A REVIEW OF REACTOR PHYSICS UNCERTAINTIES AND VALIDATION REQUIREMENTS FOR THE MODULAR HIGH-TEMPERATURE GAS-COOLED REACTOR

by

A. M. Baxter, R. K. Lane, E. Hettergott, and W. Lefler

GENERAL ATOMICS
San Diego, California, USA
ABSTRACT

The important, safety-related, physics parameters for the low-enriched Modular High-Temperature Gas-Cooled Reactor (MHTGR) such as control rod worth, shutdown margins, temperature coefficients, and reactivity worths, are considered, and estimates are presented of the uncertainties in the calculated values of these parameters. The basis for the uncertainty estimate in several of the important calculated parameters is reviewed, including the available experimental data used in obtaining these estimates. Based on this review, the additional experimental data needed to complete the validation of the methods used to calculate these parameters is presented. The role of benchmark calculations in validating MHTGR reactor physics data is also considered.
1. INTRODUCTION

The MHTGR is an advanced nuclear reactor concept being developed in the U.S.A. under a cooperative program involving the U.S. Government, the nuclear industry, and the electric utility companies (Ref. 1). As its objective, this program is developing a safe, reliable, and economic nuclear power and process heat option with potential for worldwide application. The design is based on a concept of modularization that can meet the various power demands by combining a number of 350 MW(t) reactor modules in parallel with a selected number of turbine plants in a variety of arrangements. Basic High-Temperature Gas-Cooled Reactor (HTGR) features of ceramic-coated fuel, helium coolant, and graphite are sized and configured to provide a low power density core with passive safety features. The safe behavior of the reactor plant is not dependent upon operator action and it is insensitive to operator error.

The MHTGR design is based upon generic gas-cooled reactor experience, as well as specific HTGR programs and projects. These include the carbon dioxide-cooled Magnox and Advanced Gas-Cooled Reactor (AGR), developed in the United Kingdom; the 15 MW(e) Arbeitsgemeinschaft Versuchs Reaktor (AVR) development plant, and the 300 MW(e) Thorium Hochtemperatur Reaktor (THTR) demonstration plant developed in Germany; the 40 MW(e) Peach Bottom (PB) I constructed and operated in the U.S.A.; and the 330 MW(e) Fort St. Vrain (FSV) plant in the U.S.A. The FSV facility has provided confirmation and demonstration of specific and generic HTGR core design and operating characteristics.

The active core in each MHTGR module is an annulus of graphite fuel elements about 3.5 m in outer diameter, 0.93 m annulus thickness and 7.9 m high. A plan view of the core is shown in Fig. 1. The fuel consists of coated particles of 20%-enriched fissile uranium oxycarbide
Fig. 1. Reactor plan view
(UCO) and fertile thorium oxide (THO₂). The particles are bonded together in fuel rods which are contained in the hexagonal-shaped graphite blocks. Helium coolant flows through the graphite blocks in a downward direction. Unfueled graphite blocks surround the active core to form replaceable inner and outer radial, and upper and lower axial reflectors. The outer replaceable radial reflector blocks are surrounded by permanent graphite reflectors. Reactor control is accomplished by a strong negative temperature coefficient plus moveable boron-carbide control rods located in the inner and outer reflectors as shown in Fig. 1. A second shutdown system of different design principle from the moveable control rods is also included. It consists of 12 hoppers of boronated graphite pellets which can be dropped by gravity into holes in the core columns adjacent to the inner reflector. Basic core design parameters are summarized in Table 1.

2. REACTOR PHYSICS DESIGN UNCERTAINTIES

Design requirements for the MHTGR have been developed systematically, to the degree of detail needed, from the overall objectives including safe, economical power production. In making design selections to meet the requirements, assumptions are made regarding the accuracy of the physical models and numerical methods used to calculate the basic parameters. For design and licensing purposes it is necessary to validate the accuracy of the models and methods, i.e., to show that the parameters of interest can indeed be calculated to the accuracy assumed in making the design selections, and subsequent safety analysis.

