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COMMENTS ON GCR FUEL ELEMENT DESIGN

The fuel element is one of the more important components of any reactor system. As the point of origin of the heat produced by the reactor the fuel element is also the point of highest temperature in the system. It is not possible to allow the peak fuel element temperature as calculated by heat balance to reach the maximum allowable material temperature without exceeding the limiting temperature at some point. Some margin must be allowed for the various factors which cause certain "hot spots" to exceed the average local temperature.

When liquid coolants are used their characteristic high conductivities and volumetric heat capacities tend to minimize the necessary hot spot allowance. Water, because of its local boiling phenomenon, is a particularly forgiving coolant. Gases, although possessing some desirable properties as coolants, are not so tolerant of designers' errors. When a region of gas cooled reactor tends for some reason to run hotter than the average the resulting changes in physical properties will reduce the flow of coolant to that region resulting in further temperature increase. The hot spot allowances are also related to the temperature difference between the fuel element surface and the coolant. This difference tends to be large in gas cooled reactors. As a result gas cooled reactors in general require large hot spot allowances. In the GCR-2 design study the allowance was arbitrarily set at 300°F, and subsequent work indicates this to have been a good choice subject to acceptable performance of the fuel element in other respects.

From a standpoint of reactor economics and thermodynamics it is desired to run the fuel elements as hot as possible without exceeding the temperature limits imposed by the fuel element materials; and for given materials this means, in effect, reduction of the hot spot allowance. For power reactors, reliability and long service life are required; therefore the hot spot allowances must not be reduced arbitrarily but, rather, by a careful analysis and evaluation of the causative agents and subsequent design effort to reduce the hot spot factors.

The basic geometry of a fuel element has a profound effect on the magnitude of its hot spot factors and its reaction to them. The following list of six criteria is presented as a first effort to develop a basis for judging fuel element shapes for gas cooled power reactors. Item (1), Fabricability, is self explanatory, and items (2) through (6) are all related to hot spot effects. The items are not necessarily listed in order of importance.

1. Fabricability

The importance of fabricability is obvious. The difficulty of making a fuel element directly affects its cost. Since the fabrication cost is an appreciable part of the fuel cost which is, in turn, a major item in the cost of power, the cost of fuel fabrication represents a sizeable fraction of power cost. For the GCR-2 study fuel costs represented 28% of power cost of which 10% was chargeable to fabrication. The fabrication details of the fuel element also affect the cost of fuel reprocessing.

When considering costs it is well to consider the cost of failure of a fuel element to perform as expected. This is always expensive though not always measurable in dollars.

2. Surface to Volume Ratio

The surface to volume ratio must be such that the element contains enough fuel from a nuclear standpoint and has enough surface area to permit the heat generated to be picked up by the coolant within the limits of economically obtainable heat transfer coefficients. Surface to volume ratio can be affected by choice of the basic configuration and its size or by the use of extended surfaces, i. e., fins. Where clad materials are used which have a high neutron absorption cross section there is a strong incentive to obtain configurations which make the utmost use of the cladding surface for heat transfer purposes. In this sense it should be remembered that a given quantity of material in the form of fins will have an effectiveness approaching twice that of the material in the base capsule since both sides of the fin material are available for heat transfer.

Another aspect of surface to volume ratio occurs in non-homogeneous reactors having low fuel enrichment. The ratio of fuel volume to a hypothetical surface which "sees" the moderator affects the criticality of the reactor by influencing the resonance escape probability. Where criticality is at a premium there is, therefore, an incentive to minimize the surface which "sees" the moderator.

3. Structural Suitability

The basic requirement that the fuel element be structurally capable of carrying the loads imposed on it by service is an obvious one, but there are some subtle implications which are easy to overlook. In addition to the static loads imposed by the weight of the fuel element there are also loads due to the dynamic pressure of the coolant. In GCR-2 the coolant dynamic pressure was of the order 0.5 psi. If the dynamic load had been higher by a factor of 2 it would have been possible for the fuel capsules to swing sidewise causing them to "wind up" as shown in Fig. 1.

With a factor of two margin of safety the GCR-2 element is probably satisfactory from this standpoint. The study showed, however, that lower power costs would result if the reactor heat output were increased from 700 to 1100 MwT. With the increased coolant flow at the higher rating the GCR-2 fuel element as designed would be dynamically unstable. This

14.1
FIG. 14.1 EFFECT OF DYNAMIC PRESSURE ON GCR-2 FUEL ELEMENT

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particular difficulty could be cured by restraining the capsules against swinging sidewise or by reversing the flow of coolant so that the dynamic forces tend to straighten the capsules. These examples are used for illustration only and are not specific recommendations. In the latter case, for instance, there would exist the possibility of an induced flutter.

