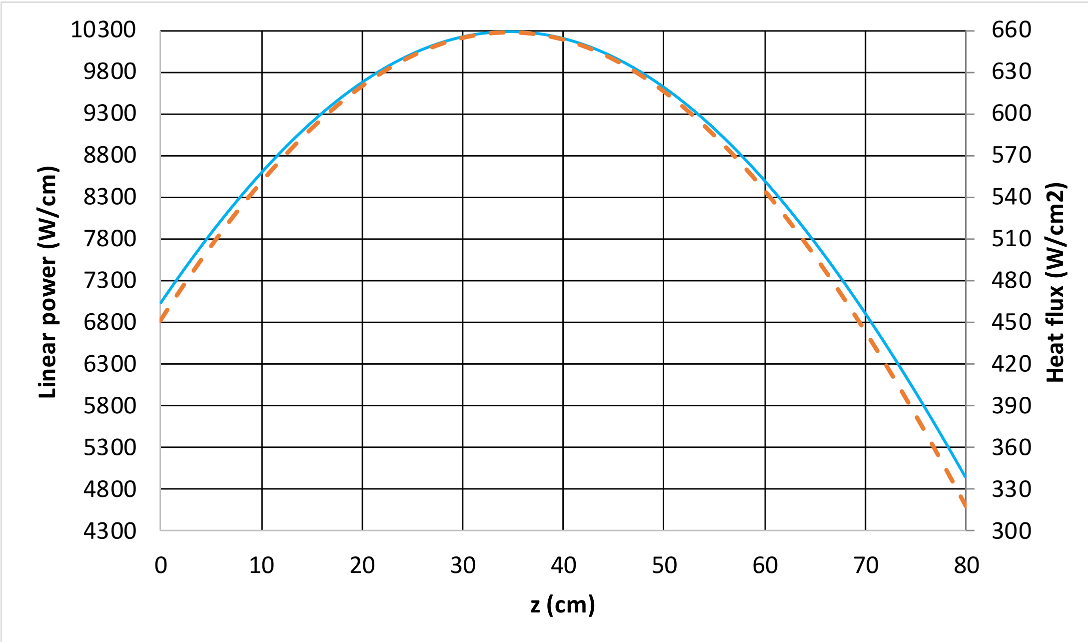

Figure B.3. Axially asymmetric power distribution – peak-to-average = 1.18 – Solid blue = linear power ; dash orange = heat flux. In this example the total plate power is 700 kW and the linear power can be expressed as $P_{lin}(z) = 1.2568{\cdot}10^{-4}{\cdot}z^4 - 1.7438{\cdot}10^{-2}{\cdot}z^3 - 1.9419{\cdot}z^2 + 176.57{\cdot}z + 7036.1$

Table B.1a. Maximum allowable plate power (MW) for W-clad UN fuel as a function of fuel meat thickness and hydrogen outlet temperature assuming axially symmetric power distribution [a]. Fuel height = 80 cm.

Fuel meat thickness (cm)	0.05	0.10	0.25	0.50	0.75	1.00
Peak UN plate power (MW) for $T_{H2,b,out}$ = 2750 K	0.532	0.510*	0.455	0.387	0.335	0.297
	$y = 0.1633x^4 - 0.4293x^3 + 0.5167x^2 - 0.5099x + 0.5563$					
Peak UN plate power (MW) for $T_{H2,b,out}$ = 2550 K	0.835	0.801	0.716	0.608	0.527	0.466
	$y = 0.1589x^4 - 0.4648x^3 + 0.6612x^2 - 0.7605x + 0.8712$					
Peak UN plate power (MW) for $T_{H2,b,out}$ = 2350 K	1.11	1.07**	0.951	0.807	0.701	0.619
	$y = -0.0057x^4 - 0.1848x^3 + 0.6164x^2 - 0.9650x + 1.1581$					

* see Figure B.4 ; ** see Figure B.5

Table B.1b. Maximum allowable plate power (MW) for W-clad UN fuel as a function of fuel meat thickness and hydrogen outlet temperature assuming axially symmetric power distribution [b]. Fuel height = 80 cm.

Fuel meat thickness (cm)	0.05	0.10	0.25	0.50	0.75	1.00
Peak UN plate power (MW) for $T_{H2,b,out}$ = 2750 K	0.710	0.681	0.608	0.516	0.448	-
	$y = -0.1828x^3 + 0.4636x^2 - 0.6347x + 0.7404$					
Peak UN plate power (MW) for $T_{H2,b,out}$ = 2550 K	0.926	0.889	0.794	0.673	0.585	-
	$y = -0.1870x^3 + 0.5423x^2 - 0.8080x + 0.9649$					
Peak UN plate power (MW) for $T_{H2,b,out}$ = 2350 K	1.1	1.06	0.944	0.801	0.696	-
	$y = -0.1933x^3 + 0.6074x^2 - 0.9482x + 1.1471$					

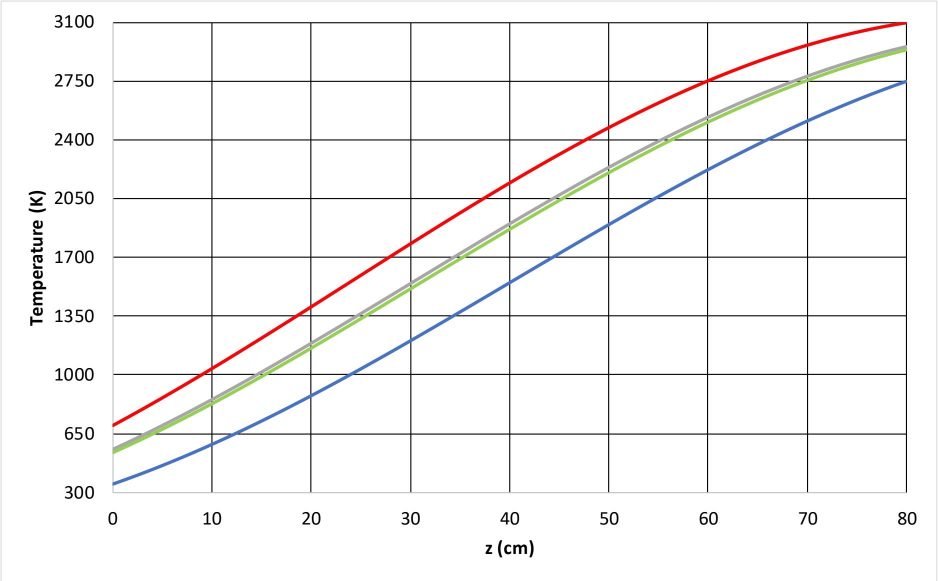

Figure B.4. Bulk H2 (blue), outside and inside cladding (green and grey), fuel centerline (red) axial temperature profiles for the 0.510 MW fuel plate. UN fuel meat thickness = 0.10 cm.

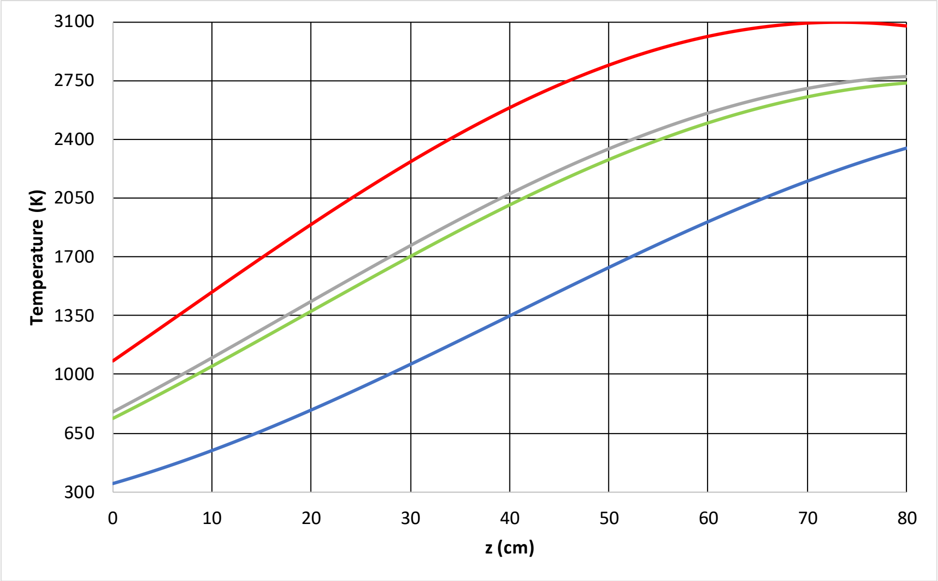

Figure B.5. Bulk H2 (blue), outside and inside cladding (green and grey), fuel centerline (red) axial temperature profiles for the 1.07 MW fuel plate. UN fuel meat thickness = 0.10 cm.

Table B.2a. Maximum allowable plate power (MW) for W-clad UC fuel as a function of fuel meat thickness and hydrogen outlet temperature assuming axially symmetric power distribution [a]. Fuel height = 80 cm.

Fuel meat thickness (cm)	0.05	0.10	0.25	0.50	0.75	1.00
Peak UC plate power (MW) for $T_{H2,b,out}$ = 2550 K	0.232	0.227	0.212	0.191	0.174	0.160
	$y = 0.0305x^2 - 0.1077x + 0.2373$					
Peak UC plate power (MW) for $T_{H2,b,out}$ = 2350 K	0.541	0.529	0.494	0.446	0.407	0.374
	$y = 0.0701x^2 - 0.2485x + 0.5529$					

Table B.2b. Maximum allowable plate power (MW) for W-clad UC fuel as a function of fuel meat thickness and hydrogen outlet temperature assuming axially symmetric power distribution [b]. Fuel height = 80 cm.

<table>
<tr><td>Fuel meat thickness (cm)</td><td>0.05</td><td>0.10</td><td>0.25</td><td>0.50</td><td>0.75</td><td>1.00</td></tr>
<tr><td rowspan="2">Peak UC plate power (MW) for $T_{H2,b,out}$ = 2550 K</td><td>0.379</td><td>0.372</td><td>0.348</td><td>0.312</td><td>0.285</td><td>-</td></tr>
<tr><td colspan="6">$y = 0.0755x^3 - 0.0382x^2 - 0.1496x + 0.3868$</td></tr>
<tr><td rowspan="2">Peak UC plate power (MW) for $T_{H2,b,out}$ = 2350 K</td><td>0.678</td><td>0.663</td><td>0.621</td><td>0.560</td><td>0.510</td><td>-</td></tr>
<tr><td colspan="6">$y = -0.00500x^3 + 0.09527x^2 - 0.31318x + 0.69340$</td></tr>
</table>

Table B.3. Maximum allowable plate power (MW) for W-clad UO2 fuel as a function of fuel meat thickness and hydrogen outlet temperature assuming axially symmetric power distribution [a]. Fuel height = 80 cm.

<table>
<tr><td>Fuel meat thickness (cm)</td><td>0.05</td><td>0.10</td><td>0.25</td><td>0.50</td><td>0.75</td><td>1.00</td></tr>
<tr><td rowspan="2">Peak UO2 plate power (MW) for $T_{H2,b,out}$ = 2750 K</td><td>0.387</td><td>0.297</td><td>0.174</td><td>0.104</td><td>0.074</td><td>0.057</td></tr>
<tr><td colspan="6">$y = 2.2471x^4 - 5.7348x^3 + 5.3252x^2 - 2.2633x + 0.4831$</td></tr>
<tr><td rowspan="2">Peak UO2 plate power (MW) for $T_{H2,b,out}$ = 2550 K</td><td>0.608</td><td>0.466</td><td>0.275</td><td>0.163</td><td>0.116</td><td>0.09</td></tr>
<tr><td colspan="6">$y = -13.4830x^5 + 37.1724x^4 - 38.6258x^3 + 19.3372x^2 - 5.1317x + 0.8208$ for $x < 0.5$ and $y = -0.4693x^3 + 1.2240x^2 - 1.1607x + 0.4960$ for $x \geq 0.5$</td></tr>
<tr><td rowspan="2">Peak UO2 plate power (MW) for $T_{H2,b,out}$ = 2350 K</td><td>0.807</td><td>0.619*</td><td>0.365</td><td>0.217</td><td>0.154</td><td>0.119</td></tr>
<tr><td colspan="6">$y = -17.5138x^5 + 48.4045x^4 - 50.4694x^3 + 25.3809x^2 - 6.7713x + 1.0881$ for $x \leq 0.55$</td></tr>
</table>

* see Figure B.6

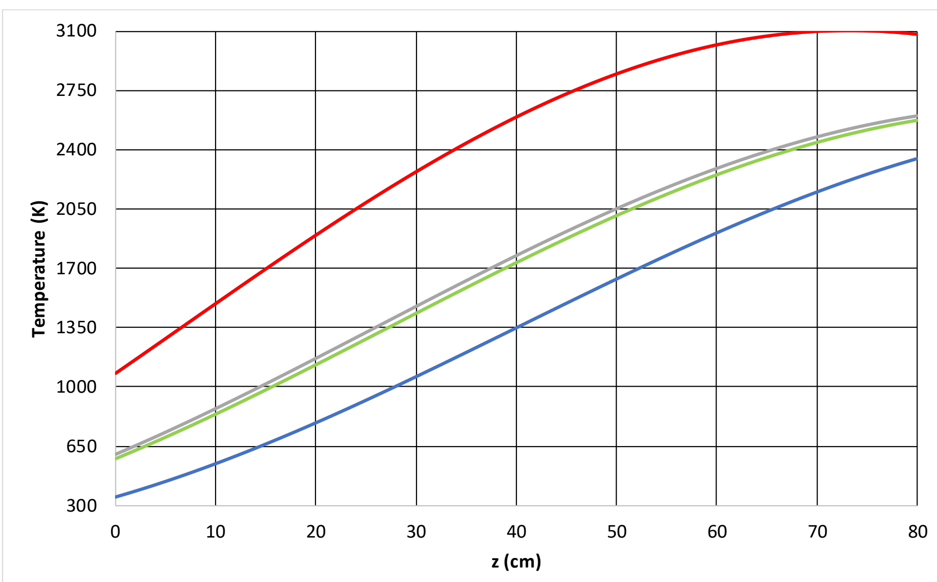

Figure B.6. Bulk H2 (blue), outside and inside cladding (green and grey), fuel centerline (red) axial temperature profiles for the 0.619 MW fuel plate. UO2 fuel meat thickness = 0.10 cm.

Table B.4. Maximum allowable plate power (MW) for Mo-clad UN fuel and Mo-clad UC fuel as a function of fuel meat thickness and hydrogen outlet temperature assuming axially symmetric power distribution [a]. Fuel height = 80 cm.

Fuel meat thickness (cm)	0.05	0.10	0.25	0.50	0.75	1.00
Peak UN plate power (MW) for $T_{H2,b,out}$ = 2200 K	0.299	0.299	0.299	0.299	0.299	0.299
Peak UN plate power (MW) for $T_{H2,b,out}$ = 2100 K	0.546	0.546	0.546	0.546	0.546	0.546

Table B.5. Maximum allowable plate power (MW) for Mo-clad UO2 fuel as a function of fuel meat thickness and hydrogen outlet temperature assuming axially symmetric power distribution [a]. Fuel height = 80 cm.

Fuel meat thickness (cm)	0.05	0.1	0.175	0.2125	0.25	0.375	0.4375	0.50	0.75	1.00
Peak UO2 plate power (MW) for $T_{H2,b,out}$ = 2200 K	0.299	0.299	0.299	0.299	0.299	0.299	0.277	0.249	0.177	0.137
	$y = 0.2702x^2 - 0.6325x + 0.4993$ for $x > 0.375$ and $y = 0.299$ for $x \le 0.375$									
Peak UO2 plate power (MW) for $T_{H2,b,out}$ = 2100 K	0.546	0.546	0.546	0.504	0.452	0.337	0.299	0.268	0.191	0.148
	$y = 0.4519x^4 - 1.9855x^3 + 3.1684x^2 - 2.3623x + 0.8755$ for $x > 0.175$ and $y = 0.546$ for $x \le 0.175$									

Table B.6. Maximum allowable plate power (MW) for W-clad UN fuel as a function of fuel meat thickness and hydrogen outlet temperature assuming axially **a**symmetric power distribution. Fuel height = 80 cm.

Fuel meat thickness (cm)	0.05	0.10	0.25	0.50	0.75	1.00
Peak UN plate power (MW) for $T_{H2,b,out}$ = 2750 K	0.644	0.617	0.552	0.467	0.406	0.358
	$y = 0.0363x^4 - 0.1889x^3 + 0.4085x^2 - 0.5688x + 0.6709$					
Peak UN plate power (MW) for $T_{H2,b,out}$ = 2350 K	1.21	1.16	1.04	0.879	0.763	0.674
	$y = 0.0498x^4 - 0.2741x^3 + 0.6711x^2 - 1.0314x + 1.2587$					

Table B.7. Maximum allowable plate power (MW) for Mo-clad UN fuel as a function of fuel meat thickness and hydrogen outlet temperature assuming axially **a**symmetric power distribution. Fuel height = 80 cm.

Fuel meat thickness (cm)	0.05	0.10	0.25	0.50	0.75	1.00
Peak UN plate power (MW) for $T_{H2,b,out}$ = 2200 K	0.361	0.361	0.361	0.361	0.361	0.361
Peak UN plate power (MW) for $T_{H2,b,out}$ = 2100 K	0.664	0.664	0.664	0.664	0.664	0.664

Table B.8. Maximum allowable plate power (MW) for W-clad UN fuel as a function of fuel meat thickness and hydrogen outlet temperature assuming axially symmetric power distribution [a]. No fuel-cladding gap assumed. Fuel height = 80 cm.

Fuel meat thickness (cm)	0.05	0.10	0.25	0.50	0.75	1.00
Peak UN plate power (MW) for $T_{H2,b,out}$ = 2750 K	0.618	0.618	0.618	0.516	0.429	0.367
	$y = 0.1067x^3 - 0.0400x^2 - 0.4247x + 0.7250$ for $0.25 \le x \le 1.00$ and $y = 0.618$ for $x < 0.25$					
Peak UN plate power (MW) for $T_{H2,b,out}$ = 2350 K	1.60	1.60	1.35	1.08	0.898	0.768
	$y = 0.8770x^4 - 2.5766x^3 + 3.1985x^2 - 2.5572x + 1.8262$ for $0.10 \le x \le 1.00$ and $y = 1.60$ for $x < 0.10$					

Table B.9. Maximum allowable plate power (MW) for W-clad UO2 fuel as a function of fuel meat thickness and hydrogen outlet temperature assuming axially symmetric power distribution [a].
No fuel-cladding gap assumed. Fuel height = 80 cm.

