American Nuclear Society
1962 Winter Meeting
Washington, D. C.,
November 26-28, 1962

UO_2 FUEL ROD PERFORMANCE
WITH A MOLTEN CENTRAL CORE

CONF-11-8

M. F. Lyons, R. C. Nelson, T. J. Pashos,

R. L. Straley, B. Weidenbaum

General Electric Company
Atomic Power Equipment Department
San Jose, California

A paper to be presented at the American Nuclear Society Winter Meeting, Washington, D.C., November 26-29, 1962.

DISCLAIMER

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

TABLE OF CONTENTS

UO_2 FUEL ROD PERFORMANCE WITH A MOLTEN CENTRAL CORE

SUMMARY

An experimental program* has been undertaken to explore the feasibility and limits of UO_2 fuel rod operation with a molten central core. Three UO_2 pellet fuel assemblies were irradiated at high thermal performance levels, under pressurized water conditions, in the GETR. The fuel rods operated with 0.565 OD peak surface heat fluxes ranging from approximately 600,000 to 1,100,000 BTU/hr-ft^2. UO_2 central melting occurred in the fuel rods operating above 600,000 BTU/hr-ft^2 heat flux and axial relocation of both fuel and fission products was evident in the higher thermal performance fuel rods.

Ten of the twelve fuel rods irradiated exhibited severe clad swelling in the peak heat flux zone, with a maximum diameter increase in one fuel rod of 0.073 inch. The mechanism for clad swelling has been identified as the UO_2 volume expansion on melting. A special test assembly was fabricated incorporating internal free volume in the fuel to accommodate the UO_2 expansion. Short time irradiation of this assembly at high thermal performance conditions produced negligible clad swelling. The assembly has been returned to the loop for a 25-day irradiation cycle. Continued freedom from swelling in this assembly following extended irradiation will permit resumption of the original program irradiation schedule.

A final maximum thermal performance pellet fuel assembly remains to be irradiated. This assembly contains fuel rods to operate at peak surface heat fluxes in the range of 1.2-1.3 x 10^6 BTU/hr-ft^2. Following fuel rod modifications similar to that in the special test assembly above, this assembly irradiation will be undertaken and continued to high burnup. The target burnup for the assembly is 20,000 MWD/T.

An identical sequence of assembly irradiations is scheduled using compacted powder UO_2 fuel rods.

Preliminary Observations and Conclusions

1. With the exception of the clad swelling effect, there has been no evidence of any failure mechanism that will prevent operation of fuel rods with appreciable central melting to long life.

2. Severe clad swelling occurs in long, unsegmented fuel rods containing solid UO_2 pellets when operated at thermal performance levels sufficient to produce central melting.

3. The clad swelling force has been identified as the volume expansion of UO_2 on melting.

---

* This program is being conducted by the Atomic Power Equipment Department of the General Electric Company and is sponsored jointly by Euratom and the United States Atomic Energy Commission, Contract AT(04-3)-189, Project Agreement No. 17.

4. The provision of internal free volume in the fuel, accessible to the molten core, has been demonstrated to prevent clad swelling for short irradiation times.

5. In view of the above method of preventing clad swelling, it should also be possible to reduce clad swelling or delay its occurrence until higher thermal performance levels by simply pre-conditioning the fuel rods through operation slightly below central melting conditions until a central void is developed.

6. A similar beneficial effect should be obtained by the use of compacted powder fuel with its inherent lower density and internal connected porosity.

7. Preliminary analyses of the post-irradiation UO_2 structure in the fuel rods indicates that the UO_2 conductivity during operation was relatively low and approximates that measured in earlier, short time capsule irradiations.[1] The improvement in UO_2 conductivity at elevated temperatures reported by Bates[2] was not evident in these fuel rods.

8. Axial relocation of both fission products and fuel is apparent in the fuel rods that operated with appreciable central melting.

INTRODUCTION

Current design practice for UO_2 fuel rods in commercial power reactors restricts the UO_2 central temperature to below the melting point (~5000 °F) at the maximum reactor power condition. This central temperature design limit may, in turn, restrict the fuel rod specific power and/or the fuel rod diameter with consequent, less favorable fuel economy. In an effort to determine the validity of central melting as a fuel rod design limit, an experimental program has been undertaken to explore the feasibility and limits of UO_2 fuel rod operation with a molten central core. Both pellet and compacted powder UO_2 fuel rods are included in the investigation.

The experimental program consists of a sequence of fuel assembly irradiations with each succeeding assembly operating at a significant increment in thermal performance level above the preceding one. The thermal performance level of the initial assembly was selected to produce a small diameter zone of central melting over a short length of each fuel rod.

This paper describes the results of the initial three UO_2 pellet fuel assemblies irradiated.

IRRADIATION CONDITIONS

The fuel irradiations are being performed in the GETR pressurized water loop. The nominal coolant conditions during operation are listed in Table I.

TABLE I

GETR-PWL COOLANT PARAMETERS

Pressure - 1000 psia

Saturation temperature - 545 °F

Fuel assembly inlet temperature - 344 °F

Fuel assembly outlet temperature $\sim$ 370 °F

Flow velocity at fuel rods - 16 to 34 ft/sec.

pH - 9.5 to 10.0

Dissolved H_2 - 25 to 65 cc/kg

The coolant conditions, particularly the suppressed assembly inlet temperature, were carefully chosen to insure that fuel rod failure would not occur due to external heat transfer limitations. Fuel rod cooling is entirely in the forced convection regime with no nucleate boiling.*

The GETR axial neutron flux profile is of particular significance to the fuel rod thermal performance conditions during these fuel assembly irradiations. Figure 1 is a plot of the relative axial flux profile and thus, the fuel rod power profile, as a function of the control rod bank position. The lowest rod bank occurs at reactor startup followed by gradual withdrawal of the rods during each reactor cycle. As a result, the peak fuel rod surface heat flux also occurs at reactor startup, at an axial position approximately 9 inches above the bottom end of the fuel column. As the reactor cycle progresses, the fuel rod peak surface heat flux both decreases in magnitude and shifts upward along the rod to a final position 18 inches above the bottom of the fuel column. To correctly interpret the post-irradiation UO_2 structure, this peak heat flux shift must be taken into account.

---

* Since the primary heat transfer consideration in the loop is one of peak surface heat flux and all of the fuel rods are all identical in geometry and very nearly the same enrichment, the thermal performance level of the fuel rods discussed in the paper has been expressed entirely in terms of peak surface heat flux during operation. Curves have been appended, Figures 19 and 20, to allow determination of the $\int_{T_s}^{T_\mathbb{¢}} kdT$ and $\int_{T_{400°C}}^{T_\mathbb{¢}} kdT$ values if desired.

FUEL DESIGN

The fuel assembly design for these experiments includes four identical fuel rods as shown in Figure 2. Each fuel rod is contained within a shroud tube to maintain uniform coolant flow. The fuel rod design for these experiments is an unsegmented rod 39 inches in over-all length with a nominal fuel column length of 34 inches, as shown in Figure 3. At the upper end of the rod is a fission gas plenum containing a compression spring to prevent fuel column separation during handling. The fuel cladding is 0.565 inch OD x 0.030 inch wall Zircaloy-2. The fuel rods of the initial three assemblies all contained 95 percent TD, sintered UO_2 pellets with an as-fabricated diametral gap of 6 mils. The fuel enrichment and exact fuel column length in each of the assemblies is given in Table II.

IRRADIATION HISTORY

Assemblies EPT-6 and EPT-8 performed satisfactorily for a 25-day GETR cycle of irradiation. Assembly EPT-10 operated for 16 days and then was removed from the loop following low level indications of fission product activity. The assembly performance conditions during irradiation, averaged over the four fuel rods, are given in Table II.

TABLE II

EURATOM PWL FUEL ASSEMBLY IRRADIATION PARAMETERS

Assembly Designation	Fuel Enrichment (Percent)	Fuel Column Length (Inches)	Fuel Rod Peak Surface Heat Flux (Average) (BTU/hr-ft^2)	Assembly Thermal Power (KW)	Average Burnup (MWD/T)	Irradiation Period
EPT-6	1.5	34 ± 1/4	645,000	200	1,180	4/23/62 - 5/19/62
EPT-8	2.2	34 ± 1/4	895,000	260	1,442	6/1/62 - 6/24/62
ETP-10	3.0	31 ± 1/4	1,010,000	310	1,182	7/3/62 - 7/19/62

POST-IRRADIATION EXAMINATION

Despite considerable effort, the source of the fission gas release during the EPT-10 assembly irradiation has not been located. Only a single burst of noble gas activity occurred and then decayed off prior to the reactor shutdown. Subsequent radiochemical analysis of the loop coolant, of water from the fuel assembly transfer can, and of solvent soaked swabs on each fuel rod cladding did not detect any fission product activity. Rod 10D was mass spectrometer leak checked with negative results. Apparently the defect is very small and might not be found even by destructive examination of all four rods. At this time, it is uncertain whether the defect was caused by the clad swelling discussed in the next section.

Dimensional Examination

Post-irradiation examination of the assemblies has revealed severe clad swelling in all of the fuel rods except two in the initial assembly. The position of peak clad swelling coincides with peak surface heat flux location in the rod at startup. Both the maximum diameter increase and the axial length of the swollen clad zone appear to increase in proportion to the fuel rod thermal performance level. Table III lists calculated thermal performance conditions of the individual fuel rods along with the gross dimensional changes.

The axial distribution of the diameter changes in each of the fuel rods are shown in the plots of Figures 4, 5, and 6. The dark shaded areas on these plots indicate differences in the diameter measurements at 0° and 90° rotational orientation of the fuel rods. The nearly perfect symmetry of the clad swelling is readily evident. The sharp dips in the clad swelling on the EPT-10 fuel rods coincide with the location of the fourth set of lateral spacer pins on the shroud tube and are believed to result from restraint of the clad swelling by the pins. The best correlation obtained between the observed clad swelling and the fuel rod thermal performance level is shown in Figure 7 where the external volume increase of the fuel rods is plotted versus the peak surface heat flux of the rod at reactor startup. The data is scattered but the fuel rod volume change definitely increases with increasing fuel rod thermal performance.

