Transformational Challenge Reactor Moderator Material Selection to Achieve Fuel Minimization

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INTRODUCTION

The Transformational Challenge Reactor (TCR) program aims at designing, licensing, building and operating a small reactor by leveraging recent scientific achievements in advanced manufacturing, nuclear materials, machine learning, and computational modeling and simulation. These scientific and technological advances enable a paradigm shift in reactor design and deployment [1, 2].

In particular, incorporation of advanced manufacturing techniques such as laser powder bed, laser directed energy deposition, and binder jet printing enable realization of structures free from geometric and material constraints inherent to conventional manufacturing, thereby opening the design space for targeted achievement of desired reactor performance outcomes [1, 2, 3].

In addition, the synergy between the reactor design and manufacturing framework provides for an accelerated development timeline relative to the conventionally manufactured reactor systems.

Minimizing the fuel mass required to achieve programmatic goals is an important aspect of core design. This work will describe how moderator materials affect the TCR fuel mass requirement and why yttrium hydride is the preferred option.

CORE DESCRIPTION

The TCR will be a helium-cooled, thermal reactor. The major reactor design features are highlighted in Fig. 1 (reproduced from [2]).

The reactor core will be housed in an annular vessel, enclosed by a control shroud, steel radial reflector, and biological shield.

The TCR core will be advanced manufactured and housed inside a conventionally manufactured and qualified vessel made from grade 304H stainless steel.

The core will consist of conventionally manufactured uranium nitride coated fuel particles (TRISO) contained in an advanced manufactured silicon carbide structure. The fuel elements are arranged within advanced manufactured grade 316L stainless steel structures.

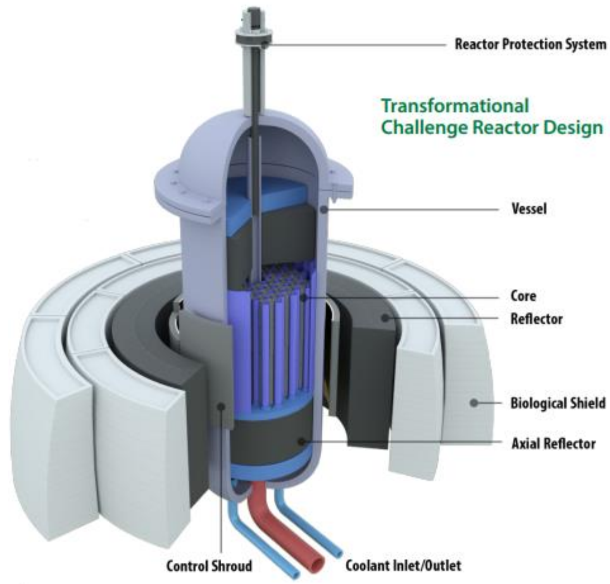

Fig. 1. TCR design [2]

MINIMIZING THE FUEL MASS

The TCR is a demonstration reactor that will operate for a relatively short period. While the performance requirements are modest (being critical), the design, licensing and construction timelines are aggressive (criticality planned for 2023 [3]).

In order to reduce unnecessary delays and cost, it is important to design a compact reactor and minimize the fuel mass requirement. Smaller reactor components translate to less time needed for manufacture and lower fuel mass can translate into fewer fuel elements to fabricate, handle, and eventually load. Safety is paramount and an under-moderated configuration would be preferred for obvious safety and reactor stability reasons.

As explained previously, the conventionally manufactured TRISO fuel particles will be contained in a silicon carbide (SiC) structure. If the SiC will provide some neutron moderation, additional moderation would help reducing the fuel mass needed to reach criticality.

A significant number of gas-cooled reactor have used graphite for moderation and as a reflector material (Fort St-Vrain [4], UHTREX [5], Peach-Bottom [6], HTTR [7], etc.). Graphite's excellent mechanical properties and behavior under irradiation was a material of choice for these reactors.

However, because conventionally manufactured TRISO fuel particles will already be encapsulated in a structure containing a relatively large amount of carbon, adding graphite would not necessarily lead to a safer, more efficient configuration.

This is why other moderator materials have been investigated. TCR temperature conditions prevent to use light or heavy water. Only materials that are stable under irradiation with a high melting point temperature can be considered. Therefore, the material selected for this investigation have been limited to beryllium, beryllium-oxide and yttrium hydride.

To simplify the analysis, neutronic calculations have been carried out in a simple spherical geometry assuming a constant volume fraction of helium and a varying volume fraction of TRISO-in-SiC and moderator. The volume fraction of conventionally manufactured TRISO particles in the TRISO-in-SiC was set at 50% (considered a reasonable estimate). The Monte-Carlo code MCNP6 was used to perform these calculations. Typical uncertainty was around 35 pcm (one standard deviation).

Results obtained in this simple geometry are shown in Fig. 2. On this figure is shown the variation of the k-effective as a function of the volume fraction of moderator. As can be seen, adding graphite, beryllium or beryllium-oxide only decreases the k-effective, which means that, with these materials, the core is already over-moderated. A notable exception is yttrium hydride (2% wt. % H).

