

2. SAFETY RELATED PHYSICS VALIDATION DATA AND NEEDS FOR ADVANCED GAS-COOLED REACTOR DESIGNS

Advanced gas-cooled reactors currently being developed are predicted to achieve a simplification of safety and licensing requirements through reliance on innovative features and passive systems. Specifically, this simplification derives from a combination of

- a) the neutron physics behavior of the reactor core
- b) reliance on ceramic coated fuel particles to retain the fission products even under extreme accident conditions
- c) the ability to dissipate decay heat by natural transport mechanisms without reaching excessive fuel temperatures
- d) the resistance of the fuel and reactor core to chemical attack (air or water ingress).

Development activities in several countries have focused on the validation of these features under experimental conditions representing realistic reactor conditions. It is important to note that validation of these features was identified as a key requirement by the U.S. Nuclear Regulatory Commission in the draft Safety Evaluation Report for the modular HTGR [2.1].

2.1. PHYSICS VALIDATION DATA NEEDS FOR ADVANCED GCRS

Innovative features employed by advanced gas cooled reactors vary according to the specific design, but include the following features, which reactor core physics codes should be able to treat with sufficient accuracy:

- LEU fuel
- control rods located both in the core and in the side reflector
- annular core
- large H/D ratio of core

Further, particularly for steam cycle concepts, the design codes must be able to accurately predict the effect of moisture ingress into the core on key safety parameters.

Tables 2.1a-d present the important core-physics parameters and the desired conditions for validation data for the design of advanced gas-cooled reactors in several participating countries. These requirements were developed early in the CRP and can be expected to change somewhat with time as designs evolve.

Parameter	Desired conditions
Core criticality	<ul style="list-style-type: none"> • Fissile and fertile particles in cylindrical fuel rods • LEU / Natural U fuel • Core average C / fissile atom ratio: <ul style="list-style-type: none"> - 3900 at BOEC * - 6500 at EOEC * • Reload ²³⁵U enrichment: <ul style="list-style-type: none"> - 19.8 wt. % in fissile particles - 15.5 wt % in fissile + fertile particles • Average ²³⁵U enrichment in both particles <ul style="list-style-type: none"> - 13.0 wt. % at BOEC* - 8.6 wt. % at EOEC* • Effects of cylindrical B₄C poison rods
Temperature coefficient	<ul style="list-style-type: none"> • To high temperature, i.e. to 1000 °C or above, if possible • Reflector contribution • Effects of moisture
Control rod worth	<ul style="list-style-type: none"> • B₄C control rods in side reflector and core • Effects of moisture
Power distribution	<ul style="list-style-type: none"> • Effects of control rods in the reflector • Effects of partly inserted control rods
Water ingress	<ul style="list-style-type: none"> • Effect on reactivity, temperature coefficient, and control rod worth • Range of interest for the average water density in the active core of the GT-MHR is up to 0.009 g/cm³ for hot conditions, and up to 0.053 g/cm³ for cold conditions.
Decay heat	LEU / natural U fuel
Reactor transients	LEU / natural U fuel
Reactor shielding	Neutron fluence on reactor vessel, and its spectral distribution

* **BOEC = Beginning of Equilibrium Cycle**
EOEC = End of Equilibrium Cycle

Table 2.1a **Advanced gas-cooled reactor physics validation needs for U.S. GT-MHR**

Parameter	Desired conditions
Core criticality	<ul style="list-style-type: none"> • LEU • C / ²³⁵U atom ratio 7000 • 8% ²³⁵U enrichment
Temperature coefficient	<ul style="list-style-type: none"> • to high temperature • effect of water ingress • reflector contribution • Pu effects
Control rod worth	<ul style="list-style-type: none"> • B₄C control rods in side reflector and core • tall, high leakage, cylindrical core • effect of water
Burnable poison worth	<ul style="list-style-type: none"> • B₄C
Neutron flux and power distribution	<ul style="list-style-type: none"> • tall, high leakage, cylindrical core • effect of reflector control rods on power distribution • effect of partly inserted rods • fluence on reactor vessel, and its spectral distribution
Water ingress effects	<ul style="list-style-type: none"> • on reactivity • on temperature coefficient • on control rod worth

