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Development of Annular-Coated-Pressurized and Sphere-pac LWR Fuels

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DISCLAIMER

DEVELOPMENT OF ANNULAR-COATED-PRESSURIZED AND SPHERE-PAC LWR FUELS

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Annular-coated (graphite)-pressurized and sphere-pac fuel rod designs, which are expected to exhibit improved PCI-failure resistance, and, thus, more reliable extended burnup performance, are being developed. Data sufficient to provide the technical bases needed to license lead test assemblies of the improved designs for irradiation in commercial LWRs are being obtained. Out-of-reactor experiments, in-reactor instumented experiments, in-reactor power-ramp tests, and lead-rod demonstration irradiations are providing the needed data to support the technical bases. Results obtained to-date confirm the expected performance improvement compared with a solid-pellet reference design. The degree of improvement with respect to PCI-resistance remains to be quantified during forthcoming power-ramp tests on fuel rod segments irradiated to moderate burnup levels in a commerical LWR.

DEVELOPMENT OF ANNULAR-COATED-PRESSURIZED AND SPHERE-PAC LWR FUELS

INTRODUCTION

Under the sponsorship of the U.S. Department of Energy, Consumers Power Company; Exxon Nuclear Company; and Battelle, Pacific Northwest Laboratory are developing pellet-cladding-interaction (PCI) resistant annular-coated (graphite)-pressurized and sphere-pac fuel rod designs for use in commercial light water reactors (LWRs). The annular pellet design combined with a graphite coating on the inner cladding surface and helium pressurization was selected because of anticipated reduced fuel temperatures, reduced fission product release, reduced fuel-cladding differential expansion, and decreased fuel-cladding friction.[1] The sphere-pac design was selected primarily because of the anticipated absence of localized cladding stresses and reduced fission product deposition at regions of high stress in the cladding.[1] The objective of the program under which these fuel designs are being developed, i.e., the Fuel Performance Improvement Program (FPIP), is to provide the technical support needed to design and license lead test assembly irradiations of the improved designsin LWRs. Demonstration of improved PCI resistance will enhance the reliability of achieving extended burnup levels.

To this end, the FPIP was structured to address key licensing needs by performing an integrated series of out-of-reactor experiments, in-reactor tests, and in-reactor lead-rod demonstration irradiations in a commercial reactor.[2] Development of the fabrication and manufacturing processes needed to implement the improved designs on a commercial basis was also accomplished as part of the program.[3-4] The out-of-reactor and instrumented in-reactor experiments portions of the FPIP have been completed; and the results from these activities comprise the primary topics presented in this paper. The satisfactory demonstration irradiation of lead rods continues in the Big Rock Point Reactor (BRPR) with peak pellet burnups of 18 MWd/kgM having been achieved. These irradiations also provide a source of segmented rods for power-ramp tests to be conducted at burnup levels in the range from 18 to 37 MWd/kgM.

FUEL DEVELOPMENT ACTIVITIES

In order to license the improved fuel concepts for the commercial irradiation of lead test assemblies, establishment of several performance characteristics for these fuel types over and above the existing technical bases for the UO_2/Zircaloy fuel rod system was needed. These performance characteristics are listed in Table 1 and fall into two basic catagories, i.e., safety-related and those associated with describing fuel behavior during normal operation. The performance characteristics listed are of singular interest for the annular-coated-pressurized and sphere-pac designs. For the licensing of lead test assemblies, calculational analyses based upon technical bases for standard fuel are considered to be adequate for operational transients such as loss-of-coolant accidents, reactivity insertion accidents, post-failure performance, and power-cooling mismatch operation.

Out-of-reactor experiments, in-reactor experiments, and in-reactor lead-rod demonstration irradiations are providing the information needed for licensing the improved concepts.

The out-of-reactor experiments have included static and kinetic friction measurements on graphite-coated cladding, determination of the thermal conductivity of the graphite coating, evaluation of the PCI-resistance of coated and non-coated cladding, and measurement of the out-gassing behavior of sphere-pac fuel.

In-reactor experiments have included the steady-state irradiation of fuel rods instrumented with fuel centerline thermocouples, rod elongation sensors and/or rod internal pressure sensors in the Halden Boiling Water Reactor (HBWR), and the power-ramping of selected rods in the HBWR. Power-ramping of fuel rod segments previously irradiated in the commercial environment of the BRPR are planned. Irradiated fuel rod types include annular-coated-pressurized, annular-coated, annular, sphere-pac (pressurized), and a reference, dished-pellet design for comparative purposes. Postirradiation examinations have been completed on selected ramped and nonramped HBWR rods at the UKAEA-Harwell hot cell facilities. A summary of the design of the HBWR and BRPR rod segments is presented in Table 2. Detailed design information has been published.[5]

Demonstration irradiations of full-length rods are being conducted in the BRPR. The current burnup in the FPIP demonstration rods is approximately 18 MWd/kgM with a goal burnup of 37 MWd/kgM. The full-length fuel rod types being irradiated also include annular-coated-pressurized, annular-coated, annular, sphere-pac (pressurized), and the reference, dished-pellet design. The design characteristics of the full-length BRPR rods are summarized in Table 2. Design details for these rods have been published.[7]

RESULTS AND DISCUSSION

Summaries of the experimental results obtained to-date for the improved, PCI-resistant fuel concepts are presented below.

ANNULAR-COATED-PRESSURIZED FUEL DESIGN

Performance characteristics for the annular-coated-pressurized design have been obtained primarily from the instrumented irradiations of annular-coated and the annular designs in the HBWR. Attention has been focused on evaluations to define the behavior of this fuel design from the standpoint of PCI-resistance and the licensing of lead test assemblies.

Chemical Reactions With Graphite Coating. The possibility of chemical reactions between the graphite coating and the fuel could result in the generation of significant quantities of carbon monoxide and/or carbon dioxide and overpressurize the rod. A reaction between the graphite coating and the Zircaloy cladding could cause the cladding to become embrittled. Based on thermodynamic considerations, the fuel and graphite will not react significantly at the normal operating temperatures of the graphite. However, graphite that might abrade from the coating during rod fabrication could encounter temperatures that would be high enough to result in the formation of CO and CO_2.

Graphite-coated fuel rods instrumented with pressure sensors to monitor internal pressure during operation were irradiated in the HBWR. Peak pellet LHGRs as high as 46 to 48 kW/m occurred to burnups of 10-12 MWd/kgM. Outgassing from the fuel and, primarily, the coating resulted in a small increase in the internal pressure of about 15 kPa within the rods after the first power cycle. Pressure increases that occurred later during the irradiations of the annular coated rods were less than in the companion reference rods and can be attributed to fission gas release. Therefore, there was no evidence of any significant CO and/or CO_2 formation during steady-state operation. Similarly, annular-coated and reference rods power-ramped to LHGRs in the range from 68 to 71 kW/m and held for eight hours showed no evidence of a reaction between the fuel and graphite based upon posstirradiation gas analyses (Table 3).

Ceramographic examination of an annular-coated rod that was power-ramped to 68 kW/m revealed no evidence of carburization of the cladding.