For this material, a substantial increase of k-effective is observed. The k-effective increases continuously from zero to approximately 50% moderator volume fraction. Above this value, the k-effective starts decreasing (the core becomes over-moderated).

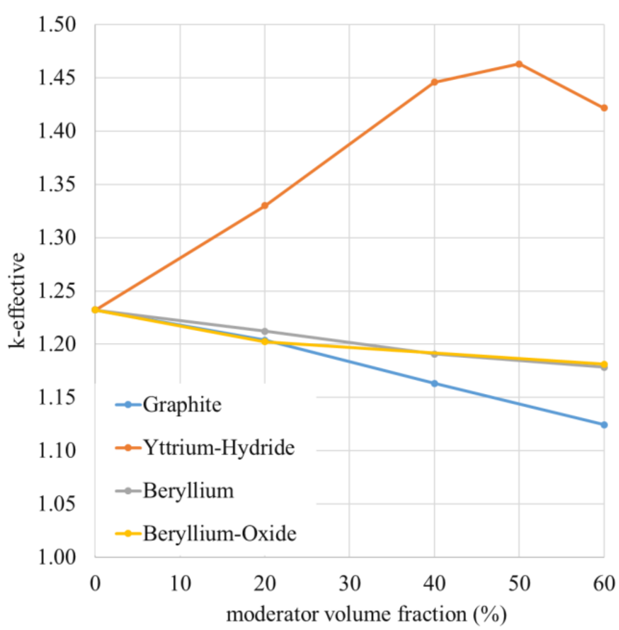

Fig. 2. K-effective variation as a function of moderator volume fraction

The substantial increase in k-effective observed by insertion of yttrium hydride (YH) can be leveraged to reduce the core size (and therefore the fuel mass).

To illustrate this point, Fig. 3 shows the relative core volume fraction needed to reach a given k-effective as a function of moderator volume fraction. It can be seen on this figure, that a configuration having a YH volume fraction of ~40%, still comfortably under-moderated, allows reducing drastically the size of the core (~2.5% of the volume of a configuration without YH).

The translation in fuel mass required is even more impressive as the core volume reduction is compounded with the reduction in relative fuel density (the fuel is "diluted" with YH) as illustrated in Fig. 4.

It can be seen on this figure, that a configuration having a YH volume fraction of ~40% allows reducing drastically the mass of fuel (~1.2% of the fuel mass of a configuration without YH).

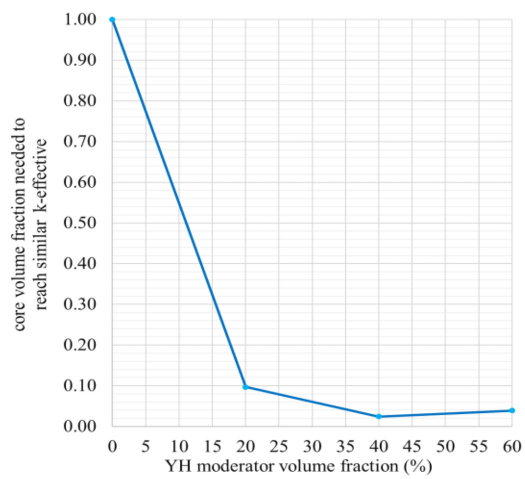

Fig. 3. Relative core volume size required to reach similar k-effective as function of YH volume fraction

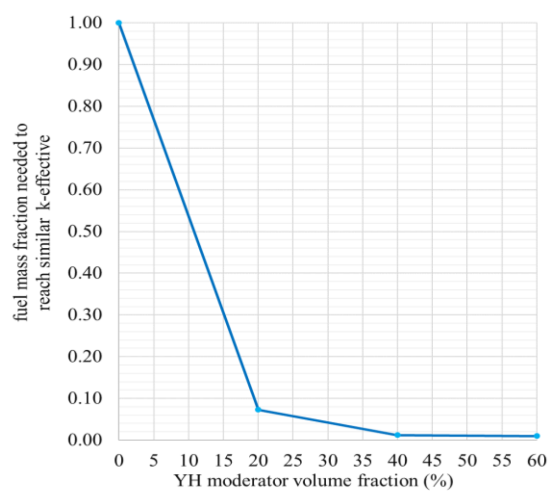

Fig. 4. Relative fuel mass required to reach similar k-effective as function of YH volume fraction

CONCLUSIONS

The TCR core will consist of conventionally manufactured uranium nitride coated fuel particles (TRISO) within an advanced manufactured silicon carbide structure. If the silicon carbide will provide some neutron moderation, additional moderation would help reducing the fuel mass needed to reach criticality. Several moderator materials have been investigated and yttrium hydride has been found to be an excellent moderator material for TCR fuel. Having an yttrium hydride volume fraction of around 40% would allow the core design to be comfortably under-moderated while allowing for a large reduction in fuel requirements. The calculations have been carried out in a simple geometry and the benefits of the yttrium hydride would certainly be reduced in a more realistic core design. Nonetheless, it is believed that the trends described in this paper would continue to apply.

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