Metallographic Examination

Rods 6D, 8A, and 10D have been destructively examined and metallographic examination completed on 6D and 8A. These examinations have produced considerable information with regard to consequences of operation with a molten UO_2 core and on the post-irradiation structural appearance of the UO_2 region that was molten during operation. In addition, the examination has contributed to an understanding of the clad swelling problem discussed above and identification of the probable clad swelling mechanism.

Figure 8 is a polished cross section of the 6D rod taken through the point of maximum swelling. It is apparent that the UO_2 entirely fills the cladding despite the approximate 47 mil increase in diameter and suggests that the internal UO_2

TABLE III

CALCULATED FUEL ROD PERFORMANCE DURING IRRADIATION

Assembly Number	Fuel Rod Number	Peak Surface Heat Flux (Startup) (BTU/hr-ft^2)	Peak Surface Heat Flux (Time Average) (BTU/hr-ft^2)	Maximum Diameter Increase (Inches)	Maximum Over-all Length Increase (Inches)	Fuel Rod Volume Increase From Swelling (Cubic Inches)	Central Void Volume (Cubic Inches)
EPT-6	6A	625,000	521,700	+ 0.001	+ 0.108	0.01	*
	6B	635,900	530,600	+ 0.006	+ 0.137	0.03	*
	6C	653,200	545,100	+ 0.044	+ 0.080	0.14	*
	6D	756,800	631,500	+ 0.047	+ 0.058	0.09	0.092
EPT-8	8A	953,000	787,000	+ 0.053	+ 0.057	0.17	0.13
	8B	921,000	760,000	+ 0.028	+ 0.062	0.097	*
	8C	781,000	645,000	+ 0.015	+ 0.056	0.048	*
	8D	916,000	756,000	+ 0.020	+ 0.054	0.096	*
EPT-10	10A	942,000	915,000	+ 0.047	+ 0.119	0.21	*
	10B	950,000	923,000	+ 0.059	+ 0.092	0.27	*
	10C	1,041,000	1,012,000	+ 0.056	+ 0.094	0.31	*
	10D	1,043,000	1,014,000	+ 0.074	+ 0.054	0.29	0.21

* No examination

movement outward forced the clad swelling. Very severe radial cracking of the UO_2 is evident around the outer periphery, but the inner end of the cracks appear to have healed by sintering. Thus, the cracking and outward fuel movement probably occurred early in the irradiation. The central region of the UO_2 is filled with fine, needle-like, columnar grains extending all the way into the edge of the small central void, as shown in the polished and etched composite in Figure 9.

Figure 10 is a polished cross section of the 6D rod taken at the position of maximum burnup. This location is also approximately the location of peak surface heat flux at the end of the irradiation. No clad swelling occurred in this region and radial cracking of the pellet is almost negligible. The fine, needle-like, columnar grains are also present in this section but they no longer extend in to the edge of the central void. Instead, there is a transition, at about one-quarter of the capsule radius, to much larger width columnar grains. Microscopic examination of these wider columnar grains, as shown in Figure 11, indicates a region a gradually increasing spherical porosity in the UO_2 inward along the radius. Both the size and density of the pores increase and then abruptly terminate at the periphery of a very dense rim of UO_2 in which porosity is almost completly absent. This same structure had been observed in previous Euratom Program capsule irradiations[1] whether or not a central void was present in the UO_2. Recent out-of-pile experiments on the melting of UO_2 have furnished some direct temperature measurement evidence[3] for believing that the border of dense spherical porosity marks the transition from solid to liquid and that the very dense UO_2 within the border was molten at the time of shutdown. This particular melt zone characteristic may be specific for high density sintered UO_2 pellets and not for other fuel types.

It should be noted that the peak surface heat flux existing at the section in Figure 10 is significantly lower than that which occurred early in the fuel rod irradiation at the section in Figure 8. This fact can be confirmed by comparing the relative size of the grain growth affected zones in the two sections as well as from a knowledge of the reactor flux profile during irradiation. Thus, if molten UO_2 is present in the section of Figure 10, a considerably larger zone of molten UO_2 must have been present early in the irradiation at the section of Figure 8. However, continued operation at gradually reduced heat flux in this zone has eliminated any distinctive evidence of melting. The grain structure present could probably have been produced entirely by operation below the melting point, although not out to the actual diameter observed.

The axial gamma activity profile of rod 6D was normal in that little evidence of fuel relocation appeared. However, some pellet separation was evident in the zone of peak clad swelling and a very high, narrow activity spike occurred at the axial center line of the rod, indicating fission product activity concentration in this zone. Autoradiographs were made of the metallographic specimen from this high activity zone, i.e., of the section in Figure 10, and also of the section in the peak clad swelling region. These autoradiographs, shown in Figures 12 and 13, strikingly indicate the concentration of activity in the peak burnup sample and also reveal annular zones of depleted activity in both cross sections. Both radial and axial migration of fission product activity appear to occur in fuel rods operating with central melting.

Subsequent axial gamma activity profiles on the fuel rods from the EPT-8 and EPT-10 have shown evidence of both fission product and UO_2 axial relocation. Multiple, sharp activity spikes are present, predominately in the lower half of the rod. The regular slope of the profile stops at about one-quarter of the rod length from the top of the fuel column and the profile is very ragged with fairly constant mean value thereafter. This change in slope of the profile is an indication of fuel relocation, which was confirmed by subsequent sectioning of the 8A rod and the 10D rod from their respective assemblies. The change in slope has been found to correspond to upper end of the UO_2 central void. The distribution of the void in these two rods is unusual but very nearly identical to that observed earlier in a 1.3 inch diameter sintered pellet UO_2 fuel rod, irradiated at central melting conditions under the AEC Fuel Cycle Program.(4) The maximum diameter of the central void occurs at its upper end. From this point the void gradually tapers down to very small diameter at the peak heat flux region of the rod. The tapering of the void is not particuarly uniform. Certain sections down the rod may show a somewhat enlarged void from that immediately above it, but the over-all trend is toward a smaller diameter. Actual "bridging" of fuel across the void was observed at many points in the 10D rod. This characteristic shape of the central void is apparently an indication that it was formed as a result of UO_2 melting, rather than by grain growth and void migration below the melting point. Central voids formed in lower thermal performance fuel rods, where no melting occurred, generally vary in diameter in proportion to fuel rod axial power profile.

Metallographic specimens have been prepared at locations in rod 8A similar to those in the 6D rod. Figure 14 is a polished cross section at the peak swelling zone corresponding to the peak surface heat flux position at startup. Again the UO_2 completely fills the clad inside diameter, despite a 53 mil increase in the cladding outside diameter. Radial cracking of the pellet outer periphery is severe. The same progression in UO_2 structure inward along a radius is evident in the section as was observed in the peak burnup section of rod 6D. Starting from the pellet surface, there is an initial annular ring of undisturbed UO_2, then a very narrow ring of equiaxed grain growth, and then a wider band of fine, needle-like, columnar grains. A relatively diffuse transition then occurs to a fourth ring containing wider columnar grains, and finally an abrupt transition to extremely large UO_2 grains with only slight columnar characteristics. This last annular region has an outside diameter greater than half the pellet diameter and is considered to be UO_2 that was molten at the time the irradiation was terminated. Each of the outer four annular rings of distinctive UO_2 structure is much narrower than the same band in the 6D rod section since the bands are relatively further out along the radius and in a steeper temperature gradient.

The peak burnup cross section for rod 8A is shown in Figure 15. The width of the columnar grain growth region in this section is very small and suggests that the wider band of columnar grains in the previous section was produced as the peak heat flux at the section decreased during the irradiation. Autoradiographs of the two 8A rod sections are shown in Figures 16 and 17. The concentration of activity in the peak burnup section is still evident, but there is considerably greater activity present at the peak heat flux section than in the same section from rod 6D. Apparently, the fission product activity distributes relatively evenly over the entire axial zone that remains molten during operation. Although the axial gamma activity profile was very uneven over the length of the rod containing these two sections, the mean value remained essentially constant.

ANALYSIS

The analysis performed to date on the fuel rods is of a preliminary nature and confined primarily to determination of the operating conditions at the various fuel rod sections examined metallographically. One particular section has been investigated in somewhat greater detail because of its very interesting operating history. This section is the peak burnup section from rod 6D shown in Figure 10. At the time of reactor startup, this section operated at 500,000 BTU/hr-ft^2, i.e., a heat flux slightly less than that required to produce central melting. The heat flux at this section increased gradually during the cycle to a maximum value of 630,000 BTU/hr-ft^2 after 18 days irradiation. During the remaining seven days of irradiation, the heat flux decreased to a final value of approximately 550,000. Despite the considerable columnar grain growth in this section, central melting did occur as indicated in the radial composite in Figure 11. If this columnar grain structure exhibited the improved elevated temperature conductivity of the magnitude reported by Bates[2], melting could not have occurred without reaching a heat flux of nearly 800,000 BTU/hr-ft^2.

The initial calculations indicate some improvement in the conductivity over that measured in earlier capsule irradiations,[(1)] but the analysis of the fuel rod operating conditions is not yet sufficiently precise for a firm conclusion.

The section from rod 8A in Figure 15 operated on startup at about 650,000 BTU/hr-ft^2 heat flux. During irradiation the heat flux increased gradually and continuously to a maximum value of 710,000 BTU/hr-ft^2 at shutdown. Columnar grain growth is very small in this section and analysis indicates a UO_2 conductivity very close to that in the capsules. However, here the analysis result is highly dependent on the choice of the exact location for melting because of the steep temperature gradient.

DISCUSSION

Considered as an entity, all of the different bits of evidence collected in the above post-irradiation examination point to an association between the clad swelling and the UO_2 melting that occurred in the fuel rods. Recent measurements have indicated a fairly large volume increase (~7 percent) in UO_2 upon melting(5) which could generate the necessary force to produce clad swelling. However, the swelling in the PWL fuel rods was unexpected based on earlier irradiations of similar capsules in the GETR Trail Cable facility(1) at essentially equivalent thermal performance levels. Careful dimensional measurements on the Trail Cable capsules had indicated no detectable clad growth.

