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HTR-M Design use and specification for internals

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Summary

This document provides elements for design use and specifications of the material used for internals of high temperature reactors. It contributes to the 5th PCRD HTR-M WP2.1 item. As requested it is focused here on control rods. It refers to GT-MHR and PBMR type reactors designs.

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1. INTRODUCTION

This document provides elements for design use and specifications of the material used for internals of high temperature reactors. It contributes to the 5^{th} PCRD HTR-M WP2.1 item. As requested it is focused here on control rods. It refers to GT-MHR and PBMR designs.

2. CASE OF A GT-MHR TYPE REACTOR

2.1 DESCRIPTION

2.1.1 Functions of control rods

The control rods are used to compensate for both fuel burn-up and power variations reactivity effects.

The control rods positioned in the reflector are used to control the reactor in normal operation modes and shutdown the reactor system.

The control rods in the fuel assemblies masonry are used to control the reactor system during start-up, at stationary operation mode they are completely armed.

In accidents all 48 control rods, inserted from any position are used.

2.1.2 Geometry

2.1.2.1 Core

The core consists of :

- the Fuel Assemblies (FAs) annular masonry,
- absorber elements of Reserve Shutdown System (RSS),
- Replaceable Side Reflector (RSR) blocks,
- control rods,
- and neutron source.

The FAs annular masonry is located within the replaceable reflector. The FAs are collected in 102 columns with 10 assemblies in each. So total number of FAs is 1020 :

- 720 from them are of the type 1, i.e. without a channel for control rods or RSS absorber elements,
- remainder 300 FAs are of the type 2, with a channel. These FAs are subdivided into :
  - FAs with holes for the RSS absorber elements – 180 pieces,
  - and FAs with holes for the control rods – 120 pieces.

  Sizes of the holes are the same, i.e. 130 mm diameter and 800 mm length.

The replaceable reflector is made of 163 columns, distributed as follows :

- Outside reflector : 102 columns,

- Inside reflector : 61 columns.

The upper and lower reflectors are located above and under the FAs masonry respectively.

2.1.2.2 Control rods

The main option is a ring-type design with cooling of absorbent elements from inside and outside of the control rod.

The control rods are located along two circumferences within channels of 130 mm diameter:

- along the inner circumference, the control rods (12 pieces) are inserted directly into the channels of the FAs masonry,
- along the outer circumference, they are inserted into the RSR (36 pieces).

One rod consists of 20 sections connected with each other by pivots (Fig 1 of appendix 1), the whole being hung up to the drive mechanism :

- 19 sections of them contain the absorber material B_4C,
- the top section has a bush for coupling with the drive gripper and ring for the rod support on the graphite masonry when it is released from the drive gripper .

Rings made of absorber material (B_4C) are installed upon the lug. From outside and inside the absorber material rings are covered by graphite bushes.

At the centre of the pivot there is a hole for the cooling gas passage (the control rod is cooled both from inside and outside).

- Rod mass : no more than 120 kg
- Total length of the rod : 9600 mm
- Length of rod active part : 9300 mm. External diameter is 118 mm, diameter of the rod top bush support ring is 130 mm.
- Absorbent mass : 40 kg (d_{B4C} = 1,4 g/cm^3)
- Absorber ring : outer Ø 102 mm, thickness 12 mm
- Full working stroke : 8000 mm
- Rod motion speed in automatic control mode : 10 to 20 mm/s
- Rod motion speed in trip mode : 800 to 1000 mm/s
- Acceleration for the rod in the trip mode : 1 g

When it is released from the drive gripper, the control rod is supported on the reflector blocks by its top section (ring 130 mm in diameter).

A perforated bush serves as a shock-arrestor in the event of an unauthorized uncoupling of the gripper or at its break off (no shock-resistant dampers are provided for in the core). The top section of the rod has to support this deceleration in the trip mode.

