Preliminary Design of a FHR Test Reactor Core

Madicken Munk, Anselmo T. Cisneros, Ehud Greenspan, Per F. Peterson

University of California, Berkeley, Nuclear Engineering Department, Berkeley CA 94720-1730 madicken@berkeley.edu

INTRODUCTION

Fluoride-Salt-Cooled High-Temperature Reactors (FHRs) use coated fuel-particles embedded in a graphite matrix similar to the fuel used in helium-cooled high temperature reactors (HTGR) but use low-pressure liquid fluoride salt for the coolant. The FHR core design concept being pursued at the University of California, Berkeley (UCB) is a pebble bed (PB-FHR) cooled by $2LiF\text{-}BeF_2$ (Flibe). As the density of the Flibe is higher than that of the pebbles, the pebbles will float. As the Flibe occupies 40% of the core volume and is made of low atomic mass elements, it contributes significantly to the neutron moderation. However, the Flibe constituents – primarily ^{6}Li – parasitically capture a non-negligible fraction of the neutrons. The equilibrium ^{6}Li concentration and, hence, the fraction of neutrons absorbed by the coolant, is a function of the core neutron spectrum (^{6}Li is produced by ^{9}Be(n,α) reaction). Additional unique features of the FHR concept include: low Prandtl number coolant, porous media flow, and need for tritium management [1]. Separate effects tests can develop an understanding in certain phenomena. However, a test reactor is required to gain insight into FHR performance. The FHTR will develop the assessment base and experience base necessary for validating simulation models and generating reliability data for licensing a prototype FHR respectively. Construction of an FHR test reactor (FHTR) will significantly help the licensing of a commercial prototype PB-FHR and subsequently a commercial PB-FHR.

This summary presents preliminary reactor neutronic analysis to support the design of the FHTR.

DESIGN REQUIREMENTS

To gain a solid experimental basis to validate modeling for FHR systems the operating conditions in the test reactor must be representative of those of the commercial FHR; they are defined in Table I.

Table 1. Design Operating Requirements for the FHTR

Characteristic Parameter	PB-FHR	FHTR
Power Density (MW/m^3)	16.2	20
Ave. Coolant Temperature (ºC)	650	650
Core Temperature Rise (ºC)	100	100
Reynolds Number	1200	460
^{6}Li content of Lithium (ppm)	10	10-50

In addition, the FHTR core should be as small as practical, should have as large as possible discharge burnup using 19.9% enriched uranium fuel, and should have a negative temperature reactivity feedback.

REACTOR DESIGN

Figure 1 shows the geometry being considered for the FHTR in comparison to the PB-FHR [2]. The study focuses on an FHTR active volume of 0.5-1.0 m^3 single channel pebble-bed type test reactor. This reactor uses 3 cm in diameter pebbles in which the fuel kernels are embedded in an annular region; the central pebble zone is made of a low-density graphite [2].

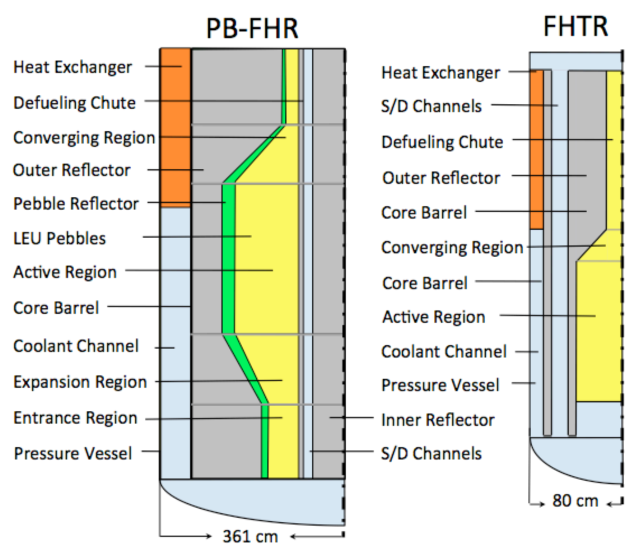

Fig. 1. Comparison of the FHTR and the PB-FHR cores

INITIAL RESULTS

The FHTR is analyzed using an in-house code, BEAU, which couples MCNP5 and ORIGEN, with the methodology described by Cisneros et al. [3] to determine the maximum discharge burnup of the fuel and identify the equilibrium core composition.