In comparing the capsules to the PWL fuel rods in an effort to explain the difference in results, it became apparent that, unintentionally, the capsules always provided a mechanism for axial expansion of the molten UO_2. As a result of flux peaking at the ends of the capsule, the end fuel pellets tended to operate with a larger fluid UO_2 zone than the average pellet in the capsule. An adjacent plenum volume in the end plug was always available to the end pellets. Axial expansion and movement of the fuel was observed in each capsule, into the adjoining plenum space. However, in the full length PWL fuel rods, the very high thermal performance region containing molten UO_2 is confined from both above and below by relatively cold, non-plastic fuel pellets. Based on previous experience in other programs, it is known that during high thermal performance operation, the fuel pellets are locked tightly in the fuel cladding and incapable of independent axial movement relative to the cladding. Consequently, it appears that the relatively large UO_2 expansion on melting may have been accommodated by axial movement in the capsules but could not be in the full length PWL fuel rods. Under these circumstances, it is believed that volume change on melting gave rise to the observed clad diametral expansion in the PWL fuel rods.

SUBSEQUENT EXPERIMENTAL WORK

In an effort to test the above hypothesis for the clad swelling mechanism, two additional experiments have been performed. First, a special fuel assembly was fabricated for irradiation in the PWL. This assembly contains fuel rods with cored UO_2 fuel pellets, thus providing an initial axial void along the length of the rod to permit UO_2 expansion. The assembly is a composite composed of the four fuel rods which were fabricated as spare rods for the initial pellet fuel assemblies. Each rod contains a different fuel enrichment so that the individual fuel rod peak surface heat fluxes are approximately 600,000; 900,000; 1,000,000; and 1,100,000 BTU/hr-ft^2 at the time of startup. The hollow core in the fuel pellets was obtained by drilling each of the fuel pellets with 0.080 to 0.090 inch diameter central hole.

This assembly was irradiated for two days at the start of GETR Cycle 37 with approximately 1-1/2 hours at full power, and then transferred to the RML for non-destructive examination. Despite operation at peak surface heat fluxes equivalent to that in the EPT-10 assembly, three of the four fuel rods exhibited no swelling and the remaining fuel rod indicated some swelling, but apparently slight. The axial gamma scans of the fuel rods indicated considerable fuel relocation in the 800,000; 1,000,000; and 1,200,000 heat flux rods, even during the short period of operation. This favorable result is very encouraging since the most probable time for the clad swelling to occur is believed to be during the initial few hours at startup.

For the second experiment, a new Trail Cable capsule was fabricated containing solid, 20 percent enriched UO_2 pellets, with no allowance for axial fuel movement, i.e., solid Zircaloy end plugs at each end. This capsule was irradiated at ~920,000 BTU/hr-ft^2 average surface heat flux. Dimensional measurements on this capsule following irradiation indicate definite clad swelling with a maximum diameter increase of 14 mils, as shown in Figure 18.

Although the diameter increase observed in the capsule is not as large as that occurring in the PWL fuel rods, the fact that swelling could be deliberately generated by preventing axial movement of the melted UO_2 is strong confirmation of the belief that the volume increase of the UO_2 on melting is the basic clad swelling mechanism.

The confirmatory results from both of the above special experiments provides considerable confidence that the correct clad swelling mechanism has been identified and a method of preventing clad swelling developed. The composite fuel assembly will be irradiated again for a full reactor cycle at the next GETR startup to determine the effect of extended power operation and power cycling on clad swelling. If the subsequent examination of the fuel assembly indicates continued freedom from swelling, the EPT-12 fuel assembly will be similarly modified and its irradiation undertaken. The EPT-12 assembly fuel rods will operate at peak surface heat fluxes of 1.2 to 1.3 x 10^6 BTU/hr-ft^2. Assuming the EPT-12 assembly operates satisfactorily, it is planned to continue its irradiation to the attainment of a very high burnup, tentatively 20,000 MWD/T.

The use of hollow pellets is not necessarily the only fabrication method possible to prevent clad swelling. The general concept involved is that free volume must be provided within the fuel, accessible to the molten zone, to accommodate the UO_2 volume expansion on melting. The use of hollow fuel pellets has the advantage of providing a relatively large, interconnected free volume, directly adjacent to point of initial fuel melting. If the amount of free volume at the zone of maximum melting is insufficient to accommodate the total UO_2 expansion, the excess molten UO_2 can flow axially to a less severely melted zone.

The results of the program to date are considered very promising. On the basis of the initial three assemblies irradiated, no physical limitation has been observed, other than clad swelling, that would indicate that full size pellet UO_2 fuel rods cannot be operated at these high thermal performance levels for long life. Even though a method of preventing clad swelling has been demonstrated, it is not considered likely that this method will have to be deliberately applied to fuel rods for operation with slight amounts of central melting. The relatively low heat fluxes at which clad swelling developed in these experimental fuel rods is not believed to be completely typical of the performance to be expected in an actual power reactor. In the GETR the fuel rods were brought to full power very rapidly - in 2 to 5 hours - allowing little time for grain growth and void migration. If the startup extended over a longer time period, as expected in a large power reactor, a central void will form before melting occurs. This void should accommodate some UO_2 expansion on subsequent melting and delay the appearance of clad swelling until higher thermal performance levels. On the above basis, a planned startup program of extended operation at less than central melting conditions should be followed for fuel rods where eventual full power operation will result in central melting.

REFERENCES

1. M. F. Lyons, et. al., "Preliminary Results, Euratom Capsule Experiments on UO_2 Central Melting"; supplementary paper to be supplied at ANS Winter Meeting, November 25-28, 1962, Washington, D.C.

2. J. L. Bates, "Thermal Conductivity of UO_2 Improves at High Temperature", Nucleonics, Vol. 19, No. 6, June, 1961, p. 83.

3. H. Hausner, "UO_2 Grain Growth and Melting Studies", High Performance UO_2 Program, Sixth Quarterly Progress Report, GEAP-3771-6.

4. H. E. Williamson, J. P. Hoffmann, "The Irradiation Performance of UO_2 With Central Melting"; paper presented at the American Ceramic Society 15th Pacific Coast Northwest Regional Meeting, Seattle, Washington, October, 1962.

5. J. A. Christensen, "Specific Volume of Molten Uranium Dioxide"; paper presented at the American Ceramic Society 15th Pacific Coast Northwest Regional Meeting, Seattle, Washington, October, 1962.