2.2 OPERATING CONDITIONS

2.2.1 Steady-state conditions

Steady-state operating conditions in nominal mode are :

	Absolute pressure (MPa)	Temperature of the rod's outer cladding (°C) top	Temperature of the rod's outer cladding (°C) bottom	He speed (m/s)
Nominal power	7,2	480	850 ± X	35

When cooling the core and reactor internal structures, helium is heated, enters the plenum where it is mixed with the remainder helium up to the average temperature of 850°C. A difference in values of coolant heating in the channels caused by the different ratios between flowrate and power removed by the coolant leads to a great non-uniformity of helium temperature at the bottom plenum inlet. That is why the maximal temperature can reach 850+X °C. For a first assessment, X can be taken to 50°C.

The envelope situation is nominal full power (100%) and partial load data are not useful here for control rod material specification and design use.

There are 3 shutdown states :

- Hot shutdown state : core average temperature is 470°C, helium inventory in the primary circuit is 7%, helium pressure of some bars (< 5 bar),
- Cold shutdown state : core average temperature is between ambient value and 100°C, helium pressure close to the atmospheric one,
- Shutdown for refuelling : this state is similar to previous one (cold state) but helium inventory is further reduced to achieve slightly sub-atmospheric pressure in the primary coolant system.

2.2.2 Transients

The transients are separated into 5 categories, according to the following classification. Probabilities of occurrence/year have been included in the following table according to FRAMATOME ANP understanding :

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Category	Definition	Probability p of occurrence per year
1	Normal transients associated to normal operating conditions of the plant during its entire service life	/
2	Design transients associated with any deviations from normal operation conditions (pressure, temperature, load, etc… which require to decrease power or to shutdown reactor to eliminate these deviations without activation of the emergency core cooling system	$10^{-2} < p$
3	Design transients caused by events defined in the design, and characterized by violation of limits and/or conditions established for safe operation, except safe operation limits for radioactive products release.	$10^{-2} < p$
4	Design accidental transients caused by events defined in the design and resulting in exceeding the safe operation limits for radioactive product release beyond boundaries provided by the design for normal operation.	$10^{-6} < p < 10^{-2}$
5	Beyond design accidental transients caused by events not defined in the design or accompanied by additional failures or personnel errors in comparison with design accidental transients	$p < 10^{-6}$

The following table provides functional specifications for a GT-MHR type reactor control rods. The envelope representative values of the following parameters are indicated :

- Helium temperature range
- Helium thermal gradients $\delta T/\delta t$ (t = time), mean and local maximum values
- Helium pressure range
- Helium pressure gradients $\delta P/\delta t$ (t = time), maximum value
- Helium temperature distribution along the control rod
- Cumulated number of occurrences (for 6 years).

Transient category	He Temperature range	He mean thermal gradient $\delta T/\delta t$	He Max. local thermal gradient $(\delta T/\delta t)$max.	He absolute pressure range	He mean pressure gradient $\delta P/\delta T$ (max)	Cumulated number of occurrences (for 6 years)
	°C	°C/h or °C/min or °C/s	°C/min or °C/h or °C/s	MPa	MPa/s or MPa/min or MPa/h	/
1	[≈ Ambient √ 900]	+ 1°C/min –10°C/min	+5°C/min –10°C/min	[≈ ambient → 7,2]	±0,1 MPa/min	1100
2 and 3	[220 √ 485]	+2°C/s -35°C/s	+10°C/s -35°C/s	[3 √ 8,25]	+1,5 MPa and –5,3 MPa instantaneous	60
4 and 5	[850 → 1600]	10°C/h	20°C/h	[0,4 √ 7,2]	-1 MPa/s during 3 seconds	5

The relevant case considered of positive reactivity addition mode is an erroneous withdrawal of a group of automatic control rods : 3 rods symmetrically located in the outer side reflector. The reactivity addition leads to the increase of both the reactor power and Helium temperature at the core outlet. This temperature increase is low (+15°C) because reactor protection system actuates emergency protection rods into the core by gravity on high power level (120% of nominal) signal. So the maximum fuel temperature does not exceed 1000°C at outlet section, and so for the control rods.

