THE LAYOUT OF THE CORE AND FUEL ELEMENTS OF THE THTR

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ABSTRACT

The continuous loading and circulation of the fuel elements in pebble bed reactors results in a number of performance differences from reactors with prismatic fuel elements. Their influence on the layout of the core and fuel elements of the THTR is described.

Introduction

The THTR is a high-temperature gas cooled pebble bed reactor, the construction of which is expected to be licensed within 1970. The THTR is operated on an uranium/thorium cycle, with fissile and fertile material mixed within each fuel element in a ratio of 1:10. The first batches of fuel elements discharged from the reactor will not undergo immediate reprocessing but will be stored for an unspecified period. Although an uranium/plutonium cycle operating at a lower enrichment would, under these conditions, result in equal or slightly lower fuel cycle costs, the uranium/thorium cycle has been selected because of its greater potential when reprocessing facilities will be available. Optimization calculations have resulted in the following design of fuel elements:

Content of fissile material (U235)	0.96 g/sphere
Content of thorium	9.62 g/sphere
Enrichment	0.93
Mean residence time in reactor	3.0 years
Mean fast neutron dose ($E \geqslant 0.1$ MeV)	$4.8 \cdot 10^{21}$ nvt
Maximum power per sphere	3.5 kW
Mean burn-up [fima]	0.12
Mean burn-up [fifa]	1.34
Mean number of circulations through core	6

The spherical fuel element has a diameter of 6 cm and consists of an exterior fuel-free graphite shell with a minimum thickness of 5 mm. Inside of this shell the coated particles are embedded in a graphite matrix of the same composition as the exterior shell.

Core Design

The initial core of the THTR consists of a mixture of approximately 350 000 of such fuel elements and an approximately equal number of graphite spheres, of the same diameter, containing no fuel. The same fuel element type is used for the initial core and the running-in period as well as for the equilibrium core, which allows a considerable reduction in the fuel element fabrication cost. The total uranium inventory of 359 kg U235 in the initial core is approximately equivalent to the sum of the contents of U235 and U233 in the equilibrium core. Because in the initial core, the thorium to uranium ratio is only half that of the equilibrium core and fission products have not yet been generated, approx. 40 000 absorber spheres must be added to the initial core, each containing 4 g of natural hafnium. Hence no trim rods are required for the initial core and the running-in period.

The core is subdivided in two radial zones. The central zone of 4 m dia is surrounded by an outer zone of 0.80 m width. In order to flatten the power and to obtain a sufficient reactivity worth of control rods inserted into the radial reflector, the ratio of fissile isotope density between the outer and inner zone is 1.5 and the burnable poison density ratio 0.66. This is achieved by mixing fuel, absorber, and graphite spheres in the two zones accordingly.

In this way a reasonable power flattening and a reactivity worth of 4.5 Nile of 36 control rods in the radial reflector is obtained. Such a worth of the reflector rods is needed to compensate for reactivity changes during load-changing between 100 and 40 % (Xe-override) and for other adjustments.

The neutron flux increase in the outer zone of the reactor core required for this purpose is close to the economically optimal neutron flux distribution. Neutron leakage is increased only slightly. During steady load operation, a major number of these rods are inserted in the reflector to compensate for 1.7 to 2.6 Nile excess reactivity which must be available for controlling partial load operation and fine adjustment. If a daily load curve is to be followed, a few additional rods must be inserted or withdrawn for a few hours. The periods during which all reflector rods are either extracted or inserted are both very short.

When power operation starts the pebble bed is circulated. The spheres pass through the core in the downward direction within average transit time of six months. By the conical shape of the core bottom, the spheres are directed towards the central discharge tube, through which they are extracted from the core. Each sphere subsequently passes through a measuring equipment, by which the type of sphere - fuel element, graphite or absorber sphere -, and the burn-up state of the fuel elements can be determined.