Coating Thermal Conductivity. The thermal conductivity of the graphite coating is important because of its possible effect on fuel temperatures, particularly at high LHGRs. Such an effect could offset the benefit of using annular fuel to reduce fuel operating temperatures during normal operation.

The thermal conductivities of Dag 4*, which was used in the annular-coated-pressurized design, and Dag 154*, which was used in the annular-coated design, coatings were determined in pure argon using the flash diffusivity method. (Figure 1). Calculations for a BWR fuel rod design using the measured thermal conductivities indicate that the temperature drop at an operating LHGR of 40 kW/m across a nominal 6.4 μm thick coating would be 25C for Dag 154 and 5C for Dag 4. Thus, any temperature increase attributable to the coating is considered to be insignificant, especially for Dag 4, which is the current design coating. This conclusion was verified by comparing the fuel temperatures of an annular-coated (Dag 154) and a noncoated annular rod during irradiation in the HBWR (Figure 2). The initial temperature difference between the annular-coated and annular rods was only 40C at an LHGR of 36 kW/m. Comparison of the fuel temperature after burnups greater than 2.5 MWd/kgM indicates that there was no difference between the annular-coated and annular designs.

Axial Relocation of Fuel in the Central Hole. Fragmentation of individual fuel pellets during fabrication, shipping, and/or normal operation and the possible axial relocation of debris into the central hole could cause localized high power regions in an annular pellet fuel rod. Neutron radiographs were taken of annular-coated rods after being shipped from the USA to Norway, irradiated and power-ramped in the HBWR, and subsequently shipped to England for post-irradiation examination. The maximum depth of fuel debris at the bottom of the central hole was only about 1.5 mm. No fuel debris was found at any other axial location. The observed amount of axial relocation in these annular fuel rods is considered to be insignificant.

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*Product of Acheson Colloids, Port Huron, MI

Stability of the Central Hole. Fuel relocation may occur within the central hole by means of a vaporization-condensation or slumping mechanism due to the high fuel temperatures that may result from off-normal operating conditions. Neutron radiographic examination of annular-coated rods power-ramped and held for about eight hours at a LHGR of approximately 68 kW/m in the HBWR showed no evidence of such axial fuel relocation. However, the diameter of the central hole became smaller during the test (Figure 3). Associated with the reduction in size of the central hole was the formation of a mid-radius zone in the fuel characterized by significant grain boundary separation. In the shutdown condition, a large mid-radius circumferential crack was found in this region. The zone of grain boundary separation created a radial heat transfer barrier that caused high fuel temperatures during the power ramp test. The reduction in the size of the central hole demonstrates that annular pellet fuel can creep inward to reduce cladding stresses during off-normal operation. However, the high central fuel temperatures in the annular pellet fuel during off-normal operation resulted in fission gas release fractions which are comparable to those characteristic of reference, dished pellet fuel subjected to similar operating conditions.

Fuel Temperature and Stored Energy. Fuel temperature is the principle driving force for fission gas (product) release and for differential fuel-cladding expansion that leads to stressing of the cladding. The stored energy in the fuel is important for LOCA analyses. Annular, annular-coated (Dag 154), and reference rods were instrumented with W/Re fuel centerline thermocouples during steady-state irradiation in the HBWR. A comparison of the operating temperatures of the three types of fuel rods during the first reactor startup is shown in Figure 4. The measured temperatures in the reference rod with a hole to accommodate the thermocouple have been adjusted to represent the temperatures that would occur in a solid pellet rod operating at the same LHGR. The effect of the central hole to reduce peak fuel temperature in the annular pellet rods compared to the solid pellet reference rod at comparable LHGRS is marked. Assuming a similar fuel-to-cladding gap for all of the pelletized designs, it is obvious that the stored energy in the annular-pellet design was significantly lower than in the reference design.

The fuel temperatures and stored energy in the annular pellet rods remained lower than for the solid pellet reference rod throughout the irradiation to burnup levels in the range from 10 to 12 MWd/kgM. This is illustrated in Figure 2 where the thermocouple data for the three rods has been corrected for decalibration of the thermocouples with burnup and the temperature data for the reference rod has been adjusted to represent the temperature that would occur in a solid pellet fuel. The fuel temperature in the reference rod as a function of burnup was affected by fission gas release, i.e., "thermal feedback", while the temperature in the annular pellet rods was nearly constant at burnups above 3 MWd/kgM, presumably because of lower fission gas release from the cooler annular fuel.

The preceding discussion addresses fuel temperature and stored energy during normal steady-state operation. As described in the section on the stability of the central hole, the fuel temperatures in ramped annular pellet rods were considerably higher than would be estimated based upon the steady-state results. This is thought to be due to the reduced thermal conductivity of a midradius region in the fuel that is characterized by grain boundary separation formed during these off-normal, high-power operating conditions. For these conditions, the amount of fission gas released from the ramped rods and an evaluation of the microstructure of the fuel indicate that the centerline fuel temperatures for the annular pellet rods and the reference rods were comparable, and therefore, as a first approximation, the amount of stored energy in the two types of rods would be comparable at these high LHGRs.

Fission Gas Release. Fission gas release from the fuel affects internal rod pressure, "gap conductance", and associated fuel temperature. Reference and annular-coated rods instrumented with pressure sensors were irradiated at peak pellet LHGRs up to 42 kW/m during steady-state irradiation in the HBWR. Because of their respective locations in the test assembly the rods were exposed to significantly different power histories and achieved different burnups, i.e., 10.3 MWd/kgM in the annular-coated rod and 7.6 MWd/kgM in the reference rod. Because of the method from which pressure sensor data were derived, and because of an indicated unquantified decalibration of these sensors, pressure data from these sensors should be considered, at best, relative. However, based upon an assessment of the pressure transducer data, the release fractions from the annular-coated and reference rods after steady-state irradiation were 4.1% and 4.7%, respectively. This is indicative of only a small effect on gas release due to the lower operating temperature in the annular-coated pellet fuel compared with the reference pellet fuel rods. The comparability of the gas release for the two fuel types is also inconsistant with the lack of "thermal feedback" in the annular pellet rods and the observed "feedback" in the reference rod as described above. The benefit, if any, of lower operating temperatures to reduce fission gas release from annular fuel during steady-state operation will be substantiated by sampling fission gas from full-length demonstration rods that are currently being irradiated in BRPR.

As indicated above, the formation during power-ramping of a mid-radius zone in the annular pellet fuel which was characterized by grain boundary separation caused higher than expected fuel temperatures and fission gas release from this fuel type, i.e., 42 to 46% from annular pellet rods versus 40% release from a solid pellet reference rod. All the rods were ramped to LHGRs in the range from 68 to 71 kW/m and held for eight hours.

Cladding Deformation. Cladding deformation, or strain, leads to rod failures and is the result of differential fuel-to-cladding thermal expansion compounded by fracture of the fuel pellets and cladding creepdown. Localized cladding stresses/strains occur at pellet-pellet interfaces as a result of pellet "hourglassing", and at pellet cracks. The general strain behavior of the cladding was used to evaluate the fuel-to-cladding mechanical interaction, one of the components of PCI, for the different fuel types.

