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Requirements for Control Rods in HTR Conditions

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Summary

The purpose of this document is to give a preliminary specification for control rods in order to be able to make a first selection of the more suitable materials. This specification covers only the control rods (not drive mechanism and so on).

Operating conditions are given. They can be considered as valid for both HTR and VHTR configurations for which the C/C composite type materials appear to be an interesting solution.

Before giving the specification, a short review of control rods design defined for other reactors is done.

The specification is established giving limit values for thermal and mechanical properties, taking into account the environmental conditions, in particular irradiation and possible oxidation.

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(1) Reactor System Design Description – Rev. 0, Nov 1997 – OKBM for the GA/Minatom GT-MHR project

(2) Gas Turbine–Modular Helium Reactor (GT-MHR) Conceptual Design Description Report – July 1996 - GA

(3) Development of carbon/carbon composite control rod for HTTR (I) and (II) – JAERI-Research 98-003

(4) PBMR Safety Analysis Report – Document n° 001929-207 rev.0a

1. Introduction

The purpose of this document is to give a preliminary specification for control rods in order to be able to make a first selection of the more suitable materials. This specification covers only the control rods (not drive mechanism and so on).

Operating conditions are given. They can be considered as valid for both HTR and VHTR configurations for which the C/C composite type materials appear to be an interesting solution.

Before giving the specification, a short review of control rods design defined for other reactors is done.

2. Review of control rods design

2.1 Prismatic block reactor type

2.1.1 American/Russian technology

It appears that components and technology used for GT-MHR were similar than those used at Fort St. Vrain (and MHTGR).

The control and shutdown system of GT-MHR consists of 2 systems different in their functions [1]:

- Reactivity compensation and emergency protection. 36 control rods located in the side replaceable reflectors at the boundary of the core ensure these functions. They are inserted to varying heights for control during operation and completely inserted for protection.

- Automatic control rods used only during startup/shutdown and refuelling operation. 12 control rods which ensure these functions are located in the active core at the boundary with the inner reflectors. They are completely removed when the core is critical.

Both types of control rods have the same design : they consist of 20 segments connected to each other. 19 segments contain the absorber material B_4C, the upper part allowing the coupling with the drive mechanism. Each control rod assembly is supported by mechanisms in the top head of reactor. The control rod is cooled both from inside and outside.

Each control rod segment consists in a ring made of absorber material B_4C dispersed in a graphite matrix, with an outer diameter of 102 mm and a thickness of 12 mm which are enclosed between two coaxial tubes and closed by a bush. Inside there is a bearing bush with lugs at the bottom providing a gap between the block channel and the rod for the cooling flow (see figure 1). A pivot connects 2 segments to each other. A flexibility of the whole control rod is allowed by a spherical contact between pivot and inner bearing bush. The total length of the rod is 9600 mm for an active part of 9300 mm.

In many Russian documents, the control rods are designed with graphite for tubes, bush and lug. However, in more recent documents graphite appears to be replaced by C/C composite. At Fort St. Vrain, the control rods structure was in Inconel.

2.1.2 Japanese technology

In the first design of HTTR, the control rods, made of alloy 800H, are inserted in 2 steps: 9 out of 16 pairs of control rods in the reflector region are inserted immediately and the seven other pairs in the core region are inserted 40 minutes later, when the temperature of the outlet coolant becomes lower than 750°C.

The use of C/C composite material has allowed avoiding this 2 steps procedure. The rod consists of 10 sleeves connected to each other by bolts and lids (figure 2). Each sleeve has a length of about 300 mm for a total length of the rod of 3094 mm. The sleeves contain compacts of B_4C, the external diameter of the outer tube is 113 mm with a thickness of 4 mm, and the external diameter of the inner tube is 75 mm with a thickness of 7.5 mm [3].

2.2 Pebble Bed reactor type

The design of PBMR control and shutdown systems is based on the German AVR technology.

The reactivity control and shutdown system (RCSS) of PBMR consists of 2 independent systems: the Reactivity Control System (RCS) which consists of control rods system, and the Reserve Shutdown System (RSS) consisting of small shutdown spheres system (ref. [4]).

Each system is able to transfer the reactor in a sub-critical state (at temperatures between 900 and 400°C). Both systems (combined) are used to maintain the reactor sub-critical in a cold condition.

