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Possibility of in-service inspection and accessibility into a HTR core cavity.

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1. INTRODUCTION

France hold the General Atomic licence for the high temperature gas cooled reactors. The possibility of access into the core cavity is not taken as a design criterium because all the fixed structures are designed for a life time equal to that of the reactor. However our operating experience of the gas-graphite, natural uranium reactor type has shown us the importance of been able to access to the core cavity in case of accidents which, even if they do not affect the plant safety, can reduce the plant reliability. For these reasons, we have conducted a series of studies, presented in this paper, on the possibilities of access into a HTR core cavity. The inspection instruments and remote removal of components have been also examined and they are briefly discussed.

2. DESCRIPTION OF A H.T.R. CORE CAVITY.

The high temperature reactors are based on the concept of coated fuel particles BISO and TRISO, graphite moderator and helium coolant. The HTR studied in France used prismatic fuel elements. The heat from the fuel is transferred to the hot helium used to produce steam. A prestressed concrete vessel contains the whole primary circuit (see Fig. 1). The core is in the central cavity. The graphite hexagonal blocks, which constitute the core, contain the fuel under the form of rods and several holes through which coolant blows. The rods are compacts of particles and graphite. The blocks form a vertical pile. The upper and lower reflectors are also made with hexagonal graphite blocks which have along a section of their height a neutrons absorbing element (iron or boron). The side reflector is made by a crown of hexagonal blocks which surrounds the core which large blocks at the outer side. The core and the reflectors lie on graphite support blocks which rest on graphite posts. The helium circulates from the upper plenum to a lower plenum. The core cavity is covered with a steel liner which has no mechanical role and is kept at a temperature of about 60°C through a thermal barrier. This barrier is of 3 classes. The class A is constituted by silicated-aluminated wool which is kept in place by steel plates; the class B which is different from the class A because of insulation thickness and because the steel is replaced by the hastelloy; and the class C with the barrier made with molten silica bricks that lay on a mattness of silicated-aluminated wool. The horizontal part of the lower plenum has a class C barrier. The vertical part of this plenum has a class B barrier. The other parts of the cavity have a class A barrier. The cover plates are fixed to the liner in the center and at the middle of each of their four sides.

Around the core, in the vessel, there are the steam generators and the auxiliary heat exchangers (emergency cooling). They are located in vertical cavities with the circulator above them. All these apparatus are removable. They communicate with the core cavity through helium ducts. The lower hot ducts have a class B thermal barrier covered with a hastelloy tube which function is to protect the insulation against hot helium streaks and the pressure gradient.

3. PROBLEM AREAS FOR THE CORE CAVITY ACCESSIBILITY.

The fixed structures of the core cavity have been designed to have a life time equal to that of the plant (40 years). A system of cameras, attached to the fuel handling machine or to a special arm allows an inspection of the cavity during the annual fuel reloading especially in the lower plenum area where the helium has his maximum temperature. The information from the cameras allows corrective and preventive actions. We cannot however eliminate the possibility of accident. The accidental drop of a block during the fuel loading can affect the core support. The most unfortunate case is when the block drops into an empty seven columns region. In this case the block drops on the permanent reflector. The core support has been design to withstand the impact but it can be a faulty one or have lost its resistance because of corrosion after water ingress events. For these reasons we have studied the possibility of replacing a support block, a post and a large lateral reflector block by remote handling. First of all the reactor is shutdown in an helium atmosphere. The circulator is removed and the handling apparatus is inserted through the cold duct into the core cavity. The operation has not been studied completely but we have conclude that it is feasible. An example of a replacement of a block is presented Fig. 2.

For the thermal barrier we can consider the situation of a loss of one of the five retainers of a class B cover plate caused by serious thermal gradients that could occur during temporary
losts of coolant. The plate has been designed to resist to these conditions but an immediate repair will be preferable at the beginning of the reactor life.

Another conceivable accident is the failure of a weld along a plate of the hot duct protective tube. Here also a repair is preferable to an evolutive lost of efficiency.

In conclusion, even if it is not necessary to penetrate into the core cavity, the access possibility can increase the plants reliability.

4. SOURCES OF RADIOACTIVITY.

The problem of the access to the lower plenum calls for a certain number of studies. The access takes place after the unloading of all the fuel blocks and with air into the reactor. The lower plenum is reached through the cold duct after the removal of the circulator.

The study we present here deals only with the radiation level of the lower plenum, because this is the limiting condition.

The core is removed so it remains activity and fission product plate out. The activity comes from the metallic structure of the loop. The contribution from the metallic and upper structures is negligible because the large reflector blocks stay in place. The dose rate from activity comes from bottom liner and from the cover plates of the lower plenum thermal barrier. Since the operations for access is very long, the dose rate comes from the long life nuclides such as cobalt and iron. The calculations have been made for reactor shut down time of 3 months. The fission product plate out is done through a series of physical processes. The metallic fission products diffuse through the kernel, then through the multicoating, then through the graphite of the blocks. We assumed that the intact TRISO particles are not permeable to metallic products. The fission products plate out come therefore from TRISO particles initially broken or that failed later because of irradiation, and from BISO particles. The diffusion rate into helium is an exponential function of the temperature. When the fission products are in helium the plate out is controlled by some isotherms of adsorption which are function of the material and of the temperature. After three months of reactor shut down, the only fission products which contribute to the dose rate are the two isotopes of cesium (Cs137, Cs134) and in a lesser amount silver (Ag 110 m).