2.3 Other thermal loadings

- Maximum heat release in structural material : 1 to 2 kW/ℓ
- Maximum heat release in the rod absorbent : 22 kW/ℓ

Thermal bending has not to be considered because the control rod consist of 20 sections connected with each other by pivots, the whole being hung up to the drive mechanism.

Other thermal effects (thermal gradient, differential thermal expansion) should be negligible because structures are practically isotherm at a given level of the core.

2.4 Seismic loading

The core shall retain its functional capability :

- at the seismic impacts of magnitude 7 on the MSK-64 earthquake scale (design basis earthquake)
- at the seismic impacts of magnitude 8 (maximum design basis earthquake)

thus providing safety for the reactor plant, including safe shutdown and shutdown cooling.

2.5 He fluid velocity

Coolant velocity in the rod channel of the block is not more than 35 m/s. The flow is directed downwards.

2.6 Irradiation level

Neutron fluence (E ≥ 0,18 MeV) in one rod for 1 year : 10^{21} n/cm^2

2.7 Functional requirements

- Allowable deformation of control rod cladding : increase in diameter should not lead to a coolant flow reduction of more than 10% in the channel ; increase in length should be within acceptable limits compared with the control rod drive mechanism working stroke.
- Friction of the control rod cladding in the holes of graphite fuel assemblies and replaceable reflectors should be negligible.

2.8 Other requirements

- Structural materials of the rods have to be resistant to radiation, corrosion, and erosion both in purified working helium flow or with high impurities content in case of emergency situations.
- Materials of control rod and control rod cladding have to be compatible with the absorbent material.

  For example, in the GT-MHR project, the top section of the rod is made of heat resistant steel while structural material of the19 others sections is graphite.
- Type of products expected are tubes, with possibly temperature and wear-resistant coatings.
- Quality controls will be performed at all stages of fabrication (raw materials, process, finish product).

2.9 Impurities content

Gaseous species in purified helium during working conditions are within the range :

- $CO + CO_2 < 6$ ppm
- $H_2O < 2$ ppm
- $H_2 < 2$ ppm
- CH_4 , N_2 : low values < about 2 ppm

3. CASE OF A PBMR TYPE REACTOR

3.1 Main characteristics

The Pebble Bed Modular Reactor is a nuclear power plant using uranium elements (coated particles) encased in graphite to form a fuel sphere (pebble). Helium is used as the coolant and energy transfer medium to a closed cycle gas turbine and generator system.

- Thermal power : 265 MWth
- Electric power : 110 Mwe
- Power density : 5 MW/m^3
- Helium temperature to the core (inlet, outlet) : 560°C ; 900°C
- Helium pressure in the core : 7.0 MPa abs. Structures design pressure : 7,2 MPa abs.
- Core dimensions : 3,5 m diameter ; 7,5 m to 8,5 m height.

3.2 The RCSS system

The Reactivity Control and Shutdown System (RCSS) is composed of two independent and diverse sub-systems :

- The Reactivity Control System (RCS) (control rods system),
- The Reserve Shutdown System (RSS) (small shutdown spheres system).

The RCSS has the following safety related functions :

- Each system must independently be able to transfer the reactor to a sub-critical state between temperatures 900°C and 400°C, and keep the reactor sub-critical for an indefinite period at these temperatures. Failure of the highest-worth RCS or RSS sub-system is postulated (single failure).
- Both systems (combined) must allow the reactor to be in a sub-critical state below 100°C and keep the reactor sub-critical for an indefinite period at this temperature.

The RCS consists of 18 Control Rod sub-systems. The RCS design consists of the following (per sub-system):

- Control Rod,
- Control Rod Drive Mechanism (CRDM), with Position Indicator,
- Rod emergency shock absorber,
- Shielding.