The RCS consists of 18 control rods sub-systems containing each a control rod, a control rod drive mechanism, a rod emergency shock absorber, a shielding. The design of this system is based on the THTR300 design.

Each control rod consists of 11 segments containing absorber material in the form of sintered B_4C rings between 2 coaxial tubes. The individual segments are joined together with a flexible coupling to form a single control rod. Both the inside and outside of the rod are cooled by cold helium inlet. The material preferred for control rods is C/C composite.

The design of RSS, which is not detailed here, is based on an existing HTR Modul technology.

3. Control Rods Requirements for HTR/VHTR

3.1 Geometry

The design of control rods for HTR/VHTR considered today is similar to that of GT-MHR or HTTR:

A ring-type design is considered with a cooling from inside and outside. The cladding consists of two co-axial tubes containing absorbent materials (graphite compact with B_4C). The internal structure is annular to let the flow cooling the rod inside and should be able to link to segments to each other. This internal structure should allow a flexibility of the rod in order not to give too much stresses in case of earthquake.

The following dimensions can be assumed :

- Cladding (co-axial tubes): - Tubes diameter ϕ_e = 60 / 120 mm, thickness between 4 and 8 mm

  - Length of tubes: 500 mm

- Connecting structures: thicker structures with an external diameter of about ϕ_e = 60 mm for a length equal to 100 mm (can be a pivot like in graphite design of GT-MHR or others).

Regarding the fabrication of these structures, the properties should not vary in large proportions between lots which means that the availability of the raw materials should be ensured on a significant period.

3.2 Environmental conditions

Assuming here that a part of control rods is devoted to startup/shutdown and another to reactivity control + shutdown as for GT-MHR, this means that the former will be less solicited in normal operation (withdrawn when reactor critical) than the latter. Nevertheless, in accidental conditions, same conditions must be withstood by both types of control rods :

	Startup/shutdown control rods	Operating control rods
Nominal conditions	< 800°C	1100°C
Accidental conditions within 100 h	1600°C	1600 °C
Max fluence (E > 0.18 MeV)	~0	$4.3\ 10^{21}$ n/cm² for 30 years (1)
Air reactivity	< 0.2 mg/g-h (2)	< 0.2 mg/g-h (2)

(1) : the life duration of the operating control rods is 30 years, assuming that the rods see a fluence per year equal to $1.43\ 10^{20}$ n/cm².

(2) : material of the rods has to be resistant to oxidation: oxidation due to the presence of small quantity of O_2 or H_2O in normal operation and also oxidation due to air (or water) entry accidents. In a first assumption, a limit of 0.2 mg/g-h of burn off rate is proposed. Also, in this objective, the content of some impurities could be limited in order to prevent an important oxidation.

The material of control rods must be compatible with the absorbent material (B_4C). Its resistance to erosion shall be greater than that of the graphite blocks.

The control rods shall operate in Helium atmosphere under a maximum (absolute) pressure of 71 bars and a Helium speed of 35 m/s.

3.3 Thermal and mechanical properties

The material has to withstand thermal stresses and should therefore offer at least the same level of thermal stability.

Regarding mechanics, a high mechanical resistance has to be specified together with a non brittle fracture behaviour and a high toughness. These properties cannot be reached by a graphite.

The following limits are to be fulfilled (unirradiated materials) :

Properties at RT	Limit values
Thermal Conductivity (W/m°C)	> 100 (1)
Strength (MPa) tensile/bending/compressive	> 80 (2)
Fracture toughness (MPa m $^{1/2}$)	> 3 (2)
Thermal shock resistance (W/m)	> 65 000

(1) : see also performances required under irradiation

(2) : to be refined. The strength limits depend on the seismic loading which is difficult to estimate today. A lower strength limit will probably be acceptable.

3.4 Performances required under irradiation

Under irradiation, the material should present stable, i.e. reasonable dimensional changes. Also to be consistent with graphite, the thermal conductivity shall not be too degraded and reach the level of graphite conductivity:

	Specified value - for temperature range : [500-1200°C] - for fluence range : [0-4 10^{21} n/cm²] (E> 0.18 MeV)
Thermal conductivity	> 30 W/m°C
Dimensional change	< 1.2 % and turn-around point not exceeded

To be noted that the control rods can be changed during the reactor life, the life duration being directly adapted to the behaviour of the material with irradiation.