Due to the relatively low coolant pressure in the HBWR, significant cladding creepdown does not occur in the test rods. However, by use of fuel rod elongation sensors, the axial mechanical interaction behavior of the different fuel rod types was evaluated during the steady-state iradiations in HBWR. The LHGR at which axial fuel-to-cladding interaction commenced was indicated by a deviation in the slope of the rod elongation curve from the cladding free thermal expansion/contraction during a series of reactor startups and shutdowns (Figure 5). The powers required for the onset of interaction were normalized by dividing by the "typical" peak LHGR that occurred early in the irradiation. Interaction in the reference rods commenced at the lowest burnup and exhibited the greatest burnup dependency. Interaction in the annular-coated rods was initiated at the highest burnup and exhibited little, if any, burnup dependency. The annular rods exhibited intermediate behavior. These results demonstrate that the graphite coating is effective in reducing friction between the cladding and the fuel pellets. However, it is also shown that the annular pellet design contributes to a reduction in the axial mechanical interaction. The decrease in friction is consistent with out-of-reactor friction measurements made at 300C in dry oxygen-free helium on noncoated and coated cladding (Table 4).[8]

PCI Behavior. The PCI-failure resistance of a particular fuel rod design is evaluated by means of ramp testing to high power conditions. To date, power-ramps in the FPIP have been performed only on HBWR rods, i.e., fuel rods not subject to cladding creepdown. As a result, none of the fuel rods have failed during these tests. However, significant differences in the elongation and interaction behavior were apparent during the ramp tests (Figure 6). Permanent elongation occurred in the reference rods as a result of the power-ramp tests, indicating yielding or significant creep of the cladding to reduce the ramp-induced stress level in the cladding.[9] The amount of elongation measured during the ramp indicates a hoop-to-axial stress ratio of about one, which in turn indicates possible yielding or rapid creep in the diametral direction.[9] No permanent axial deformation occurred in the annular-coated or annular rods. Therefore, the stress state required for yielding or rapid creep was not achieved in these rods. The gradual change in the rate of elongation in the annular pellet rods as a function of power during the ramp indicates that the effect of the axial force was dominant. For this case, the hoop-to-axial stress ratio would be less than 1.0 and no yielding in the diametral direction would be expected. Postirradiation profilometry measurements made on the ramped rods showed that a change in ovality occured in the cladding tubes. As a result, the postulated diametral deformation in the reference rods could not be confirmed. However, the degree of ovality change, as a result of the ramp tests, was greater in the reference rods than in the annular pellet rods. Because of a lack of creepdown in these pelletized rods during irradiation in HBWR, the mechanical behavior may not be typical on an absolute basis of that which would occur in a commercial environment.

Because significant amounts of fission products were deposited on the inner surface of the coated cladding in the ramped rods, visual confirmation of the presence of the graphite coating in the fueled region could not be made. However, the coating was intact in the plenum region. Scanning electron microscopic examination (in the x-ray dispersive mode) of scrapings taken from the inner suface of ramped annular-coated rods substantiated the presence of fission products on the surfaces adjacent to the fuel. However, it is significant that no fission products could be detected on the surface of the coating adjacent to the cladding. This indicates that the graphite coating sorbs fission products, thus preventing reaction with the cladding and the resulting crack formation by stress corrosion. This result is consistent with out-of-reactor sealed ampoule experiments which showed that the graphite coating retarded the reaction rate between free iodine and Zircaloy cladding by at least a factor of 25.[8]

General Performance. The satisfactory irradiation performance of annular-coated pellet fuel rod to 16-18 MWd/kgM in HBWR and BRPR, annular pellet fuel to 12 MWd/kgM in HBWR and 18 MWd/kgM in BRPR, and annular-coated-pressurized fuel to 10 MWd/kgM in HBWR and 18 MWd/kgM in BRPR indicates that no deleterious generic failure mechanism is operative in the annular-coated-pressurized design.

SPHERE-PAC DESIGN

Evaluation of the performance characteristics of the sphere-pac (pressurized) fuel design has been accomplished primarily by means of instrumented irradiations in the HBWR. Data are also available from the lead rod demonstration irradiations underway in the BRPR.

Sphere-Pac Thermal Conductivity. The smear density of a three-fraction sphere-pac fuel bed is typically in the range from 87-89% T.D., whereas, typical commercial urania pellet densities are about 95% T.D. Because of this difference, the thermal conductivity of a sphere-pac bed would intuitively be expected to be lower than for solid pellet fuel.[10] (Note: The smear densities for the two fuel types are essentially equivalent because of the fuel-to-cladding gap in pellet fuel rods. The effect of the gap is important when considering operating temperatures in these fuel types, as discussed below). Indeed, the derived effective thermal conductivity of the three-fraction sphere-pac fuel bed pressurized with 455 kPa of helium is lower than for the 95% T.D. pellet fuel. The effective thermal conductivity of sphere-pac fuel during various stages of irradiation in the HBWR is compared with 95% T.D. pellet fuel in Figure 7. The effective thermal conductivity values were derived from fuel temperature measurements and represent the combined effects of the sphere-pac particle bed and the interstitial helium gas. The "base value" shown in Figure 7 is the derived value after the first reactor startup and up to a burnup of 1.3 MWd/kgM. In the derivation of effective thermal conductivities of sphere-pac fuel, a high value for "gap conductance", i.e., 2.5 x 10^4W/m^2-C, was used.[11]

It should be noted that the pressurization level of 455 kPa of helium was selected as the standard design pressure for the FPIP sphere-pac rods in order to promote free molecular (Knudsen) conduction in the gas volumes immediately adjacent to sphere-to-sphere and sphere-to-cladding contact points. Although not measured experimentally as part of this program, it is apparent that this effect contributes significantly to the enhancement of the effective thermal conductivity of the sphere-pac fuel and the fuel-to-cladding contact conductance.

Fuel Temperature and Stored Energy. Because of the lower effective thermal conductivity of the sphere-pac fuel bed compared with solid reference pellet fuel, it might be expected that fuel temperatures and stored energy would be greater in sphere-pac fuel. The opposite was observed to occur during the irradiation of instrumented rods in the HBWR (Figure 8). The measured fuel centerline temperatures were adjusted to represent both solid reference pellets and a sphere-pac particle bed with no thermocouple hole. The apparent anomaly between the measured thermal conductivities of the two fuel types and the measured centerline temperatures can be explained on the basis of the gap conductance. The "gap conductance" of sphere-pac fuel, perhaps more correctly, the conductance of the sphere particle layer in the region immediately adjacent to the cladding inner surface, is relatively high because of the numerous fuel-to-cladding contact points and the contribution of free molecular conduction.[11] Correspondingly, the gap conductance in the solid pellet reference rod is relatively low because of the presence of a residual gap and the fact that this particular rod was not pressurized. This residual diametral gap has been estimated to be in the range from 10 to 60 μm in pellet fuel[12] and may actually be larger for the FPIP reference rods irradiated in the HBWR because of the lack of cladding creepdown. The effect of the higher gap conductance in the sphere-pac rod is to reduce the fuel surface temperature in the sphere-pac rod by about 180C lower than in the reference pellet rod. The net result of this difference in fuel surface temperature in the HBWR is: 1) reduced centerline fuel temperatures; 2) reduced volumetric-average fuel temperatures; and 3) reduced stored energy in the sphere-pac fuel, when compared to the reference fuel. The lack of cladding creepdown in the reference rod in the HBWR may have caused the fuel surface temperature in the reference rod to be higher than if creepdown had occurred.