Initially, some of the graphite and absorber spheres entering into the measuring equipment but no fuel elements are discharged from the system. An equal number of new fuel elements are added to the core to compensate fuel burn-up. The new fuel elements, together with the other spheres not discharged from the system, are lifted pneumatically through guiding tubes and drop on the pebble bed from a low height, thus closing the circulation loop.

The flow lines on which the spheres pass through the core, and the time required for passing through the core on different core radii have been experimentally determined in models of similar geometry. Specifically, it has been verified that the separation of the initial core into an inner and outer zone is maintained sufficiently distinct in spite of the circulation process. A mixing of the two zones which occurs in a region of two or three sphere diameters at the zone boundary is desirable, since steep gradients of power at the boundary are avoided.

In order to maintain the subdivision of the core into zones, three refuelling tubes point at the core center, and twelve at the outer zone. By an appropriate distribution of fresh and recirculated spheres to both of these tube systems any desired width of the core-zones can be established, but cones of different heights over both core-zones must be accepted.

With increasing burn-up the recirculated fuel elements, graphite and absorber spheres are distributed to the inner and outer zone of the core such as to maintain the power distribution of the initial core. After approximately one and a half years of full power operation - i.e., at a mean fima value of approximately 4.5 % - all graphite spheres will have been replaced by new fuel elements. At this time the overall thorium: uranium ratio has largely been shifted towards the equilibrium value, and fission products have accumulated to a considerable degree.

As power operation is continued, the first burnt fuel elements must be discharged from the core and replaced by new fuel elements. The burn-up measuring facility insures the discharge of fuel elements with highest burn-up; during the running-in phase these are the fuel elements of the initial core.

After a total of 3 years of full power operation the equilibrium phase in reactor fuelling is almost achieved. From then on the core composition and hence also the power distribution remains constant. Every day 621 new fuel elements must be added to compensate fuel burn-up.

To maintain the desired different fuel concentrations in both core zones during the equilibrium phase the fuel elements are divided into 3 classes, as determined by the measuring facility. Fuel elements having remained in the reactor more than 2.9 years of full power are discharged. Because of the different times for passing through the core at different radii this value corresponds to a mean residence time of the fuel elements of 3.0 years at full power. Fuel elements with a burn-up corresponding to a residence time between 1.6 and 2.9 years are subsequently added to the inner zone of the core. Fuel elements with a residence time of less than 1.6 years and all fresh elements are added at a ratio of 79 % to the outer zone and 21 % to the inner zone.

Figure 1 shows the residence time spectrum of the discharged fuel elements. Since it is required that only a negligibly small share of the burnt fuel elements (approx. 10^{-4}) remains in the reactor longer than 4.2 years of full power (corresponding to 14 % fima), the burn-up measuring facility must determine the uranium content of these elements to an accuracy of approx. ± 15 mg U235 equivalent. The fissile material content at discharge amounts to approx. 50 mg U235 and 250 mg U233. It has been confirmed by experiments that this condition can be met by measuring and evaluating the reactivity increase caused by the fuel elements passing through a measuring reactor of some hundred Watts of power. When the operation of the THTR or further irradiation tests permit an increase of the maximum residence time, the accuracy of burn-up measurement can be reduced.

The distribution of the fuel residence time round the mean value of three years is of small influence on the reactivity and hence on fuel cycle costs.

By recirculating the fuel elements with higher burn-up into the inner zone and by adding the new and the fuel elements of low burn-up preferably to the outer zone, the reactivity worth of the reflector rods of 4.5 Nile can be maintained also in the equilibrium core. Figure 2 shows the radial power distribution taken from a two-dimensional calculation at the core height of maximum power for completely withdrawn, completely inserted reflector rods, and for a rod position corresponding to full load operation. At full power operation leakage losses are 8.5 %. The maximum fluctuation of the local gas temperature caused by the shifting of the reflector rods are 200 - 250 °C, however with a gradient of less than 10 °C/min. The maximum fuel and gas temperatures have been calculated at 1250 °C, and 935 °C respectively.

The fuel temperatures in the THTR are favourably influenced by the mode of fuelling the reactor. Since the fuel elements are added from the top and part of their fissile material is burnt during their transit through the core, the power maximum is shifted towards the upper half of the core, that is towards the cold gas side.