Fuel meat thickness (cm)	0.05	0.10	0.25	0.50	0.75	1.00
Peak UO2 plate power (MW) for $T_{H2,b,out}$ = 2750 K	0.516	0.367	0.197	0.111	0.775	0.0594
	$y = 2.2156x^4 - 5.9347x^3 + 5.8602x^2 - 2.6620x + 0.5803$ for $x \geq 0.10$ and $y = -2.9800x + 0.6650$ for $x \leq 0.10$					
Peak UO2 plate power (MW) for $T_{H2,b,out}$ = 2350 K	1.08	0.768	0.412	0.232	0.162	0.124
	$y = 4.6368x^4 - 12.4240x^3 + 12.2710x^2 - 5.5745x + 1.2147$ $x \geq 0.10$ and $y = -6.2400x + 1.3920$ for $x \leq 0.10$					

Table B.10. Core characteristics for various assembly designs: **W-clad UN fuel**; Cladding thickness = **0.5 mm**; H2 flow gap = **1 mm**; Number of plates/assembly = 7 to 31; Axially symmetric power distribution [a]. Assumed peak-to-average fuel assembly power ratio = 1.35. No moderator blocks. – FA Identifier = number of fuel plates–fuel meat thickness–clad thickness–H2 gap thickness

Assembly identifier	7-9.1-0.5-1	10-5.8-0.5-1	13-4.0-0.5-1	16-2.8-0.5-1	19-2.1-0.5-1	22-1.5-0.5-1	25-1.1-0.5-1	28-0.7-0.5-1	31-0.5-0.5-1
T-H2-out = 2750 K	mH2 = 6.5 kg/s for 250 MW assuming T-H2-inlet = 350 K								
Pmax Plate (MW)	0.308	0.369	0.412	0.443	0.468	0.488	0.505	0.519	0.531
Pmax FA(MW)	2.16	3.69	5.35	7.09	8.90	10.74	12.63	14.54	16.47
U mass per FA (kg)	51.2	46.4	41.6	36.8	32.0	27.2	22.4	17.6	12.8
m-H2 (kg/s)	0.0562	0.0961	0.1394	0.1847	0.2316	0.2798	0.3288	0.3786	0.4289
v-outlet (m/s) @ 4 MPa	300	359	401	431	455	475	491	505	517
# FA to meet TH constraints for 250 MW	157	91	63	48	38	31	27	23	20
U mass (kg) to meet TH constraints for 250 MW	8017	4245	2624	1752	1215	855	599	409	262
W mass (kg) to meet TH constraints for 250 MW	2238	1629	1346	1183	1077	1002	947	904	870
Average power density (W/cm3)	312	534	774	1026	1287	1554	1827	2103	2383
Core diameter (cm) to meet TH constraints for 250 MW	126	98	79	70	63	57	52	49	46
Core + Refector diameter (cm)	166	138	119	110	103	97	92	89	86
Radial+Axial reflector mass (kg)	1644	1234	990	879	794	727	677	640	613
Total mass (mT)	11.9	7.1	5.0	3.8	3.1	2.6	2.2	2.0	1.7
T-H2-out = 2550 K	mH2 = 7.1 kg/s for 250 MW assuming T-H2-inlet = 350 K								
Pmax Plate (MW)	0.484	0.580	0.647	0.697	0.736	0.768	0.794	0.815	0.834
Pmax FA(MW)	3.39	5.80	8.41	11.16	13.99	16.89	19.84	22.83	25.84
U mass per FA (kg)	51.2	46.4	41.6	36.8	32.0	27.2	22.4	17.6	12.8
m-H2 (kg/s)	0.1060	0.1812	0.2629	0.3486	0.4372	0.5279	0.6201	0.7134	0.8076
v-outlet (m/s) @ 4 MPa	565	677	755	814	860	896	927	952	973
# FA to meet TH constraints for 250 MW	100	58	40	30	24	20	17	15	13
U mass (kg) to meet TH constraints for 250 MW	5098	2702	1670	1114	772	544	381	260	167
W mass (kg) to meet TH constraints for 250 MW	1423	1037	856	752	685	637	602	576	555
Average power density (W/cm3)	491	839	1217	1614	2024	2444	2871	3303	3739
Core diameter (cm) to meet TH constraints for 250 MW	102	76	64	56	50	46	44	42	41
Core + Refector diameter (cm)	142	116	104	96	90	86	84	82	81
Radial+Axial reflector mass (kg)	1291	955	815	715	650	608	581	563	551
Total mass (mT)	7.8	4.7	3.3	2.6	2.1	1.8	1.6	1.4	1.3

Table B.11a. Core characteristics for various assembly designs: **W-clad UN fuel**; Cladding thickness = **0.5 mm**; H2 flow gap = **0.75 mm**; Number of plates/assembly = 7 to 34; Axially symmetric power distribution [a]. Assumed peak-to-average fuel assembly power ratio = 1.35. No moderator blocks. – FA Identifier = number of fuel plates–fuel meat thickness–clad thickness–H2 gap thickness

Assembly identifier	7-9.4-0.5-0.75	10-6.0-0.5-0.75	13-4.2-0.5-0.75	16-3.1-0.5-0.75	19-2.3-0.5-0.75	22-1.8-0.5-0.75	25-1.4-0.5-0.75	28-1.0-0.5-0.75	31-0.8-0.5-0.75	34-0.5-0.5-0.75
T-H2-out = 2750 K	mH2 = 6.5 kg/s for 250 MW assuming T-H2-inlet = 350 K									
Pmax Plate (MW)	0.305	0.364	0.405	0.436	0.460	0.479	0.495	0.509	0.520	0.530
Pmax FA(MW)	2.13	3.64	5.27	6.97	8.74	10.54	12.38	14.24	16.12	18.02
U mass per FA (kg)	52.6	48.4	44.2	40.0	35.8	31.6	27.4	23.2	19.0	14.8
m-H2 (kg/s)	0.0555	0.0947	0.1372	0.1816	0.2275	0.2745	0.3223	0.3708	0.4199	0.4693
v-outlet (m/s) @ 4 MPa	395	472	526	565	596	621	642	660	675	687
# FA to meet TH constraints for 250 MW	158	93	64	48	39	32	27	24	21	19
U mass (kg) to meet TH constraints for 250 MW	8330	4493	2832	1937	1384	1012	747	550	398	277
W mass (kg) to meet TH constraints for 250 MW	2268	1657	1370	1206	1099	1024	968	925	891	864
Average power density (W/cm3)	308	526	762	1009	1264	1525	1791	2060	2333	2607
Core diameter (cm) to meet TH constraints for 250 MW	126	102	79	70	63	57	53	49	47	45
Core + Refector diameter (cm)	166	142	119	110	103	97	93	89	87	85
Radial+Axial reflector mass (kg)	1644	1291	998	885	801	733	683	645	617	596
Total mass (mT)	12.2	7.4	5.2	4.0	3.3	2.8	2.4	2.1	1.9	1.7
T-H2-out = 2550 K	mH2 = 7.1 kg/s for 250 MW assuming T-H2-inlet = 350 K									
Pmax Plate (MW)	0.479	0.571	0.637	0.685	0.723	0.753	0.778	0.799	0.817	0.832
Pmax FA(MW)	3.35	5.71	8.28	10.97	13.74	16.58	19.46	22.37	25.32	28.28
U mass per FA (kg)	52.6	48.4	44.2	40.0	35.8	31.6	27.4	23.2	19.0	14.8
m-H2 (kg/s)	0.1047	0.1786	0.2587	0.3427	0.4294	0.5180	0.6080	0.6991	0.7911	0.8837
v-outlet (m/s) @ 4 MPa	745	889	991	1067	1126	1173	1211	1244	1271	1295
# FA to meet TH constraints for 250 MW	101	59	41	31	25	20	17	15	13	12
U mass (kg) to meet TH constraints for 250 MW	5300	2860	1802	1231	880	644	475	350	253	177
W mass (kg) to meet TH constraints for 250 MW	1443	1055	872	767	699	651	616	589	568	550
Average power density (W/cm3)	485	827	1198	1587	1988	2398	2815	3237	3662	4091
Core diameter (cm) to meet TH constraints for 250 MW	102	77	65	56	50	46	44	42	41	40
Core + Refector diameter (cm)	142	117	105	96	90	86	84	82	81	80
Radial+Axial reflector mass (kg)	1291	961	821	720	654	612	584	566	553	544
Total mass (mT)	8.0	4.9	3.5	2.7	2.2	1.9	1.7	1.5	1.4	1.3

Table B.11b. Core characteristics for various assembly designs: **W-clad UC fuel**; Cladding thickness = **0.5 mm**; H2 flow gap = **0.75 mm**; Number of plates/assembly = 7 to 34; Axially symmetric power distribution [a]. Assumed peak-to-average fuel assembly power ratio = 1.35. No moderator blocks. – FA Identifier = number of fuel plates–fuel meat thickness–clad thickness–H2 gap thickness

Assembly identifier	7-9.4-0.5-0.75	10-6.0-0.5-0.75	13-4.2-0.5-0.75	16-3.1-0.5-0.75	19-2.3-0.5-0.75	22-1.8-0.5-0.75	25-1.4-0.5-0.75	28-1.0-0.5-0.75	31-0.8-0.5-0.75	34-0.5-0.75
T-H2-out = 2550 K	mH2 = 7.1 kg/s for 250 MW assuming T-H2-inlet = 350 K									
Pmax Plate (MW)	0.163	0.183	0.197	0.207	0.214	0.219	0.223	0.226	0.229	0.232
Pmax FA(MW)	1.14	1.83	2.56	3.31	4.06	4.82	5.58	6.34	7.11	7.87
U mass per FA (kg)	46.3	42.6	38.9	35.2	31.5	27.8	24.1	20.4	16.7	13.0
m-H2 (kg/s)	0.0297	0.0477	0.0667	0.0861	0.1057	0.1254	0.1453	0.1651	0.1851	0.2050
v-outlet (m/s) @ 4 MPa	211	238	256	268	277	284	289	294	297	300
# FA to meet TH constraints for 250 MW	296	184	132	102	83	70	61	53	47	43
U mass (kg) to meet TH constraints for 250 MW	13682	7839	5123	3592	2619	1948	1458	1086	794	558
W mass (kg) to meet TH constraints for 250 MW	4236	3288	2818	2544	2366	2241	2149	2078	2022	1977
Average power density (W/cm3)	165	265	371	478	587	697	807	917	1028	1139
Core diameter (cm) to meet TH constraints for 250 MW	>140	>140	115	102	91	84	77	73	70	66
Core + Reflector diameter (cm)	>180	>180	155	142	131	124	117	113	110	106
Radial+Axial reflector mass (kg)	>1.9	>1.9	1481	1291	1139	1054	971	920	878	840
Total mass (mT)	>19.8	>13	9.4	7.4	6.1	5.2	4.6	4.1	3.7	3.4
T-H2-out = 2350 K	mH2 = 7.8 kg/s for 250 MW assuming T-H2-inlet = 350 K									
Pmax Plate (MW)	0.381	0.428	0.460	0.482	0.498	0.511	0.520	0.528	0.534	0.540
Pmax FA(MW)	2.67	4.28	5.98	7.71	9.47	11.23	13.00	14.78	16.56	18.35
U mass per FA (kg)	46.3	42.6	38.9	35.2	31.5	27.8	24.1	20.4	16.7	13.0
m-H2 (kg/s)	0.0695	0.1115	0.1557	0.2009	0.2465	0.2925	0.3387	0.3849	0.4313	0.4778
v-outlet (m/s) @ 4 MPa	495	555	597	625	646	662	675	685	693	700
# FA to meet TH constraints for 250 MW	126	79	56	44	36	30	26	23	20	18
U mass (kg) to meet TH constraints for 250 MW	5850	3356	2195	1540	1123	835	626	466	341	239
W mass (kg) to meet TH constraints for 250 MW	1811	1407	1207	1090	1014	961	922	892	868	848
Average power density (W/cm3)	386	620	865	1116	1370	1625	1881	2139	2396	2654
Core diameter (cm) to meet TH constraints for 250 MW	113	91	75	67	61	56	52	49	46	45
Core + Reflector diameter (cm)	153	131	115	107	101	96	92	89	86	85
Radial+Axial reflector mass (kg)	1448	1139	943	847	771	712	669	636	612	593
Total mass (mT)	9.1	5.9	4.3	3.5	2.9	2.5	2.2	2.0	1.8	1.7

Table B.11c. Core characteristics for various assembly designs: **Mo-clad UN or UC fuel**; Cladding thickness = **0.5 mm**; H2 flow gap = **0.75 mm**; Number of plates/assembly = 7 to 34; Axially symmetric power distribution [a]. Assumed peak-to-average fuel assembly power ratio = 1.35. No moderator blocks. – FA Identifier = number of fuel plates–fuel meat thickness–clad thickness–H2 gap thickness

Assembly identifier	7-9.4-0.5-0.75	10-6.0-0.5-0.75	13-4.2-0.5-0.75	16-3.1-0.5-0.75	19-2.3-0.5-0.75	22-1.8-0.5-0.75	25-1.4-0.5-0.75	28-1.0-0.5-0.75	31-0.8-0.5-0.75	34-0.5-0.5-0.75
T-H2-out = 2200 K	mH2 = 8.4 kg/s for 250 MW assuming T-H2-inlet = 350 K									
Pmax Plate (MW)	0.299	0.299	0.299	0.299	0.299	0.299	0.299	0.299	0.299	0.299
Pmax FA(MW)	2.09	2.99	3.89	4.78	5.68	6.58	7.48	8.37	9.27	10.17
U mass per FA (kg)	52.6	48.4	44.2	40.0	35.8	31.6	27.4	23.2	19.0	14.8
m-H2 (kg/s)	0.0545	0.0779	0.1012	0.1246	0.1479	0.1713	0.1947	0.2180	0.2414	0.2647
v-outlet (m/s) @ 4 MPa	388	388	388	388	388	388	388	388	388	388
# FA to meet TH constraints for 250 MW	161	113	87	71	59	51	45	40	36	33
U mass (kg) to meet TH constraints for 250 MW	8485	5466	3839	2823	2128	1622	1238	936	692	492
Mo mass (kg) to meet TH constraints for 250 MW	1221	1065	981	929	893	867	847	832	819	809
Average power density (W/cm3)	303	433	562	692	822	952	1081	1211	1341	1471
Core diameter (cm) to meet TH constraints for 250 MW	126	109	93	84	77	72	68	65	61	58
Core + Reflector diameter (cm)	166	149	133	124	117	112	108	105	101	98
Radial+Axial reflector mass (kg)	1644	1388	1176	1059	963	907	859	816	779	746
Total mass (mT)	12.4	8.9	6.9	5.6	4.8	4.2	3.7	3.3	3.0	2.8
T-H2-out = 2100 K	mH2 = 8.9 kg/s for 250 MW assuming T-H2-inlet = 350 K									
Pmax Plate (MW)	0.546	0.546	0.546	0.546	0.546	0.546	0.546	0.546	0.546	0.546
Pmax FA(MW)	3.82	5.46	7.10	8.74	10.37	12.01	13.65	15.29	16.93	18.56
U mass per FA (kg)	52.6	48.4	44.2	40.0	35.8	31.6	27.4	23.2	19.0	14.8
m-H2 (kg/s)	0.0995	0.1422	0.1848	0.2275	0.2702	0.3128	0.3555	0.3981	0.4408	0.4834
v-outlet (m/s) @ 4 MPa	708	708	708	708	708	708	708	708	708	708
# FA to meet TH constraints for 250 MW	88	62	48	39	33	28	25	22	20	18
U mass (kg) to meet TH constraints for 250 MW	4647	2993	2103	1546	1165	888	678	512	379	269
Mo mass (kg) to meet TH constraints for 250 MW	669	583	537	509	489	475	464	456	449	443
Average power density (W/cm3)	553	790	1027	1264	1501	1738	1975	2212	2449	2686
Core diameter (cm) to meet TH constraints for 250 MW	93	78	70	63	58	54	50	48	46	44
Core + Reflector diameter (cm)	133	118	110	103	98	94	90	88	86	84
Radial+Axial reflector mass (kg)	1176	981	878	801	739	692	656	629	608	591
Total mass (mT)	7.1	5.1	4.0	3.3	2.8	2.5	2.2	2.0	1.8	1.7

Table B.11d. Core characteristics for various assembly designs: **Mo-clad UO2 fuel**; Cladding thickness = **0.5 mm**; H2 flow gap = **0.75 mm**; Number of plates/assembly = 7 to 34; Axially symmetric power distribution [a]. Assumed peak-to-average fuel assembly power ratio = 1.35. No moderator blocks. – FA Identifier = number of fuel plates–fuel meat thickness–clad thickness–H2 gap thickness

Assembly identifier	7-9.4-0.5-0.75	10-6.0-0.5-0.75	13-4.2-0.5-0.75	16-3.1-0.5-0.75	19-2.3-0.5-0.75	22-1.8-0.5-0.75	25-1.4-0.5-0.75	28-1.0-0.5-0.75	31-0.8-0.5-0.75	34-0.5-0.5-0.75
T-H2-out = 2200 K	mH2 = 8.4 kg/s for 250 MW assuming T-H2-inlet = 350 K									
Pmax Plate (MW)	0.144	0.216	0.279	0.299	0.299	0.299	0.299	0.299	0.299	0.299
Pmax FA(MW)	1.01	2.16	3.63	4.78	5.68	6.58	7.48	8.37	9.27	10.17
U mass per FA (kg)	52.6	48.4	44.2	40.0	35.8	31.6	27.4	23.2	19.0	14.8
m-H2 (kg/s)	0.0262	0.0561	0.0946	0.1246	0.1479	0.1713	0.1947	0.2180	0.2414	0.2647
v-outlet (m/s) @ 4 MPa	186	280	362	388	388	388	388	388	388	388
# FA to meet TH constraints for 250 MW	336	157	93	71	59	51	45	40	36	33
U mass (kg) to meet TH constraints for 250 MW	17670	7582	4110	2823	2128	1622	1238	936	692	492
Mo mass (kg) to meet TH constraints for 250 MW	2542	1478	1051	929	893	867	847	832	819	809
Average power density (W/cm3)	145	312	525	692	822	952	1081	1211	1341	1471
Core diameter (cm) to meet TH constraints for 250 MW		126	102	84	77	72	68	65	61	58
Core + Reflector diameter (cm)		166	142	124	117	112	108	105	101	98
Radial+Axial reflector mass (kg)		1644	1291	1059	963	907	859	816	779	746
Total mass (mT)	>22.4	12.0	7.4	5.6	4.8	4.2	3.7	3.3	3.0	2.8
T-H2-out = 2100 K	mH2 = 8.9 kg/s for 250 MW assuming T-H2-inlet = 350 K									
Pmax Plate (MW)	0.158	0.227	0.306	0.390	0.470	0.542	0.546	0.546	0.546	0.546
Pmax FA(MW)	1.11	2.27	3.98	6.25	8.94	11.93	13.65	15.29	16.93	18.56
U mass per FA (kg)	52.6	48.4	44.2	40.0	35.8	31.6	27.4	23.2	19.0	14.8
m-H2 (kg/s)	0.0289	0.0591	0.1036	0.1627	0.2327	0.3108	0.3555	0.3981	0.4408	0.4834
v-outlet (m/s) @ 4 MPa	205	294	397	506	610	704	708	708	708	708
# FA to meet TH constraints for 250 MW	304	149	85	54	38	28	25	22	20	18
U mass (kg) to meet TH constraints for 250 MW	16022	7203	3750	2162	1353	894	678	512	379	269
Mo mass (kg) to meet TH constraints for 250 MW	2305	1404	959	712	568	478	464	456	449	443
Average power density (W/cm3)	160	328	576	904	1293	1727	1975	2212	2449	2686
Core diameter (cm) to meet TH constraints for 250 MW		124	93	74	62	54	50	48	46	44
Core + Reflector diameter (cm)		164	133	114	102	94	90	88	86	84
Radial+Axial reflector mass (kg)		1614	1176	926	792	694	656	629	608	591
Total mass (mT)	>20.4	11.5	6.7	4.4	3.2	2.5	2.2	2.0	1.8	1.7

Table B.12. Core characteristics for various assembly designs: **W-clad UN fuel**; Cladding thickness = **0.5 mm**; H2 flow gap = **0.5 mm**; Number of plates/assembly = 7 to 37; Axially symmetric power distribution [a]. Assumed peak-to-average fuel assembly power ratio = 1.35. No moderator blocks. – FA Identifier = number of fuel plates–fuel meat thickness–clad thickness–H2 gap thickness

Assembly identifier	7-9.6-0.5-0.5	10-6.3-0.5-0.5	13-4.5-0.5-0.5	16-3.4-0.5-0.5	19-2.6-0.5-0.5	22-2.0-0.5-0.5	25-1.6-0.5-075	28-1.3-0.5-0.5	31-1.0-0.5-0.5	34-0.8-0.5-0.5	37-0.6-0.5-0.5
T-H2-out = 2750 K	mH2 = 6.5 kg/s for 250 MW assuming T-H2-inlet = 350 K										
Pmax Plate (MW)	0.301	0.359	0.399	0.429	0.452	0.470	0.486	0.498	0.509	0.519	0.527
Pmax FA(MW)	2.11	3.59	5.19	6.86	8.58	10.35	12.14	13.96	15.79	17.64	19.50
U mass per FA (kg)	54.0	50.4	46.8	43.2	39.6	36.0	32.4	28.8	25.2	21.6	18.0
m-H2 (kg/s)	0.0549	0.0934	0.1351	0.1786	0.2235	0.2694	0.3161	0.3634	0.4112	0.4594	0.5079
v-outlet (m/s) @ 4 MPa	586	698	776	834	879	915	945	970	991	1009	1026
# FA to meet TH constraints for 250 MW	160	94	65	49	39	33	28	24	21	19	17
U mass (kg) to meet TH constraints for 250 MW	8644	4747	3046	2127	1558	1175	901	697	539	413	312
W mass (kg) to meet TH constraints for 250 MW	2296	1685	1395	1229	1122	1046	990	947	913	885	862
Average power density (W/cm3)	305	519	751	992	1242	1497	1756	2019	2285	2552	2822
Core diameter (cm) to meet TH constraints for 250 MW	131	102	80	71	64	58	53	50	47	45	44
Core + Refector diameter (cm)	171	142	120	111	104	98	93	90	87	85	84
Radial+Axial reflector mass (kg)	1716	1291	1006	891	807	740	689	650	622	600	584
Total mass (mT)	12.7	7.7	5.4	4.2	3.5	3.0	2.6	2.3	2.1	1.9	1.8
T-H2-out = 2550 K	mH2 = 7.1 kg/s for 250 MW assuming T-H2-inlet = 350 K										
Pmax Plate (MW)	0.473	0.563	0.627	0.674	0.710	0.740	0.763	0.783	0.800	0.815	0.827
Pmax FA(MW)	3.31	5.63	8.15	10.78	13.50	16.27	19.09	21.94	24.81	27.70	30.61
U mass per FA (kg)	54.0	50.4	46.8	43.2	39.6	36.0	32.4	28.8	25.2	21.6	18.0
m-H2 (kg/s)	0.1035	0.1760	0.2547	0.3370	0.4218	0.5085	0.5965	0.6855	0.7753	0.8657	0.9566
v-outlet (m/s) @ 4 MPa	1105	1315	1464	1574	1659	1727	1783	1829	1868	1902	1932
# FA to meet TH constraints for 250 MW	102	60	41	31	25	21	18	15	14	12	11
U mass (kg) to meet TH constraints for 250 MW	5503	3021	1939	1352	991	747	573	443	343	263	199
W mass (kg) to meet TH constraints for 250 MW	1462	1072	888	782	713	665	630	602	581	563	549
Average power density (W/cm3)	479	815	1179	1560	1953	2354	2761	3174	3589	4008	4429
Core diameter (cm) to meet TH constraints for 250 MW	102	77	65	57	51	47	44	42	41	40	40
Core + Refector diameter (cm)	142	117	105	97	91	87	84	82	81	80	80
Radial+Axial reflector mass (kg)	1291	967	826	726	659	615	587	568	555	546	539
Total mass (mT)	8.3	5.1	3.7	2.9	2.4	2.0	1.8	1.6	1.5	1.4	1.3