Fission Product Release. Because of the higher surface area and shorter diffusion paths to free surfaces for sphere-pac fuel when compared to reference solid pellet fuel, it might be anticipated that the fission gas/product release fractions would be higher for sphere-pac. Higher release fractions would result in higher internal rod pressures and, possibly, a higher concentration of stress corrodent species deposited on the inner surface of the cladding, which would promote PCI failures. The fission gas release from a sphere-pac rod irradiated to 7 MWd/kgM at LHGRs up to 42 kW/m was 4%. This value is lower than what might intuitively be expected for sphere-pac fuel and is comparable to what would be expected from reference pellet fuel irradiated under similar conditions. The probable reason for the lower than anticipated release is the sintering that occurred in the central portion of the fuel bed (Figure 9). (Note: The bulk of the fine fraction and some of the medium fraction spheres were lost during ceramographic specimen preparation.) The longer diffusion paths for fission gas in the hotter sintered region in combination with lower peak fuel temperatures in sphere-pac compared with reference pellet fuel might account for the comparable release fractions in the two types.

The fission gas releases from a sphere-pac rod and a reference rod power-ramped to 71 kW/m and held for eight hours were 34% and 40%, respectively. Postirradiation examination showed that the fuel areas inside the grain boundary swelling radii for the rods were 41% and 50% for the sphere-pac and reference rods, respectively. Because the bulk of the release from both fuels would be expected to come from the hotter central region of the fuel, the releases and areas within the grain boundary swelling radii for the two types of rods correlate well with the lower average and central fuel temperatures measured in the sphere-pac rods during steady-state irradiation, as described above. Again, it is pointed out that because of the lack of cladding creepdown in the HBWR, fuel temperatures and fission gas release values may have been higher for the reference rod than if cladding creepdown had occurred.

Cladding Deformation. Typically, during the initial startup of a sphere-pac fuel rod, the fuel interacts mechanically with the cladding as evidenced by a deviation in elongation from free cladding thermal expansion (Figure 10). However, after an initial rapid rate of elongation, the elongation rate becomes parallel to the free cladding thermal expansion rate; indicating that a constant stress state is achieved in the fuel-cladding system during the additional power increase. After achieving the steady-state power and while being held at that power, the rod elongation decreased to nearly the free cladding thermal expansion value. The lack of permanent cladding deformation associated with the peak stress state achieved indicates that the stress levels were below the yield strength and that a fuel-associated mechanism, e.g., central sphere bed sintering or creep, is operative in reducing the stress in the system. Upon subsequent power ascensions the elongation behavior of the sphere-pac rods was similar to the free cladding thermal expansion up to values of about 90% of the previous peak power (Figure 10). This is indicative of a low stress state in the cladding after the initial "conditioning" of the rod. If the previous peak power is exceeded, fuel-to-cladding mechanical interaction occurs and the rod becomes "conditioned" to the new power level. Because fuel-to-cladding contact in a HBWR sphere-pac fuel rod is not dependent upon cladding creepdown, the elgonation behavior described above is typical of what would occur in a commercial LWR environment.

PCI Behavior. Sphere-pac rods were power-ramped to an LHGR of 71 kW/m at a burnup of 7 MWd/kgM without failure. As discussed in the previous section, because the lack of cladding creepdown in HBWR does not affect fuel-to-cladding contact and hence the mechanical behavior of sphere-pac rods, power ramp tests of sphere-pac rods in HBWR provide a valid test of PCI-resistance for this fuel type. The elongation behavior of the sphere-pac rods during the ramps (Figure 11) was significantly different than the behavior of the pellet rods (Figure 6). The decrease in rod elongation below the cladding free thermal expansion line for sphere-pac rods and the small amount of permanent rod shortening in one of the rods are indicative of a significant contribution to the rod elongation by forces in the radial direction, i.e., a permanent positive strain in the hoop direction results in rod shortening in the axial direction. The hoop-to-axial stress ratio during the peak power hold and the power decrease is indicated to be greater than 1.7.[9] The sphere-pac rods exhibited the largest change in ovality of all the rods tested which prevented confirmation of the postulated diametral deformation in these rods.

General Performance. As with the annular pellet fuel concepts, the satisfactory irradiation behavior of the sphere-pac fuel to burnups of 7 MWd/kgM in HBWR and 18 MWD/kgM in BRPR in indicative that no unexpected, generic, deleterious failure mechanism is present in the sphere-pac design.

CONCLUSIONS

Results obtained to-date from the elongation of the annular-coated-pressurized and sphere-pac LWR fuel rod designs confirm the bases upon which these fuel concepts were selected for improved PCI-resistance. The degree of improvement of PCI-resistance remains to be quantified during the forthcoming power-ramp tests on fuel rod segments irradiated in the commercial environment of the BRPR to burnups as high as 37 MWd/kgM. The successful demonstration of improved PCI-resistance for these fuel types will enhance the reliability of achieving extended burnup.

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Table 1. Categorization of Performance Characteristics for the Annular-Coated-Pressurized and Sphere-Pac Fuel Designs

LICENSING NEEDS	FUEL CONCEPTS
Safety-Related Data Needs	
Chemical reactions between graphite coating and fuel and/or cladding	Annular-coated-pressurized
Coating thermal conductivity	Annular-coated-pressurized
Effect of axial relocation of fuel into the central hole (normal operation)	Annular-coated-pressurized
Stability of the central hole (off normal operation)	Annular-coated-pressurized
Fuel bed thermal conductivity	Sphere-pac
Fission product release characteristics	Sphere-pac
Data Needs for Normal Operating Conditions	
Fuel temperature and stored energy	Both
Fission Gas Release	Annular-coated-pressurized
PCI behavior	Both
General satisfactory performance	Both

Table 2. Summary of Design and Operational Characteristics

					Steady-State	
Fuel Type(1)	Smear Density, % T.D.	Fuel Density, % T.D.	Pressuriaton Level (HBWR/BRPR), kPa	Coating Thickness, μm	LHGR-HBWR, kW/m(2)	LHGR-HBWR, kW/m(2)
Annular-Coated-Pressurized	80.5(3)	93-95	460/460	6.4(6)	32-46	26
Annular-Coated	80.5(3)	93-95	100/460	6.4(6)	32-38	26
Annular	80.5(3)	93-95	100/460	--	32-38	26
Sphere-pac	87.5(4)	98.0	460/460	--	32-42	26
Reference	80.5(5)	93-95	100/460	--	32-46	26

(1) Cladding for all rods was cold-worked and stress-relieved Zircaloy-2. O.D. X I.D. equaled 12.33 X 10.51 mm for HBWR rods and 11.46 X 9.68 mm for BRPR rods. Fuel lengths were 460 mm for HBWR rods, 1778 mm for full-length BRPR rods, and 618 mm for BRPR segmented rods. Fuel-Cladding diametral gaps for pellet designs were 260 μm for HBWR rods and 240 μm for BRPR rods.
(2) Typical peak pellet values.
(3) Annular pellet designs have a central hole equivalent to 10 vol. % of a solid pellet.
(4) Three size-fraction mixture.
(5) Reference pellets have dished ends equivalent to 0.5 vol. % (each end) for HBWR rods and 1.0 vol. % (each end) for BRPR rods.
(6) Dag 4.
(7) Dag 154.