Because of the continuous flow of the fuel elements the maximum temperatures in the fuel elements occur only during a short period, compared to their life time. The maximum temperatures occur at the gas stagnation area between the main coolant gas flow and the bypass which cools the element discharge tube. This area occupies approx. 10^{-4} of the core volume.

The fuel elements pass through this region within approx. 20 days. The maximum temperatures are generated in the fuel elements only during this time and only if all margins left for calculation errors on the reflector rod effectiveness sum up to the pessimistic side, which then requires insertion of all rods. During later transits through the core the fuel elements have already reached a partial burn-up so that lower fuel temperatures result after the first transit.

During operation no reactivities must be compensated other then the reactivity fluctuations resulting essentially from partial load operation, which are to be compensated by the reflector rods. Thus the 42 absorber rods located above the core are required for reactor shut-down exclusively, and can remain in withdrawn position during almost the entire power operation. Only for start-up after an extended shut-down, several absorber rods must remain inserted to compensate the positive reactivity due to the reduced xenon concentrations and to the decay of protactinium into uranium-233 during the shut-down period.

The requirement of the reactivity worth of these 42 rods must be calculated for the end of a shut-down period of several months. Then the protactinium has completely decayed into U233. A balance at that time is shown in Table 1.

Calculation Procedures

The calculation methods applied for the design of pebble bed reactors largely coincide with the procedures for other high temperature reactors. In addition to these standard methods computer programs were developed by which the unique method of charging pebble bed reactors can be taken into account.

The isotope distribution within the core, essential for calculating criticallity, power distribution and control rod worth results only if the burn-up state and the local position of the individual fuel elements are known, which however depend on the neutron flux distribution, the flow behaviour of the spheres, and the charging strategy. Therefore, for calculating the equilibrium isotope distribution, a flux distribution must be assessed, and a charging strategy assumed.

For several fictive concentric flow channels, the increase of the fuel element burn-up is determined for each transit. By averaging the nuclide concentrations over appropriate volume fractions, an improved neutron flux distribution is calculated. If after several steps of iteration this distribution differs too much from the desired distribution, the charging strategy is varied.

The computer program which calculates this position-dependent core composition for a given charging strategy, takes into account the different transit times of the fuel elements in different flow channels, the influence of the burn-up measuring accuracy on the distribution of the recirculated fuel elements to the inner and outer core, and their final discharge from the reactor circuit[1]. The 2-dimensional flux calculations in r,z-geometry must be carried out with a rather fine subdivision of the core volume into material zones, in order to represent the flow paths of the elements sufficiently.

During the running-in period the core composition and the power distribution are time dependent. Therefore, burn-up calculations are carried out starting with the power distribution of the initial core. The core is subdivided into a number of sphere packages. Using the neutron flux averaged over such a sphere package, the burn-up in the fuel elements of this package is calculated for a time increment with the assumption that the circulation movement can be neglected. Subsequently the individual sphere packages are shifted according to the paths advanced due to their movement during this time increment. The calculation of the further increase in burn-up is then performed with the neutron flux at the new position of each sphere package. After a number of time increments, the flux distribution must be recalculated. A difficult data storage problem within this procedure is the follow-up of the nuclide concentration in those sphere packages which are recirculated after a transit through the core and where individual spheres are either assigned to different core zones or partly discharged. The nuclide concentrations must be distributed accordingly.

The temperature distribution is also calculated in r,z-geometry. The geometry is described by a mesh layout. The mass flow distribution is determined by similar methods as developed in electrical network theory. The mass flow and temperature dependence of the flow resistance is taken into account.

For determining the release of fission products the temperature and burn-up history of one representative fuel element during its residence time is calculated. As transport mechanism of solid fission products, temperature-activated solid-state diffusion and evaporation from the surface of the fuel element into the coolant gas are considered. The time-dependent diffusion equation is solved numerically under variable temperature and power conditions for the fuel particles, the fuel coating, the graphite matrix, and the fuel-free shell of the fuel element. The contamination of the coating and the matrix by fission material during fabrication and the diffusion of inert gas predecessors for various radioactive decay chains are taken into account.