Table B.13a. Core characteristics for various assembly designs: **W-clad UN fuel**; Cladding thickness = **0.25 mm**; H2 flow gap = **1 mm**; Number of plates/assembly = 7 to 37; Axially symmetric power distribution [a]. Assumed peak-to-average fuel assembly power ratio = 1.35. No moderator blocks. – FA Identifier = number of fuel plates–fuel meat thickness–clad thickness–H2 gap thickness

Assembly identifier	7-9.6-0.25-1	10-6.3-0.25-1	13-4.5-0.25-1	16-3.4-0.25-1	19-2.6-0.25-1	22-2.0-0.25-1	25-1.6-0.25-1	28-1.3-0.25-1	31-1.0-0.25-1	34-0.8-0.25-1	37-0.6-0.25-1
T-H2-out = 2750 K	mH2 = 6.5 kg/s for 250 MW assuming T-H2-inlet = 350 K										
Pmax Plate (MW)	0.301	0.359	0.399	0.429	0.452	0.470	0.486	0.498	0.509	0.519	0.527
Pmax FA(MW)	2.11	3.59	5.19	6.86	8.58	10.35	12.14	13.96	15.79	17.64	19.50
U mass per FA (kg)	54.0	50.4	46.8	43.2	39.6	36.0	32.4	28.8	25.2	21.6	18.0
m-H2 (kg/s)	0.0549	0.0934	0.1351	0.1786	0.2235	0.2694	0.3161	0.3634	0.4112	0.4594	0.5079
v-outlet (m/s) @ 4 MPa	293	349	388	417	439	457	472	485	496	505	513
# FA to meet TH constraints for 250 MW	160	94	65	49	39	33	28	24	21	19	17
U mass (kg) to meet TH constraints for 250 MW	8644	4747	3046	2127	1558	1175	901	697	539	413	312
W mass (kg) to meet TH constraints for 250 MW	1622	1118	885	755	672	614	572	539	514	493	476
Average power density (W/cm3)	305	519	751	992	1242	1497	1756	2019	2285	2552	2822
Core diameter (cm) to meet TH constraints for 250 MW	131	102	80	71	64	58	53	50	47	45	44
Core + Refector diameter (cm)	171	142	120	111	104	98	93	90	87	85	84
Radial+Axial reflector mass (kg)	1716	1291	1006	891	807	740	689	650	622	600	584
Total mass (mT)	12.0	7.2	4.9	3.8	3.0	2.5	2.2	1.9	1.7	1.5	1.4
T-H2-out = 2550 K	mH2 = 7.1 kg/s for 250 MW assuming T-H2-inlet = 350 K										
Pmax Plate (MW)	0.473	0.563	0.627	0.674	0.710	0.740	0.763	0.783	0.800	0.815	0.827
Pmax FA(MW)	3.31	5.63	8.15	10.78	13.50	16.27	19.09	21.94	24.81	27.70	30.61
U mass per FA (kg)	54.0	50.4	46.8	43.2	39.6	36.0	32.4	28.8	25.2	21.6	18.0
m-H2 (kg/s)	0.1035	0.1760	0.2547	0.3370	0.4218	0.5085	0.5965	0.6855	0.7753	0.8657	0.9566
v-outlet (m/s) @ 4 MPa	553	658	732	787	829	863	891	915	934	951	966
# FA to meet TH constraints for 250 MW	102	60	41	31	25	21	18	15	14	12	11
U mass (kg) to meet TH constraints for 250 MW	5503	3021	1939	1352	991	747	573	443	343	263	199
W mass (kg) to meet TH constraints for 250 MW	1033	711	564	480	427	390	364	343	327	314	303
Average power density (W/cm3)	479	815	1179	1560	1953	2354	2761	3174	3589	4008	4429
Core diameter (cm) to meet TH constraints for 250 MW	102	77	65	57	51	47	44	42	41	40	40
Core + Refector diameter (cm)	142	117	105	97	91	87	84	82	81	80	80
Radial+Axial reflector mass (kg)	1291	967	826	726	659	615	587	568	555	546	539
Total mass (mT)	7.8	4.7	3.3	2.6	2.1	1.8	1.5	1.4	1.2	1.1	1.0

Table B.13b. Core characteristics for various assembly designs: **W-clad UO2 fuel**; Cladding thickness = **0.25 mm**; H2 flow gap = **1 mm**; Number of plates/assembly = 7 to 37; Axially symmetric power distribution [a]. Assumed peak-to-average fuel assembly power ratio = 1.35. No moderator blocks. – FA Identifier = number of fuel plates–fuel meat thickness–clad thickness–H2 gap thickness

Assembly identifier	7-9.6-0.25-1	10-6.3-0.25-1	13-4.5-0.25-1	16-3.4-0.25-1	19-2.6-0.25-1	22-2.0-0.25-1	25-1.6-0.25-1	28-1.3-0.25-1	31-1.0-0.25-1	34-0.8-0.25-1	37-0.6-0.25-1
T-H2-out = 2750 K	mH2 = 6.5 kg/s for 250 MW assuming T-H2-inlet = 350 K										
Pmax Plate (MW)	-	-	-	0.135	0.164	0.198	0.233	0.269	0.302	0.334	0.364
Pmax FA(MW)	-	-	-	2.15	3.11	4.35	5.83	7.52	9.37	11.36	13.46
U mass per FA (kg)	-	-	-	29.6	27.1	24.6	22.2	19.7	17.2	14.8	12.3
m-H2 (kg/s)	-	-	-	0.0560	0.0811	0.1133	0.1519	0.1958	0.2441	0.2959	0.3506
v-outlet (m/s) @ 4 MPa	-	-	-	131	159	192	227	261	294	325	354
# FA to meet TH constraints for 250 MW	-	-	-	157	108	78	58	45	36	30	25
U mass (kg) to meet TH constraints for 250 MW	-	-	-	4635	2937	1910	1282	884	621	439	309
W mass (kg) to meet TH constraints for 250 MW	-	-	-	2407	1852	1460	1189	1001	865	765	689
Average power density (W/cm3)	-	-	-	311	450	630	844	1088	1356	1644	1948
Core diameter (cm) to meet TH constraints for 250 MW	-	-	-	127	104	91	76	68	61	55	51
Core + Refector diameter (cm)	-	-	-	167	144	131	116	108	101	95	91
Radial+Axial reflector mass (kg)	-	-	-	1645	1325	1139	952	857	775	709	659
Total mass (mT)	-	-	-	8.7	6.1	4.5	3.4	2.7	2.3	1.9	1.7
T-H2-out = 2550 K	mH2 = 7.1 kg/s for 250 MW assuming T-H2-inlet = 350 K										
Pmax Plate (MW)	-	-	0.183	0.230	0.268	0.310	0.357	0.408	0.462	0.517	0.572
Pmax FA(MW)	-	-	2.38	3.68	5.10	6.82	8.92	11.43	14.33	17.59	21.17
U mass per FA (kg)	-	-	32.0	29.6	27.1	24.6	22.2	19.7	17.2	14.8	12.3
m-H2 (kg/s)	-	-	0.0620	0.0958	0.1328	0.1775	0.2323	0.2977	0.3732	0.4580	0.5512
v-outlet (m/s) @ 4 MPa	-	-	178	224	261	301	347	397	450	503	557
# FA to meet TH constraints for 250 MW	-	-	142	92	66	50	38	30	24	19	16
U mass (kg) to meet TH constraints for 250 MW	-	-	4541	2713	1793	1219	839	582	406	284	196
W mass (kg) to meet TH constraints for 250 MW	-	-	1930	1409	1131	932	778	658	566	494	439
Average power density (W/cm3)	-	-	344	532	738	986	1291	1654	2073	2545	3062
Core diameter (cm) to meet TH constraints for 250 MW	-	-	124	98	81	71	63	55	49	45	43
Core + Refector diameter (cm)	-	-	164	138	121	111	103	95	89	85	83
Radial+Axial reflector mass (kg)	-	-	1614	1234	1016	893	793	707	644	601	572
Total mass (mT)	-	-	8.1	5.4	3.9	3.0	2.4	1.9	1.6	1.4	1.2

Table B.14a. Core characteristics for various assembly designs: **W-clad UN fuel**; Cladding thickness = **0.25 mm**; H2 flow gap = **0.75 mm**; Number of plates/assembly = 7 to 43; Axially symmetric power distribution [a]. Assumed peak-to-average fuel assembly power ratio = 1.35. No moderator blocks. – FA Identifier = number of fuel plates–fuel meat thickness–clad thickness–H2 gap thickness

Assembly identifier	7-9.9-0.25-0.75	10-6.6-0.25-0.75	13-4.7-0.25-0.75	16-3.6-0.25-0.75	19-2.9-0.25-0.75	22-2.3-0.25-0.75	25-1.9-0.25-0.75	28-1.5-0.25-0.75	31-1.3-0.25-0.75	34-1.0-0.25-0.75	37-0.9-0.25-0.75	40-0.7-0.25-0.75	43-0.6-0.25-0.75
T-H2-out = 2750 K	mH2 = 6.5 kg/s for 250 MW assuming T-H2-inlet = 350 K												
Pmax Plate (MW)	0.298	0.353	0.393	0.422	0.444	0.462	0.476	0.489	0.499	0.508	0.516	0.523	0.529
Pmax FA(MW)	2.09	3.53	5.11	6.75	8.43	10.16	11.91	13.68	15.48	17.28	19.10	20.92	22.75
U mass per FA (kg)	55.4	52.4	49.4	46.4	43.4	40.4	37.4	34.4	31.4	28.4	25.4	22.4	19.4
m-H2 (kg/s)	0.0544	0.0920	0.1330	0.1757	0.2197	0.2645	0.3102	0.3564	0.4030	0.4500	0.4973	0.5448	0.5925
v-outlet (m/s) @ 4 MPa	387	458	510	547	576	599	618	634	647	659	669	678	686
# FA to meet TH constraints for 250 MW	162	95	66	50	40	33	28	25	22	20	18	16	15
U mass (kg) to meet TH constraints for 250 MW	8958	5006	3265	2322	1737	1343	1060	849	685	555	449	362	288
W mass (kg) to meet TH constraints for 250 MW	1643	1138	902	771	687	628	585	553	527	506	489	474	462
Average power density (W/cm3)	302	511	739	976	1220	1470	1723	1980	2239	2500	2763	3027	3292
Core diameter (cm) to meet TH constraints for 250 MW	131	102	81	71	64	58	54	50	48	46	44	43	42
Core + Refector diameter (cm)	171	142	121	111	104	98	94	90	88	86	84	83	82
Radial+Axial reflector mass (kg)	1716	1291	1015	897	814	746	694	655	626	604	587	574	564
Total mass (mT)	12.3	7.4	5.2	4.0	3.2	2.7	2.3	2.1	1.8	1.7	1.5	1.4	1.3
T-H2-out = 2550 K	mH2 = 7.1 kg/s for 250 MW assuming T-H2-inlet = 350 K												
Pmax Plate (MW)	0.468	0.555	0.617	0.663	0.698	0.726	0.749	0.768	0.785	0.798	0.811	0.821	0.830
Pmax FA(MW)	3.28	5.55	8.03	10.61	13.27	15.98	18.73	21.52	24.32	27.15	29.99	32.84	35.70
U mass per FA (kg)	55.4	52.4	49.4	46.4	43.4	40.4	37.4	34.4	31.4	28.4	25.4	22.4	19.4
m-H2 (kg/s)	0.1024	0.1736	0.2508	0.3315	0.4146	0.4993	0.5854	0.6724	0.7601	0.8484	0.9372	1.0263	1.1158
v-outlet (m/s) @ 4 MPa	729	864	961	1032	1087	1130	1166	1196	1221	1243	1262	1278	1292
# FA to meet TH constraints for 250 MW	103	61	42	32	25	21	18	16	14	12	11	10	9
U mass (kg) to meet TH constraints for 250 MW	5708	3186	2078	1477	1105	854	674	540	436	353	286	230	183
W mass (kg) to meet TH constraints for 250 MW	1047	724	574	490	437	399	372	351	335	322	311	302	294
Average power density (W/cm3)	474	803	1161	1535	1919	2312	2710	3113	3519	3928	4339	4751	5166
Core diameter (cm) to meet TH constraints for 250 MW	102	77	66	57	51	47	44	43	41	40	40	39	34
Core + Refector diameter (cm)	142	117	106	97	91	87	84	83	81	80	80	79	74
Radial+Axial reflector mass (kg)	1291	973	832	731	663	619	590	570	557	547	540	535	482
Total mass (mT)	8.0	4.9	3.5	2.7	2.2	1.9	1.6	1.5	1.3	1.2	1.1	1.1	1.0

Table B.14b. Core characteristics for various assembly designs: **W-clad UN fuel**; Cladding thickness = **0.25 mm**; H2 flow gap = **0.75 mm**; Number of plates/assembly = 7 to 43; Axially symmetric power distribution [**b**]. Assumed peak-to-average fuel assembly power ratio = 1.35. No moderator blocks. – FA Identifier = number of fuel plates–fuel meat thickness–clad thickness–H2 gap thickness

Assembly identifier	7-9.9-0.25-0.75	10-6.6-0.25-0.75	13-4.7-0.25-0.75	16-3.6-0.25-0.75	19-2.9-0.25-0.75	22-2.3-0.25-0.75	25-1.9-0.25-0.75	28-1.5-0.25-0.75	31-1.3-0.25-0.75	34-1.0-0.25-0.75	37-0.9-0.25-0.75	40-0.7-0.25-0.75	43-0.6-0.25-0.75
T-H2-out = 2750 K	mH2 = 6.5 kg/s for 250 MW assuming T-H2-inlet = 350 K												
Pmax Plate (MW)	0.389	0.472	0.524	0.563	0.593	0.617	0.637	0.653	0.667	0.679	0.689	0.698	0.706
Pmax FA(MW)	2.72	4.72	6.81	9.00	11.26	13.57	15.92	18.29	20.68	23.09	25.50	27.93	30.36
U mass per FA (kg)	55.4	52.4	49.4	46.4	43.4	40.4	37.4	34.4	31.4	28.4	25.4	22.4	19.4
m-H2 (kg/s)	0.0710	0.1230	0.1774	0.2344	0.2933	0.3534	0.4145	0.4763	0.5385	0.6012	0.6641	0.7273	0.7906
v-outlet (m/s) @ 4 MPa	505	612	680	730	769	800	826	847	865	881	894	906	916
# FA to meet TH constraints for 250 MW	124	71	50	37	30	25	21	18	16	15	13	12	11
U mass (kg) to meet TH constraints for 250 MW	6865	3747	2449	1741	1301	1005	793	635	513	415	336	271	216
W mass (kg) to meet TH constraints for 250 MW	1259	851	677	578	514	470	438	413	394	379	366	355	346
Average power density (W/cm3)	394	683	985	1302	1629	1964	2303	2646	2992	3340	3689	4040	4392
Core diameter (cm) to meet TH constraints for 250 MW	113	85	71	62	55	51	47	45	43	42	41	40	40
Core + Refector diameter (cm)	153	125	111	102	95	91	87	85	83	82	81	80	80
Radial+Axial reflector mass (kg)	1447	1070	894	789	712	657	620	594	575	562	552	545	540
Total mass (mT)	9.6	5.7	4.0	3.1	2.5	2.1	1.9	1.6	1.5	1.4	1.3	1.2	1.1
T-H2-out = 2550 K	mH2 = 7.1 kg/s for 250 MW assuming T-H2-inlet = 350 K												
Pmax Plate (MW)	-	0.616	0.683	0.734	0.774	0.806	0.832	0.853	0.871	0.886	0.899	0.911	0.921
Pmax FA(MW)	-	6.16	8.88	11.75	14.71	17.73	20.79	23.88	27.00	30.13	33.28	36.44	39.60
U mass per FA (kg)	-	52.4	49.4	46.4	43.4	40.4	37.4	34.4	31.4	28.4	25.4	22.4	19.4
m-H2 (kg/s)	-	0.1604	0.2314	0.3060	0.3830	0.4616	0.5414	0.6219	0.7031	0.7847	0.8666	0.9489	1.0314
v-outlet (m/s) @ 4 MPa	-	799	886	953	1004	1045	1079	1106	1130	1150	1167	1182	1195
# FA to meet TH constraints for 250 MW	-	55	38	29	23	19	16	14	13	11	10	9	9
U mass (kg) to meet TH constraints for 250 MW	-	2873	1877	1333	996	770	607	486	393	318	258	208	165
W mass (kg) to meet TH constraints for 250 MW	-	653	519	443	394	360	335	317	302	290	280	272	265
Average power density (W/cm3)	-	891	1285	1700	2128	2565	3008	3455	3906	4359	4815	5272	5730
Core diameter (cm) to meet TH constraints for 250 MW	-	74	63	54	49	45	43	41	40	40	39	39	38
Core + Refector diameter (cm)	-	114	103	94	89	85	83	81	80	80	79	79	78
Radial+Axial reflector mass (kg)	-	931	794	698	637	599	575	559	548	540	535	531	528
Total mass (mT)	-	4.5	3.2	2.5	2.0	1.7	1.5	1.4	1.2	1.1	1.1	1.0	1.0

Table B.14c. Core characteristics for various assembly designs: **W-clad UC fuel**; Cladding thickness = **0.25 mm**; H2 flow gap = **0.75 mm**; Number of plates/assembly = 7 to 43; Axially symmetric power distribution [a]. Assumed peak-to-average fuel assembly power ratio = 1.35. No moderator blocks. – FA Identifier = number of fuel plates–fuel meat thickness–clad thickness–H2 gap thickness