Table 3. Gas Sampling Results From Ramped Rods

	Species, Vol. %					
Rod Type	He	O	CO + N	CO_2	Kr	Xe
Reference	18.19	0.06	0.21	0.12	10.71	70.17
Annular-coated	17.24	0.002	0.27	0.07	10.84	71.56

Table 4. Friction Test Results

	Friction Coefficient(1)	
Cladding Condition	3.3 to 13.2 Kg Load	26.3 Kg Load
Noncoated	$0.39_s - 0.31_k$	$0.32_s - 0.28_k$
Dag 4 Coating	0.06_k	0.06_k

(1) S = static value
K = kinetic value

Figure 1. Thermal Conductivity of Dag 4 and 154 as a Function of Temperature

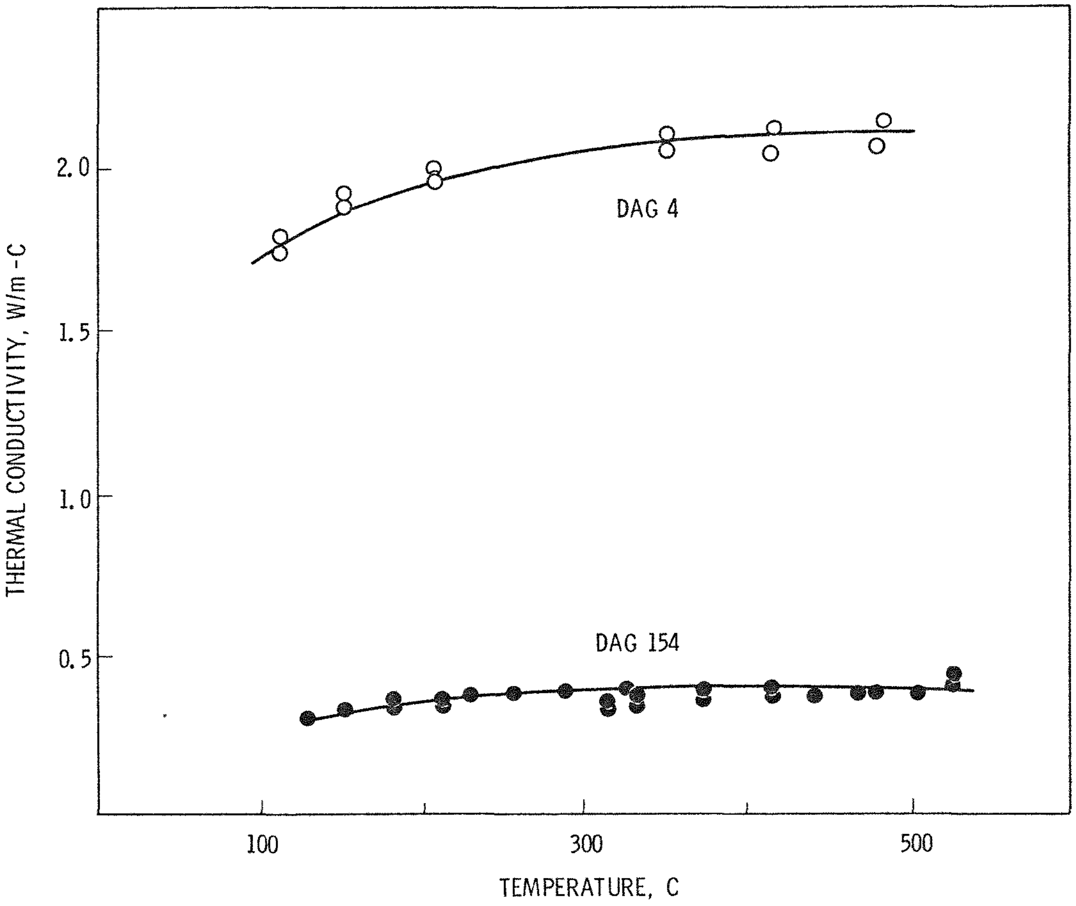

Figure 2. Fuel Centerline Temperatures in Annular-Coated, Annular, and Reference Fuel Rods as a Function of Burnup at 36 kW/m.

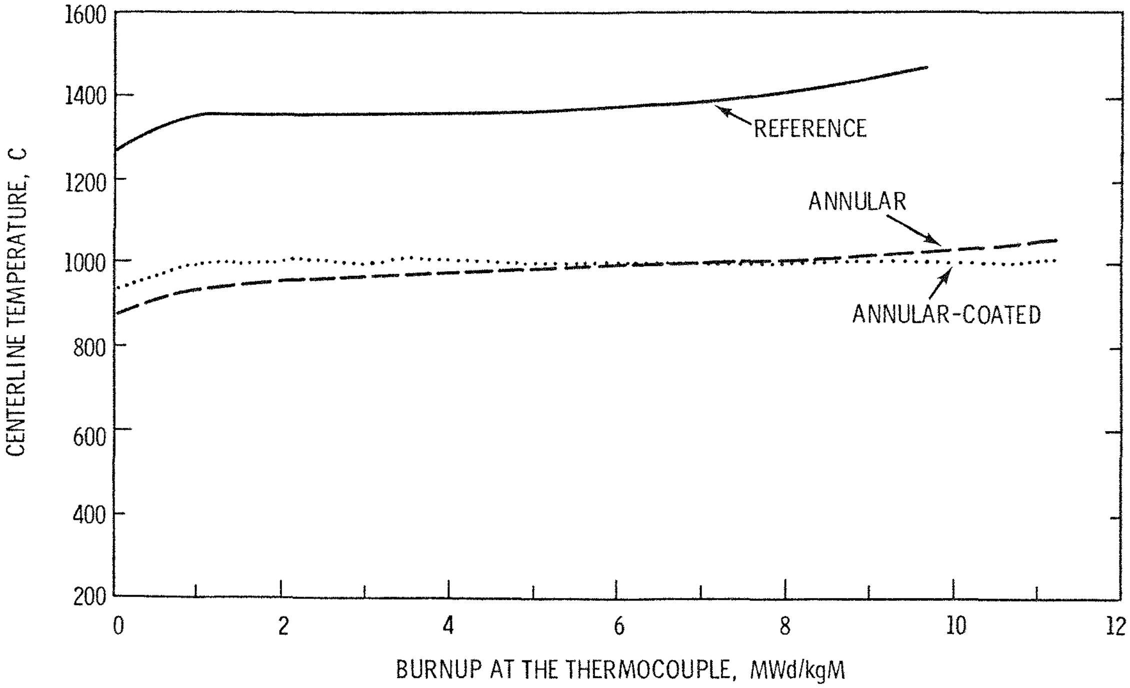

Figure 3. Transverse and Longitudinal Ceramographic Sections From an Annular-Coated Rod Power-Ramped to 68 kW/m and Held for 8 hr. (Lines on figure indicate original annular hole diameter.)