GETR FLUX SHAPE AS A FUNCTION OF ROD BANK IN INCHES

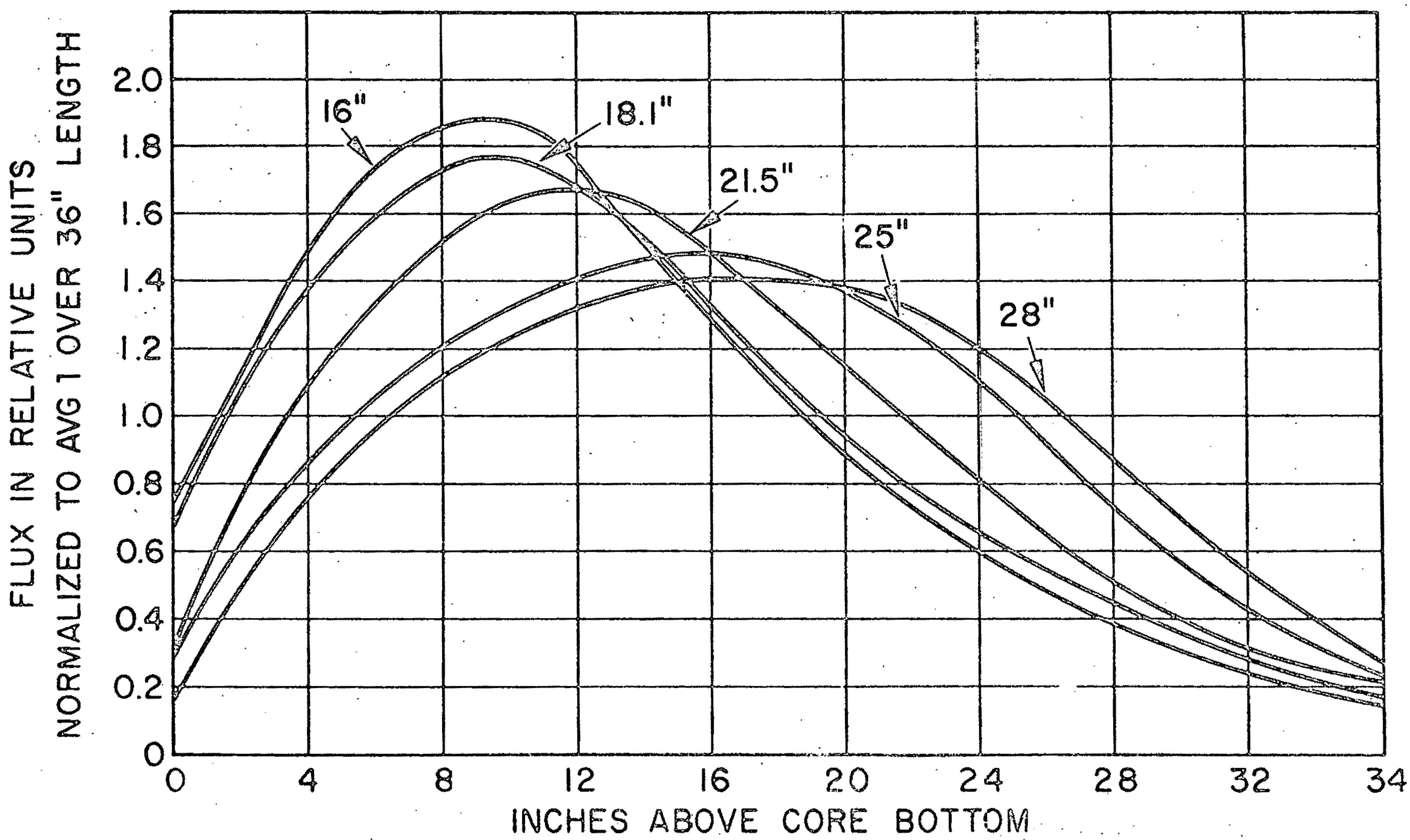


FIG. 1

EURATOM PWL FUEL ASSEMBLY

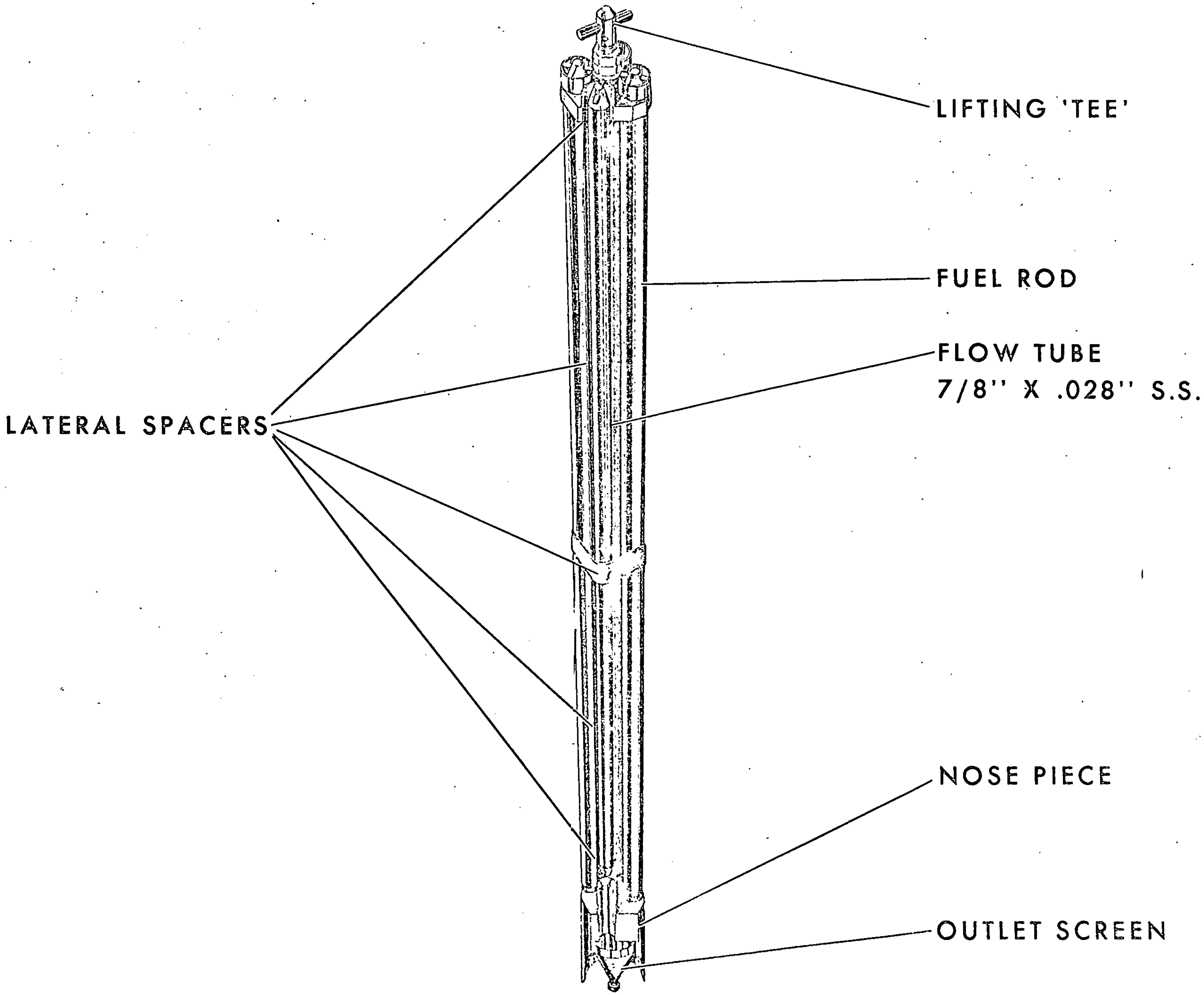


Figure 2

FUEL ROD DESIGN

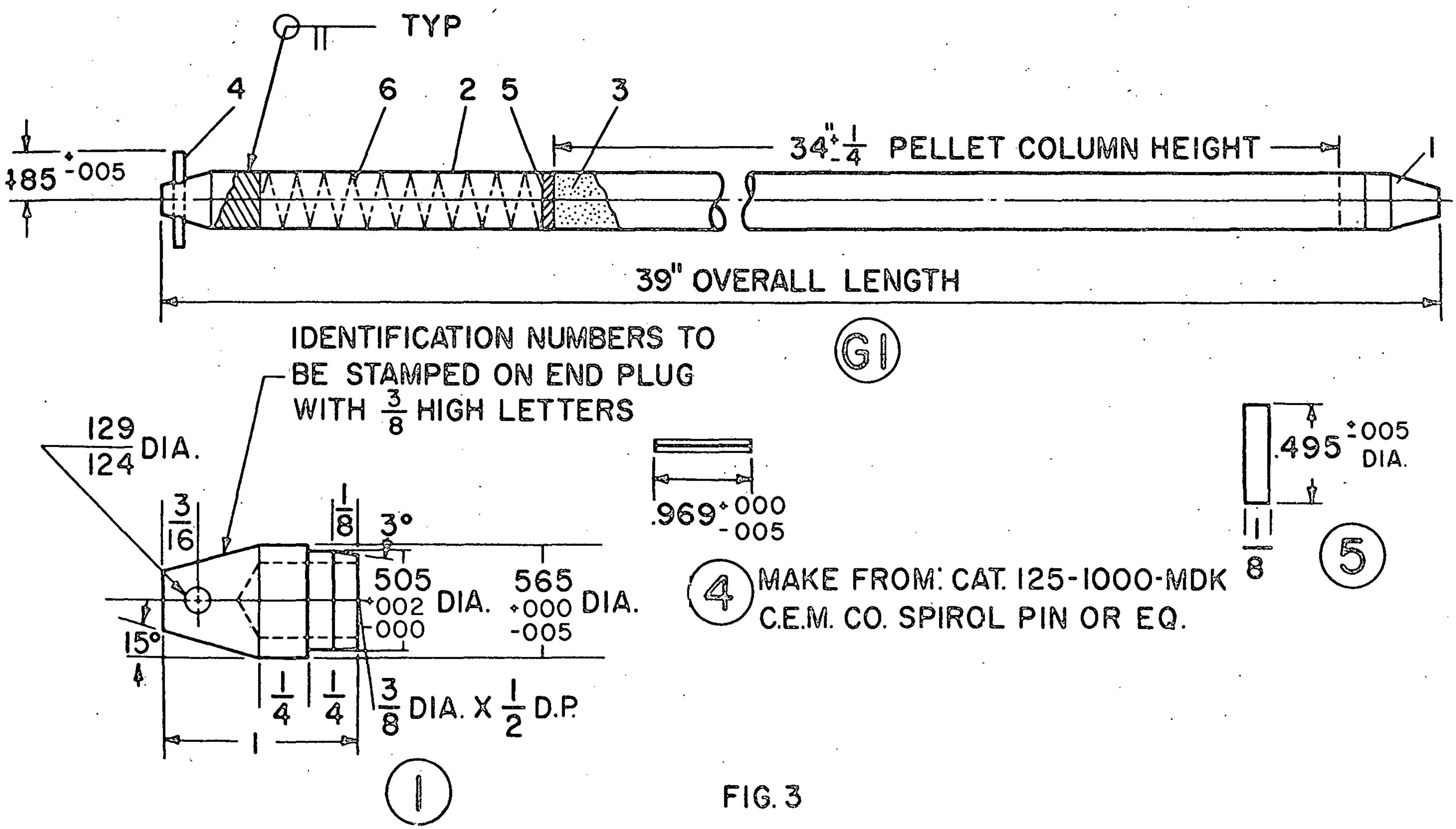


FIG. 3

DIMENSIONAL INCREASES ON EPT-6

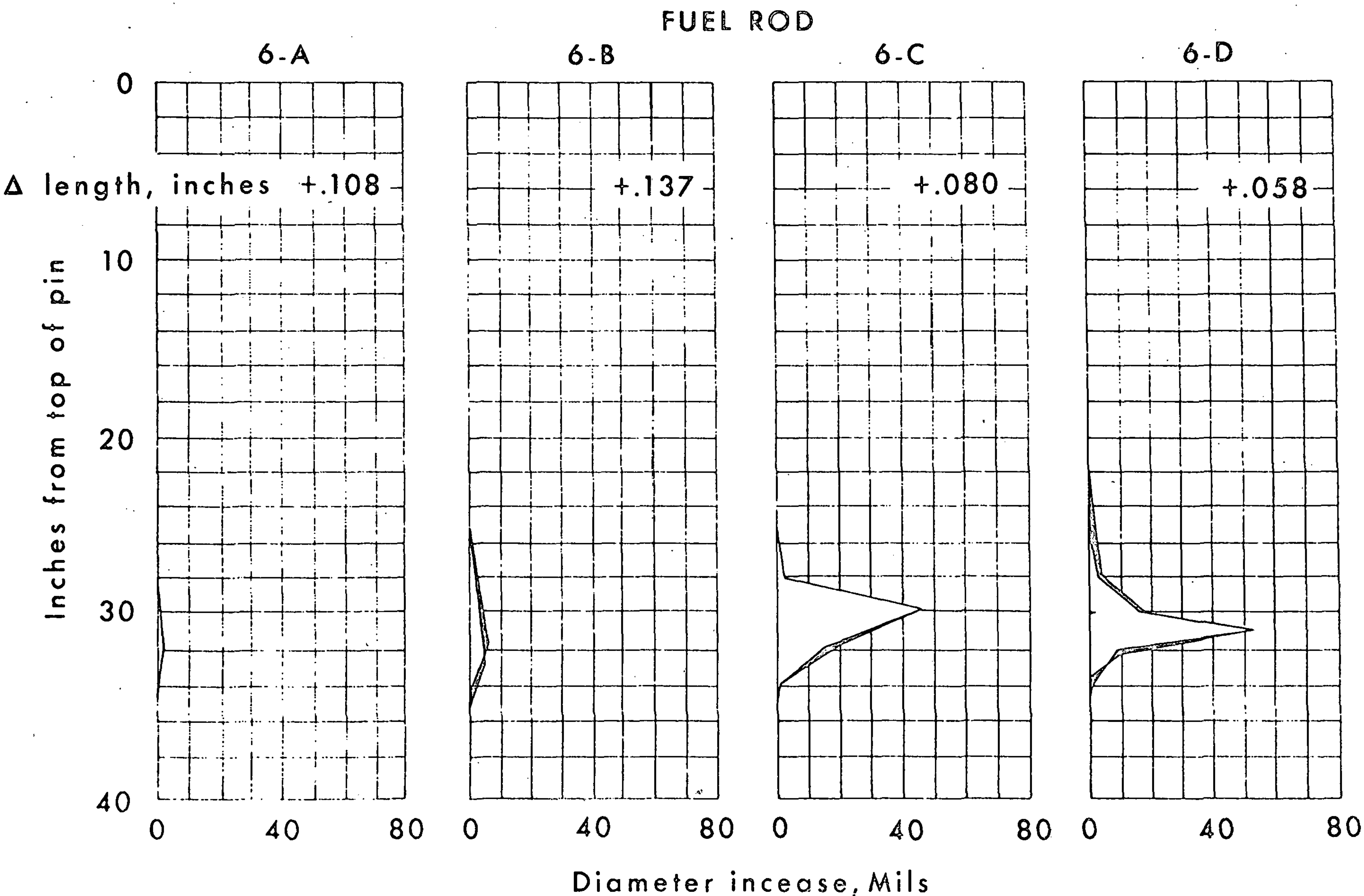


Figure 4

DIMENSIONAL INCREASES ON EPT-8

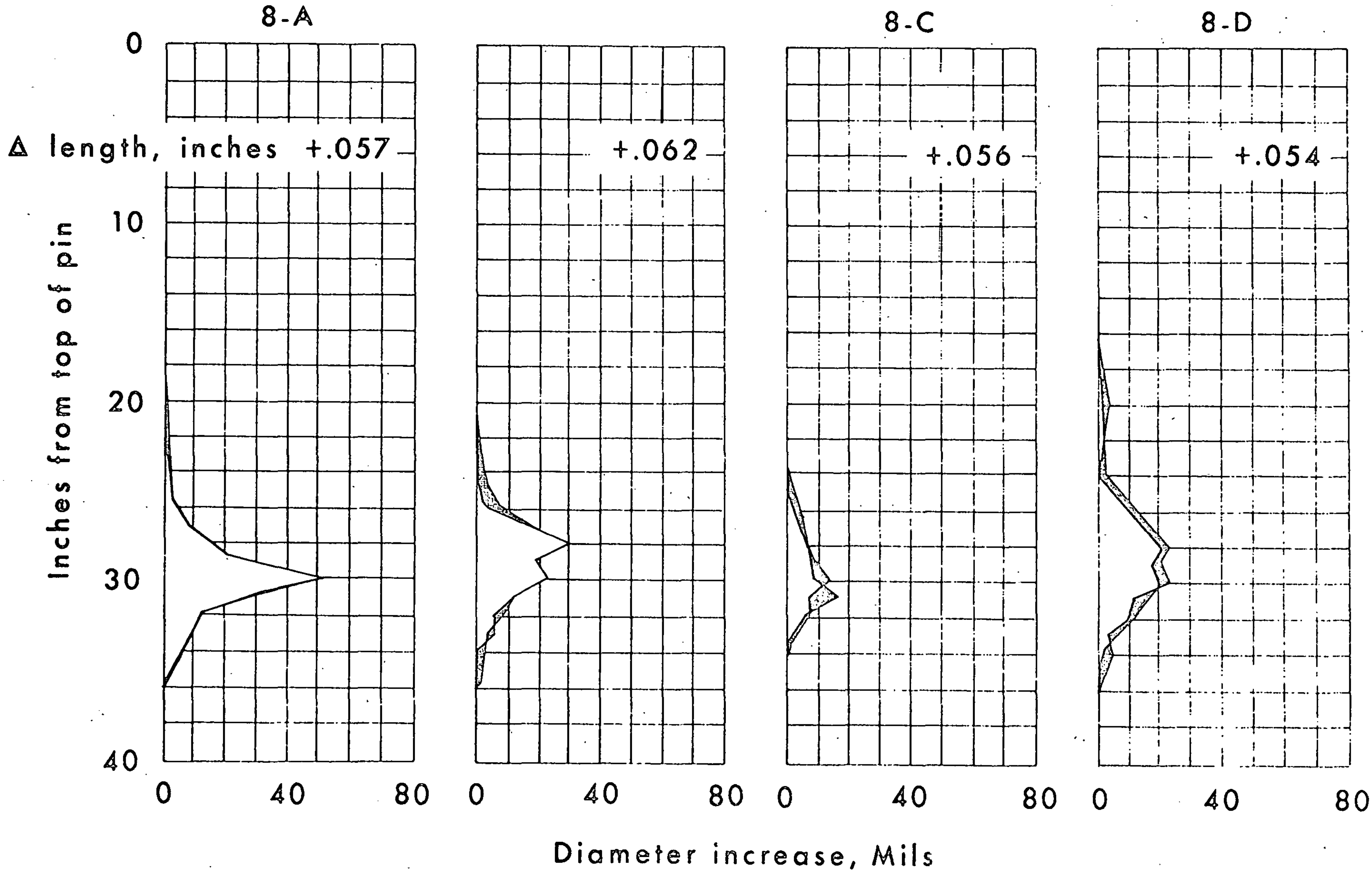