Assembly identifier	7-9.9-0.25-0.75	10-6.6-0.25-0.75	13-4.7-0.25-0.75	16-3.6-0.25-0.75	19-2.9-0.25-0.75	22-2.3-0.25-0.75	25-1.9-0.25-0.75	28-1.5-0.25-0.75	31-1.3-0.25-0.75	34-1.0-0.25-0.75	37-0.9-0.25-0.75	40-0.7-0.25-0.75	43-0.6-0.25-0.75
T-H2-out = 2550 K	mH2 = 7.1 kg/s for 250 MW assuming T-H2-inlet = 350 K												
Pmax Plate (MW)	-	0.180	0.193	0.202	0.209	0.214	0.218	0.221	0.224	0.226	0.228	0.230	0.231
Pmax FA(MW)	-	1.80	2.51	3.24	3.97	4.71	5.46	6.20	6.95	7.70	8.45	9.20	9.95
U mass per FA (kg)	-	46.5	43.8	41.1	38.5	35.8	33.2	30.5	27.8	25.2	22.5	19.9	17.2
m-H2 (kg/s)	-	0.0468	0.0653	0.0843	0.1034	0.1227	0.1421	0.1615	0.1810	0.2004	0.2200	0.2395	0.2590
v-outlet (m/s) @ 4 MPa	-	233	250	262	271	278	283	287	291	294	296	298	300
# FA to meet TH constraints for 250 MW	-	188	134	104	85	72	62	54	49	44	40	37	34
U mass (kg) to meet TH constraints for 250 MW	-	8719	5891	4291	3270	2566	2051	1660	1352	1104	900	729	584
W mass (kg) to meet TH constraints for 250 MW	-	2235	1837	1607	1458	1354	1278	1219	1173	1136	1105	1079	1057
Average power density (W/cm3)	-	260	363	468	575	682	789	897	1005	1114	1222	1331	1439
Core diameter (cm) to meet TH constraints for 250 MW	-	145	120	102	93	85	78	74	70	67	64	62	59
Core + Refector diameter (cm)	-	185	160	142	133	125	118	114	110	107	104	102	99
Radial+Axial reflector mass (kg)	-	1931	1548	1293	1176	1072	981	929	886	848	813	782	753
Total mass (mT)	-	12.9	9.3	7.2	5.9	5.0	4.3	3.8	3.4	3.1	2.8	2.6	2.4
T-H2-out = 2350 K	mH2 = 7.8 kg/s for 250 MW assuming T-H2-inlet = 350 K												
Pmax Plate (MW)	-	0.420	0.451	0.472	0.488	0.500	0.509	0.516	0.523	0.528	0.532	0.536	0.539
Pmax FA(MW)	-	4.20	5.86	7.55	9.27	10.99	12.72	14.46	16.20	17.94	19.69	21.43	23.18
U mass per FA (kg)	-	46.5	43.8	41.1	38.5	35.8	33.2	30.5	27.8	25.2	22.5	19.9	17.2
m-H2 (kg/s)	-	0.1094	0.1526	0.1967	0.2413	0.2862	0.3313	0.3765	0.4219	0.4673	0.5127	0.5582	0.6037
v-outlet (m/s) @ 4 MPa	-	545	585	612	633	648	660	670	678	684	690	695	699
# FA to meet TH constraints for 250 MW	-	80	58	45	36	31	27	23	21	19	17	16	15
U mass (kg) to meet TH constraints for 250 MW	-	3732	2523	1839	1402	1100	880	712	580	474	386	313	250
W mass (kg) to meet TH constraints for 250 MW	-	957	787	689	625	581	548	523	503	487	474	463	453
Average power density (W/cm3)	-	608	848	1093	1341	1590	1841	2092	2344	2596	2848	3101	3354
Core diameter (cm) to meet TH constraints for 250 MW	-	91	76	68	61	56	52	49	47	45	44	43	42
Core + Refector diameter (cm)	-	131	116	108	101	96	92	89	87	85	84	83	82
Radial+Axial reflector mass (kg)	-	1139	951	855	779	720	675	641	616	597	582	571	562
Total mass (mT)	-	5.8	4.3	3.4	2.8	2.4	2.1	1.9	1.7	1.6	1.4	1.3	1.3

Table B.14d. Core characteristics for various assembly designs: **W-clad UC fuel**; Cladding thickness = **0.25 mm**; H2 flow gap = **0.75 mm**; Number of plates/assembly = 7 to 43; Axially symmetric power distribution [**b**]. Assumed peak-to-average fuel assembly power ratio = 1.35. No moderator blocks. – FA Identifier = number of fuel plates–fuel meat thickness–clad thickness–H2 gap thickness

Assembly identifier	7-9.9-0.25-0.75	10-6.6-0.25-0.75	13-4.7-0.25-0.75	16-3.6-0.25-0.75	19-2.9-0.25-0.75	22-2.3-0.25-0.75	25-1.9-0.25-0.75	28-1.5-0.25-0.75	31-1.3-0.25-0.75	34-1.0-0.25-0.75	37-0.9-0.25-0.75	40-0.7-0.25-0.75	43-0.6-0.25-0.75
T-H2-out = 2550 K	mH2 = 7.1 kg/s for 250 MW assuming T-H2-inlet = 350 K												
Pmax Plate (MW)	-	0.294	0.315	0.331	0.343	0.351	0.358	0.363	0.367	0.371	0.374	0.376	0.378
Pmax FA(MW)	-	2.94	4.10	5.30	6.51	7.73	8.95	10.17	11.39	12.61	13.83	15.05	16.26
U mass per FA (kg)	-	46.5	43.8	41.1	38.5	35.8	33.2	30.5	27.8	25.2	22.5	19.9	17.2
m-H2 (kg/s)	-	0.0765	0.1067	0.1380	0.1696	0.2013	0.2331	0.2648	0.2966	0.3284	0.3601	0.3918	0.4236
v-outlet (m/s) @ 4 MPa	-	381	409	430	445	456	464	471	477	481	485	488	491
# FA to meet TH constraints for 250 MW	-	115	82	64	52	44	38	33	30	27	24	22	21
U mass (kg) to meet TH constraints for 250 MW	-	5340	3608	2621	1994	1564	1251	1012	825	674	550	446	357
W mass (kg) to meet TH constraints for 250 MW	-	1369	1125	982	889	825	779	744	716	693	675	659	646
Average power density (W/cm3)	-	425	593	767	942	1118	1295	1471	1648	1824	2001	2177	2353
Core diameter (cm) to meet TH constraints for 250 MW	-	114	91	79	72	67	62	58	55	52	50	48	47
Core + Refector diameter (cm)	-	154	131	119	112	107	102	98	95	92	90	88	87
Radial+Axial reflector mass (kg)	-	1461	1139	995	910	846	792	746	708	677	653	632	615
Total mass (mT)	-	8.2	5.9	4.6	3.8	3.2	2.8	2.5	2.2	2.0	1.9	1.7	1.6
T-H2-out = 2350 K	mH2 = 7.8 kg/s for 250 MW assuming T-H2-inlet = 350 K												
Pmax Plate (MW)	-	0.528	0.566	0.592	0.612	0.626	0.638	0.648	0.655	0.662	0.667	0.672	0.676
Pmax FA(MW)	-	5.28	7.35	9.47	11.62	13.78	15.95	18.13	20.31	22.50	24.69	26.88	29.07
U mass per FA (kg)	-	46.5	43.8	41.1	38.5	35.8	33.2	30.5	27.8	25.2	22.5	19.9	17.2
m-H2 (kg/s)	-	0.1374	0.1915	0.2467	0.3026	0.3589	0.4155	0.4722	0.5290	0.5859	0.6429	0.6999	0.7570
v-outlet (m/s) @ 4 MPa	-	685	734	768	793	813	828	840	850	858	865	872	877
# FA to meet TH constraints for 250 MW	-	64	46	36	29	24	21	19	17	15	14	13	12
U mass (kg) to meet TH constraints for 250 MW	-	2971	2011	1466	1118	877	702	568	463	378	308	249	200
W mass (kg) to meet TH constraints for 250 MW	-	762	627	549	498	463	437	417	401	389	378	369	362
Average power density (W/cm3)	-	764	1064	1371	1681	1994	2308	2623	2939	3255	3572	3889	4206
Core diameter (cm) to meet TH constraints for 250 MW	-	79	69	61	55	50	47	45	43	42	41	40	40
Core + Refector diameter (cm)	-	119	109	101	95	90	87	85	83	82	81	80	80
Radial+Axial reflector mass (kg)	-	997	865	771	702	653	619	595	578	565	555	548	542
Total mass (mT)	-	4.7	3.5	2.8	2.3	2.0	1.8	1.6	1.4	1.3	1.2	1.2	1.1

Table B.14e. Core characteristics for various assembly designs: **W-clad UO2 fuel**; Cladding thickness = **0.25 mm**; H2 flow gap = **0.75 mm**; Number of plates/assembly = 7 to 43; Axially symmetric power distribution [a]. Assumed peak-to-average fuel assembly power ratio = 1.35. No moderator blocks. – FA Identifier = number of fuel plates–fuel meat thickness–clad thickness–H2 gap thickness

Assembly identifier	7-9.9-0.25-0.75	10-6.6-0.25-0.75	13-4.7-0.25-0.75	16-3.6-0.25-0.75	19-2.9-0.25-0.75	22-2.3-0.25-0.75	25-1.9-0.25-0.75	28-1.5-0.25-0.75	31-1.3-0.25-0.75	34-1.0-0.25-0.75	37-0.9-0.25-0.75	40-0.7-0.25-0.75	43-0.6-0.25-0.75
T-H2-out = 2750 K	mH2 = 6.5 kg/s for 250 MW assuming T-H2-inlet = 350 K												
Pmax Plate (MW)	-	-	-	0.128	0.152	0.181	0.211	0.242	0.271	0.299	0.325	0.349	0.371
Pmax FA(MW)	-	-	-	2.05	2.90	3.98	5.28	6.76	8.40	10.15	12.01	13.95	15.97
U mass per FA (kg)	-	-	-	31.7	29.7	27.6	25.6	23.5	21.5	19.4	17.4	15.3	13.3
m-H2 (kg/s)	-	-	-	0.0534	0.0754	0.1037	0.1376	0.1762	0.2186	0.2644	0.3128	0.3634	0.4159
v-outlet (m/s) @ 4 MPa	-	-	-	166	198	235	274	313	351	387	421	452	482
# FA to meet TH constraints for 250 MW	-	-	-	165	117	85	64	50	40	33	28	24	21
U mass (kg) to meet TH constraints for 250 MW	-	-	-	5230	3460	2342	1635	1174	864	646	488	371	281
W mass (kg) to meet TH constraints for 250 MW	-	-	-	2538	1999	1602	1319	1118	971	861	777	711	658
Average power density (W/cm3)	-	-	-	296	419	576	764	979	1215	1469	1738	2019	2310
Core diameter (cm) to meet TH constraints for 250 MW	-	-	-	136	114	93	79	71	64	58	54	50	47
Core + Refector diameter (cm)	-	-	-	176	154	133	119	111	104	98	94	90	87
Radial+Axial reflector mass (kg)	-	-	-	1793	1457	1176	997	896	815	746	692	650	619
Total mass (mT)	-	-	-	9.6	6.9	5.1	4.0	3.2	2.6	2.3	2.0	1.7	1.6
T-H2-out = 2550 K	mH2 = 7.1 kg/s for 250 MW assuming T-H2-inlet = 350 K												
Pmax Plate (MW)	-	-	0.173	0.219	0.254	0.289	0.327	0.368	0.412	0.456	0.500	0.544	0.586
Pmax FA(MW)	-	-	2.25	3.51	4.83	6.36	8.18	10.32	12.76	15.51	18.51	21.76	25.21
U mass per FA (kg)	-	-	33.8	31.7	29.7	27.6	25.6	23.5	21.5	19.4	17.4	15.3	13.3
m-H2 (kg/s)	-	-	0.0585	0.0913	0.1259	0.1657	0.2130	0.2686	0.3324	0.4038	0.4821	0.5666	0.6566
v-outlet (m/s) @ 4 MPa	-	-	224	284	330	375	424	478	534	592	649	706	761
# FA to meet TH constraints for 250 MW	-	-	150	96	70	53	41	33	26	22	18	16	13
U mass (kg) to meet TH constraints for 250 MW	-	-	5075	3056	2073	1466	1056	770	568	423	317	238	178
W mass (kg) to meet TH constraints for 250 MW	-	-	2051	1483	1198	1003	852	733	639	564	504	456	417
Average power density (W/cm3)	-	-	325	507	699	920	1183	1492	1847	2243	2679	3148	3648
Core diameter (cm) to meet TH constraints for 250 MW	-	-	124	102	84	73	65	58	52	48	45	42	41
Core + Refector diameter (cm)	-	-	164	142	124	113	105	98	92	88	85	82	81
Radial+Axial reflector mass (kg)	-	-	1614	1291	1051	919	825	741	674	625	592	569	553
Total mass (mT)	-	-	8.7	5.8	4.3	3.4	2.7	2.2	1.9	1.6	1.4	1.3	1.1

Table B.15. Core characteristics for various assembly designs: **W-clad UN fuel**; Cladding thickness = **0.25 mm**; H2 flow gap = **0.5 mm**; Number of plates/assembly = 7 to 46; Axially symmetric power distribution [a]. Assumed peak-to-average fuel assembly power ratio = 1.35. No moderator blocks. – FA Identifier = number of fuel plates–fuel meat thickness–clad thickness–H2 gap thickness

Assembly identifier	7-10-0.25-0.5	10-6.8-0.25-0.5	13-5.0-0.25-0.5	16-3.9-0.25-0.5	19-3.1-0.25-0.5	22-2.5-0.25-0.5	25-2.1-0.25-0.5	28-1.8-0.25-0.5	31-1.5-0.25-0.5	34-1.3-0.25-0.5	37-1.1-0.25-0.5	40-0.9-0.25-0.5	43-0.8-0.25-0.5	46-0.7-0.25-0.5
T-H2-out = 2750 K	mH2 = 6.5 kg/s for 250 MW assuming T-H2-inlet = 350 K													
Pmax Plate (MW)	0.296	0.348	0.387	0.415	0.436	0.454	0.468	0.479	0.489	0.498	0.506	0.512	0.518	0.523
Pmax FA(MW)	2.07	3.48	5.03	6.64	8.29	9.98	11.69	13.42	15.17	16.93	18.71	20.49	22.27	24.07
U mass per FA (kg)	56.8	54.4	52.0	49.6	47.2	44.8	42.4	40.0	37.6	35.2	32.8	30.4	28.0	25.6
m-H2 (kg/s)	0.0539	0.0907	0.1310	0.1729	0.2160	0.2599	0.3045	0.3496	0.3951	0.4410	0.4871	0.5335	0.5800	0.6267
v-outlet (m/s) @ 4 MPa	575	678	753	807	849	883	910	933	952	969	984	996	1008	1018
# FA to meet TH constraints for 250 MW	163	97	67	51	41	34	29	25	22	20	18	16	15	14
U mass (kg) to meet TH constraints for 250 MW	9270	5272	3489	2522	1922	1516	1224	1006	837	702	592	501	424	359
W mass (kg) to meet TH constraints for 250 MW	1662	1158	920	786	701	642	599	566	540	519	501	487	474	464
Average power density (W/cm3)	299	504	728	961	1200	1444	1691	1942	2195	2450	2706	2964	3222	3482
Core diameter (cm) to meet TH constraints for 250 MW	131	102	82	72	65	59	54	51	48	46	44	43	42	41
Core + Refector diameter (cm)	171	142	122	112	105	99	94	91	88	86	84	83	82	81
Radial+Axial reflector mass (kg)	1716	1291	1024	903	820	752	700	660	630	608	590	577	566	558
Total mass (mT)	12.6	7.7	5.4	4.2	3.4	2.9	2.5	2.2	2.0	1.8	1.7	1.6	1.5	1.4
T-H2-out = 2550 K	mH2 = 7.1 kg/s for 250 MW assuming T-H2-inlet = 350 K													
Pmax Plate (MW)	0.463	0.548	0.608	0.652	0.686	0.713	0.736	0.754	0.770	0.783	0.794	0.805	0.813	0.821
Pmax FA(MW)	3.24	5.48	7.91	10.44	13.04	15.70	18.39	21.11	23.86	26.62	29.39	32.18	34.98	37.78
U mass per FA (kg)	56.8	54.4	52.0	49.6	47.2	44.8	42.4	40.0	37.6	35.2	32.8	30.4	28.0	25.6
m-H2 (kg/s)	0.1013	0.1711	0.2470	0.3262	0.4075	0.4905	0.5747	0.6597	0.7455	0.8318	0.9186	1.0057	1.0931	1.1807
v-outlet (m/s) @ 4 MPa	1082	1279	1420	1523	1602	1666	1717	1760	1797	1828	1855	1878	1899	1918
# FA to meet TH constraints for 250 MW	104	62	43	32	26	22	18	16	14	13	11	10	10	9
U mass (kg) to meet TH constraints for 250 MW	5914	3354	2221	1605	1222	964	778	640	532	446	377	319	270	229
W mass (kg) to meet TH constraints for 250 MW	1061	737	585	500	446	408	381	360	343	330	319	310	302	295
Average power density (W/cm3)	469	792	1144	1510	1887	2271	2661	3054	3451	3851	4253	4656	5060	5466
Core diameter (cm) to meet TH constraints for 250 MW	102	78	66	58	52	47	45	43	41	40	40	40	40	34
Core + Refector diameter (cm)	142	118	106	98	92	87	85	83	81	80	80	80	80	74
Radial+Axial reflector mass (kg)	1291	979	838	737	668	623	593	573	559	549	542	544	544	482
Total mass (mT)	8.3	5.1	3.6	2.8	2.3	2.0	1.8	1.6	1.4	1.3	1.2	1.2	1.1	1.0

Appendix C. Fuel thermal conductivities

The average fuel thermal conductivities used in the heat removal scoping studies are simply evaluated from thermal conductivity integrals available in the literature.

UO2: k_f = Int (3120 K) – Int (873 K) ÷ (3120 – 873) = 2.53 W/m-K
UN: k_f = Int (2300 K) – Int (873 K) ÷ (2300 – 873) = 24.8 W/m-K
UC: k_f = Int (2573 K) – Int (873 K) ÷ (2573 – 873) = 44.8 W/m-K

Source: Thermophysical Properties of Materials for Nuclear Engineering, IAEA (2008)

UO2				**UN**				**UC**			
T (K)	kg/m3	k (W/m-K)	Int (W/m)	T (K)	kg/m3	k (W/m-K)	Int (W/m)	T (K)	kg/m3	k (W/m-K)	Int (W/m)
300	10950	7.59	53	298	14330	13	64.8	298	13500	25.3	127
373	10930	6.83	579	373	14310	14.2	1806	373	13460	24.5	1991
473	10900	5.98	1280	473	14278	15.6	2831	473	13420	23.6	4392
573	10870	5.3	1780	573	14245	16.8	4450	573	13370	23.1	6728
673	10830	4.74	2282	673	14211	17.9	6184	673	13320	23	9030
773	10800	4.28	2732	773	14176	18.9	8021	773	13270	23.1	11332
873	10770	3.89	3140	850	14148	19.6	9501	873	13220	23.6	13666
973	10740	3.55	3511	873	14140	19.8	9954	973	13170	24.4	16065
1073	10700	3.26	3851	973	14103	20.6	11975	1073	13120	25.6	18560
1173	10670	3.01	4165	1000	14093	20.9	12536	1173	13070	27	21186
1273	10630	2.79	4455	1073	14065	21.4	14079	1273	13010	28.8	23974
1373	10590	2.61	4724	1173	14027	22.2	16261	1373	12960	30.9	26957
1473	10560	2.45	4977	1273	13987	22.9	18517	1473	12900	33.4	30167
1573	10520	2.32	5215	1373	13946	23.6	20843	1573	12840	36.1	33638
1673	10470	2.22	5442	1473	13904	24.3	23236	1673	12790	39.2	37402
1773	10430	2.14	5659	1573	13862	24.9	25693	1773	12730	42.6	41491
1873	10380	2.09	5871	1673	13818	25.5	28213	1873	12670	46.4	45936
1973	10330	2.06	6078	1700	13806	25.7	28902	1973	12610	50.4	50775
2073	10280	2.06	6284	1773	13773	26.1	30790	2073	12550	54.8	56036
2173	10230	2.08	6491	1800	13761	26.2	31946	2173	12490	59.6	61752
2273	10170	2.12	6702	1873	13728	26.6	33246	2273	12420	64.6	67957
2373	10110	2.18	6917	1900	13715	26.8	34147	2373	12350	70	74683
2473	10050	2.26	7138	1973	13681	27.2	36117	2473	12290	75.7	81963
2573	9982	2.35	7369	2073	13633	27.7	38862	2573	12220	81.7	89828
2673	9912	2.45	7608	2173	13585	28.2	41660				
2773	9839	2.56	7859	2273	13535	28.7	44507				
2873	9762	2.68	8120	2300	13522	28.9	45285				
2973	9681	2.8	8394								
3073	9596	2.93	8681								
3120	9555	2.99	8820								

Appendix D. Hydrogen heat transfer coefficient

The hydrogen heat transfer coefficient is obtained using the Dittus-Bolter correlation.

$$h_{H2}D_h/k_{H2} = Nu = 0.023 \cdot Re^{0.8} \cdot Pr^{0.4} \text{ with } Pr = 0.7$$

In order to evaluate Reynolds numbers, inlet and outlet hydrogen velocities were calculated for two fuel assemblies. One with 16 plates and a relatively high-power density (1820 W/cm3) and another one with 43 plates and a very high-power density (5459 W/cm3). Hydrogen heat transfer coefficient appears to increase as it heats up and accelerates in the core. Despite significant geometric differences between the two assemblies, the heat transfer coefficients are similar and vary between about 1.3-1.4 W/cm^2-K at the inlet and 3.1-3.4 W/cm^2-K at the outlet.