4. Internal Thermal Path

The nature of the internal thermal path influences the temperature structure within the fuel body. This, in turn, determines the maximum internal temperature and the thermal stresses which exist in the fuel element. With fused UO_2 fuel differences of opinion exist as to the maximum allowable material temperature and the seriousness of thermally induced cracks in the fuel body. A generally accepted peak internal temperature for UO_2 fuel is expressed by the equation:

$$T_{max} = T_{wall} + 0.9(T_{melt} - T_{wall})$$

With regard to thermal cracking, designs are to be avoided in which the temperature pattern tends to induce "spalling" which would produce small particles having a tendency to "ratchet" with temperature cycling. Gross cracks resulting in large particles which remain in place, for example: one or two radial cracks in a GCR-2 type slug, are not believed to be as serious.

The point to point temperature differences existing in a given fuel element are directly proportional to power density and inversely proportional to the heat conductivity of the fuel. Uranium oxide is a poor heat conductor. Its specific conductivity is approximately 5% that of stainless steel or graphite at typical gas cooled reactor temperatures. If a fuel material were available with higher conductivity by even a factor of 2 the benefit would be great. While our work relative to the Kaiser-ACF reactor effort is limited to uranium oxide, it is hoped that for advanced studies other materials such as uranium carbide or uranium-uranium oxide or uranium oxide-graphite mixtures can be considered.

5. External Thermal Path

The external thermal path is the result of the shape of the coolant passage which surrounds the fuel element. It influences the variation of fuel element surface temperature at a given location in the reactor. A less obvious but nevertheless real effect is to increase the average fuel element surface temperature over that calculated by a running heat and material balance along a coolant channel. This effect was brought out in an analysis of the temperature structure of the GCR-2 fuel elements* and is due to a passage shape efficiency factor which is analogous to fin

* CF 58-5-97

efficiency in solid conductors. For configurations which are generally symmetrical or two dimensional in either polar or rectangular geometry this factor would be 1.0, and the surface temperatures at a given location would be constant at the theoretical value calculated by heat balance. Three dimensional configurations will give a factor less than 1.0.

The best spacing of the GCR-2 capsules relative to channel walls was calculated to give a passage efficiency factor of 0.85 with a resulting surface temperature variation of $\pm 100^{\circ}\text{F}$ from the mean. The external thermal path of the GCR-2 fuel element configuration therefore forces the mean fuel element surface temperature to run approximately 100°F lower than could be allowed with a two dimensional configuration keeping the same maximum hot spot temperature limit (i. e. 1500°F for GCR-2) and the same allowance for hot spots from other causes. Since the maximum heat balance temperature for the GCR-2 fuel element was 1200°F , a two dimensional fuel element could be run at 1300°F . The GCR-2 study indicated the minimum power cost at 1200°F to be 9.6 mils/kwh while the minimum cost at 1300°F was 9.0 mils/kwh. The fuel fabrication costs amounted to approximately 1.0 mil/kwh. We could therefore pay up to 60% more for fuel fabrication in order to obtain fuel elements with a more efficient external thermal path.

The effect of the external thermal path is influenced by the thermal conductivity of the fuel. Surface temperature differences tending to exist because of details of the external thermal path would be dampened by fuel having high conductivity and in good thermal contact with the inside of the capsule.

The effect of misalignment both of the individual components of the element relative to each other and of the fuel element assembly relative to the channel must be considered. It is expected that any fuel element configuration will be sensitive to misalignment in some degree. Study is currently under way to determine which configurations are least sensitive. Pending results of the study it can be postulated that if the fuel element design is such that some point on the surface runs at higher than average temperature that point will be more sensitive to misalignment than the remainder of the fuel element. It follows, then, under this assumption that the configurations least sensitive to misalignment are those which either have no points at higher than average temperature, or if such points exist they are so located that the adjacent layer of coolant is not subject to "pinching" by misalignment. An example of the first case is a two dimensional element which has no surface temperature variation. An example of the first case is a two dimensional element which has no surface temperature variation. An example of the second case is a single longitudinally finned cylinder in a cylindrical channel. The hottest region, i. e., the capsule wall, is farthest from the channel wall and least sensitive to misalignment of the assembly in the channel.

6. Thermal Stability of Structure

The problems of thermal stability of fuel and capsule materials are universally recognized. It is not so widely realized that certain mechanical shapes are inherently stable, i. e., tend to retain their shape, under fuel element operating conditions, and some are inherently unstable. This is a property of the shape rather than the material, although material properties can modify the effect.

Consider an MTR type fuel element consisting of a series of parallel slabs, spaced at the edges, with the coolant flowing longitudinally as shown in Fig. IIa.