5. METHODS OF CALCULATION

5.1. Dose rate in the lower plenum from structures activity.

The calculation is done in two steps:
1 - Calculation of the thermal flux on the structures.
2 - Activity and dose rate in the plenum.

The lower shielding is characterized by three points:
1 - It is a graphite shield.
2 - It contains in his hight a thermal neutrons shield.
3 - It contains helium channels which make the shielding unhomogeneous towards the neutrons.

The calculation of the thermal flux through the axis of the shielding was made in two steps:
1 - A calculation with an homogeneous geometry using the one dimensional removal-diffusion program SABINE.
2 - Two calculations of Monte Carlo with the program TRIPOLI with the real geometry.

The first with epithermal neutrons up to the thermal neutrons shield; the second with thermal neutrons for the lower part of the shield. The first calculation is done to correct the level of the neutrons flux leaving the thermal shield. The second calculation is done to correct the thermal neutron propagation in the support blocks.

To calculate the thermal flux to the plenum side wall we used the program DOT which is a two dimensional-transport diffusion program.

An homogeneous geometry and diffusion theory were used. We have obtained in this way the relative variation of the thermal flux from the axis to the periphery of the plenum. The dose rates were then calculated with point kernel MERCURE IV program after the determination of the saturation gamma sources.

5.2. Dose rate from plate out.

The plate out is calculated with the programs:
- TREVER which gives the temperature distributions and broken particles in the core from a power distribution, thermal data and a failure model.
- TRAFFIC which calculates the sources of fission products in the helium using diffusibility and absorption data from materials and the results of TREVER.
- RAD and PAD which calculate plate out from adsorption isothermas data. We used for these calculations the data of General Atomic.

The dose rates were then calculated with MERCURE IV.

5.3. Accuracy of the calculations.

The accuracy of the activity calculations is very good. The Monte Carlo results have an accuracy between 10 to 15% with 66% of confidence. The dose rates are given with an uncertainty factor of two.

The accuracy of plate out calculation is much worse. This is due to the lack of knowledge of the cesium migration law which is not a simple Fick law. Dose calculations were performed from the average value of a statistic study where the 95% confidence value is 10 times greater.

6. DESIGN OF THE VERBOIS NUCLEAR PLANT

France has accepted a bid from Electricité Ouest Suissse Company for a 3000 Mw reactor in Verbois. The principal characteristics of this reactor are given in Table I. We see that the mean particles failure level is of 0,29 % and
Table 1. Principal characteristics.

<table>
<thead>
<tr>
<th>Reactors</th>
<th>Verbois</th>
<th>RHTF2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Thermal power (MW)</strong></td>
<td>3000</td>
<td>3000</td>
</tr>
<tr>
<td><strong>Average power (W/cm²)</strong></td>
<td>8.4</td>
<td>6.3</td>
</tr>
<tr>
<td><strong>Fuel residence time (h)</strong></td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td><strong>Burn up (MWJ/T)</strong></td>
<td>97 000</td>
<td>101 000</td>
</tr>
<tr>
<td><strong>Particle maximum temperature (°C)</strong></td>
<td>1350</td>
<td>1380</td>
</tr>
<tr>
<td><strong>Fast fluence (10²¹n/cm²-F.6)</strong></td>
<td>9.3</td>
<td>7.3</td>
</tr>
<tr>
<td><strong>Outlet helium temperature (°C)</strong></td>
<td>750</td>
<td>650</td>
</tr>
<tr>
<td><strong>Particle type</strong></td>
<td>TRISO</td>
<td>UC, ThO₂</td>
</tr>
<tr>
<td><strong>Silica fiber (d=0,02)</strong></td>
<td>7.6</td>
<td>15.25</td>
</tr>
<tr>
<td><strong>Support block</strong></td>
<td>99</td>
<td>100</td>
</tr>
<tr>
<td><strong>Hastelloy plate</strong></td>
<td>0,09</td>
<td></td>
</tr>
<tr>
<td><strong>Silica fiber (d=0.02)</strong></td>
<td>10</td>
<td>10.15</td>
</tr>
<tr>
<td><strong>Steel plate</strong></td>
<td>0,73</td>
<td>10.15</td>
</tr>
<tr>
<td><strong>Liner</strong></td>
<td>1,9</td>
<td>10.15</td>
</tr>
<tr>
<td><strong>Average particle failure (%)</strong></td>
<td>0.25</td>
<td>0.01</td>
</tr>
</tbody>
</table>

The maximum particles temperature is 1350°C. The lower shielding is described in Table 2 and Fig. 3. The thermal neutrons shield is constituted by 70 cm height steel pins located in the permanent bottom reflector at 50 cm from the core boundary. There are three helium channels per block with the exception of the central column of a 7 column region which has the control rods and the reserved shut down holes. In this column the cooling channels merge into a collector in the last 30 cm of the permanent reflector block.