FA Identifier = number of fuel plates–fuel meat thickness–clad thickness–H2 gap thickness	16-3.6-0.25-0.75	43-0.6-0.25-0.75
duct inside dimension (cm)	7.8	7.8
H2 channels width (cm)	0.075	0.075
H2 hydraulic diameter (cm)	0.15	0.15
H2 flow area (cm2)	9.36	25.155
fuel height (cm)	80	80
number of plates	16	43
Av. Power per FA (MW)	8.86	26.57
Av H2 mass flow per FA (kg/s)	0.231	0.692
P (MPa)	4	4
Average heat flux (W/cm2)	444	495
average power density (W/cm3)	1820	5459
dH2 (kg/m3) @ 400 K (inlet)	2.379	
v-H2 (m/s) @ 400 K (inlet)	103.6	115.6
dH2 (kg/m3) @ 1600 K (mid-plane)	0.6029	
v-H2 (m/s) @ 1600 K (mid-plane)	408.9	456.2
dH2 (kg/m3) @ 2800 K (outlet)	0.3431	
v-H2 (m/s) @ 2800 K (outlet)	718.5	801.7
Viscosity @ 400K (m2/s) (inlet)	4.59E-06	
Viscosity @ 1600K (m2/s) (mid-plane)	4.65E-05	
Viscosity @ 2800K (m2/s) (outlet)	1.19E-04	
Re @ 400K (inlet)	33,899	37,826
Re @ 1600K (mid-plane)	13,203	14,733
Re @ 2800K (outlet)	9,056	10,106
Nu @ 400K (inlet)	83.9	91.6
Nu @ 1600K (mid-plane)	39.5	43.1
Nu @ 2800K (outlet)	29.2	31.9
k @ 400K (W/cm-K) (inlet)	2.31E-03	
k @ 1600K (W/cm-K) (mid-plane)	6.57E-03	
k @ 2800K (W/cm-K) (outlet)	1.61E-02	
h @ 400K (W/cm2-K) (inlet)	1.292	1.411
h @ 1600K (W/cm2-K) (mid-plane)	1.728	1.886
h @ 2800K (W/cm2-K) (outlet)	3.132	3.419

H2 data from “Selected Properties of Hydrogen (Engineering Design Data), McCarthy, Hord, Roder”

TABLE 8

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THERMODYNAMIC PROPERTIES OF NORMAL HYDROGEN (ISOBARS, SI UNITS)

4.00 MPA ISOBAR

TEMPERATURE K	DENSITY KG/CU M	CP KJ / KG-K	THERMAL CONDUCTIVITY W/K-M X 10^3	VISCOSITY KG/M-S X 10^7
140.	6.7673	12.89	99.99	54.14
160.	5.9050	13.23	112.22	59.03
180.	5.2440	13.53	124.34	63.79
200.	4.7197	13.78	136.11	68.41
220.	4.2927	13.98	147.43	72.90
240.	3.9379	14.14	158.25	77.28
260.	3.6382	14.26	168.60	81.55
280.	3.3814	14.35	178.50	85.72
300.	3.1584	14.41	188.00	89.81
350.	2.7134	14.49	210.28	99.66
400.	2.3790	14.52	230.95	109.08
450.	2.1183	14.53	250.49	118.13
500.	1.9092	14.54	269.25	126.86
550.	1.7378	14.55	287.46	135.32
600.	1.5947	14.56	305.29	143.53
650.	1.4734	14.58	322.89	151.53
700.	1.3693	14.61	340.34	159.33
750.	1.2790	14.65	357.71	166.96
800.	1.1998	14.70	375.06	174.43
850.	1.1299	14.76	392.42	181.76
900.	1.0677	14.83	409.84	188.96
950.	1.0119	14.90	427.33	196.04
1000.	.9617	14.99	444.90	203.01
1100.	.8750	15.17	475.56	216.65
1200.	.8025	15.37	511.01	229.92
1300.	.7412	15.58	546.90	242.87
1400.	.6886	15.80	583.20	255.54
1500.	.6429	16.03	619.89	267.93
1600.	.6029	16.25	656.59	280.08
1700.	.5677	16.47	693.79	292.00
1800.	.5363	16.70	731.94	303.70
2000.	.4828	17.21	814.69	326.46
2200.	.4389	17.92	917.70	344.92
2400.	.4022	19.02	1062.13	366.33
2600.	.3707	20.75	1279.42	387.41
2800.	.3431	23.39	1609.45	408.39
3000.	.3184	27.21	2096.71	429.59

Appendix E. Neutronics – Straight plate designs

1.0 OBJECTIVE and SCOPE

The objective of the neutronics analysis is to determine the limit of using LEU fuel (U-235 content less than 19.75%) with the number of fuel assemblies obtained from the heat-removal analysis discussed in Appendix B for various of assembly designs discussed in Appendix A. For this scoping study, the criticality requirement of k-effective=1.02 is used. The impacts of following parameters on core reactivity are discussed.

- Enrichment of U-235 in fuel and W-184 in tungsten
- H2 outlet temperature
- Fuel (UN, UC, and UO2) materials
- Moderation with W, Mo, and enriched W cladding materials

2.0 COMPUTATIONAL MODELS

The MCNP6 code [1] is used for performing the neutronic calculations. MCNP models for various assembly designs were built to determine whether these designs fulfill the criticality requirement. Figure E.1 gives the examples of the radial layout of assemblies with 13 and 19 plates. The square fuel assembly is designed with a duct dimension of 8-cm. The thickness of fuel plates depends on geometrical design parameters such as the number of fuel plates, thickness of cladding, etc. The general assembly and core design parameters are summarized in Table E.1.

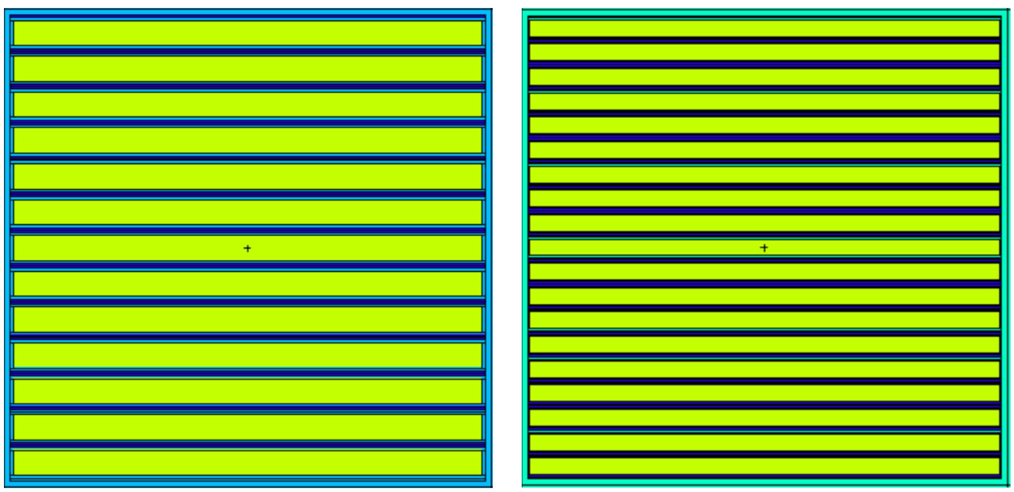

Figure E.1. Examples of the MCNP assembly model with 13 and 19 fuel plates (x-y view, 8x8 cm).

Table E.1. Straight-plate-fuel core dimensions and parameters.

Assembly design parameters		Core design parameters	
Duct outer, cm	8	Inner SS core container, cm	0.5
Thickness of duct, cm	0.1	Radial Be reflector, cm	20
Thickness of Mo cladding, mm	0.5	Center crescent-shape of B4C, cm	4
Thickness of W cladding, mm	0.5/0.25	Outer SS system container, cm	2
Thickness of H2 flow channel, mm	0.5/0.75/0.1	Active core height, cm	80
		Axial upper Be reflector, cm	20

*: note that the # of plates per FA, # of FAs, and diameter of core/system vary with designs

Figure E.2 shows the example of layouts of the core with 45 fuel assemblies. In the MCNP models, the 20-cm upper axial reflector is modeled with 90% of Be and 10% of H2 and the 20-cm lower axial reflector is modeled with 90% void and 10% of H2. The active core height is 80-cm and the total core height is 120-cm. The core diameter depends on the number of fuel assemblies determined from the heat-removal analysis. The core is surrounded by a 20-cm radial Be reflector containing 12 rotatable control drums. Each Be control drum contains a crescent-shape of B4C (90% enriched B-10) with a maximum thickness of 4-cm. The radial reflector is located in between a 0.5-cm inner SS-316 core container and a 2-cm outer SS-316 system container. Note that in the current MCNP models, the height of the radial reflector is 120-cm but it can be reduced to 80-cm as that of the active core height. The impact of this change on core criticality is expected to ineffective and this should not change any technical findings of this study.

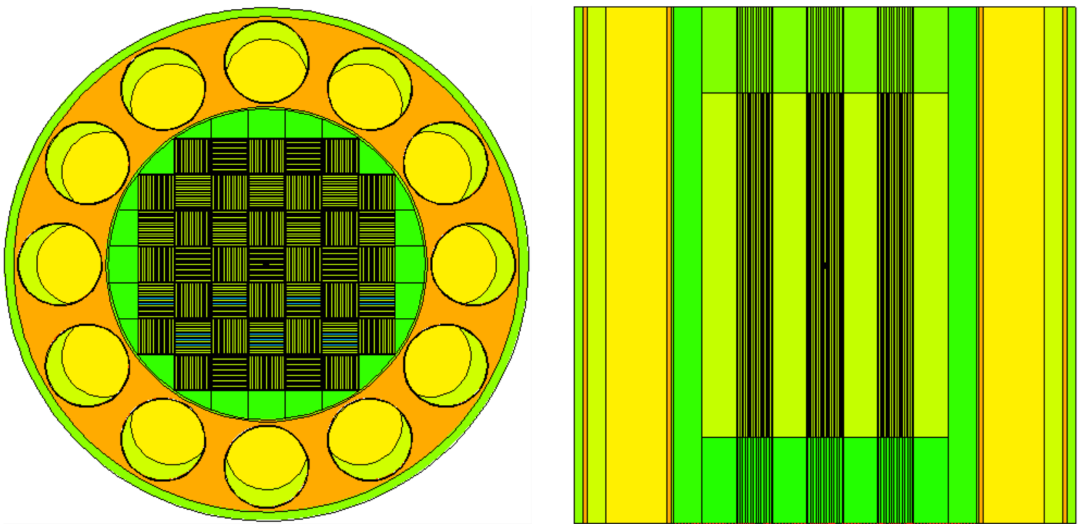

Figure E.2. An example of the MCNP core model (120x120 cm) with 45 fuel assemblies. The center point for the left-hand radial model (xy-view) and the right-hand axial model (yz-view) is (0, 0, 60) cm.

Table E.2 presents the number densities for the materials used in MCNP calculations. The temperature shown in Table E.2 corresponds to the temperature for the MCNP neutron cross-section data libraries. The number density of hydrogen assumes a temperature of 1200 K and 4 MPa. The number densities for fuel materials assume a temperature of 2000 K.

Table E.2. Material number densities (atom/barn-cm) used in the calculations.

material	Number density	material	Number density	material	Number density
H2 (1200K)		W (900K)		SS-316 (600K)	
H-1	4.7952E-04	W-182	1.6754E-02	Fe-54	3.2697E-03
UN (19.75 % U-235) (1200K)		W-183	9.0470E-03	Fe-56	5.1327E-02
U-235	6.2524E-03	W-184	1.9371E-02	Fe-57	1.1854E-03
U-238	2.5084E-02	W-186	1.7974E-02	Fe-58	1.5775E-04
N-14	3.1223E-02	Be (600K)		Cr-50	6.7739E-04
N-15	1.1407E-04	Be-9	1.2349E-01	Cr-52	1.3063E-02
UC (19.75 % U-235) (1200K)		BeO (1200K)		Cr-53	1.4812E-03
U-235	5.8310E-03	Be-9	6.8860E-02	Cr-54	3.6870E-04
U-238	2.3394E-02	O-16	6.8860E-02	Ni-58	6.6375E-03
C-12	2.9225E-02	ZrH1.6 (900K)		Ni-60	2.5568E-03
UO2 (19.75 % U-235) (1200K)		H-1	5.8226E-02	Ni-61	1.1114E-04
U-235	4.4223E-03	Zr-90	1.8723E-02	Ni-62	3.5436E-04

U-238	1.7742E-02	Zr-91	4.0831E-03	Ni-64	9.0246E-05
O-16	4.4329E-02	Zr-92	6.2411E-03	Mo-92	1.8402E-04
Mo (900K)		Zr-94	6.3248E-03	Mo-94	1.1470E-04
Mo-92	9.5208E-03	Zr-96	1.0190E-03	Mo-95	1.9741E-04
Mo-94	5.9345E-03	ZrC40 (60% porous) (900K)		Mo-96	2.0683E-04
Mo-95	1.0214E-02	B-10	7.4348E-10	Mo-97	1.1842E-04
Mo-96	1.0701E-02	B-11	2.7218E-09	Mo-98	2.9921E-04
Mo-97	6.1270E-03	C-12	1.5721E-03	Mo-100	1.1941E-04
Mo-98	1.5481E-02	Zr-90	8.2072E-04	Mn-55	1.7400E-03
Mo-100	6.1783E-03	Zr-91	1.7700E-04	Si-28	1.5679E-03
B4C (900K)		Zr-92	2.6761E-04	Si-29	7.9614E-05
B-10	1.0474E-01	Zr-94	2.6542E-04	Si-30	5.2482E-05
B-11	1.0585E-02	Zr-96	4.1868E-05		
C-12	2.8831E-02				

3.0 REFERENCE

[1] Christopher. J. Werner (editor), MCNP USER'S MANUAL, Code Version 6.2, LA-UR-17-29981, Rev. 0, Los Alamos National Laboratory (2017).

Appendix F. Flow induced vibrations – Straight plate designs

1.0 Scope and Brief Introduction

Plate-type fuel is currently being explored for use in the reactor core of a nuclear thermal propulsion (NTP) rocket engine. Questions have been raised about the potential for flow-induced vibration of the fuel plates. The primary sources of flow induced vibrations are from vortices shedding from bluff bodies and boundary layer separation in turbulent flows. If the rate that these flow phenomena are occurring coincides with the natural frequencies of the structural components (i.e. fuel plates) the vibrations will quickly amplify (resonance) and may cause failure of the structural components. This preliminary analysis will evaluate the natural frequencies of the fuel plates with the finite element analysis (FEA) code, Abaqus [1] and compare them to the frequency that vortices will be shedding from the trailing edges (coolant outlet) of the fuel plates. To evaluate the vortex shedding frequency a computational fluid dynamics (CFD) model was built in the CFD code, Star-CCM+ [2].

2.0 NTP Fuel Element Description

A 3D-CAD model of the NTP fuel element is shown in Figure 1. The element is 8 cm by 8 cm by 80 cm and contains 16 fuel plates. The 4.125 mm fuel plates contain 3.125 mm of uranium nitride (UN) fuel surrounded by 0.5 mm of molybdenum cladding. The fuel plates are separated by 0.075 mm molybdenum spacers (5 in each coolant channel) and hydrogen coolant flows between the plates.

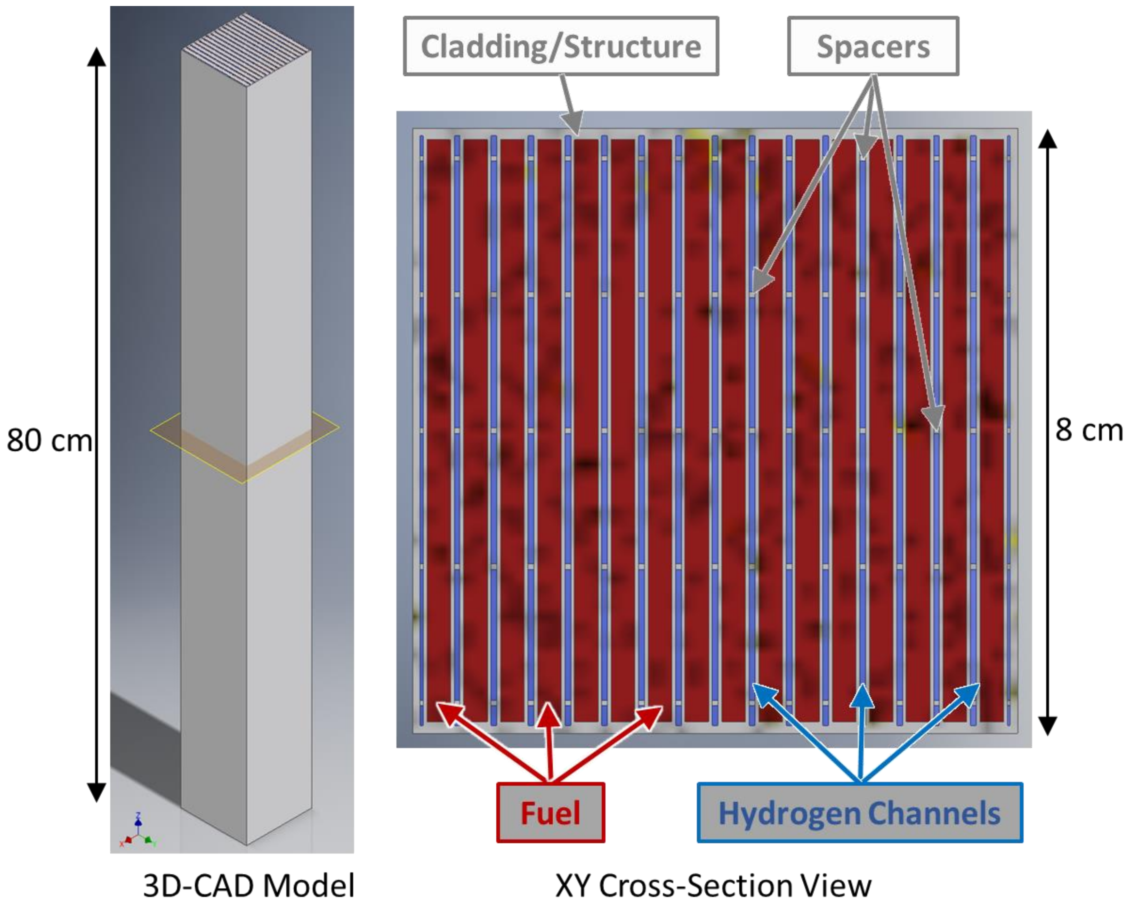

Figure 1. 3D-CAD model of the NTP fuel element.

3.0 General Modeling Assumptions

1. No fluid damping due to the hydrogen coolant was considered in the natural frequency calculations.

2. The fuel plates were assumed to be at a constant uniform temperature in the natural frequency calculations.

3. All solid materials were assumed to be elastic and did not include non-linear material properties, such as plasticity.

4. Steady state was assumed in all models except for the Star-CCM+ model.

5. The viscosity, density, thermal conductivity, and heat capacity of the hydrogen coolant were specified to vary with temperature in the Star-CCM+ model.

6. A Reynolds-Averaged Navier-Stokes turbulence model was used to model the turbulent flow in the Star-CCM+ model.

4.0 Model Development

4.1 Analytic Modeling

Initially, natural frequencies of simplified geometries were calculated using analytic formulas. These analytic calculations will be compared to the natural frequencies computed in Abaqus to provide greater confidence in the Abaqus results. The vortex shedding frequency was also estimated using the Strouhal number. This helped guide the size of the time step to use in the Star-CCM+ model.

4.1.1 Natural Frequency of a Flat Plate

Since the geometry of the entire NTP fuel element is complex to calculate the natural frequency analytically, the geometry was simplified to a single unfueled plate. Figure 2 details the dimensions and boundary conditions that were assumed for the simplified geometry. The edges along the length of the plate were assumed to be clamped (i.e. fixed) and the leading and trailing edges along the width of the plate were assumed to be free.