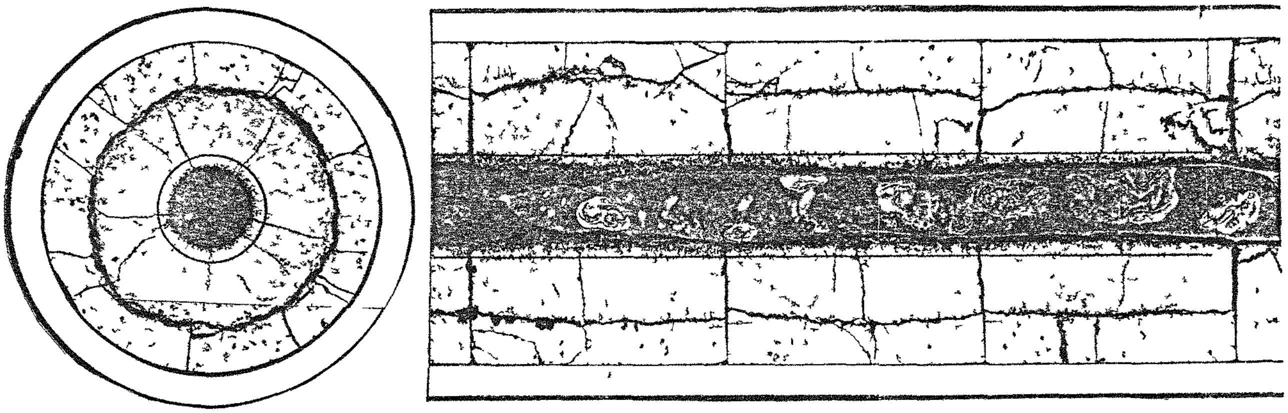

Figure 4. Fuel Centerline Temperatures in Annular-Coated, Annular, and Reference Fuel Rods During First Power Ascension. (Reference temperature adjusted to represent pellet with no thermocouple hole.)

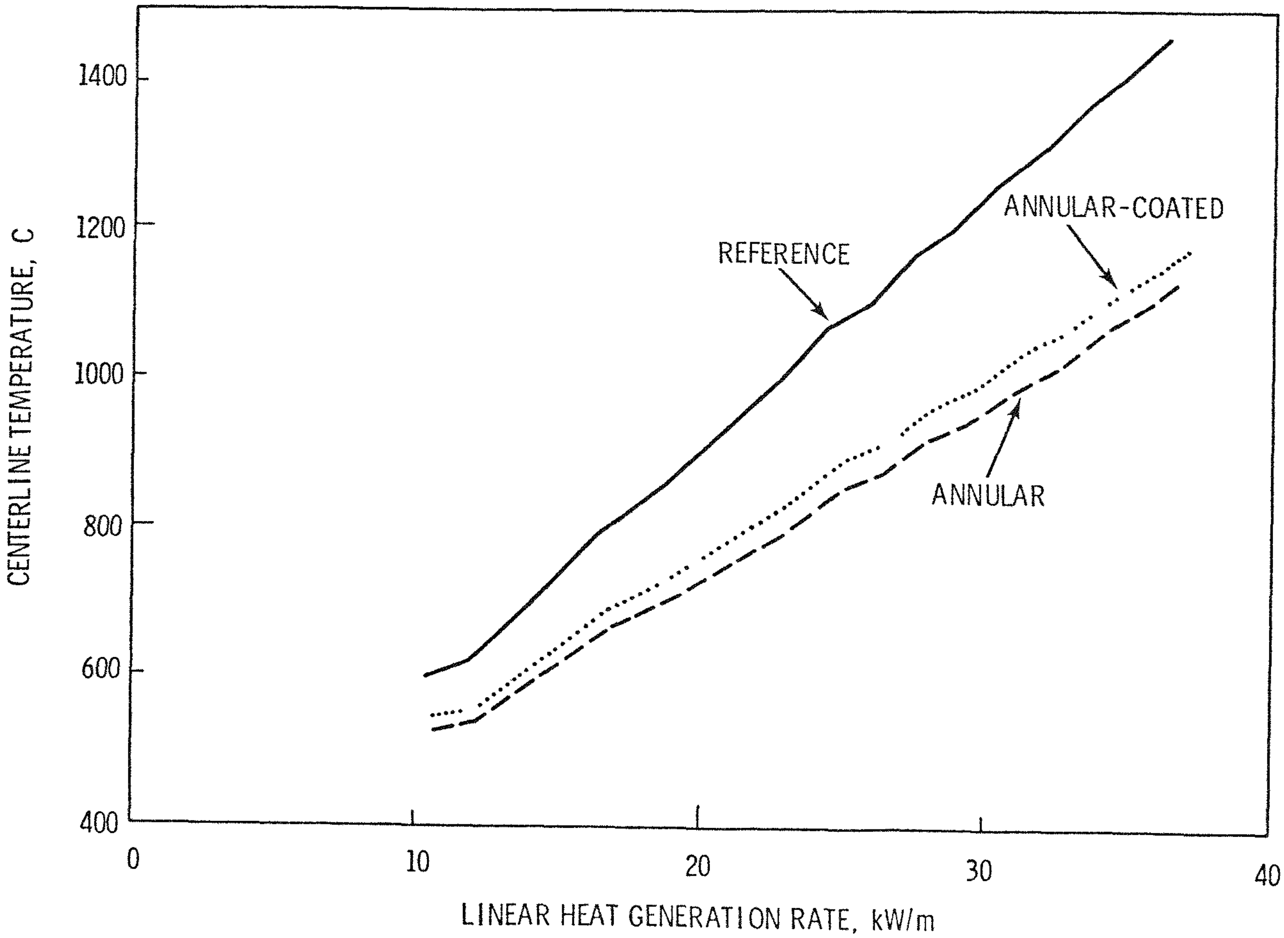

Figure 5. Onset of PCMI in Annular-Coated, Annular, and Reference Rods

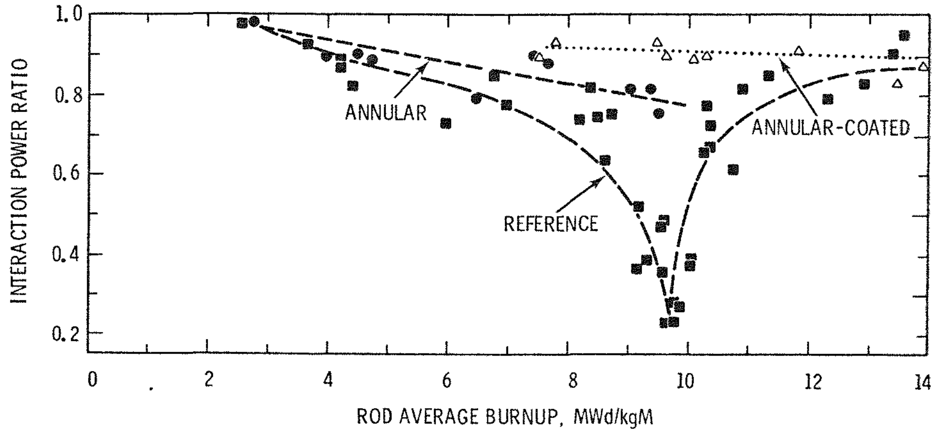

Figure 6. Rod Elongation Behavior in Annular-Coated, Annular, and Reference Rods During Power-Ramping in the HBWR at Burnups in the Range From 10 to 12 MWd/kgM. Time Plots Show Rod Elongation Behavior During the 8-hr Hold Period at Constant Power. (Dashed line represents cladding free-thermal expansion.)