3.5 Other requirements

For the commissioning of the plant, 48 rods shall be manufactured, and 48 others at the mid-life time i.e. 96 rods consisting of two co-axial tubes and an annular internal structure. Same raw materials for each one is required.

Regarding safety, the control rods are systems important for safety and should be manufactured with an important level of quality. 100% of the products should be checked including control of raw materials, control of the fabrication process, control of the finished products.

4. Conclusions

A preliminary specification for control rods in HTR/VHTR conditions is established. This will allow making a first selection of the most suitable materials for control rods.

Figure 1
GT-MHR Control rod geometry

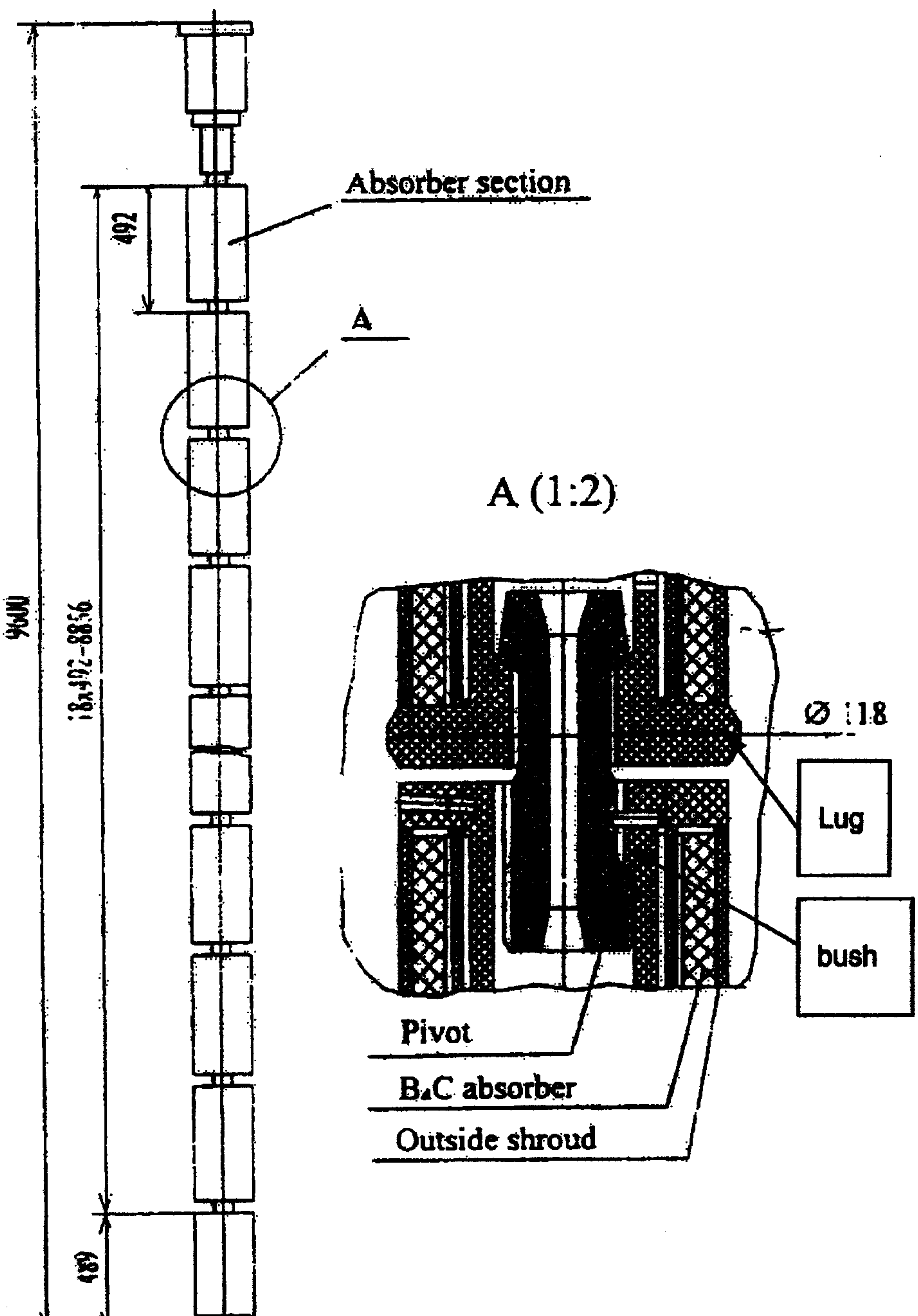
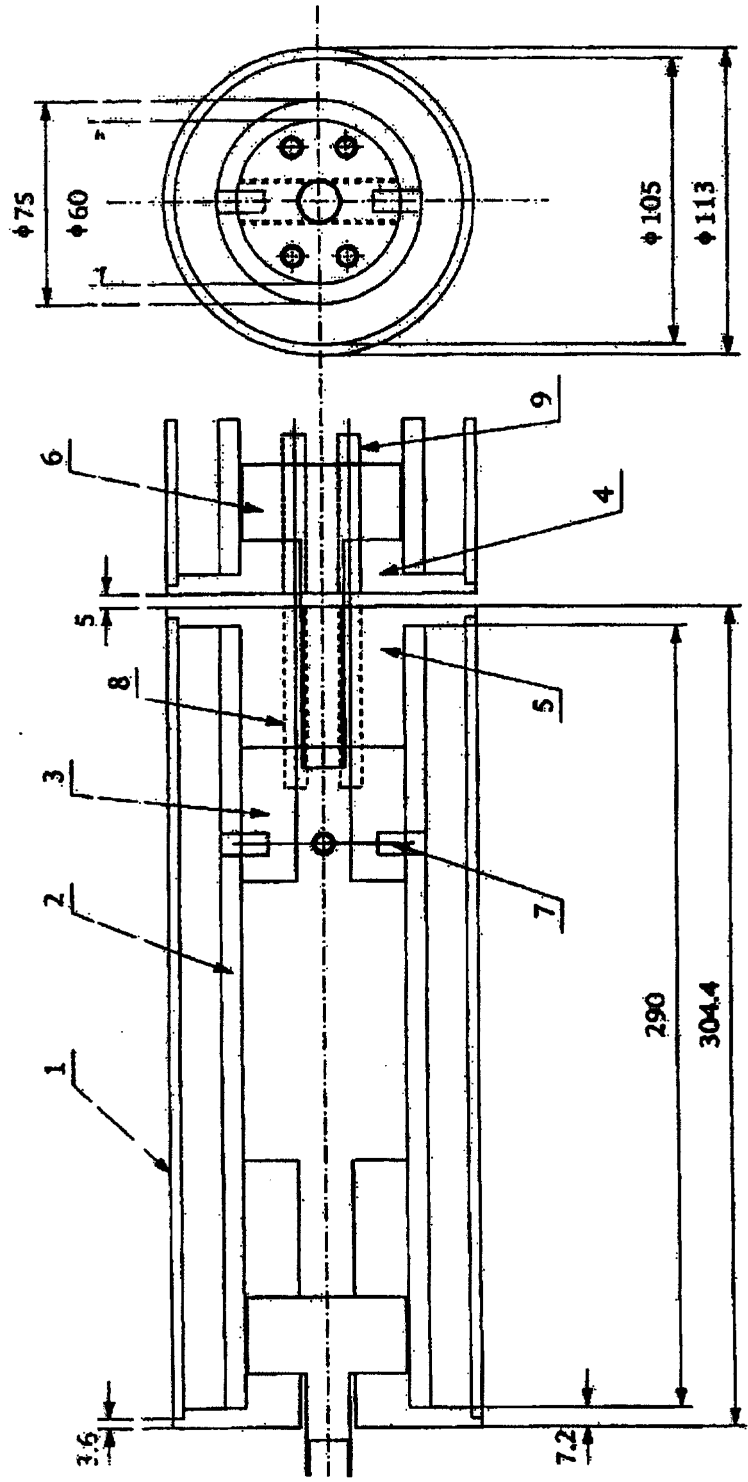


Figure 2
HTTR Control rod geometry



No.	Component	Material	Quantity
1	Outer tube	C/C	1
2	Inner tube	C/C	1
3	Lid supporting plug	C/C	1
4	Upper lid	C/C	1
5	Lower lid	C/C	1
6	M16 Bolt	C/C	1
7	M8 Bolt	C/C	8
8	M8 Bolt	C/C	4
9	M8 Bolt	C/C	4