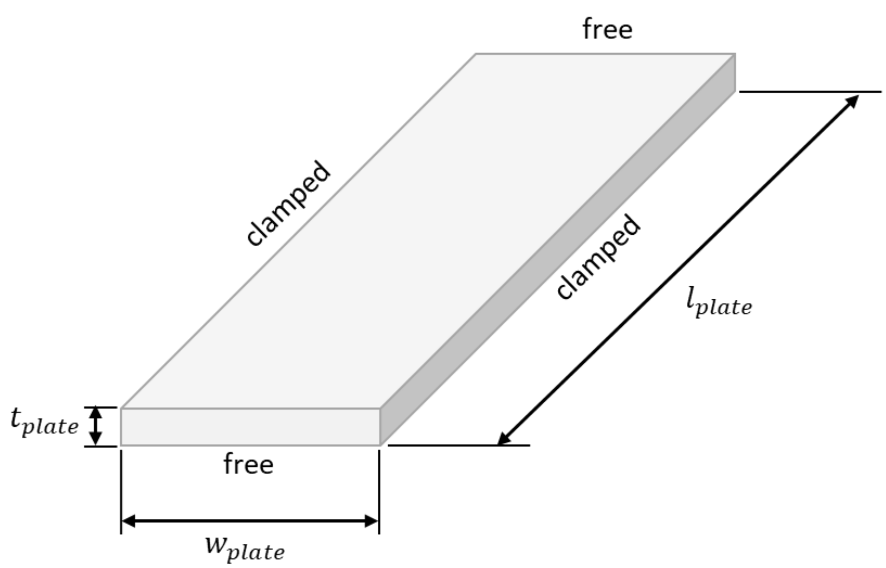

Figure 2. Dimensions and boundary conditions for natural frequency calculation of a plate.

The natural frequency of a plate was calculated using:

$$f_{ij} = \frac{\lambda_{ij}^2}{2\pi {w_{plate}}^2}\left(\frac{E t_{plate}^2}{12\rho(1-\upsilon^2)}\right)^{1/2} \tag{1}$$

where w_{plate}, is the width of the plate; t_{plate}, is the thickness of the plate; E, is the elastic modulus of the plate material, υ, is Poisson's ratio, γ, is the mass density of the plate, and λ_{ij} is a dimensionless parameter which is a function of the mode indices i and j, Poisson's ratio, the plate geometry, and the boundary conditions on the plate. The mode indices, i and j, for a rectangular plate are the number of half-waves in the mode shape along the horizontal (width) and vertical (length) axes of the plate, respectively. This analysis focuses on the fundamental natural frequency (i.e. the first mode) of the plate where

$$\lambda_{11} = \sqrt{22.3} \tag{2}$$

These equations are from Table 11-4 in Formulas for Natural Frequency and Mode Shape by Blevins [2].

4.1.2 Vortex Shedding Frequency

Vortex shedding is a flow phenomenon that occurs when a fluid flows around a bluff body causing vortices to form and periodically shed into the wake behind the body. These shedding vortices can significantly load the body if the frequency of the vortex shedding coincides with the natural frequencies of the body. The dimensionless Strouhal number is used to estimate the frequency at which vortex shedding will occur and is described by:

$$S = \frac{f_v L_c}{V} \tag{3}$$

where S is the Strouhal number, f_v is the frequency of the vortex shedding, L_c is the characteristic length, and V is the velocity of the fluid flow [3]. For this analysis, the vortex shedding frequency will be evaluated with the characteristic length equal to the plate thickness as well as the hydraulic diameter of the hydrogen coolant channels. According to Fluid-Dynamic Drag by Horner, the Strouhal number varies from about 0.11 to 0.21 for plates (Figure 7 in [3]).

4.2 Abaqus Modeling

4.2.1 Single Plate Model

A model of a single fuel plate was built in Abaqus as shown in Figure 3. The geometry in Figure 3 shows cross section cuts perpendicular to the X and Y axes revealing the fuel (red) inside the cladding (grey). Two models were completed: one with the same material definitions in the fuel and the cladding (i.e. a homogeneous plate) and one with separate material definitions in the two regions (i.e. a fueled plate). The first model was completed to have a direct comparison to the analytic model described by Equations (1) and (2) in the previous section. This comparison will help validate the Abaqus model's results and provide more confidence in the results of the more complicated Abaqus models of the full NTP element which are too complicated to model analytically. The second model was completed to reveal how the natural frequencies vary when the plate contains fuel.

The cladding is molybdenum and the fuel is uranium nitride. To calculate modal frequencies the density and stiffness properties (elastic modulus and Poisson's ratio) of these materials are required and are detailed in Table 1 [4] [5] [6]. The properties of uranium nitride in Table 1 are at 1473 K (the highest temperature available for the elastic properties in [6]) and the properties of molybdenum in Table 1 are at ~2000 K.

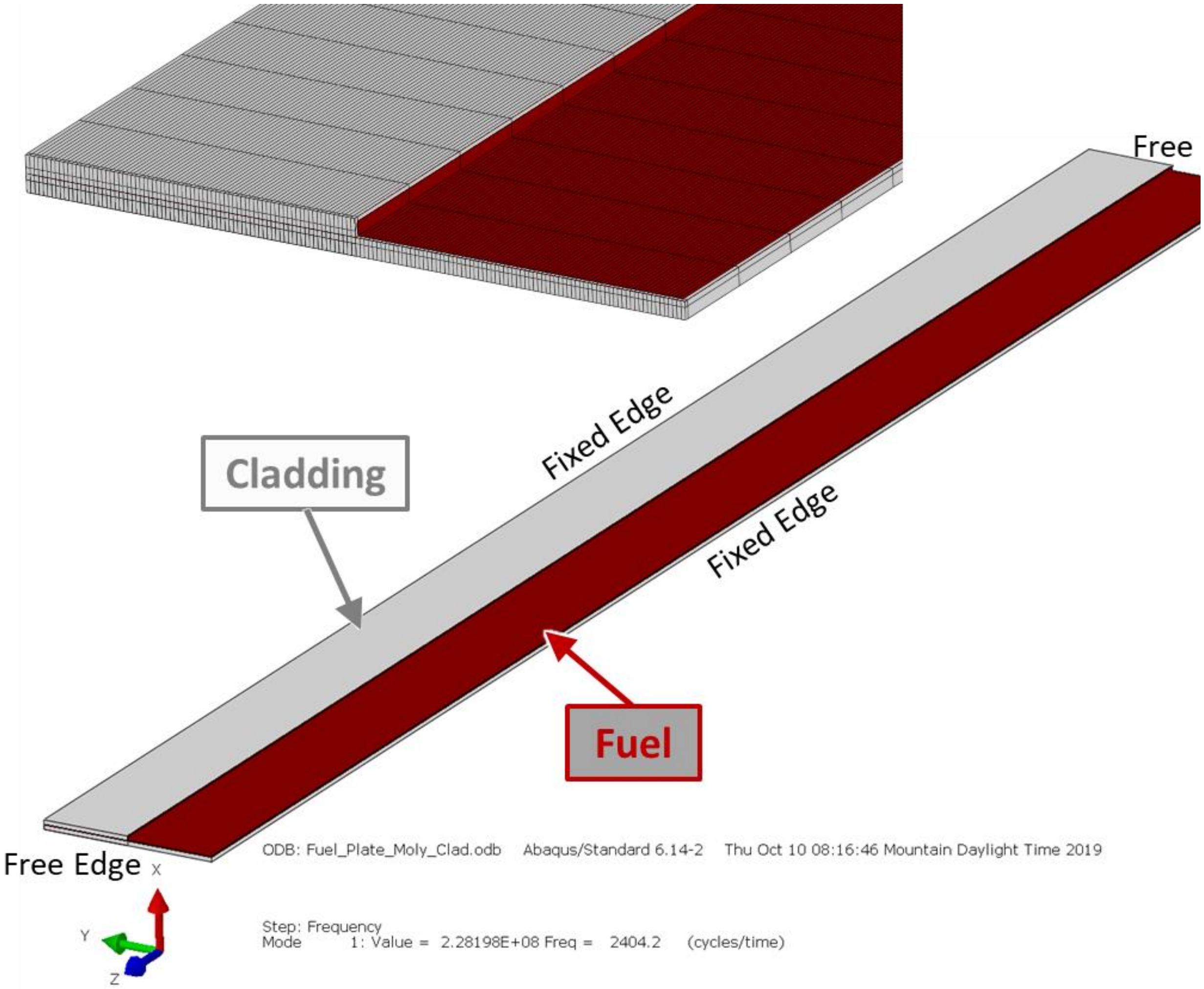

Figure 3. Geometry, mesh, and boundary conditions for single plate Abaqus model.

Table 1. Material properties for molybdenum and uranium nitride [4] [5] [6].

Material	Mass Density	Elastic Modulus	Poisson's Ratio
	kg/m^3	GPa	(-)
Molybdenum	10,280	103.4	0.31
Uranium Nitride	13,904	208.7	0.26

4.2.2 Fuel Element Model

The Abaqus model of the fuel element is shown in Figure 4. This model contains 16 of the fuel plates from the single plate model, the exterior element structure (green part in Figure 4), and 5 spacers in each of the coolant channels between the fuel plates. The exterior faces of the element structure (green part in Figure 4) were fixed in the X, Y, and Z directions. Tie constraints were created between all the parts in the model to rigidly tie the parts together. A model with and without the channel spacers was completed to understand how the spacers affect the frequency response of the fuel element.

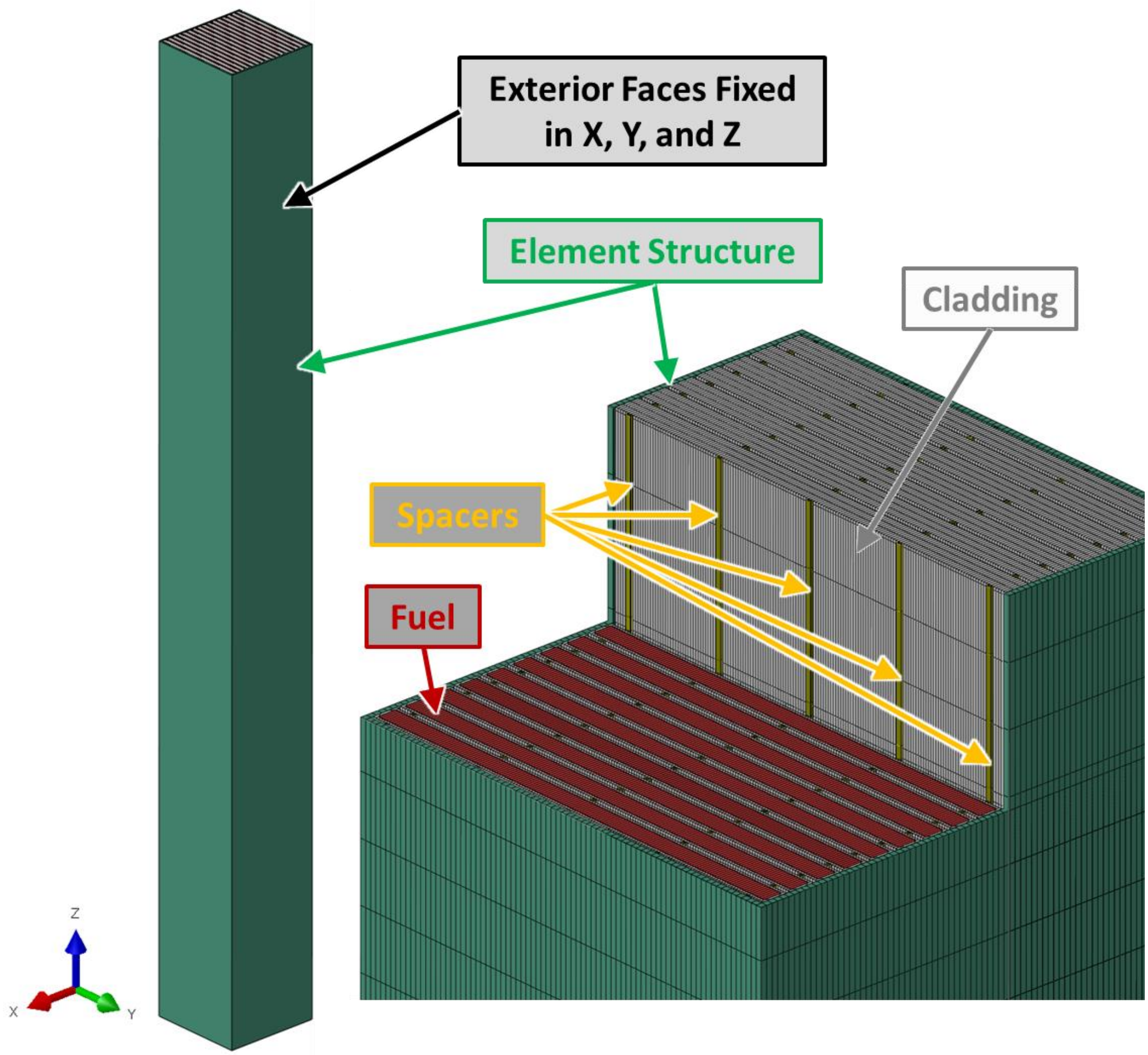

Figure 4. Geometry, mesh, and boundary conditions for full element Abaqus model.

4.3 Star-CCM+ Fluid Model

The purpose of building a CFD model in Star-CCM+ model was to capture the rate that vortex shedding will occur at the trailing edge of the fuel plates. To accomplish this a transient model was completed with a time step of 2.5 microseconds. This yields a sampling frequency of 400 kHz and a Nyquist frequency of 200 kHz. The fluid pressure was recorded at point probes (red points in Figure 5) near the fuel plate's trailing edges after each time step. The frequency spectra at these points were then obtained using a discrete Fourier transform. Figure 5 also shows the one quarter geometry that was modeled since the fuel element is symmetric in the XZ and YZ planes as well as the boundary conditions.

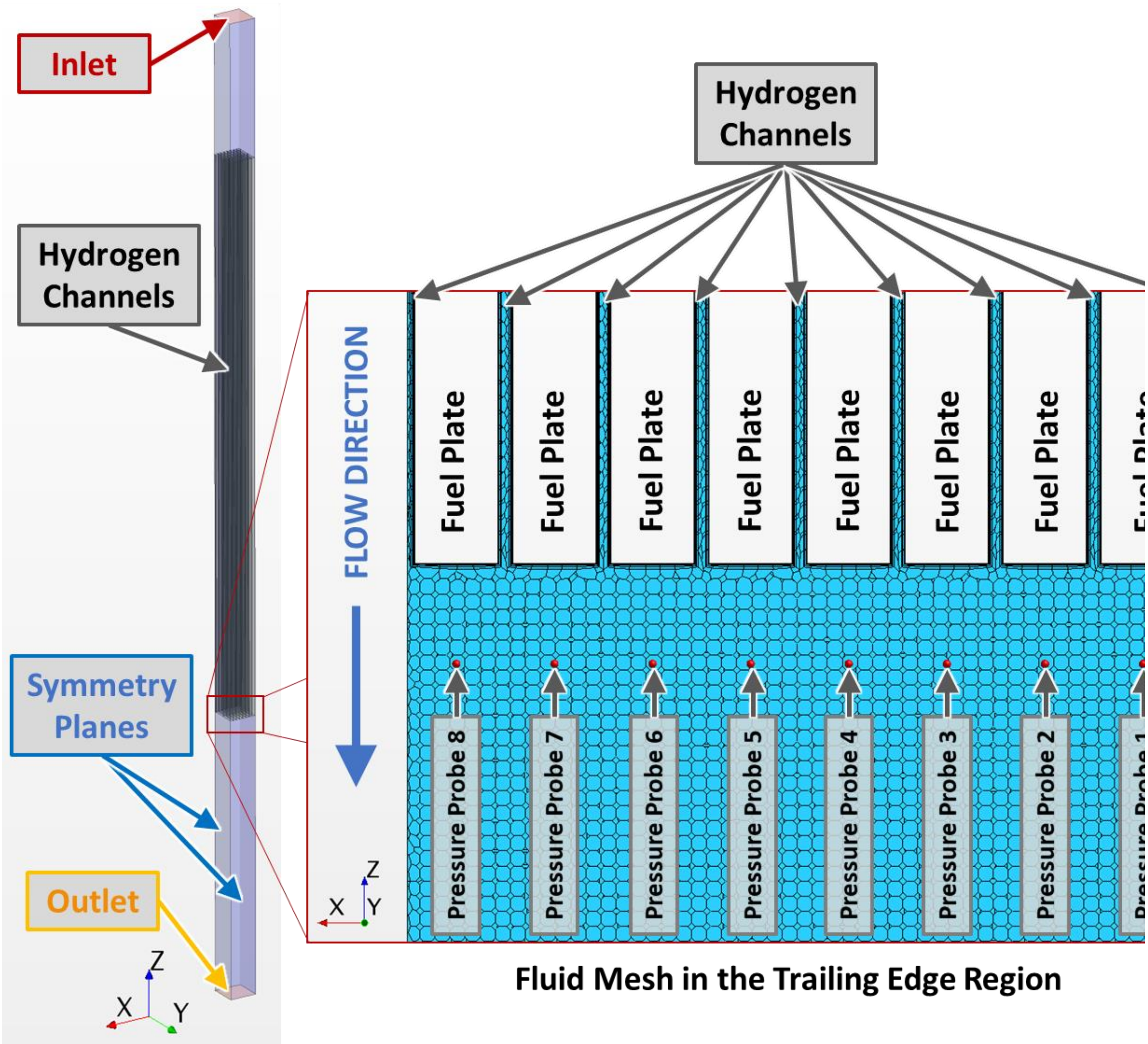

Figure 5. Geometry, mesh, and boundary conditions for the Star-CCM+ model.

The flow through the fuel element was assumed to be compressible, turbulent, and pressurized to 4 MPa. The turbulent flow was modeled with Menter's version of the Reynolds-Averaged Navier-Stokes (RANS) k-Omega turbulence model. To accurately capture the turbulent boundary layer, a prism layer mesh was added to the fluid mesh which adds mesh refinement near the walls in the model. This near wall mesh refinement yielded an average wall y+ value (non-dimensional distance from the wall) within the coolant channels of about 0.7. Typically, wall y+ values should be less than 5 and ideally less than 1 to accurately capture the fluid solution in the viscous sublayer of the turbulent boundary layer. All walls were assumed to be no-slip and smooth.

The thermal power level of the fuel element is 10 MW. The assumed axial heat flux distribution at 10 MW is shown in Figure 6. Since the fuel plates were not included in the model, this heat flux distribution was applied to all surfaces within the voided regions of the fluid mesh where the fuel plates would reside if they were included. The fuel plates were not included because the fuel and cladding temperatures were not of interest in this analysis. The velocity and temperature at the inlet were specified to be 17.5 m/s and 350 K. These inlet conditions combined with the 10 MW power level yielded an average channel velocity of about 856 m/s near the trailing edge of the fuel plates as well as an average outlet temperature of about 2512 K.

The density, thermal conductivity, heat capacity, and dynamic viscosity of the hydrogen were all specified to vary with temperature. These properties were defined by fitting polynomials to data extracted from the thermodynamics property tables in "Selected Properties of Hydrogen (Engineering Design Data)" [7]. All the properties were accessed at a constant pressure of 4 MPa since it was assumed that they would not vary significantly with modest changes in pressure. The one exception is density which can change significantly with relatively small changes in pressure. Therefore, if more accurate results are desired the model can be re-ran with density that varies with both temperature and pressure.

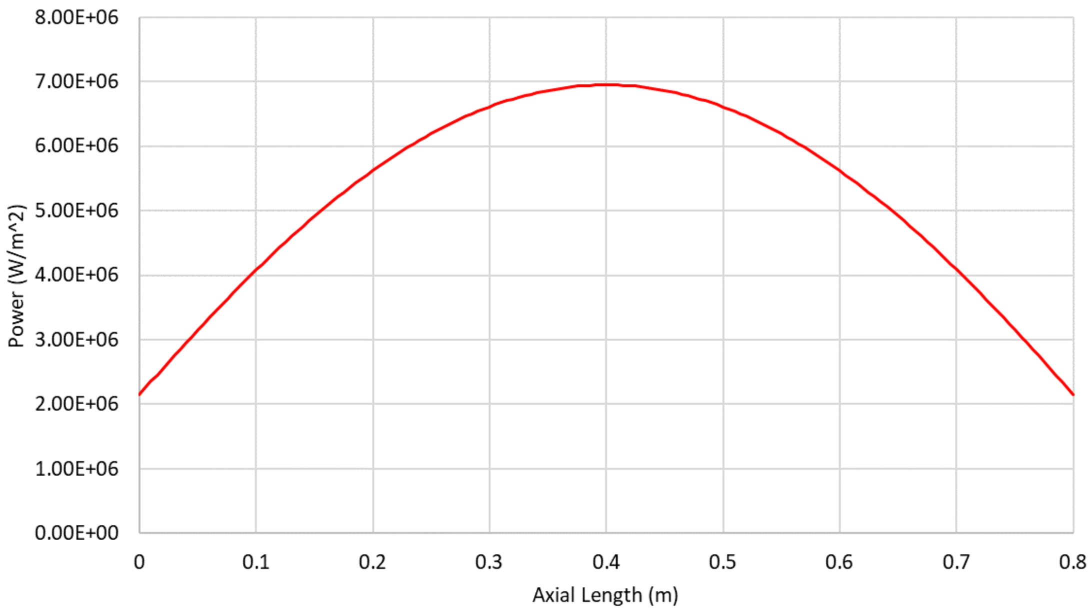

Figure 6. Axial heat flux distribution for a fuel element power level of 10 MW.