Table 2.1b Advanced gas-cooled reactor physics validation needs for the Russian VGM

Parameter	Desired conditions
Core criticality	<ul style="list-style-type: none"> • LEU (18% ^{235}U enrichment) • BOC C / ^{235}U ratio = 4000 • EOC C / ^{235}U ratio = 10000 • with no control rods in core or nearby reflector • core height 1.76m, core diameter 1.90m • stochastic effects • streaming effects
Temperature coefficient	<ul style="list-style-type: none"> • to high temperatures • around room temperature also useful
Control rod worth	<ul style="list-style-type: none"> • close to core (6cm) • effect of moisture
Burnable poison worth	<ul style="list-style-type: none"> • pebbles with 4.2g hafnium and 40mg boron • effect of moisture • effect of a layer of absorber pebbles on top of core
Water ingress	<ul style="list-style-type: none"> • especially around 7kg per cubic meter in core
Neutron balance components	<ul style="list-style-type: none"> • reaction rate ratios
Neutron flux and power distribution	<ul style="list-style-type: none"> • desirable
Other	<ul style="list-style-type: none"> • reactivity effect of nitrogen in core • reactivity effect of fuel pebbles in discharge pipe • reactivity effect of fuel pebbles in different positions

Table 2.1c **Advanced gas-cooled reactor physics validation needs for HTR-10 (China)**
- adopted from [2.2]

Parameter	Desired conditions
Core criticality	<ul style="list-style-type: none"> • LEU • C/U atom ratio 450 to 650 (1000 also desirable) • 7 to 10 % ²³⁵U enrichment
Temperature coefficient	<ul style="list-style-type: none"> • from ambient to high temperature • effect of moisture/steam • reflector influence • Pu effects
Control rod worth	<ul style="list-style-type: none"> • B₄C control rods in side reflector • small B₄C absorber spheres (KLAK) • small core, high leakage • influence of moisture/steam
Neutron flux and power distribution	<ul style="list-style-type: none"> • small, tall core geometry • effect of partly inserted reflector rods • fluence on reactor vessel
Water ingress effects	<ul style="list-style-type: none"> • reactivity as function of H₂O concentration • effect of inhomogeneous H₂O distribution • influence on control rod / KLAK reactivity • influence on power distribution • influence on temperature coefficient <p>(The water density range of interest is up to equivalent 70 bar saturated steam to cover hypothetical accident scenarios)</p>

TABLE 2.1d **Advanced gas-cooled reactor physics validation needs for Germany (HTR modul)**

2.2. SUMMARY OF VALIDATION DATA BASE (PRIOR TO CRP)

The adequacy of computational methods used to compute safety-related physics parameters for advanced gas cooled reactors must be supported by comparisons with experimental data covering an appropriate range of conditions. Validation data is available from power reactors as well as past critical experiments. These are listed in Table 2.2, along with a summary of experimental conditions and references to reports providing more detailed information. Note that most of the existing validation data is for HEU/Th fueled systems.

Facility	Description	Measurements	Refs.
THTR-300 Reactor Germany (1983-1989)	<ul style="list-style-type: none"> • pebble-type • control rods in reflector and core 	<ul style="list-style-type: none"> ◆ k_{eff} ◆ control rod worth ◆ temp coef 	[2.13]
	<ul style="list-style-type: none"> • power 308MWe • B/Hf absorber pebbles in core • cylindrical core • height 5m, diameter 5m • fuel type HEU (93%) / Th fuel form (UTh)O₂ 		[2.14]

Table 2.2 Sources of gas cooled reactor physics methods validation data and summary of conditions
Part 1. Reactors (continued)