For the MHTGR reactor physics design, the basic parameters related to safety are core temperature coefficient, control rod reactivity worth and core shutdown margin, core power distributions, core reactivity behavior over life, water ingress effects, and decay heat levels. During the MHTGR conceptual physics design, a review was conducted of the available experimental data, and an estimate of the accuracy of the methods for calculating these parameters was made.
### TABLE 1
**BASIC MHTGR CORE DESIGN PARAMETERS**

<table>
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<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Inner diameter - active core, m/ft</td>
<td>1.66/5.43</td>
</tr>
<tr>
<td>Outer diameter - active core, m/ft</td>
<td>3.50/11.48</td>
</tr>
<tr>
<td>Height - active core, m/ft</td>
<td>7.93/26.02</td>
</tr>
<tr>
<td>Outer replaceable radial reflector thickness, m/ft</td>
<td>0.65/2.13</td>
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<tr>
<td>Power density, w/cc</td>
<td>5.91</td>
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<td>Control rod location</td>
<td>Top mounted</td>
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<tr>
<td>Number of columns in active core</td>
<td>66</td>
</tr>
<tr>
<td>Number of fuel elements in active core</td>
<td>660</td>
</tr>
<tr>
<td>Number of control rods</td>
<td>24 in outer reflector, 6 in inner reflector, 12 in inner core row</td>
</tr>
<tr>
<td>Reserve shutdown system</td>
<td>2-segment, graded cycle(2)</td>
</tr>
<tr>
<td>Refueling method(1)</td>
<td></td>
</tr>
<tr>
<td>He temp. @ core outlet, rated power, °C/°F</td>
<td>687/1268</td>
</tr>
<tr>
<td>He temp. @ core inlet, rated power, °C/°F</td>
<td>238/497</td>
</tr>
<tr>
<td>Core inlet pressure, MPa/psia</td>
<td>6.37/924.5</td>
</tr>
<tr>
<td>Core outlet pressure MPa/psia</td>
<td>6.34/916.5</td>
</tr>
<tr>
<td>Pressure drop across core, kPa/psid</td>
<td>29/4.2</td>
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<tr>
<td>Core circulation direction</td>
<td>Downflow</td>
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<tr>
<td>Coolant volume fraction</td>
<td>0.19</td>
</tr>
<tr>
<td>Fuel loading(3), initial core: kg U/kg Th</td>
<td>1358/2350</td>
</tr>
<tr>
<td>Fuel loading(3), equilibrium reloads: kg U/kg Th</td>
<td>1006/705</td>
</tr>
</tbody>
</table>

(1)Shutdown for approximately 14.6 days at end of cycle; equilibrium cycle: 19.8 months.

(2)Half of core replaced after each reload interval.

(3)LEU/Th; uranium (19.9% enriched in U-235) plus thorium.
These uncertainty estimates are summarized in Table 2, and are based on a careful review of available data, both experimental, and from operating reactors. While all of the parameters in Table 2 are important, the discussions in this paper are limited to the variables of temperature coefficient, control rod worth, and water ingress reactivity effects, as described below.

2.1. TEMPERATURE COEFFICIENT

The isothermal temperature coefficient of reactivity for the MHTGR core is shown at beginning of the initial core (BOC-IC) and at the end of a typical burnup cycle (EOC-equ) in Fig. 2 (Ref. 2). The temperature coefficient is the only contributor of any significance to the overall core power coefficient. It consists of a prompt Doppler effect due to the U-238 and Th-232 resonances, and a moderator effect due to thermal spectrum changes as the graphite moderator temperature changes. A notable feature is the large negative feedback effect due to absorptions in the Pu-240 resonance at about 1.1 eV. This effect shows up strongly, after the start of critical core operation, above normal operating temperatures as the thermal flux moves into this energy region.

The uncertainty in the calculation of the temperature coefficients for the MHTGR conceptual design is judged to be 20%. This estimate is based on data from previous validation work as discussed below.

- The PB HTGR measured temperature defect, from which the temperature coefficient is calculated (reactivity change over a specified temperature range), agreed with the calculated value to within 4% (Ref. 3). PB was a small, graphite-moderated, high leakage core.