Figure 5

DIMENSIONAL INCREASES ON EPT-10

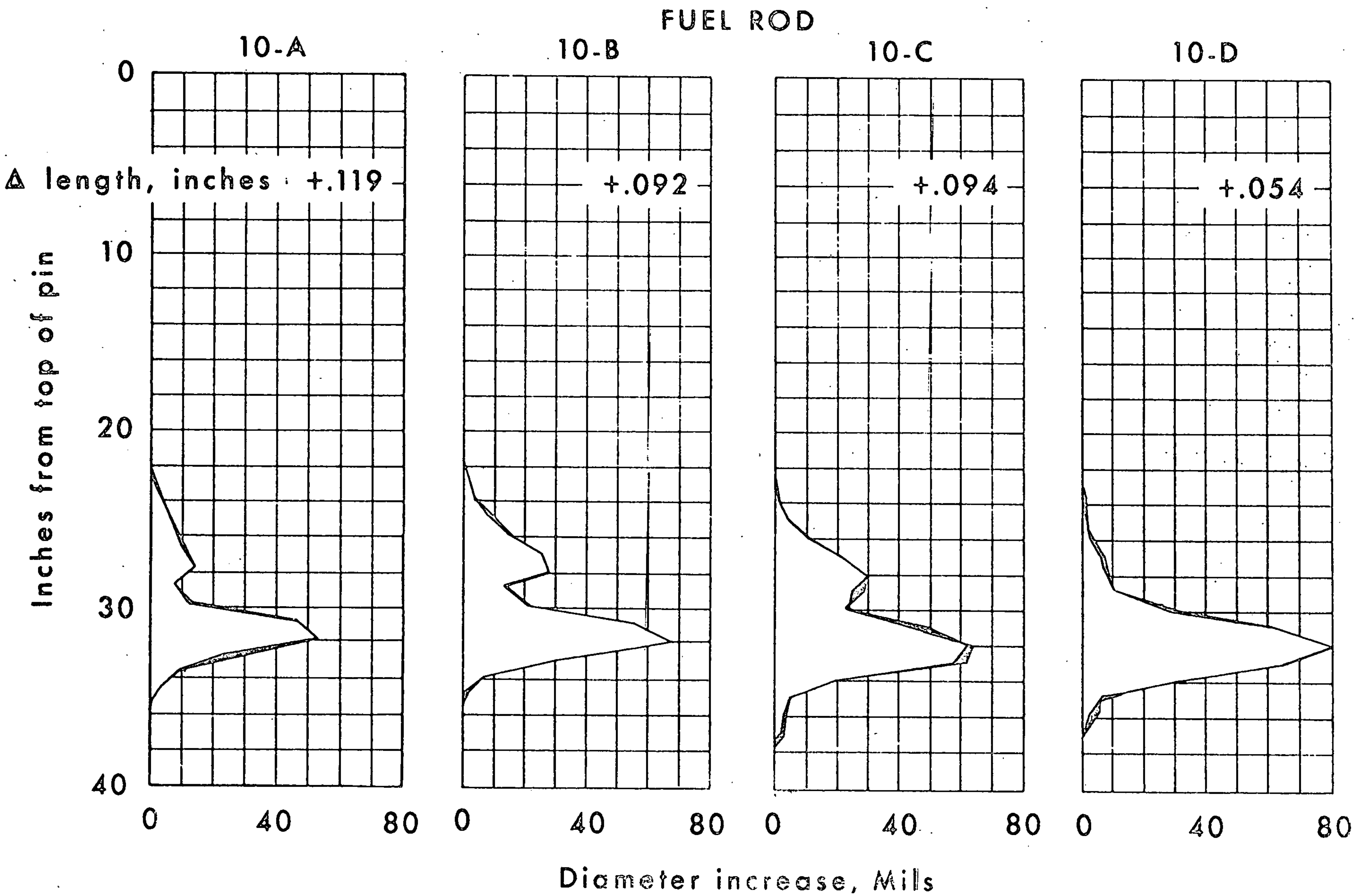


Figure 6

EURATOM PROGRAM

FUEL ROD VOLUME INCREASE VERSUS PEAK SURFACE HEAT FLUX AT STARTUP

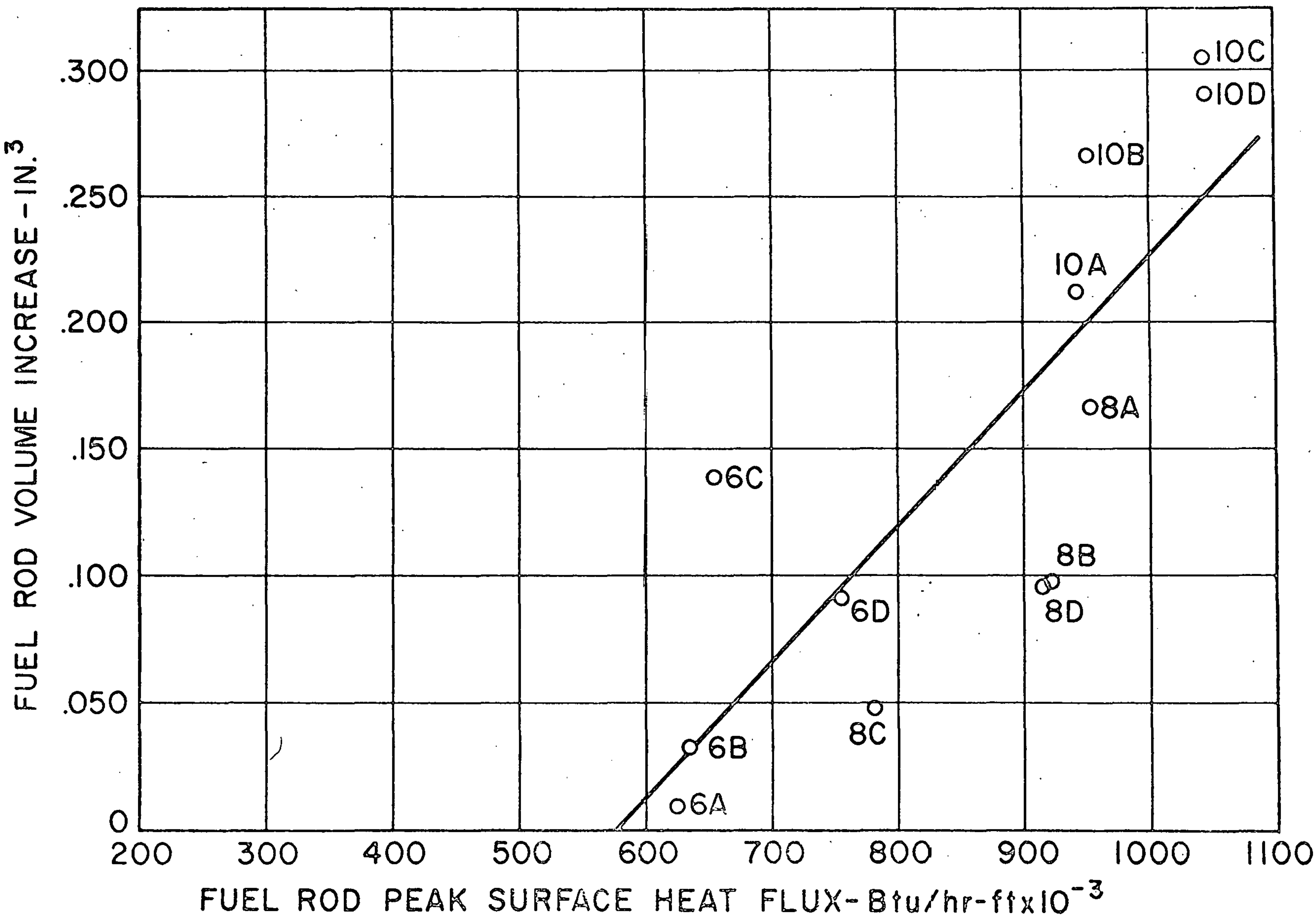
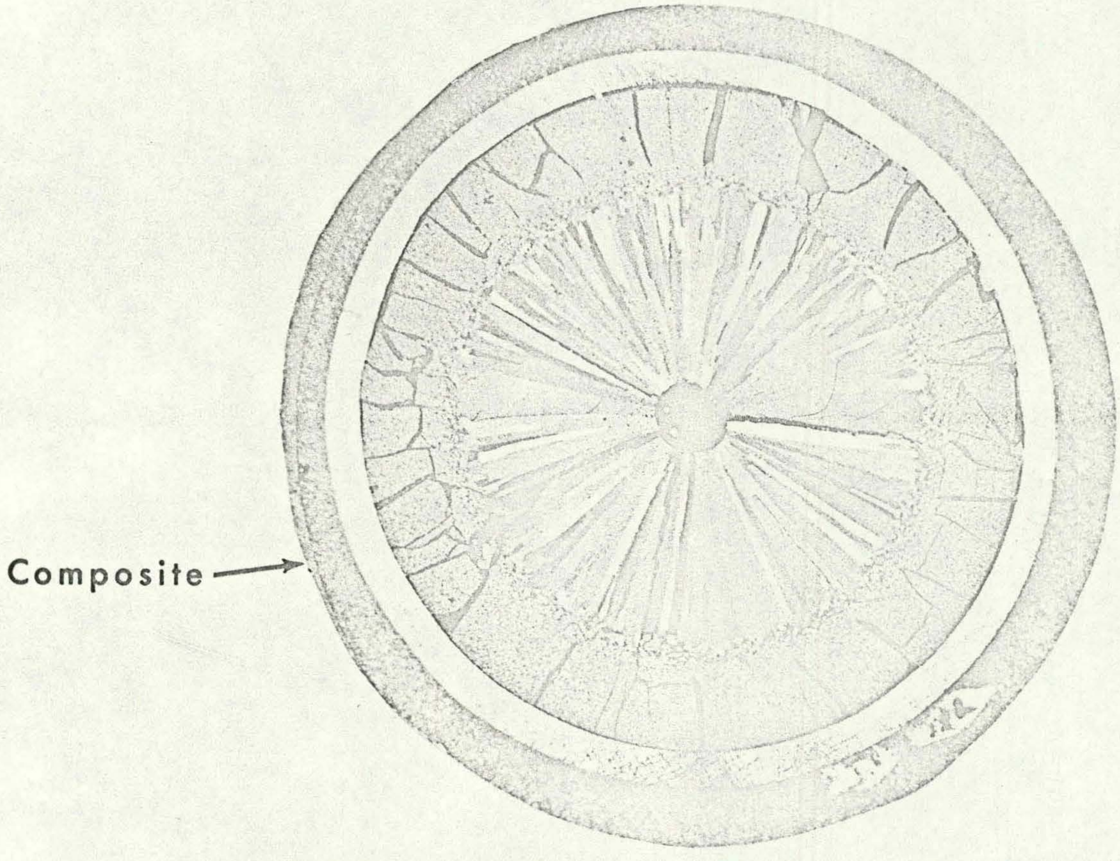


FIG. 7

FUEL CROSS SECTION



Location: Rod 6-D, Assembly EPT-6, 8" above bottom of fuel column (peak heat flux zone, region of maximum clad swelling)