The results are time-dependent release rates of one representative element and - by integration over the core volume and time - the total release of the core.

With similar procedures corrosion rates and stresses are calculated, the latter program makes use of an existing computer code "STRETCH", adapted to the requirements of a moving fuel bed.

Consequences for the Fuel Elements Layout

The major part of activity in the primary circuit is due to gasous fission products caused by the contamination of the fuel elements with fissile material, either directly or indirectly by decay of a gaseous predecessor.

The favourable influence of the moving fuel on the total release from the core can be demonstrated by comparing a static core with a continuously flowing core of identical temperature distribution and residence times.

The release rates of long-lived fission products from the moving fuel elements are far below those of the static core; for strontium 90 e.g. they are lower by approx. 3 orders of magnitude. Therefore, even without having a secondary containment around the primary circuit no layer of SiC is required in the coating of particles. This is important for improving the neutron economy, and lowering both fabrication and reprocessing costs.

Since the fuel elements will remain within the region of high temperatures for relatively short periods only, no stringent requirements are needed for the irradiation resistance of the graphite. The graphite selected for the fuel elements (see Figure 3) starts expanding at temperatures of approx. 900 °C and doses of 8×10^{21} nvt ($E \geqslant 0.1$ MeV). This has to be compared with the maximum dose of 6.3×10^{21} nvt in the reactor, which is only reached by a fraction of 10^{-4} of all elements discharged.

The results of stress analysis for the fuel elements in reactor operation are shown in Figure 4. The maximum tensile stresses occur after the first transit through the core, since then the temperature gradient disappears because of the sharp reduction of power production. In the core the temperature gradient partially compensates the stresses caused by dimensional changes due to irradiation. The sudden change of tension decreases with increasing burn-up. A comparison with calculated stresses of irradiation experiments shows (see Figure 5) that the maximum stresses occuring in these experiments are much higher than those to be expected in the THTR. Therefore, there will be no damage of the fuel elements by irradiation-induced and thermal stresses.

REFERENCES

1. L. Massimo, Nukleonik 11, 72 (1968)

Table 1. Reactivity Balance

Requirement		
1.7	Nile	Xe-override between full and 40 % load (normally compensated by reflector rods)
2.0	Nile	Temperature
3.8	Nile	Xe-equilibrium
3.6	Nile	Pa-233 decay and U233 build up
0.5	Nile	Margin to compensate fluctuations due to deviations from refuelling plan
11.6 + 1.1		Total
Rod efficiency		
17.3	Nile	Calculated worth of 42 rods
1.3	Nile	Worth of the two most efficient rods
16.0 + 2		
4.4 ± 3.1		Shut-down margin

Table 2. Fission Product Release into Primary Circuit

Isotope	moving core		static core	
	from impurities	from kernel	from impurities	from kernel
Xe 133	1300 Ci	-	1300 Ci	-
Xe 135	150 Ci	-	150 Ci	-
Kr 88	1350 Ci	-	1350 Ci	-
Kr 85m	750 Ci	-	750 Ci	-
J 131	10^{-2} Ci	-	50 Ci	-
J 132	10^{-2} Ci	-	10^{-2} Ci	-
J 133	10^{-2} Ci	-	0.1 Ci	-
Sr 90	-	70 Ci	-	ca.10^{5} Ci
Cs 137	260 Ci	-	1500 Ci	8-10000 Ci