The class C thermal barrier includes 7,62 cm of molten silica. The silicated-aluminated wool is covered by a 0,09 cm hastelloy plate.

In the standard design hastelloy contains 0.5% cobalt and the stainless steel 200 ppm.


The calculus of the thermal flux gives

\[ \dot{\vartheta}_{th} = 7.5 \times 10^{10} \text{n/cm}²/\text{sec} \] at the axis of the plenum

\[ \dot{\vartheta}_{th} = 10^{10} \text{n/cm}²/\text{sec} \] on the wall.

(These values are for an equivalent neutron rate of \( v = 2200 \text{ m/s} \)).

The result of the calculations is given Table 3.

Table 2. Bottom shielding dimensions (cm).

<table>
<thead>
<tr>
<th>Reactors</th>
<th>Verbois</th>
<th>RHTF2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Replaceable bottom reflector</strong></td>
<td>40</td>
<td>80</td>
</tr>
<tr>
<td><strong>Permanent block</strong></td>
<td>80</td>
<td>40</td>
</tr>
<tr>
<td><strong>Support block</strong></td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td><strong>Silica fiber (d=0.05)</strong></td>
<td>7.6</td>
<td>15.25</td>
</tr>
<tr>
<td><strong>Hastelloy plate</strong></td>
<td>0.09</td>
<td></td>
</tr>
<tr>
<td><strong>Silica fiber (d=0.02)</strong></td>
<td>7.6</td>
<td>10.4</td>
</tr>
<tr>
<td><strong>Steel plate</strong></td>
<td>0.73</td>
<td>0.97</td>
</tr>
<tr>
<td><strong>Si₃N₄-Al₂O₃ fiber</strong></td>
<td>10.15</td>
<td>10.15</td>
</tr>
<tr>
<td><strong>Liner</strong></td>
<td>1.9</td>
<td>1.9</td>
</tr>
</tbody>
</table>

6.2. Accessibility.

As a result of preceding calculus we see that the access to the plenum is impossible since we have at the end of reactor life

D = 107 rad/h at the axis

D = 306 rad/h on the lateral wall.

For an operating time of one year the dose rate is of 13.8 rad/h at the axis (3.8 from fission products).

Though it has been shown that the fission product plate out alone do not allow the access, it was nevertheless interesting to see that the use of low cobalt material lower the dose rate substantially.

A calculation was done with a stainless steel with 60 ppm of cobalt and hastelloy with 200 ppm issued from low cobalt nickel ore.

Results are shown in Table 3.

As the dose rate from the plate out does not change for the 40 years of operating time,
we obtain a total dose rate of $D = 36$ rad/h.

Fig. 4 shows the change of the dose rate with the operating time.

The values of the dose rate do not allow access but we are right on the limit for short times.

7. DESIGN OF THE RHTF2 REACTOR

After the Verbois reactor we have designed a new version reactor called RHTF2. This reactor was designed not with a better accessibility in mind but in view of a greater safety at the component level for the same cost of the kilowatt-hour that for the Verbois plant. The principal characteristics of this reactor are given in Table 1. The outlet helium temperature is lowered of $90^\circ$C and as a result, with the lowering of the average power, the fuel maximum temperature is $170^\circ$C lower and the maximum fast fluence is of $7.3 \times 10^{13}$ n/cm$^2$ (F.$6$). The thermal calculations made with TREVER show that there is no particles failure.

The lower shielding is different from the Verbois plant (see Fig. 5). Steel is replaced by boron pins. The boronated shield is $20$ cm high located $80$ cm from the core. It is more homogeneous. At his level the large helium collectors are reduced in size and the central column contains also boronated pins.

In the thermal barrier the thickness of molten silica is increased of $7$ cm and the hastelloy plate is replaced by a stainless steel one.

The thermal flux calculations give

$$\phi = 1.9 \times 10^{10} \text{ n/cm}^2/\text{sec at the centre of plenum}$$

$$\phi = 2 \times 10^9 \text{ n/cm}^2/\text{sec at the wall of plenum}$$

We performed calculations of dose rates from activation with standard and low cobalt materials.

The results are shown in Table 3.

For the fission product plate out we have not performed accurate calculations, except for particles failures. The lower temperature (with respect the Verbois plant) decreases the diffusion rate but increases the plate out in the plenum. These effects balance each other and we have used for the variation of dose rate from one design to the other only the ratio of particle failure. For the RHTF2 a manufactured failure level of $10^{-6}$ was used. The result is shown in Table 3.

Accessibility

Fig. 6 and 7 show the evolution of the dose as a function of the operating time for standard and low cobalt materials.

The dose rate permissible for a rapid and a lasting action are respectively of $2$ rad/h and $0.3$ rad/h. With these assumptions and from
Fig. 7 R.H.I.E. 2—low cobalt materials. Dose rate in the lower plenum.