Facility	Description	Measurements	Refs.
Peach Bottom Critical USA (1959-62)	• block-type	◆ k_{eff}	[2.15]
	• control rods in core	◆ control rod worth	[2.16]
	• cylindrical core	◆ power distributions	
	• height 1.2m, diameter 1.5m	◆ temp coef./defect	
	• fuel type HEU (93%) / Th	◆ water ingress	
	• fuel form U_3O_8 • C / ^{235}U ratio 2775		
HTLTR Critical USA (1970-71)	• block-type	◆ temp coef./defect	[2.17]
	• control rods in core		[2.18]
	• cubic core		
	• height 3.0m, width 1.5m		
	• fuel type Pu&HEU (93%)/Th		
	• fuel form $\text{UC}_2\text{-ThO}_2$ & U_3O_8 • C / ^{235}U ratio 5710		
HTGR Critical USA (1966-69)	• block-type	◆ k_{eff}	[2.16]
	• control rods in core	◆ control rod worth	[2.19]
	• rectangular core, split table	◆ temp coef./defect	[2.20]
	• height 1.8m, width 2.1m		
	• fuel type HEU (93%)/Th		
	• fuel form U_3O_8 • C / ^{235}U ratio 2680		
HITREX-2 Critical USA (1971-75)	• block-type	◆ k_{eff}	[2.21]
	• control rods in core and refl.	◆ control rod worth	[2.22]
	• hexagonal core	◆ power distributions	
	• height 2.0m, diameter 2.5m		
	• fuel type LEU (3.5%)		
	• fuel form UO_2 • C / ^{235}U ratio 10300		

Table 2.2 Sources of gas cooled reactor physics methods validation data and summary of conditions
Part 2. Critical experiments

Facility	Description	Measurements	Refs.
CNPS Critical USA (1987-89)	<ul style="list-style-type: none"> • block-type • control rods in core • cylindrical core • height 1.1m, diameter 1.2m • fuel type LEU (20%) • fuel form UCO • C / ²³⁵U ratio 3000 	<ul style="list-style-type: none"> ◆ k_{eff} ◆ control rod worth ◆ temp coef./defect ◆ water ingress 	[2.23]
SHE Critical Japan (1975-1985)	<ul style="list-style-type: none"> • block-type (split-table) • various core shapes • height 2.4m, diameter 2.4m • fuel type LEU (20%) • fuel form UO₂ • C / ²³⁵U ratio 2000-16000 	<ul style="list-style-type: none"> ◆ k_{eff} ◆ control rod worth ◆ temp coef. at 700°C ◆ flux distributions 	[2.24] [2.25] [2.26] [2.27]
VHTRC Critical Japan (1985-1995)	<ul style="list-style-type: none"> • block-type (split-table) • control rods in core • hexagonal core • height 2.4m, diameter 2.4m • fuel type LEU (2, 4, 6 %) • fuel form UO₂ • C / ²³⁵U ratio 8800-17500 	<ul style="list-style-type: none"> ◆ k_{eff} ◆ k_{eff} with burnable poison ◆ control rod worths in core and reflector ◆ temp. coef (up to 200°C) ◆ flux distributions ◆ water ingress ◆ kinetic parameter ($\beta_{\text{eff}}/\Lambda$) ◆ β_{eff} 	[2.28] [2.29] [2.30]
KAHTER Critical Germany (1973-75)	<ul style="list-style-type: none"> • pebble-type • control rods in core and refl. • cylindrical core • height 2.8m, diameter 2.2m • fuel type HEU (93%) / Th • fuel form (UTh)O₂ • C / ²³⁵U ratio 7550 	<ul style="list-style-type: none"> ◆ k_{eff} ◆ control rod worths in core and reflector ◆ flux distributions ◆ water ingress???? 	[2.31] [2.32] [2.33]

Table 2.2 Sources of gas cooled reactor physics methods validation data and summary of conditions
Part 2. Critical experiments (continued)