3.2.1 Control Rods

Each control rod consists of 11 segments containing absorber material in the form of sintered B_4C rings between two coaxial tubes.

Gaps between the tubes and the B_4C rings are calculated to prevent constraint forces from arising due to radiation induced swelling of the B_4C. Pressure equalising openings expose the B_4C to the primary coolant.

The individual segments are joined together with a flexible coupling to form a single control rod.

The rods are freely suspended in the holes in the side reflector of the core internals. Guides are not required between the ceramic core structures and the rods. Because the annular clearance between the reflector and the rod is sufficiently large, sticking of the control rods is not expected to occur.

Both the inside and outside of the control rod are cooled by a leak stream of cold helium inlet.

3.2.2 Control Rod Drive Mechanism

The control rod drive mechanism has the following main functions:

- To raise and lower the control rods in the upper half of the core, and to hold them at any position in the their travel range,
- To guarantee shutdown in the event of reactor scram, cutting power to the drive motors allows the rods to drop by gravity,
- To limit drop velocity and to absorb the kinetic energy of the falling rod when the rod reaches the lower travel range during a reactor scram condition.

The control rod drive mechanisms are integrated into the reactor pressure vessel top dome, and consist of the following main items:

- A link chain which connects the control rods with the gear of the drive mechanism,
- A stepper motor drive,
- Shock absorber,
- Rod position indicators,
- Rod holding mechanism (to hold the control in its upper position during replacement of the rod).

The control rod is moved up and down in the side reflector holes by a stepper motor. The stepper motor drive rod is connected to a chain sprocket, which moves the link chain up or down. When the rods are raised the link chain is stored in a loose pile in a box. When the rods are lowered, the link chain is drawn from the box.

3.2.3 Back-up Shock Absorber

In the postulated event of a rod drop due to mechanical failure of the drive parts or a chain break, damage to the ceramic core internals is prevented by a shock absorber installed inside the holes in the side reflector. The lower end of the rod, which is conically shaped for this purpose, centres on the top part of the shock absorber. The energy of the falling rod causes plastic deformation of the concentric tubes beneath the top part of the shock absorber.

3.2.4 Shielding

Provision is made for adequate shielding using ALARA principles, for activities during maintenance operations.

3.3 OPERATING CONDITIONS

The plant lifetime is 80 years, comprising a 40 years operating period (35 years at full power) followed by a further 40 years period during which the module serves as an interim spent fuel storage facility. Lifetime of the control rods can be taken equal to 6 years similarly to the GT-MHR type reactor case.

Accidental conditions with hypothetical assumptions, so corresponding to category 5 events of paragraph 2.2.2 for the GT-MHR type reactor case (withdrawal of all control rods cumulated with the following events : no reactor scram and depressurised loss of forced coolant) leads to a maximum temperature not exceeding 1600°C during the transient.

So for a first assessment, because fuel temperature limits of GT-MHR type reactor (1600°C) is not exceeded, because nominal design pressure is equal to GT-MHR case (7,2 MPa), it is recommended to consider GT-MHR data of paragraph 2 as also applicable to PBMR control rods.

3.4 SEISMIC LEVEL

- 0,2 g peak ground acceleration in horizontal direction for Operating Basis Earthquake (OBE)
- 0,4 g peak ground acceleration in horizontal direction for Safe Shutdown Earthquake (SSE).

4. APPLICABLE CODES AND STANDARD

Mainly RCC-M or ASME are to be used. Other references are possible but regulations and guidelines to be used in the design of the structures are to be internationally recognised.

5. CONCLUSION

In this document specifications have been given for control rods essentially for a reactor of GT-MHR type.

Concerning control rods of a PBMR type reactor design, in a first assessment it is possible to apply the same operating conditions than the GT-MHR one. Beyond here-given informations on PBMR reactor type control rods, other needed specifications have to be asked to partners and in particular to German colleagues.