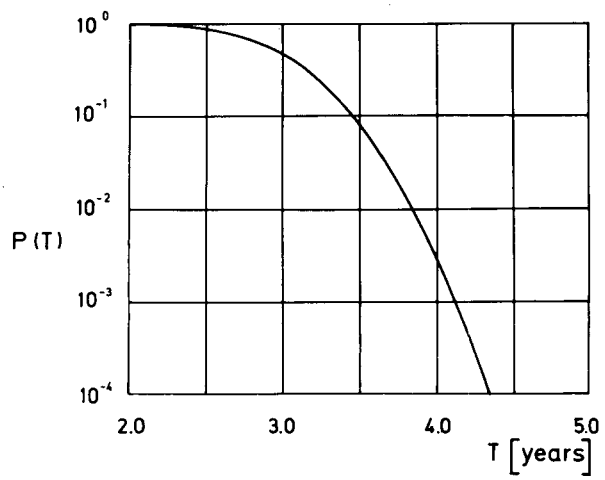

Fig. 1. THTR Fuel Element Residence Time Distribution Function.

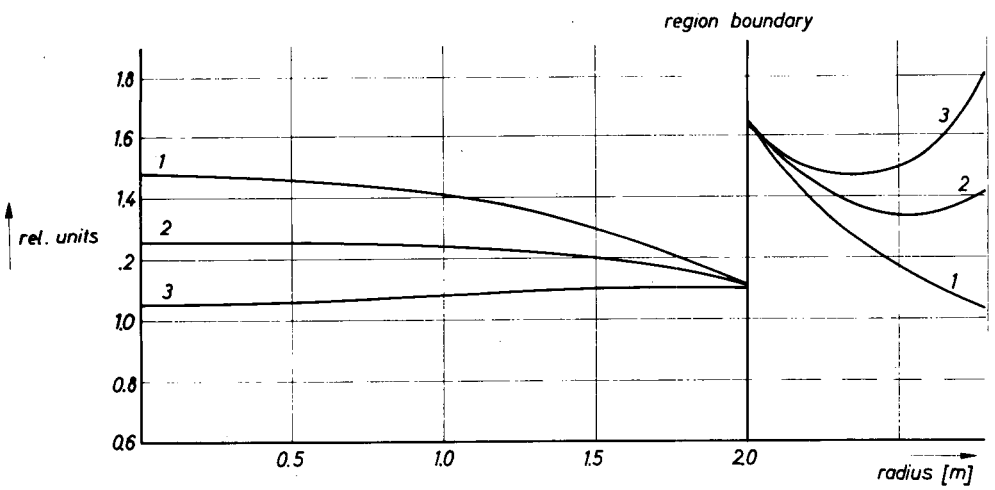

Fig. 2. Radial Power Distribution in THTR Equilibrium Core.

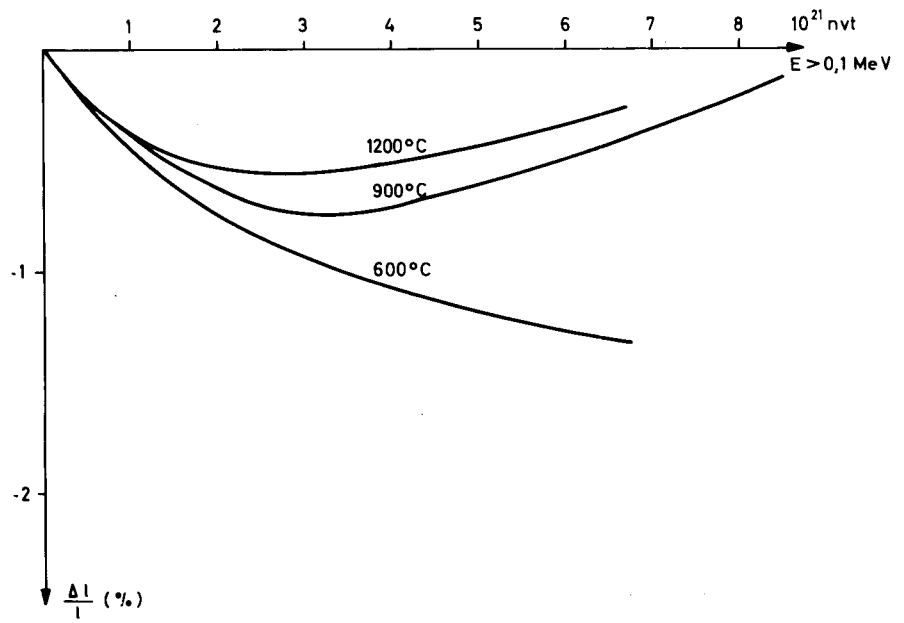

Fig. 3. Dimensional Changes of THTR Fuel Element Graphite.