Maximum Surface Heat Flux: 756,800 $Btu/hr\text{-}ft^2$

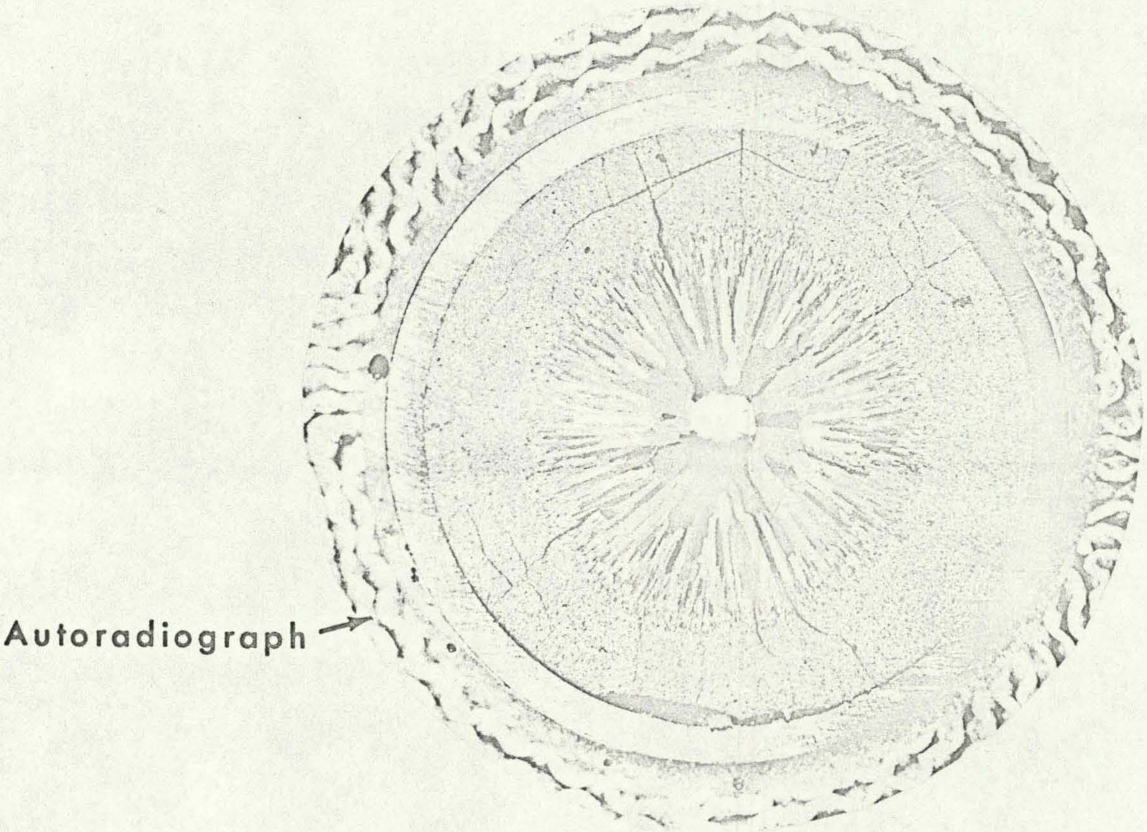
Preparation: Polished (600 grit SiC), Oblique light

Figure 8

LOCATION: ROD 6D, ASSEMBLY EPT–6, 8 INCHES ABOVE BOTTOM OF FUEL COLUMN (FROM CROSS SECTION OF FIGURE 5.1)
MAXIMUM SURFACE HEAT FLUX: 756,800 Btu/hr.–ft.^{2}
PREPARATION: FINE POLISH, 10% HNO_3 – 20% H_2O_2 ETCH
MAGNIFICATION: 100X REDUCTION: 44%