14.2a
Fig. IIa

14.2b
Fig. IIb

If, for some reason, the temperature in one coolant channel runs hotter than its neighbors the adjoining slabs will deflect thermally so that their hotter sides are convex. Since the slabs are spaced at both edges this results in their movement toward each other. The flow passage is "pinched" and therefore suffers a further temperature increase giving more deflection etc. Such a configuration may be said to have a "positive feed-back". It is possible to change this into a "negative feed-back" so that thermal distortion tends to open the hot channel by simply removing the spacing at one edge and supporting the fuel slabs as cantilevers from the other edge as shown in Fig. IIb. Adjacent fuel slabs will then deflect away from a hot channel. The feed back effect, either positive or negative, may be insignificant if the fuel elements are short, if the materials have low coefficients of thermal expansion, or if the coolant passage configuration is such that the fuel element surface temperature is insensitive

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to deflection. In the other extreme the feed-back can be divergent if the surface temperature differences brought about by a deflection are greater than the original temperature differences which produced it. Then, if the feed-back is negative the fuel elements will "hunt"; if it is positive they will continue to deflect in the original direction until they are restrained in some way, probably by contact with other parts of the fuel element-channel assembly. From their temperature analysis* it is strongly suspected that the GCR-2 fuel elements as described in ORNL-2500 will be in the latter category.

It should be noted that stiffening the fuel element by increasing the moment of inertia of the capsule cross section is not effective in decreasing the deflection of a fuel element of a given length which is subjected to a given transverse temperature gradient. The moment of inertia of the section influences the stiffness of the capsule and the moment tending to deflect it in the same degree, and the two effects cancel. There may be a second order benefit of stiffness in that a stiffer structure would be easier to maintain in alignment which would result in decreased temperature differences and, consequently, decreased deflections.

The use of spacers to restrain thermal deflection of fuel element members is regarded with extreme suspicion. If the forces which would produce deflection in an unrestrained assembly still exist something must "give". When it is remembered that the capsule walls are approximately 0.020 in. thick and are at temperatures up to 1500°F it is not difficult to imagine what part it will be. Our experience with development of high temperature radiators indicated that a "soft" structure was required rather than a stiff one. The principal difference between the radiator and a reactor fuel element is that in the former the maximum temperature is limited to the temperature of the heat transfer medium.

All of the discussion thus far has been based on consideration of steady-state temperatures. Variation of temperature with time is to be expected when the reactor is undergoing changes in power level, and high frequency variations can occur due to local non-steady flow of coolant even though the reactor is operating at constant power. Support members which are transverse to the direction of coolant flow and certain types of fuel element configurations will give rise to trailing vortices which can result in time variations of the local heat transfer coefficient of approximately $\pm 25\%$ of the time-average value. The Calder Hall type transverse fin fuel elements are an example of those types in which time variations of temperature exist. These are apparently satisfactory from a standpoint of thermal cycling at Calder Hall conditions. It is by no means certain, however, that this type fuel element could be extrapolated to the higher temperatures and heat fluxes and the lower conductivity capsule materials being contemplated in our gas cooled reactor studies.

* CP 58-5-97

The basic fuel element configuration for GCR-2 was chosen primarily from the standpoint of fabricability. The surface to volume ratio requirements were met by allowing the diameters of the capsules to vary, and structural requirements were limited to consideration of dead-weight loads. The internal thermal path was considered briefly, and the external thermal path and structural thermal stability were not considered at all.

The resulting fuel element design rates high from a standpoint of fabricability; it is satisfactory with regard to surface to volume ratio and internal thermal path; structural suitability is marginal, and much is to be desired from a standpoint of external thermal path and thermal stability.

If the problem of fuel element design is approached with all the requirements in mind it is possible to examine various shapes and apply relative ratings on the six points of consideration.

The following table is an attempt to begin such a comparison. The ratings 1, 3, and 5 mean good, marginal, and bad, respectively. The ratings are in some instances first impressions which are listed in an effort to begin a systematic evaluation of fuel element forms. It would be appreciated if the recipients of this memorandum would apply their own ratings to the shapes given and also add any desired additional shapes or additional criteria by which the various shapes can be rated. Information under item (1), both with regard to the fuel bodies and capsules is especially desired. The effect on item (1) of use of fuel materials other than uranium oxide, for instance, uranium carbide, is also of interest.

It is hoped that a few basic configurations can be found which are good compromises on all points and from which a fuel element can be developed which will allow the full potential of gaseous coolants to be realized.

CONFIGURATION	(1)	(2)	(3)	(4)	(5)	(6)	Remarks
<div>40 in. long</div> <div>20 in. long</div>	1	1	3	1	4	5	Rods Located At Optimum Radius Suspended From Above - Spaced Top and Bottom
	2	1	2	1	3	3
1	2	2	1	1	3	Down-Rated on (2) For Nuclear Reasons
2	1	1	2	2	1	Fins Carry Fuel
2	1	1	2	3	1	Fins For Heat Transfer Only
2	1	1	1	1	2	Slabs Spaced At Each Edge
2	1	1	1	1	1	Slabs Cantilevered From One Edge

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