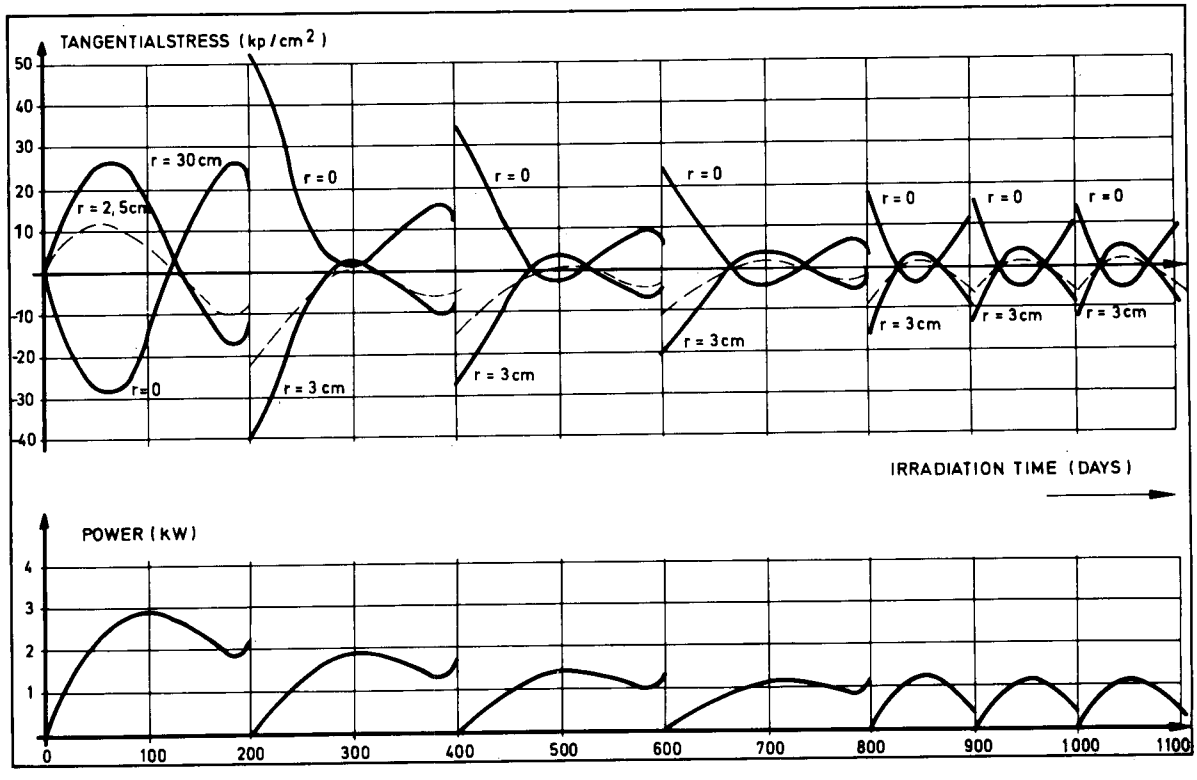

Fig. 4. Reference Fuel Element: Tangential Stresses and Power in THTR.