FIGURE 9 RADIAL COMPOSITE

FUEL CROSS SECTION

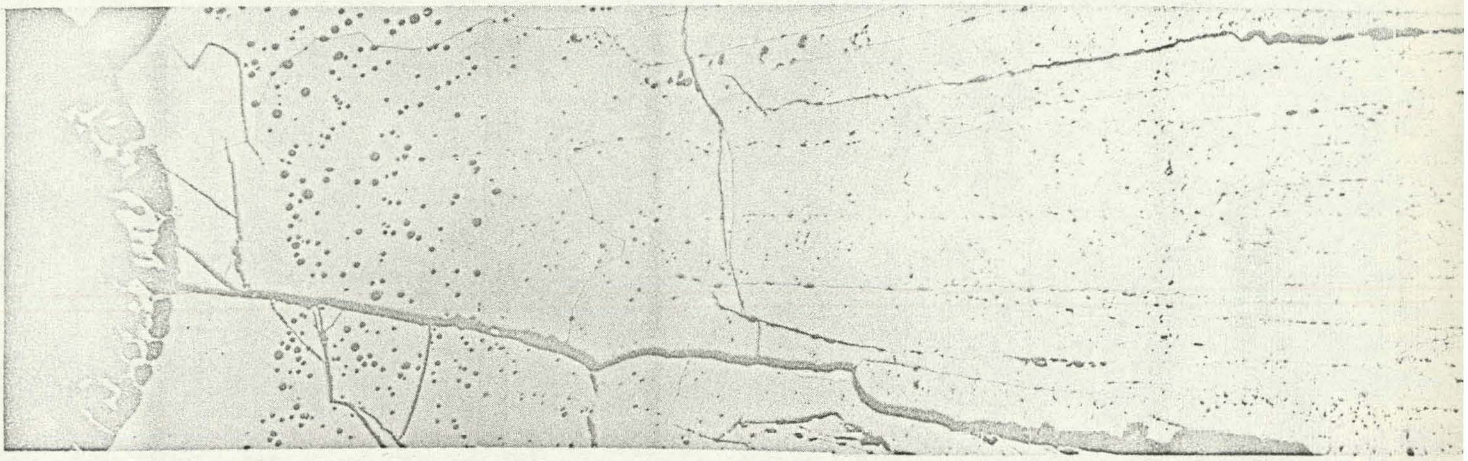


Location: Rod 6-D, Assembly EPT-6, 18'' above bottom of fuel column (peak burnup zone)

Maximum Surface Heat Flux: 631,500 Btu/hr-ft^2

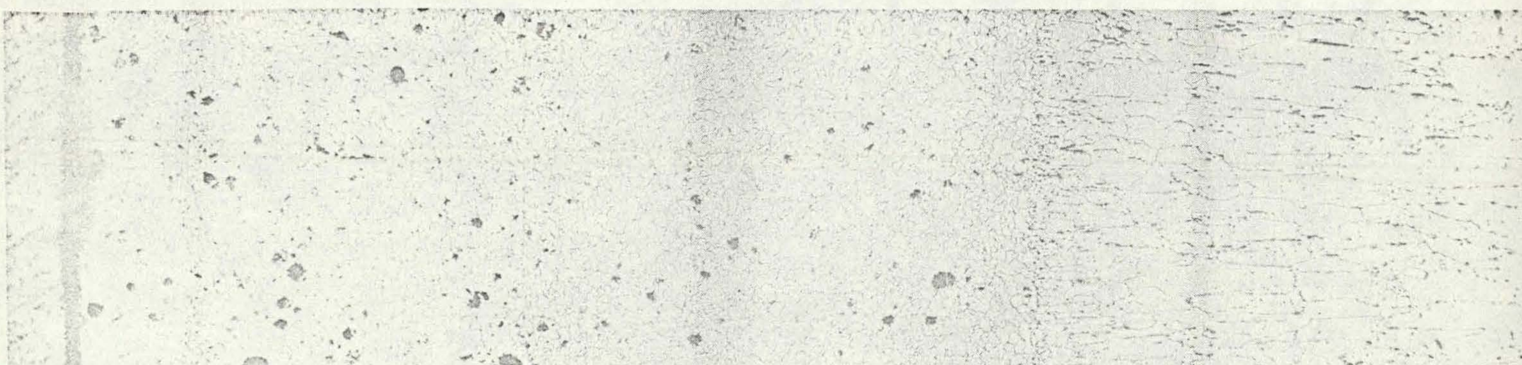
Preparation: Polished (600 grit SiC), Oblique light

Figure 10

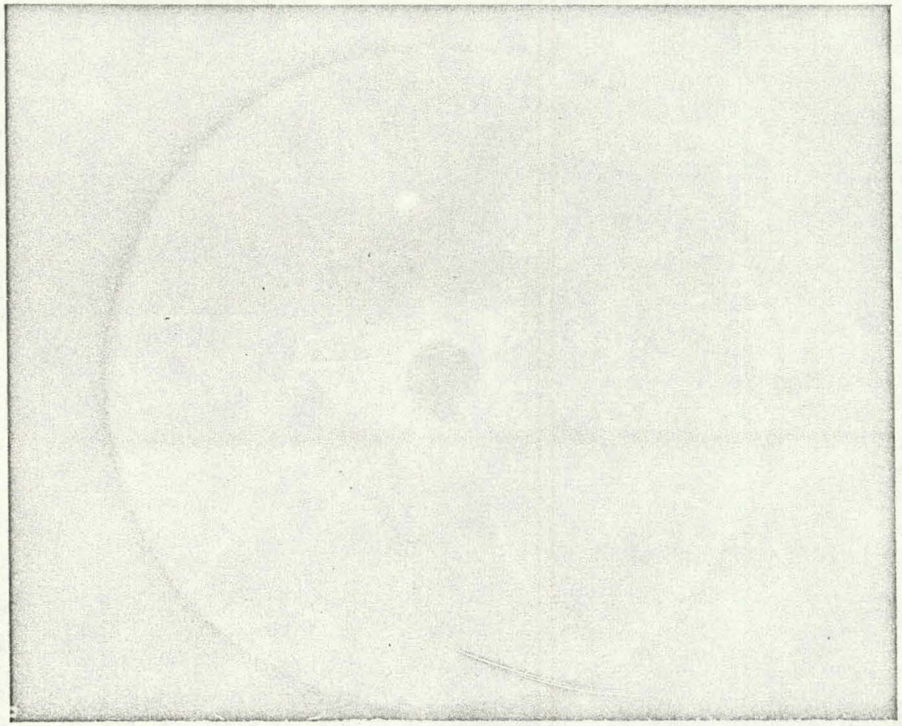


LOCATION: ROD 6D, ASSEMBLY EPT–6, 18 INCHES ABOVE BOTTOM OF FUEL COLUMN (FROM CROSS SECTION OF FIGURE 5.3)
MAXIMUM SURFACE HEAT FLUX: 631,500 $Btu/hr.-ft.^2$
PREPARATION: FINE POLISH, 10% HNO_3 – 20% H_2O_2 ETCH
MAGNIFICATION: 100X REDUCTION: 32-1/2 %

FIGURE 11 RADIAL COMPOSITE



AUTORADIOGRAPH - FUEL CROSS SECTION

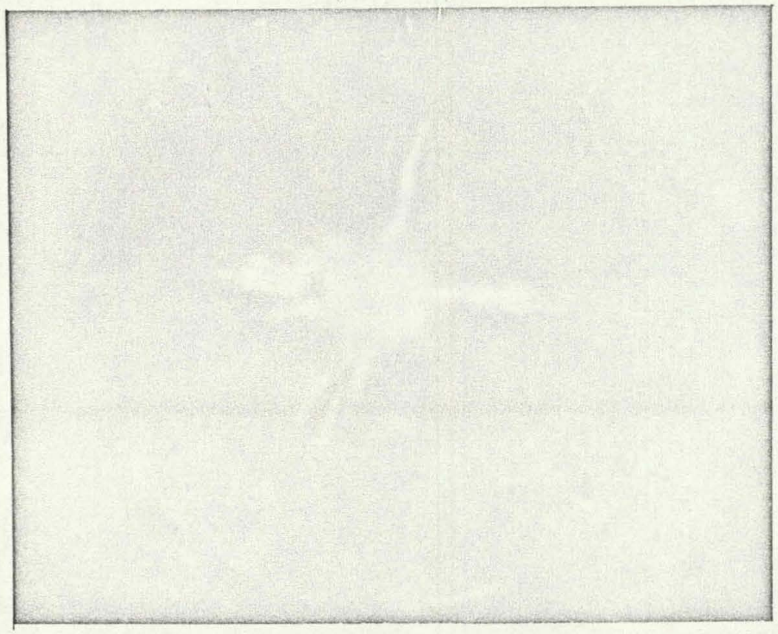


Location: Rod 6-D, Assembly EPT-6, 8" above bottom of fuel column (peak heat flux zone, region of maximum clad swelling)

Maximum Surface Heat Flux: 756,800 Btu/hr-ft2

Figure 12

AUTORADIOGRAPH - FUEL CROSS SECTION

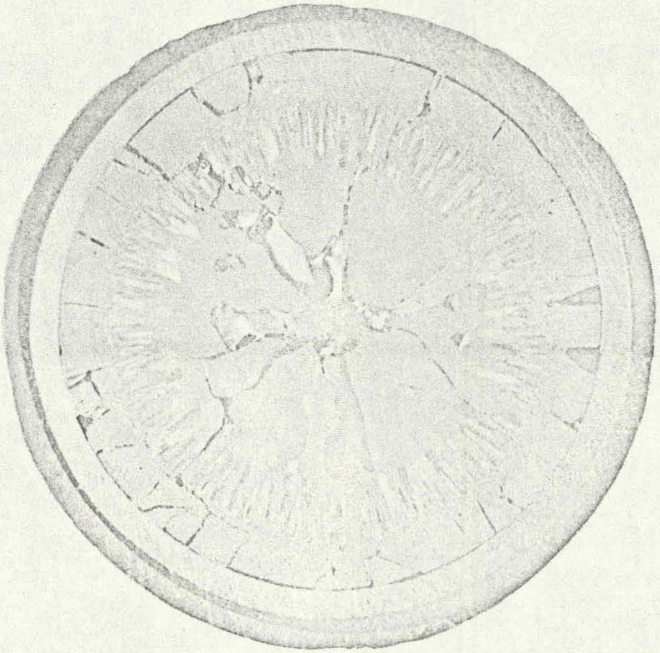


Location: Rod 6-D, Assembly EPT-6, 18'' above bottom of fuel column (peak burnup zone)