- The FSV HTGR temperature defect measurements, which include xenon effects, agreed with calculations to within 10% (Ref. 4).
The core physics experimental data base is adequate to ensure that:

- The temperature coefficient can be calculated with an uncertainty of ≤20%.
- The control rod bank reactivity worth can be calculated with an uncertainty of ≤10%.
- Local power distributions can be calculated with an uncertainty of ≤13%.
- The core reactivity can be calculated at nominal full power conditions with an uncertainty of ≤1.5% Δρ.
- The water ingress effects can be calculated with an uncertainty of ≤10%.
- The decay heat production can be calculated with an uncertainty of ≤10%.
Fig. 2. MHTGR core isothermal temperature coefficient
Doppler coefficient measurements on Th-232, which were made in the HTGR critical assembly, agreed with the calculations to within 6% (Ref. 5).

Temperature coefficient measurements made in the high-temperature lattice test reactor (HTLTR) with a graphite assembly containing plutonium fuel, agreed with GA calculations to within 6%, and to within 9% for the U-235 fueled case (Ref. 6). Note that this is not just a doppler coefficient measurement, but a complete temperature coefficient measurement.

In summary, the data base used to evaluate the accuracy of the calculation methods included operating HTGR reactors, critical experiments with High Enriched Uranium (HEU) fuel, measurements and comparison calculations on LEU and plutonium fueled systems and benchmark calculations. A summary comparison between these measurements and calculations is provided in Fig. 3. A perfect agreement line is shown and compared to a best straight line fit through the data points. A 20% uncertainty band based on the perfect agreement line is also shown. Overall, the deviation between experiment and calculation is less than 20%. These results indicate that an assumed accuracy of 20% in the calculational model for MHTGR temperature coefficients is conservative.
Fig. 3. Comparison between HTGR temperature coefficient calculations and experiments.
2.1.1. **Control Bank Worth and Shutdown Margins**

Reactivity control in the MHTGR during normal operation is accomplished by 30 moveable boron carbide control rods located in the inner and outer reflectors immediately adjacent to the core.

For the core nuclear conceptual design, an uncertainty of 10% in the calculated control worths was assumed for the purpose of evaluating both cold or hot shutdown margins. These uncertainties were based on previous validation studies in which measured and calculated control rod reactivity worth were compared, i.e.:

- The reactivity worth of the PB control rods was measured during the initial startup and rise-to-power. These control rod reactivity worths and total shutdown bank worths were predicted to within 10% with similar models and neutron cross sections as currently in use at GA (Ref. 3).

- Measurements of the reactivity worth of both single rods and control rod pairs were made in the HTGR critical assembly (Ref. 5). Comparisons of these measurements to calculations indicated that single rod worths were overestimated by ~4% and the control rod pair worths were overestimated by ~11%.

- Control rod pair reactivity worths were measured during the initial rise-to-power for each FSV operating cycle (Ref. 4). Comparisons of the measured and calculated reactivity worth of control rod groups over these three cycles of operation show that the difference is typically ±5% for the cumulative worth; with the lower worth rod groups having a higher measurement uncertainty.

- Numerous measurements of the control rod reactivity worth have been made in the Dragon reactor (Refs. 7 and 8) which utilized
control rods located in the radial reflector as in the MHTGR design. The calculated control bank worth, using GA developed models, agreed with the measured value to within 11%. Significantly, the calculation underestimated the measured bank worth.

These comparisons of measured and calculated control rod reactivity worth support the 10% uncertainty band assumed for the MHTGR conceptual design. This accuracy estimate based on experimental data is also supported by an evaluation of the individual contributors to the MHTGR control rod reactivity model. The modeling must consider correction factors related to gaps between poison control rod compacts, clad material composition, finite height effects, axial streaming effects, etc. Uncertainties must also be considered from the cross section models, loading tolerances, local temperature effects, and power shape. A comparison between measured and calculated data similar to that for the temperature coefficient is shown in Fig. 4.