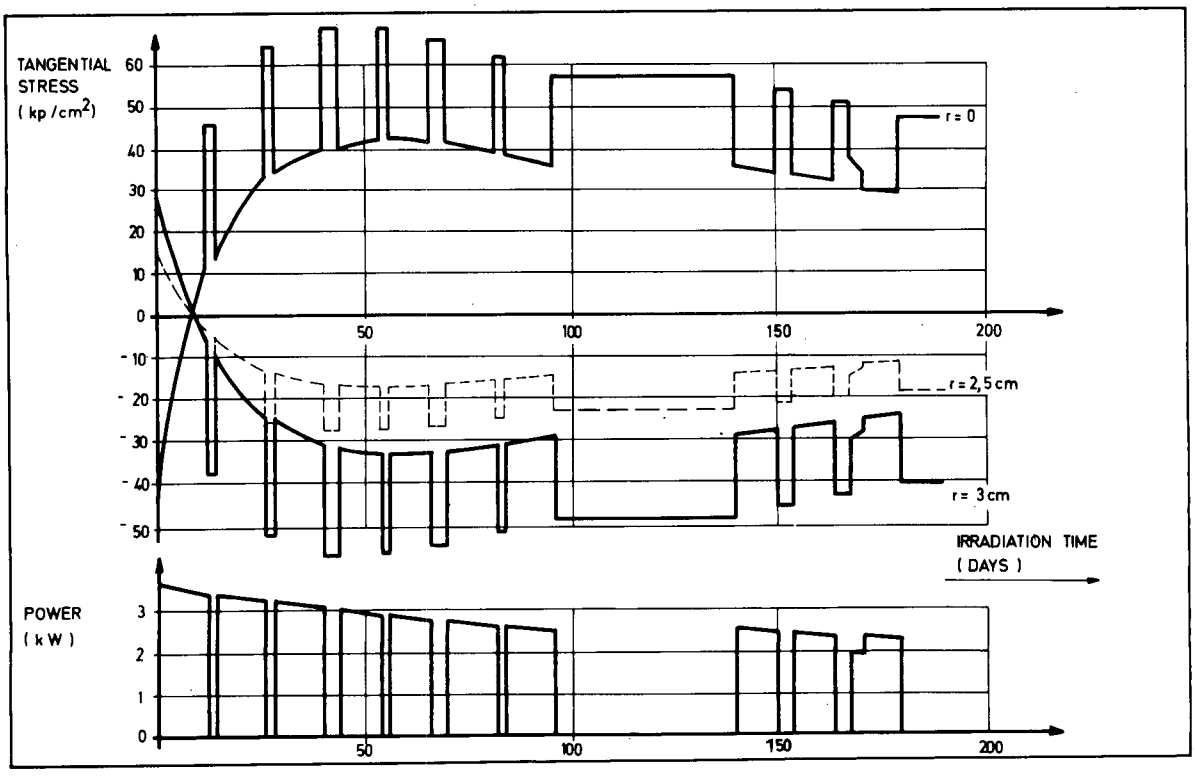

Fig. 5. Reference Fuel Element: Tangential Stresses and Power in Irradiation Experiment.

DISCUSSION

J. D. Thorn: What is the design value of R/B?

H. Harder: 1×10^{-4}.

L. W. Graham: In looking at the stresses in the ball, have you considered the effects of the differential dimensional changes between the fuel and unfueled parts?

H. Harder: No. The stresses shown in the slide concern a sphere of homogeneous graphite matrix.

J. D. Thorn: What changes in heat transfer are expected around the fuel element ball?

H. Harder: Not significant.

F. P. O. Ashworth: There is a complex vector field of ball velocities and swell times in the core. Is there a probability of a ball staying in the core long enough for the release to exceed the tolerable core total for a particular fission product?

H. Harder: There is only an extremely small probability that spheres remain in the core for such a long time. Even then this would result in a negligible effect on total activity of the primary coolant.

T. A. Jaeger: This question concerns the diagram showing the results of a thermoviscoelastic analysis of the spherical fuel element. Could you give some details on the underlying assumptions and the method of analysis utilized, e.g., did you include considerations on the affects of contact pressures and local heat transfer disturbances?

H. Harder: The temperature distribution due to the power produced in a fuel element during its several transits through the core and the stresses resulting from the time-dependent temperature gradients in the sphere have been calculated. The stresses due to irradiation affects have been determined by piecewise evaluation of the curves representing shrinkage of graphite versus neutron dose as measured in irradiation experiments at the corresponding temperatures. This includes some approximation because the temperature in each of these experiments has been