Facility	Description	Measurements	Refs.
CESAR-II Critical France (1970-1972)	<ul style="list-style-type: none"> • pebble-type (driven) • fuel type LEU 	<ul style="list-style-type: none"> ◆ critical mass ◆ flux distributions ◆ reaction rates ◆ spectral indices ◆ Pu effects 	<p>[2.34]</p> <p>[2.35]</p>
ARGONAUT Critical Austria (1970s)	<ul style="list-style-type: none"> • fuel type LEU (driven) 	<ul style="list-style-type: none"> ◆ water ingress 	<p>[2.36]</p>
GROG Critical Russia (1980-1995)	<ul style="list-style-type: none"> • pebble-type • control rods in refl. and in core • square and circular cores • height 1.0-3.5m, diameter 1.0-3.5 m • fuel type LEU (10%) • fuel form UO₂ • C / ²³⁵U ratio 2500 - 7500 	<ul style="list-style-type: none"> ◆ critical mass ◆ flux distributions ◆ control rod worths ◆ spectral indices 	<p>[2.37,2.38,2.39]</p>
ASTRA Critical Russia (1980-1995)	<ul style="list-style-type: none"> • pebble-type • control rods in refl. • circular, square and octagonal core • height 1.7-4.2 m, diameter 1.0-1.8 m • fuel type LEU (21%, 6.5%) • fuel form UO₂ • C / ²³⁵U ratio 7680 	<ul style="list-style-type: none"> ◆ critical mass ◆ flux distributions ◆ control rod worths ◆ spectral indices ◆ water ingress 	<p>[2.38,2.39]</p>

Table 2.2 Sources of gas cooled reactor physics methods validation data and summary of conditions
Part 2. Critical experiments (continued)

2.3. PLANNING OF PROTEUS EXPERIMENTS TO PROVIDE VALIDATION DATA

The PROTEUS graphite moderated LEU critical experiments were planned to fill gaps in the base of validation data. The constraints included room temperature and 5500 LEU fuel pebbles supplied by the KFA Research Center, Jülich, Germany. Specifically, the experiments which could be conducted at the PROTEUS facility with the available AVR LEU fuel are summarized in Table 2.3.

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- clean critical cores
 - LEU pebble-type fuel with 16.76% U²³⁵ enrichment
 - a range of C/U atom ratio of 946 to 1890 (achieved by varying the moderator-to-fuel pebble ratio from 0.5 to 2.0)
 - core (equivalent) diameter = 1.25 m
 - core height = 0.843 m to 1.73 m (with simulated water ingress smaller core heights are possible)
 - core H/D from 0.7 to 1.4
 - flux distribution measurements and spectral distribution measurements (including measurements in side reflector)
 - kinetic parameter measurements
 - worth of reflector control rods (partly and fully inserted)
 - worth of in-core control rod (partly and fully inserted)
 - effects of moisture ingress over range of water density up to 0.25 gm H₂O/cm³ void (corresponds to 0.065 gm H₂O/cm³ core for PROTEUS). Water is simulated with polyethylene inserts.
 - ◆ effect on core reactivity
 - ◆ effect on worth of reflector control rods
 - ◆ effect on worth of in-core control rod
 - ◆ effect on burnable poison worth
 - ◆ effect on prompt neutron lifetime
 - ◆ effect on flux and power distributions
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Table 2.3 Summary of PROTEUS critical experiments

PROTEUS results fill certain gaps in required experimental data for code validation for advanced gas-cooled reactors which are under development. Comparing the data needs (from Table 2.1) with the experimental conditions achievable at PROTEUS (from Table 2.3) demonstrates the following:

- The PROTEUS criticals provide validation data for low-enriched uranium fuel with an enrichment near to that planned for advanced GCR designs.
- PROTEUS moisture ingress experiments will investigate the effects which are important for advanced GCR designs (i.e., reactivity worth of moisture, and the effect of moisture on control rod and burnable poison worth and on reaction rate distributions) over the range of moisture densities of interest.
- The achievable range of C/U atom ratio at PROTEUS is near to, but higher than that of advanced GCR designs (this ratio is an important factor in determining the neutron energy spectrum).
- PROTEUS provides validation data
 - for the worth of reflector control rods
 - for the worth of an in-core control rod
 - for the worth of small samples of burnable poison (B₄C)
 - for fission rate distributions in core and reflector.

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