Implementing the baseline PB-FHR fuel design in the smaller FHTR core yields a significantly softer neutron spectrum compared to the PB-FHR; see Fig. 2. The graphite reflector has more influence over the spectrum of FHTR because a higher fraction of the core volume of the core is within one mean free path of the reflector, 19.% in the FHTR v. 6.4% in the PB-FHR.

Furthermore, the baseline PB-FHR uses a graphite pebble reflector that is 40% Flibe (a less effective moderator) and ~37% of the volume in the FHTR core has increased moderation from the coolant due to increased porosity due to wall effects [4].

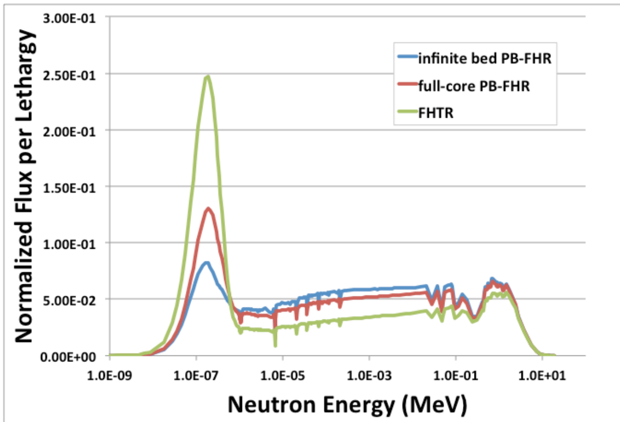

Fig. 2. Comparison of neutron spectrum in the PB-FHR and FHTR fuel

To harden the FHTR core spectrum, it is proposed that two types of fuel pebbles will be used. – the majority of the pebbles will have a smaller Carbon-to-Heavy Metal (C/HM) ratio and/or higher enrichment than the PB-FHR core and a small fraction of pebbles will replicate the PB-FHR fuel design for fuel qualification. The C/HM of the majority of the FHTR pebbles will be adjusted to impose the FHTR core spectrum to be similar to that of the PB-FHR and to provide negative coolant temperature reactivity feedback. The limited number of fuel qualification pebbles will circulate through the test reactor until they reach the design PB-FHR burnup level (216 GWd/MT) [2].

Table II compares preliminary neutronic characteristics and baseline fuel designs calculated for the preliminary FHTR core with those of the reference PB-FHR. The coolant and fuel temperature reactivity coefficients are negative although they do not match the corresponding values of the PB-FHR. Preliminary results predict shutdown margins on the order of ~4000 pcm for cold zero power at room temperature, with two out of three control elements engaged, ensuring that subcriticality can be maintained in the bounding scenario of the FHTR coolant freezing after insertion. The low C/HM test pebbles can reach burnups of 180 GWd/MT, which, though significantly less than the burnup for the PB-FHR, is an acceptable burnup for an experimental reactor.

Table II. PB-FHR vs. FHTR Design Performance Characteristics and Fuel Design Comparison

Parameter	PB-FHR	FHTR
Power Level (MW_{th})	900	20
Core Outer Radius (m)	2.4	0.44
Core Active Volume (m^3)	56	1.0
Pebble Diameter (cm)	3.0	3.0
Thickness of Active Annular Region in Pebble (mm)	2.57	2.49
Inert Graphite Pebble Core Radius (cm)	1.243	1.251
Fuel Particles per Pebble	9990	4730
Density of Inner Kernel (g/cc)	1.594	1.519
Fuel Particle Diameter (μm)	810	810
Fuel Particle Packing Fraction	40%	40%
Power per Particle (mW)	47	81
Carbon to Heavy Metal (C/HM)	300	201
Enrichment (wt% ^{235}U/U)	19.9%	19.9%
Burnup (GWd/MT)	216	180
Fuel Reactivity Coefficient (pcm/K)	-4.5±0.2	-1.6±0.2
Coolant Reactivity Coefficient (pcm/K)*	-0.49±0.1	-1.5±0.2

*accounting for temperature dependent volume change

CONCLUSION

The preliminary neutronics studies performed indicate that it is feasible to design a 1.0 m^3 FHR core that could operate at prototypical conditions of the reference commercial PB-FHR. Further design optimization is required.

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