5.0 Results

5.1 Analytic Model Results

Using Equations (1) and (2) the fundamental natural frequency (first mode) of a homogeneous molybdenum plate was calculated to be 2317.3 Hz. This was calculated using the properties of molybdenum at ~2000 K as detailed in Table 1. This frequency will increase if the assumed temperature was decreased due to the higher elastic modulus at lower temperatures and vice versa.

Shown in Figure 7 are the results of using Eq. (3) to calculate the vortex shedding frequency as a function of Strouhal number. The red and blue points show the shedding frequencies with the characteristic length equal to the thickness of the plates and the hydraulic diameter of the coolant channels between those plates, respectively. The flow velocity was assumed to be 856 m/s (assumed velocity near the trailing edge of the plates) These results were utilized when choosing a time step size for the Star-CCM+ model to ensure that the vortex shedding frequency would be captured in the model.

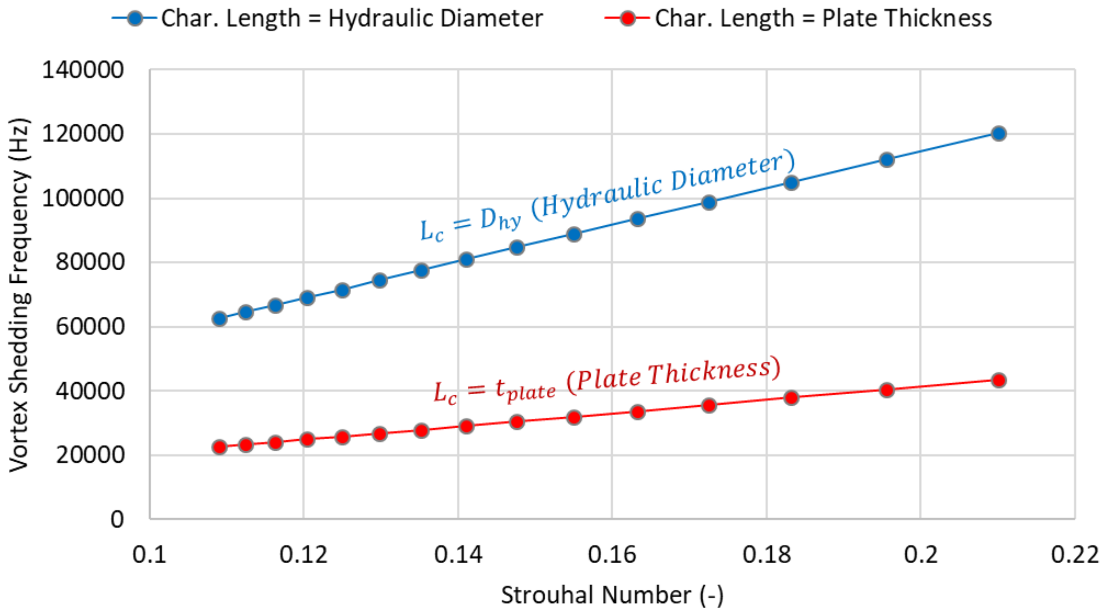

Figure 7. Vortex shedding frequency as a function of Strouhal number with L_c (characteristic length) equal to hydraulic diameter (blue) and plate thickness (red).

5.2 Abaqus Model Results

Using the homogeneous single plate model in Abaqus the frequency of the first mode was calculated to be 2278.8 Hz. This is about 1.7% less than the frequency calculated with equations (1) and (2), which is pretty good agreement. To quantify how much the natural frequency changes when the plate is fueled, the molybdenum in the fueled region (red area in Figure 3) was replaced with uranium nitride. This increased the frequency of the first mode to 2404.2 Hz. This modest increase makes sense if one examines the material properties of uranium nitride and molybdenum (Table 1) with Eq. (1). The elastic modulus of uranium nitride is higher than molybdenum, which will increase the natural frequency. However, the mass of uranium nitride is also higher than molybdenum which conversely decreases the natural frequency. Hence the only 5.5% increase in the natural frequency with a fueled plate.

The results of the full element model are shown in Figure 8 and Figure 9. Figure 8 shows a top down view (coolant flow would be into the page) of the first and fifth modes of the fuel element showing how the displacement diminishes from the center to the exterior surfaces of the element where the fixed boundary condition was prescribed. Figure 9 shows the mode shapes and frequencies of the first five modes. Only the central two plates are shown because the highest displacements are seen in these plates. Overall, the frequencies are more than 3 times larger than the frequencies calculated in the single plate models.

To obtain a better understanding of how the spacers between the fuel plates affect the frequencies and possibly explain why the fuel element's frequencies were so much larger than the single plate model's frequencies, another model was completed with the spacers removed from the fuel element. With the spacers removed, the frequency of the first mode decreased to 2236.1 Hz. Table 2 summarizes the natural frequencies of the first five modes of all the Abaqus models that were completed. In general, the frequencies of the first five modes are quite close to each other which is likely due to the length and high aspect ratio of the plates,

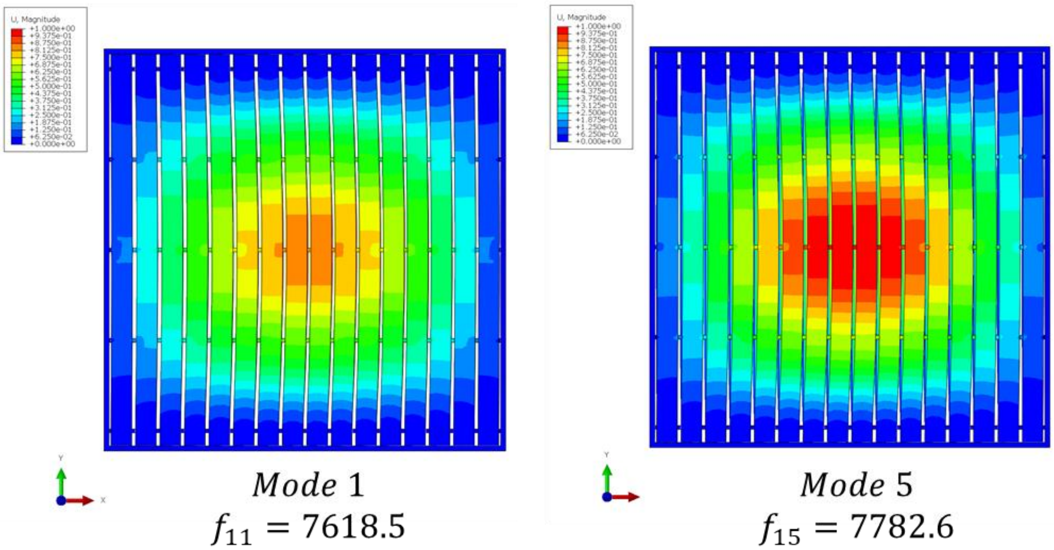

Figure 8. Top down view of the 1st and 5th modal shapes and frequencies for the fuel element model with channel spacers.

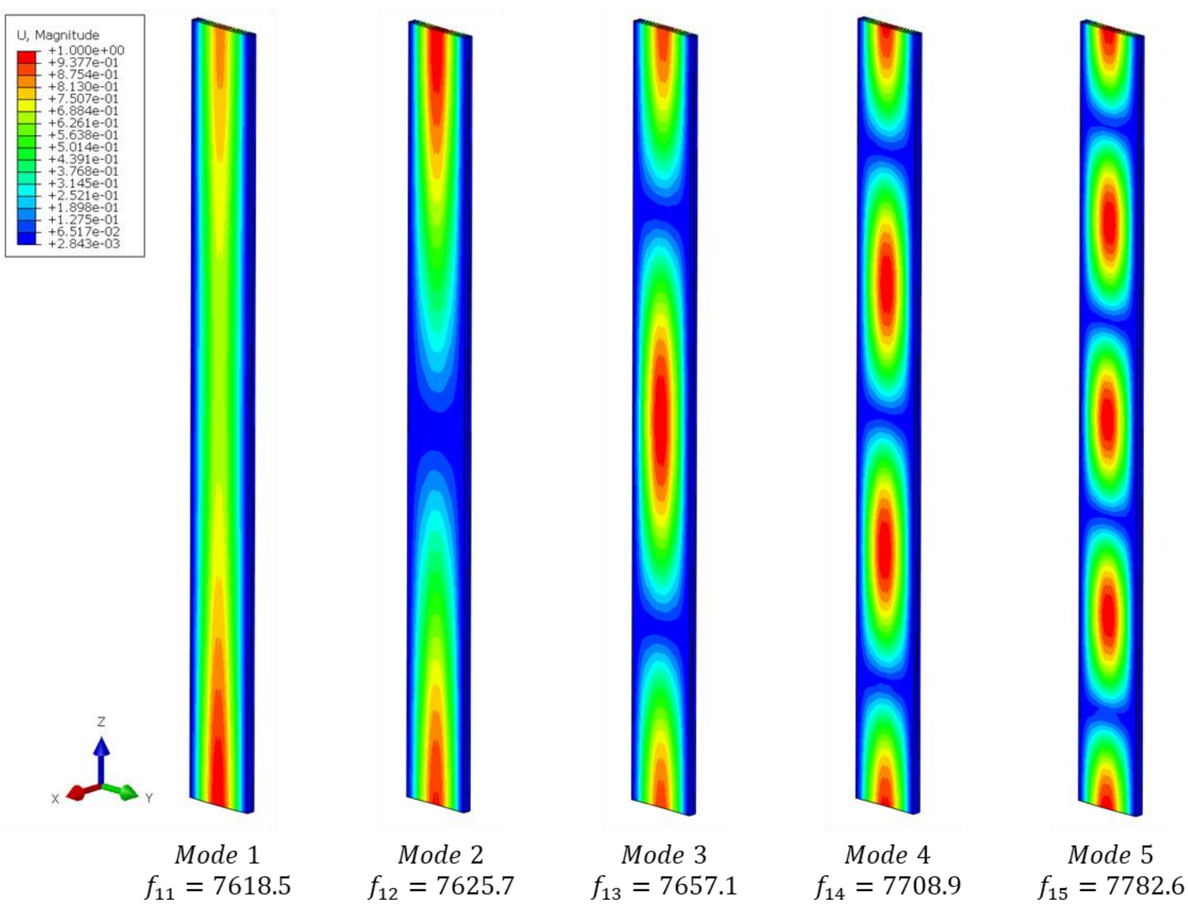

Figure 9. Mode shapes and frequencies of the central two plates in the fuel element model with channels spacers.

Table 2. Summary of Abaqus modeling.

Abaqus Model	Frequency (Hz)				
	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5
Homogenous Plate	2278.8	2280.9	2297.4	2322.4	2358.3
Fueled Plate	2404.2	2406.6	2423.1	2448.5	2485.2
Fuel Element with Spacers	7618.5	7625.7	7657.1	7708.9	7782.6
Fuel Element without Spacers	2236.1	2238.8	2255.4	2272.0	2272.0

5.3 Star-CCM+ Model Results

The focus of the Star-CCM+ model was the vortex shedding at the trailing edge of the fuel plates. To illustrate this vortex shedding the velocity of the hydrogen gas is shown in Figure 10. Six snapshots at 7.5 microsecond time intervals (the model's time step was 2.5 microseconds) are also included. These snapshots show one cycle of the vortex shedding from two of the fuel plates. This provides an estimate of the rate of the vortex shedding. The first snapshot is at a time interval of 0.0 s and the sixth snapshot is at 4.5 microseconds. This correlates to a vortex shedding frequency of about 22,222 Hz. This vortex shedding frequency is further confirmed by the frequency spectra in Figure 11. The top plot is the spectra for Pressure Probes 1 through 4 and the bottom plot is the spectra for Pressure Probe 5 through 8. The highest peak occurs at about 22,322 Hz which agrees very well with the vortex shedding frequency estimated using the snapshots in Figure 10. There are also peaks at 44,465 Hz and 66,969 Hz, but it is possible these peaks are caused by aliasing from the discrete Fourier transform.

Interestingly, the peak at about 22,322 Hz is at the low end of the vortex shedding frequencies estimated using the Strouhal number (Figure 7). The Strouhal number for parallel plate array geometries could not be found in the literature, hence the logic for computing the vortex shedding frequency at a range of values for the Strouhal number. Furthermore, for the internal flow of this geometry, one would expect the characteristic length (L_c in Eq. (3)) to be the hydraulic diameter, however it appears the shedding frequencies calculated with L_c equal to the plate thickness align better with the Star-CCM+ results. This might be due to the plate thickness being much larger than the thickness of the coolant channels.

To directly compare the vortex shedding frequency calculated in the Star-CCM+ model to the natural frequencies calculated in Abaqus, the natural frequencies are overlaid on the frequency spectra plots in Figure 11. The solid and dashed vertical lines are the natural frequencies for the fuel element model with and without the spacers (7618.5 Hz and 2236 Hz), respectively. Since the frequencies calculated in Abaqus change very little for the first five modes, only the frequency of the first mode is included. This clearly shows that the vortex shedding frequency calculated in the Star-CCM+ model is much higher than the natural frequencies calculated in Abaqus.

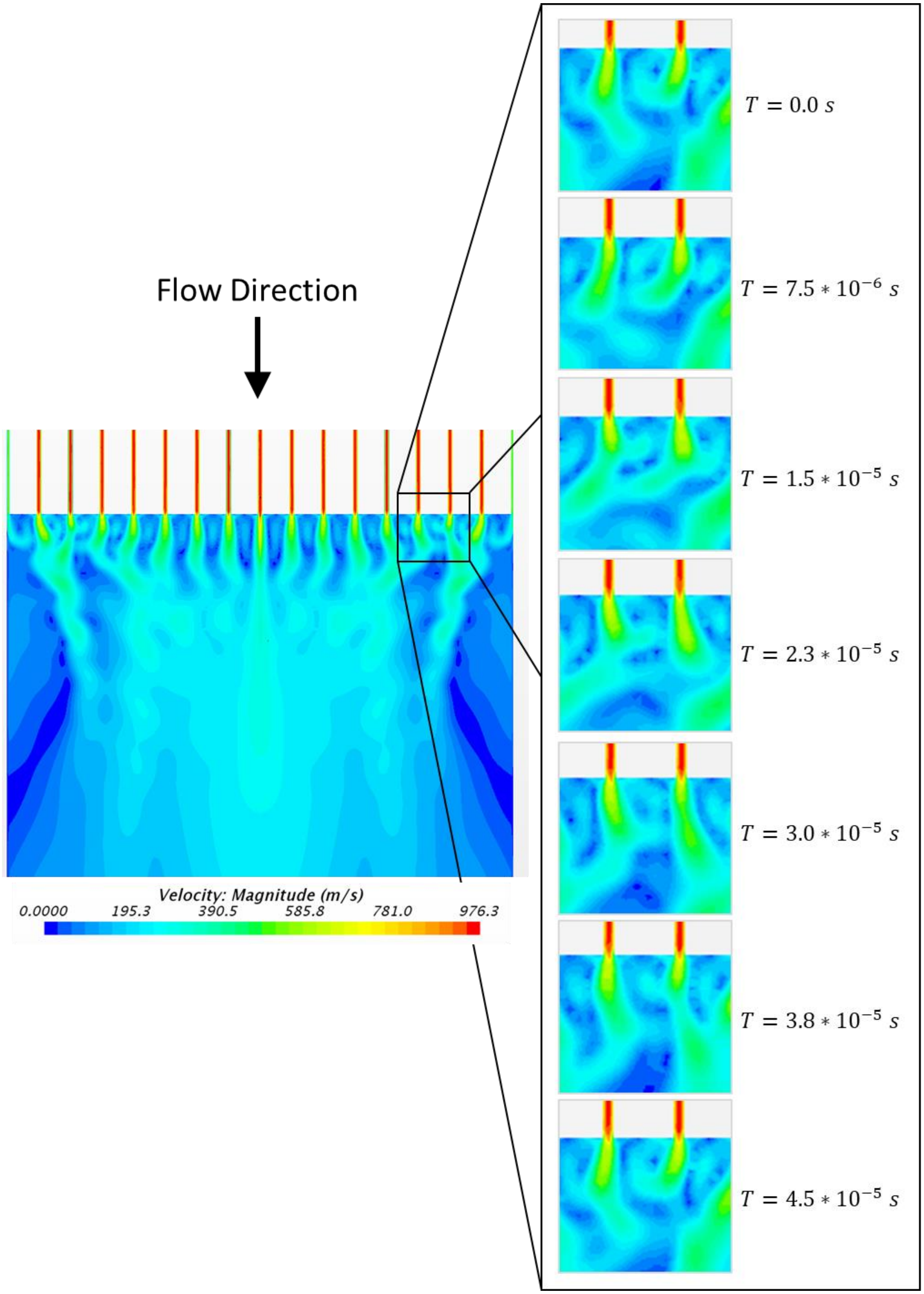

Figure 10. Vortex shedding at the trailing edge of the fuel plates in Star-CCM+.

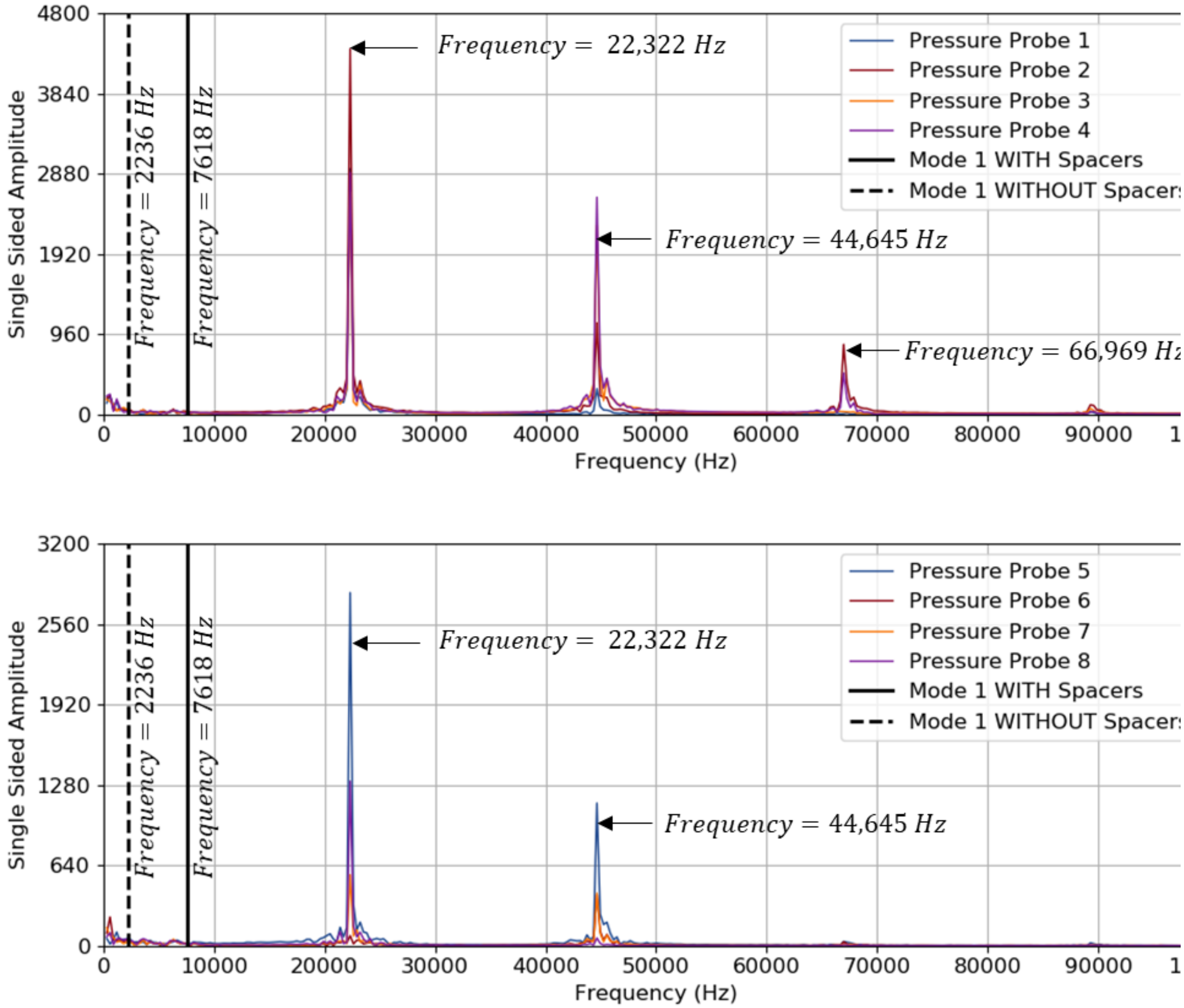

Figure 11. Frequency spectra from Pressure Probes 1-4 (top plot) and 5-8 (bottom plot).