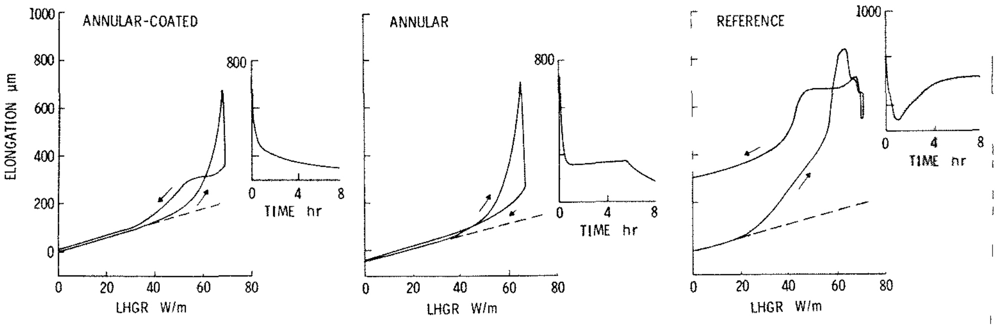

Figure 7. Calculated Sphere-Pac Thermal Conductivity Compared to 95% TD UO_2

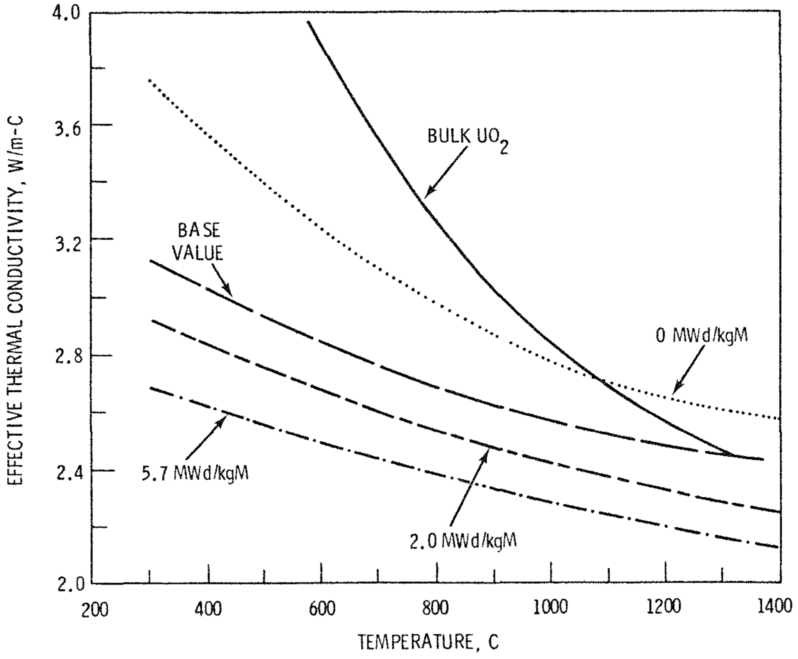

Figure 8. Fuel Temperature in Sphere-Pac and Reference Fuels During Third Power Ascension. (Both sets of data were adjusted to represent fuel with no thermocouple hole.)

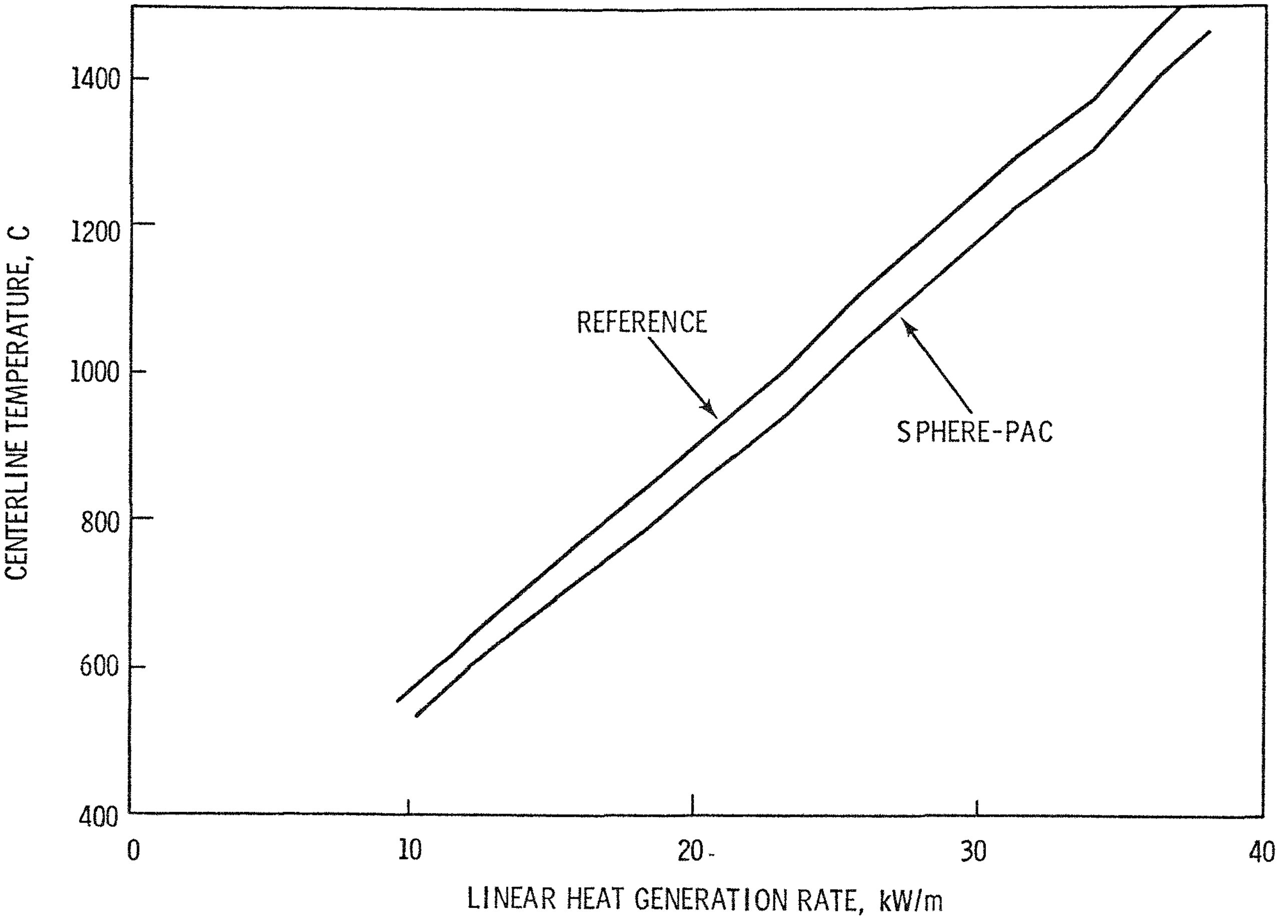

Figure 9. Longitudinal Ceramographic Section at the Centerline of a Sphere-Pac Rod After Irradiation at LHGRs up to 42 kW/m