Water Ingress Effects

An addition of water to the MHTGR core initially produces a positive reactivity feedback effect. This positive feedback effect is caused by the moderating property of hydrogen which reduces resonance absorption in U-238 and Th-232, and results in a more thermalized neutron flux spectrum. Core neutron leakage is also reduced, which adds to the positive reactivity feedback. Eventually, as the amount of moisture is increased, thermal neutron absorption in hydrogen becomes dominant, causing a negative reactivity feedback. Thus the reactivity change due to moisture goes through a maximum, and has the general shape illustrated in Fig. 5, for near-critical core configurations. In this case, the calculated reactivity changes for large moisture ingress under cold conditions are shown for two time points in operation; i.e., beginning-of-cycle-initial-core (BOC-IC), and end-of-cycle equilibrium-core (EOC-equil), which bound the operating range.
Fig. 4. Comparison of calculated and measured control rod bank reactivity worths for HTGRs.

Legend
- FSV Cycle 1
- FSV Cycle 2
- FSV Cycle 3
- PB Core 1
- PB Core 2
- HTGR Critical

Perfect Agreement
+10%
-10%
Least Squares Fit to Data
Fig. 5. MHTGR-reactivity effects of water ingress (cold, unrodded, no xenon)
The reactivity feedback effects due to a given amount of core moisture are larger in the hot operating core than under cold conditions because the hot core has a harder neutron flux spectrum. This harder spectrum results in a maximum reactivity worth due to moisture that is approximately 25% higher than for the cold conditions.

Specific analyses of the uncertainties related to moisture ingress reactivity worths have not been performed to date as part of the MHTGR conceptual design. Based on limited data from water-moderated critical experiments, the predicted reactivity worth of uniformly distributed moisture is expected to be within 10%, an accuracy which is experimentally supported by small pebble-bed reactor subcritical assembly measurements (Ref. 9).

3. VALIDATION OF CORE PHYSICS METHODS

GA core physics methods have, in general, been validated for HEU/Th-fueled HTGRs. Most of the experimental data were derived from HTGR-type critical experiments performed at GA and from the operation of the PB and FSV reactors. The MHTGR with LEU/Th fuel, an annular core, and reflector control rods, requires a reassessment of the validation of these methods. This assessment will include one or more of the following:

- Reanalysis of selected previous validation studies.
- Documentation of selected previous validation studies.
- Comparison of new experimental data to GA calculations.
- Comparison of other (non-GA) calculations with GA calculations.

A major emphasis of this program will involve reanalysis and/or documentation of selected previous validation studies. Many of these studies were done years ago with other than the current neutron cross
sections and/or methods. Selected recalculation using the current reference cross sections and methods will be sufficient to justify the use of these previous studies in the validation program. It is also planned to obtain new supplemental LEU fuel experimental data.

Because of the limited amount of experimental data that is applicable to the LEU fueled MHTGR, carefully designed benchmark calculations will also be used as part of the validation for the physics design methods. In particular, benchmark calculations will be used in validating methods for temperature coefficient, and water ingress reactivity worth calculations, where suitable experimental data is very limited. In this regard, data from the proposed PROTEUS (Ref. 10) critical experiments will provide extremely useful confirmation of methods for calculating water ingress effects in the MHTGR.

The principal sources of experimental data (FSV, PB, etc.) which may be used to validate the MHTGR physics methods are given in Table 3, along with a listing of the key physics parameters (temperature coefficient, control rod worth, etc.) which are measured. A significant amount of measured data are available from many of these data sources. However, not all of these data are required, applicable, and/or adequately documented for use in the MHTGR core physics methods validation program. As the validation program proceeds, a determination will be made as to which of these measured data and how many of the data sets are appropriate for use in the validation of the methods for calculation of each core physics parameter. At that time, a determination will also be made as to the need for additional measurements.
### TABLE 3
**MHTCR CORE PHYSICS EXPERIMENTAL DATA**

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</table>

*(a)*Experimental data source description (i.e., the experimental facility) is given in Appendix B.

*(b)* = data available or expected to be available for validation program.

*(c)* = no data available from this component to validate the corresponding parameter.

*(d)* KFA subcritical.
ACKNOWLEDGEMENT

Some of the work reported in this paper was supported by the Department of Energy, San Francisco Operations Office Contract DE-AC03-89SF17885.

REFERENCES