6.0 Summary and Conclusions

This preliminary analysis focused on assessing the potential for flow-induced vibrations of the fuel plates within the reactor core of the NTP rocket engine. The primary sources of flow induced vibrations are from vortices shedding from bluff bodies and boundary layer separation in turbulent flows. If the rate that these flow phenomena are occurring coincides with the natural frequencies of the structural components (i.e. fuel plates) the vibrations will quickly amplify (resonance) and may cause failure of the structural components. Due to the size and complex nature of the entire NTP reactor core, one fuel element (comprised of 16 fuel plates) was analyzed in the FEA code, Abaqus and the CFD code, Star-CCM+. The Abaqus model was used to calculate the natural frequencies and mode shapes of the fuel element. The Star-CCM+ model was used to model the hydrogen coolant flow to assess the rate that vortices will shed from the trailing edges of the fuel plates.

The fundamental natural frequency (first mode) of the fuel element was calculated to be 7618 Hz. The natural frequency of the next four mode shapes were nearly equal to the frequency of the first mode. This is likely due to the length and high aspect ratio of the fuel plates. The vortex shedding frequency was calculated to be 22,322 Hz or about three times the natural frequencies of the fuel element. This indicates that it is unlikely that vortex shedding will cause resonance in the first five modes of the fuel plates. The RANS based turbulence model that was utilized in this analysis can tend to overly dissipate turbulent vortices therefore a future and more detailed analyses should consider using a Large Eddy Simulation to model the turbulent flow more accurately. Additionally, a more accurate assessment of the natural frequencies of the fuel element could be obtained by using temperature dependent material properties with realistic temperature distributions throughout the fuel element. These temperature distributions could be obtained from a conjugate heat transfer model. However, with the large margin between the vortex shedding and natural frequencies calculated in this preliminary analysis it is unlikely adding these additional features to the models will dramatically alter the overall conclusions of this analysis.

7.0 References

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Appendix G. Fuel assembly geometrical descriptions – Curved plates

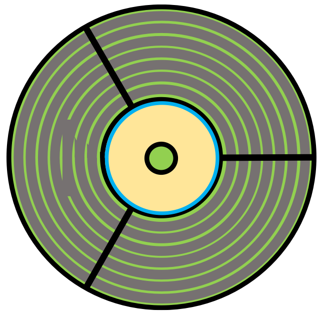


Figure G.1. Fuel assembly schematic (7 fuel plates represented in grey)

Curved plate assembly design A (fuel meat thickness = 2.5 mm, cladding thickness = 0.5 mm)

	r-in	r-out
H2	0	0.50
Mo	0.50	0.55
ZrH1.6	0.55	1.15
ZrC	1.15	1.35
Mo duct	1.35	1.5

Fuel plate	r-h2-in	r-clad-in	r-fuel-in	r-fuel-out	r-clad-out	r-h2-out
1	1.5	1.5375	1.5875	1.8375	1.8875	1.925
2	1.925	1.9625	2.0125	2.2625	2.3125	2.35
3	2.35	2.3875	2.4375	2.6875	2.7375	2.775
4	2.775	2.8125	2.8625	3.1125	3.1625	3.2
5	3.2	3.2375	3.2875	3.5375	3.5875	3.625
6	3.625	3.6625	3.7125	3.9625	4.0125	4.05
7	4.05	4.0875	4.1375	4.3875	4.4375	4.475
8	4.475	4.5125	4.5625	4.8125	4.8625	4.9

	r-in	r-out
Mo duct	4.9	5.05

The three separators are 0.15-cm thick

Volume fractions between r = 1.5 cm and r = 5.05 cm

%H2	16.145%
%Fuel	53.816%
%Struct	30.039%

Heat transfer surface of the 8 fuel plates = 314.5 cm x 80 cm = 25,160 cm^2

Fuel assembly heat transfer surface to volume ratio (S/V) = 4.3 cm^{-1}

Curved plate assembly design B (fuel meat thickness = 3.0 mm cladding thickness = 0.25 mm)

	r-in	r-out
H2	0	0.50
Mo	0.50	0.55
ZrH1.6	0.55	1.15
ZrC	1.15	1.35
Mo duct	1.35	1.5

Fuel plate	r-h2-in	r-clad-in	r-fuel-in	r-fuel-out	r-clad-out	r-h2-out
1	1.5	1.5375	1.5625	1.8625	1.8875	1.925
2	1.925	1.9625	1.9875	2.2875	2.3125	2.35
3	2.35	2.3875	2.4125	2.7125	2.7375	2.775
4	2.775	2.8125	2.8375	3.1375	3.1625	3.2
5	3.2	3.2375	3.2625	3.5625	3.5875	3.625
6	3.625	3.6625	3.6875	3.9875	4.0125	4.05
7	4.05	4.0875	4.1125	4.4125	4.4375	4.475
8	4.475	4.5125	4.5375	4.8375	4.8625	4.9

	r-in	r-out
Mo duct	4.9	5.05

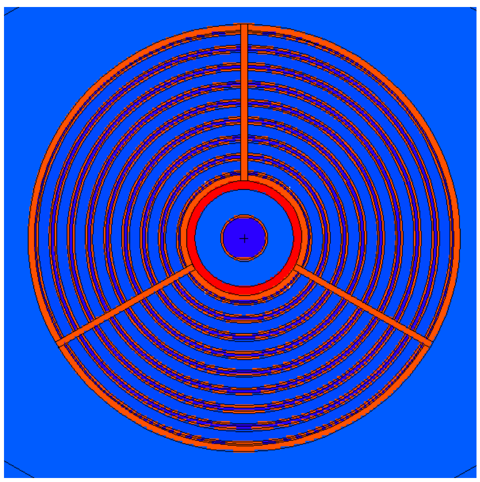
The three separators are 0.15-cm thick

Volume fractions between r = 1.5 cm and r = 5.05 cm

%H2	16.145%
%Fuel	64.579%
%Struct	19.276%

Heat transfer surface of the 8 fuel plates = 314.5 cm x 80 cm = 25,160 cm^2

Fuel assembly heat transfer surface to volume ratio (S/V) = 4.3 cm^{-1}



Curved plate assembly design C (fuel meat thickness = 1.58333 mm cladding thickness = 0.25 mm)

	r-in	r-out
H2	0	0.50
Mo	0.50	0.55
ZrH1.6	0.55	1.15
ZrC	1.15	1.35
Mo duct	1.35	1.5

Fuel plate	r-h2-in	r-clad-in	r-fuel-in	r-fuel-out	r-clad-out	r-h2-out
1	1.5	1.5375	1.5625	1.720833	1.745833	1.783333
2	1.783333	1.820833	1.845833	2.004167	2.029167	2.066667
3	2.066667	2.104167	2.129167	2.2875	2.3125	2.35
4	2.35	2.3875	2.4125	2.570833	2.595833	2.633333
5	2.633333	2.670833	2.695833	2.854167	2.879167	2.916667
6	2.916667	2.954167	2.979167	3.1375	3.1625	3.2
7	3.2	3.2375	3.2625	3.420833	3.445833	3.483333
8	3.483333	3.520833	3.545833	3.704167	3.729167	3.766667
9	3.766667	3.804167	3.829167	3.9875	4.0125	4.05
10	4.05	4.0875	4.1125	4.270833	4.295833	4.333333
11	4.333333	4.370833	4.395833	4.554167	4.579167	4.616667
12	4.616667	4.654167	4.679167	4.8375	4.8625	4.9

	r-in	r-out
Mo duct	4.9	5.05

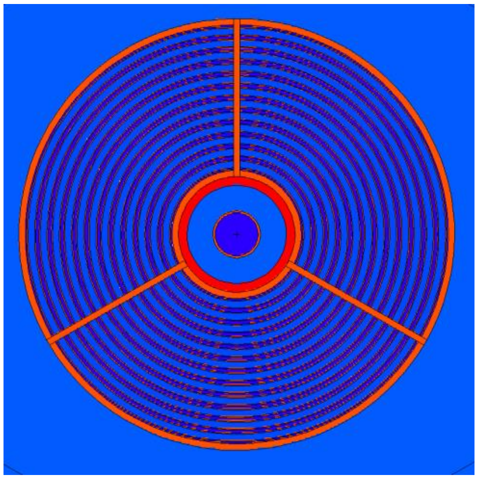
The three separators are 0.15-cm thick

Volume fractions between r = 1.5 cm and r = 5.05 cm

%H2	24.217%
%Fuel	51.125%
%Struct	24.658%

Heat transfer surface of the 12 fuel plates = 471.75 cm x 80 cm = 37,740 cm^2

Fuel assembly heat transfer surface to volume ratio (S/V) = 6.5 cm^{-1}



Curved plate assembly design D (fuel meat thickness = 0.0875mm cladding thickness = 0.25 mm)

	r-in	r-out
H2	0	0.50
Mo	0.50	0.55
ZrH1.6	0.55	1.15
ZrC	1.15	1.35
Mo duct	1.35	1.5

Fuel plate	r-h2-in	r-clad-in	r-fuel-in	r-fuel-out	r-clad-out	r-h2-out
1	1.5	1.5375	1.5625	1.65	1.675	1.7125
2	1.7125	1.75	1.775	1.8625	1.8875	1.925
3	1.925	1.9625	1.9875	2.075	2.1	2.1375
4	2.1375	2.175	2.2	2.2875	2.3125	2.35
5	2.35	2.3875	2.4125	2.5	2.525	2.5625
6	2.5625	2.6	2.625	2.7125	2.7375	2.775
7	2.775	2.8125	2.8375	2.925	2.95	2.9875
8	2.9875	3.025	3.05	3.1375	3.1625	3.2
9	3.2	3.2375	3.2625	3.35	3.375	3.4125
10	3.4125	3.45	3.475	3.5625	3.5875	3.625
11	3.625	3.6625	3.6875	3.775	3.8	3.8375
12	3.8375	3.875	3.9	3.9875	4.0125	4.05
13	4.05	4.0875	4.1125	4.2	4.225	4.2625
14	4.2625	4.3	4.325	4.4125	4.4375	4.475
15	4.475	4.5125	4.5375	4.625	4.65	4.6875
16	4.6875	4.725	4.75	4.8375	4.8625	4.9

	r-in	r-out
Mo duct	4.9	5.05

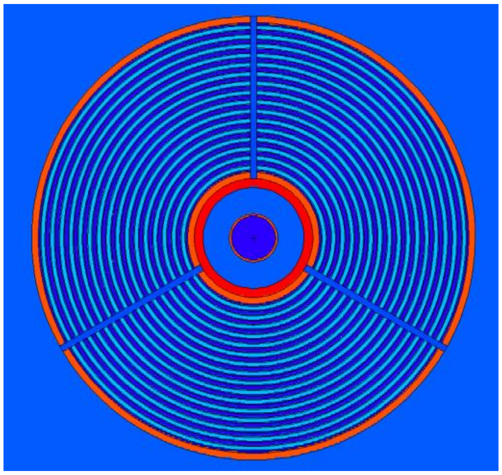
The three separators are 0.15-cm thick

Volume fractions between r = 1.5 cm and r = 5.05 cm

%H2	32.289%
%Fuel	37.671%
%Struct	30.039%

Heat transfer surface of the 16 fuel plates = 629 cm x 80 cm = 50,320 cm^2

Fuel assembly heat transfer surface to volume ratio (S/V) = 8.6 cm^{-1}



Appendix H. Heat removal for curved plate designs

The objective of the heat removal scoping analyses is to estimate the maximum fuel assembly power acceptable given an assumed set of design requirements:

- Maximum Mo and W allowable temperatures are, respectively, 2320 K and 3000 K corresponding to about 80% of their melting temperatures.
- Maximum UN, UC and UO2 allowable centerline temperatures assumed in the analyses are, respectively, 3100 K, 2700 K and 3100 K corresponding to their melting temperature.
- Fuel active height = 80 cm

Unlike for straight plate geometry, simple heat transfer equations are not readily available for curved geometry. Hence, the estimation of the maximum allowable assembly power is based on the results obtained with straight plates that are presented in Appendix B.

The maximum allowable straight plate powers presented in Tables B.1 to B.9 are divided by their heat transfer area (2×7.8×80 = 1248 cm^2) which then provides the maximum allowable heat flux (W/cm^2) as a function of fuel meat thickness and for different combinations of H2 outlet temperatures, cladding material and fuel material. Correlations are then derived giving maximum allowable heat fluxes as a function of fuel meat thickness and for different combinations of H2 outlet temperatures, cladding material and fuel material. These maximum allowable heat fluxes are then multiplied by the total heat transfer area of the 8-, 12- and 16-plate assemblies (respectively 25,160 cm^2, 37,740 cm^2 and 50,320 cm^2, see Appendix G) to obtain the maximum allowable curved-plate assembly powers (Table H.1).

Table H.1. Maximum allowable assembly power (MW) for the 4 curved-plate designs

FA Identifier	A	B	C	D
plate #	8	8	12	16
Cladding thickness (mm) / material	0.5 / Mo	0.25 / W	0.25 / W	0.25 / W
Fuel thickness (mm) / material	2.50 / UN	3.00 / UN	1.58 / UN	0.09 / UN
T-H2-out = 2750 K	-	8.86	14.8	20.8
T-H2-out = 2550 K	-	13.9	23.2	32.6
T-H2-out = 2100 K	11.0	-	-	-

Once the maximum allowable assembly power is determined, core dimensions and masses can be estimated using simple algebra. Table H.2 presents some UN/Mo core characteristics. Table H.3 and H.4 present some UN/W core characteristics for two H2 outlet temperatures (2750 K and 2550 K). For each temperature, core dimensions and masses are also presented for three assembly pitches (11.1 cm, 15 cm and 20 cm). Increasing the fuel assembly pitch increases the neutron moderation and, consequently, lowers the critical mass. However, the core diameter increases as well and, with it, the total mass of the system. The data presented in Tables H.3 and H.4 indicates that a core could use assembly designs C and D with a 20-cm pitch in a Beryllium casing and still maintain a reasonable mass (3-4 tonnes). These cores contain only 300-900 kg of U.

Table H.2. Core characteristics for curved-plate assembly designs: **Mo**-clad UN fuel; Axially symmetric power distribution [a]. Assumed peak-to-average fuel assembly power ratio = 1.35. T-H2-out = **2100** K. Core masses are presented for 3 different pitches (11.1 cm, 15 cm and 20 cm). m_{H2} = 8.9 kg/s for 250 MW assuming T-H2-inlet = 350 K

FA Identifier	A
plate #	8
H2 %	16.14%
Fuel %	53.82%
Struct %	30.04%
H-active (cm)	80
H2 flow area (cm2)	11.79
Pmax FA (MW)	11.02
U mass per FA (kg)	40.9
m-dot (kg/s)	0.2870
v-outlet (m/s) @ 4 MPa	709
Min # FA to meet TH constraints for 250 MW	31
Min U mass (kg) to meet TH constraints for 250 MW	1253
Mo mass (kg) to meet TH constraints for 250 MW	554
Average power density (W/cm3)	1274
FA pitch (cm)	11.1
Core diameter (cm) to meet TH constraints for 250 MW	78
Core + Reflector diameter (cm)	118
Beryllium casing in-core mass (kg)	278
Radial+Axial reflector mass (kg)	976
Total mass (mT)	3.1
FA pitch (cm)	15
Core diameter (cm) to meet TH constraints for 250 MW	105
Core + Reflector diameter (cm)	145
Beryllium casing in-core mass (kg)	800
Radial+Axial reflector mass (kg)	1334
Total mass (mT)	3.9
FA pitch (cm)	20
Core diameter (cm) to meet TH constraints for 250 MW	140
Core + Reflector diameter (cm)	180
Beryllium casing in-core mass (kg)	1697
Radial+Axial reflector mass (kg)	1852
Total mass (mT)	5.4

Table H.3. Core characteristics for curved-plate assembly designs: **W**-clad UN fuel; Axially symmetric power distribution [a]. Assumed peak-to-average fuel assembly power ratio = 1.35. T-H2-out = **2750** K. Core masses are presented for 3 different pitches (11.1 cm, 15 cm and 20 cm). m_{H2} = 6.5 kg/s for 250 MW assuming T-H2-inlet = 350 K

FA Identifier	B	C	D
plate #	8	12	16
H2 %	16.14%	24.22%	32.29%
Fuel %	64.58%	51.13%	37.67%
Struct %	19.28%	24.66%	30.04%
H-active (cm)	80	80	80
H2 flow area (cm2)	11.79	17.69	23.59
Pmax FA (MW)	8.86	14.75	20.79
U mass per FA (kg)	49.0	38.8	28.6
m-dot (kg/s)	0.2308	0.3842	0.5414
v-outlet (m/s) @ 4 MPa	570	633	669
Min # FA to meet TH constraints for 250 MW	38	23	16
Min U mass (kg) to meet TH constraints for 250 MW	1866	888	464
W mass (kg) to meet TH constraints for 250 MW	828	636	550
Average power density (W/cm3)	1024	1705	2403
FA pitch (cm)	11.1	11.1	11.1
Core diameter (cm) to meet TH constraints for 250 MW	78	67	56
Core + Reflector diameter (cm)	118	107	96
Beryllium casing in-core mass (kg)	192	200	135
Radial+Axial reflector mass (kg)	976	841	712
Total mass (mT)	3.9	2.6	1.9
FA pitch (cm)	15	15	15
Core diameter (cm) to meet TH constraints for 250 MW	105	90	75
Core + Reflector diameter (cm)	145	130	115
Beryllium casing in-core mass (kg)	714	584	401
Radial+Axial reflector mass (kg)	1334	1132	942
Total mass (mT)	4.7	3.2	2.4
FA pitch (cm)	20	20	20
Core diameter (cm) to meet TH constraints for 250 MW	140	120	100
Core + Reflector diameter (cm)	180	160	140
Beryllium casing in-core mass (kg)	1611	1243	859
Radial+Axial reflector mass (kg)	1852	1548	1266
Total mass (mT)	6.2	4.3	3.1

Table H.4. Core characteristics for curved-plate assembly designs: W-clad UN fuel; Axially symmetric power distribution [a]. Assumed peak-to-average fuel assembly power ratio = 1.35. T-H2-out = **2550** K. Core masses are presented for 3 different pitches (11.1 cm, 15 cm and 20 cm). m_{H2} = 7.1 kg/s for 250 MW assuming T-H2-inlet = 350 K

FA Identifier	B	C	D
plate #	8	12	16
H2 %	16.14%	24.22%	32.29%
Fuel %	64.58%	51.13%	37.67%
Struct %	19.28%	24.66%	30.04%
H-active (cm)	80	80	80
H2 flow area (cm2)	11.79	17.69	23.59

Pmax FA (MW)	13.94	23.18	32.65
U mass per FA (kg)	49.0	38.8	28.6
m-dot (kg/s)	0.3631	0.6037	0.8502
v-outlet (m/s) @ 4 MPa	897	994	1050
Min # FA to meet TH constraints for 250 MW	24	15	10
Min U mass (kg) to meet TH constraints for 250 MW	1186	565	296
W mass (kg) to meet TH constraints for 250 MW	526	405	350
Average power density (W/cm3)	1611	2679	3773

FA pitch (cm)	11.1	11.1	11.1
Core diameter (cm) to meet TH constraints for 250 MW	67	56	56
Core + Reflector diameter (cm)	107	96	96
Beryllium casing in-core mass (kg)	185	154	203
Radial+Axial reflector mass (kg)	841	712	712
Total mass (mT)	2.7	1.8	1.6

FA pitch (cm)	15	15	15
Core diameter (cm) to meet TH constraints for 250 MW	90	75	75
Core + Reflector diameter (cm)	130	115	115
Beryllium casing in-core mass (kg)	568	421	469
Radial+Axial reflector mass (kg)	1132	942	942
Total mass (mT)	3.4	2.3	2.1

FA pitch (cm)	20	20	20
Core diameter (cm) to meet TH constraints for 250 MW	120	100	100
Core + Reflector diameter (cm)	160	140	140
Beryllium casing in-core mass (kg)	1227	878	927
Radial+Axial reflector mass (kg)	1548	1266	1266
Total mass (mT)	4.5	3.1	2.8