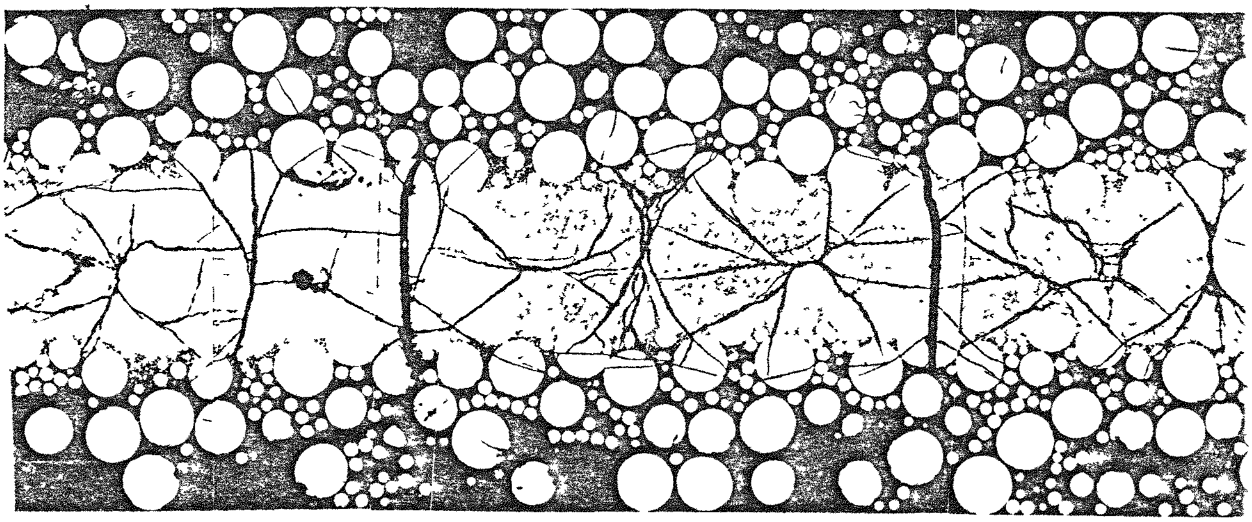

Figure 10. Typical Rod Elongation Behavior in a Sphere-Pac Fuel Rod During the Initial and Third Power Ascensions

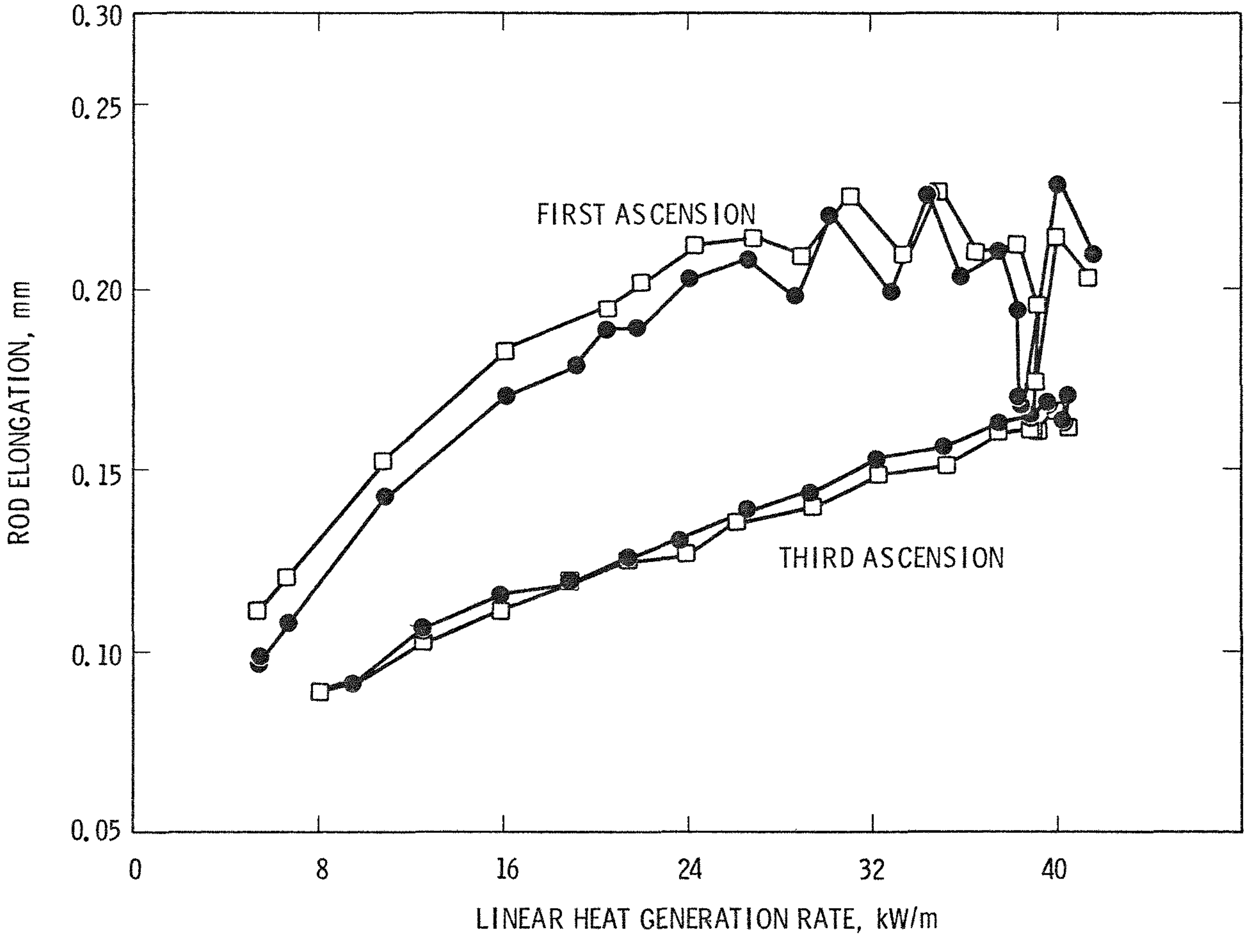

Figure 11. Elongation Behavior of Two Sphere-Pac Rods During Power-Ramp Testing