Maximum Surface Heat Flux: 631,500 Btu/hr-ft2

Figure 13

UO_2 CROSS SECTION

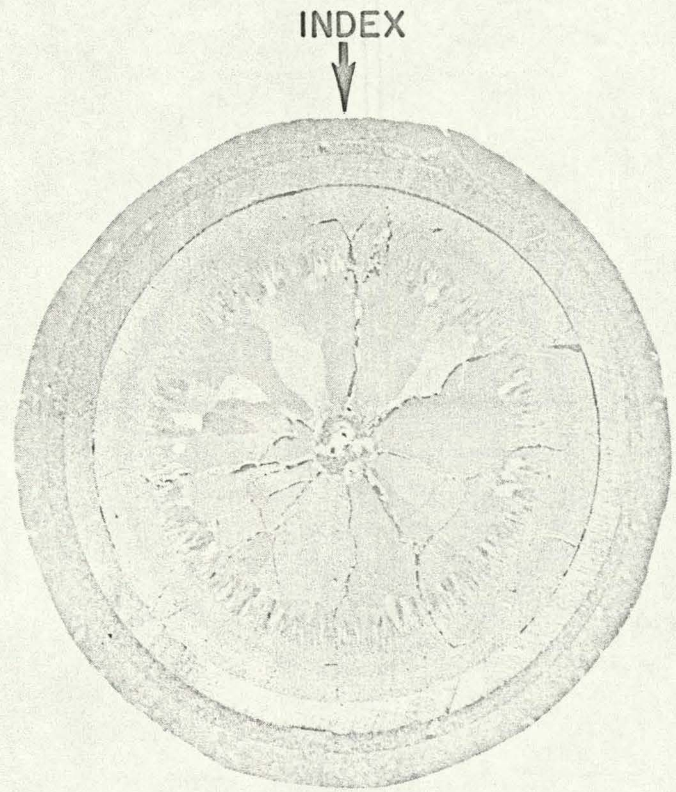


Location: Assembly EPT-8 Rod 8-A Peak Heat flux zone
(9 in. above bottom end plug)

Surface heat flux - 9 3,000 Btu/hr-ft^2

Figure 14

FUEL CROSS SECTION



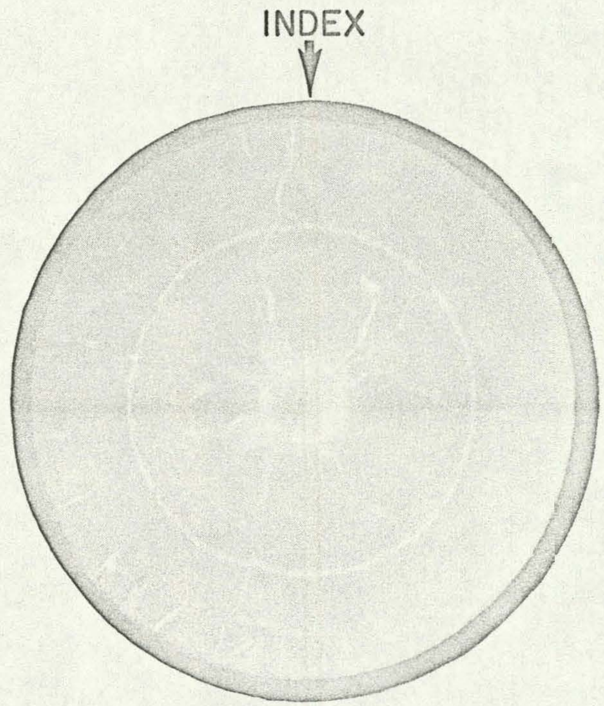
LOCATION: ROD 8A, ASSEMBLY EPT-8, 17" ABOVE BOTTOM
OF FUEL COLUMN (PEAK BURN-UP ZONE)

MAXIMUM SURFACE HEAT FLUX: 710,000 $Btu/hr-ft^2$

PREPARATION: POLISHED (600 GRIT SIC), OBLIQUE LIGHT

FIG. 15

AUTO RADIOGRAPH – FUEL CROSS SECTION

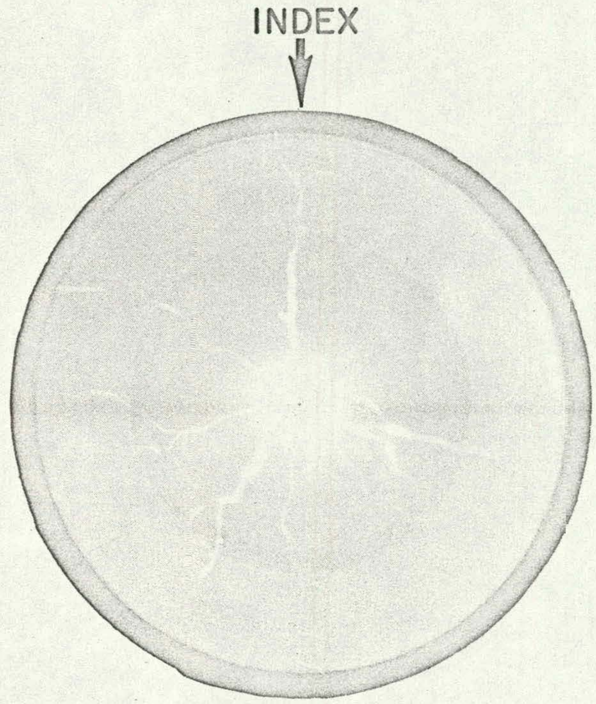


LOCATION: ROD 8A, ASSEMBLY EPT – 8, 9" ABOVE BOTTOM OF FUEL COLUMN (PEAK HEAT FLUX ZONE)

MAXIMUM SURFACE HEAT FLUX: 953,000 Btu/hr – ft^2

FIG. 16

AUTO RADIOGRAPH - FUEL CROSS SECTION



LOCATION: ROD 8A, ASSEMBLY EPT-8, 17" ABOVE BOTTOM OF FUEL COLUMN (PEAK BURN-UP ZONE)

MAXIMUM SURFACE HEAT FLUX: 710,000 Btu/hr-ft^2

FIG. 17

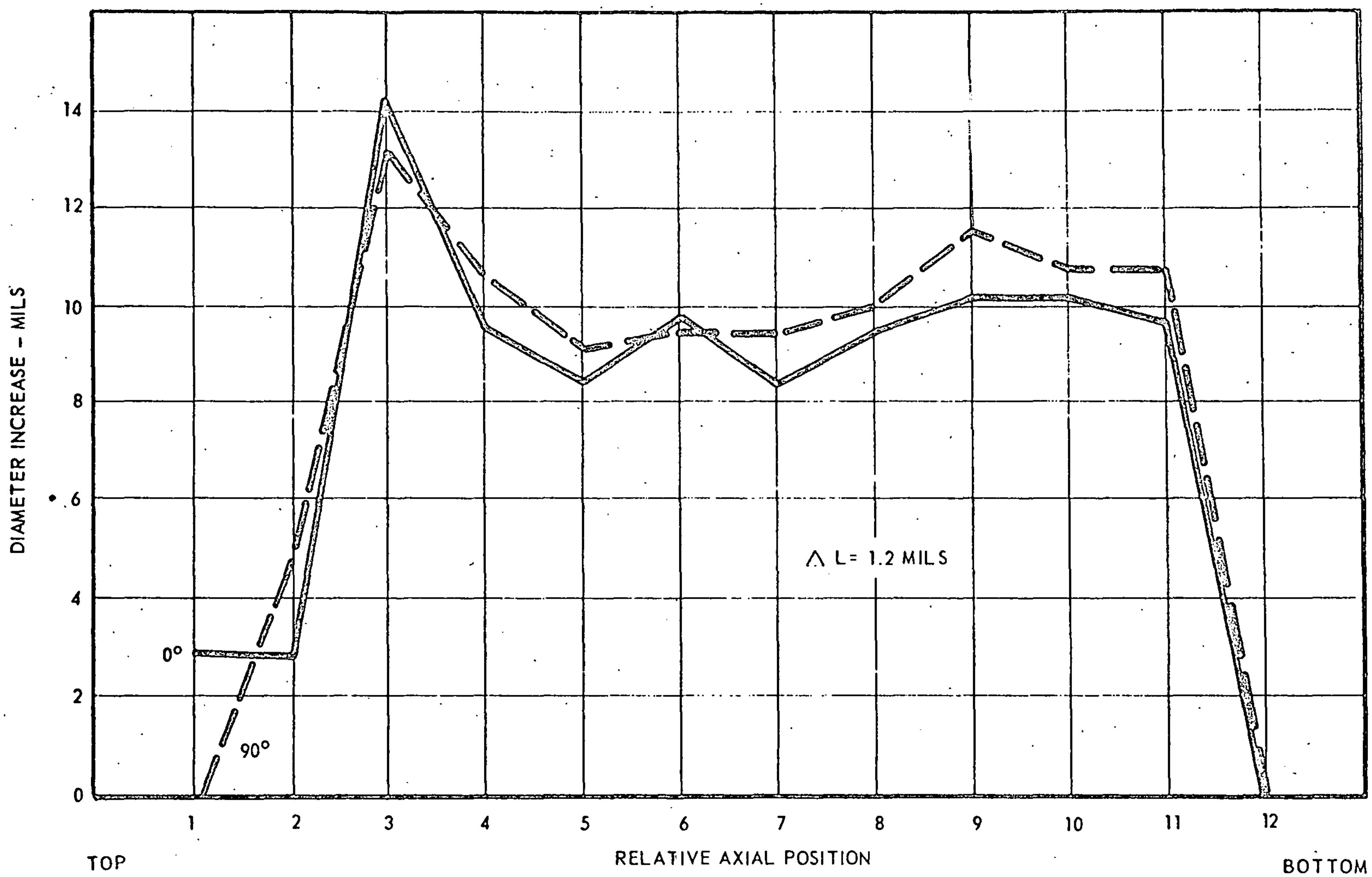


FIGURE 18 POST IRRADIATION DIMENSIONAL CHANGES
EURATOM CAPSULE #8
AVERAGE q/A = 920,000 BTU/hr–ft^2

CONVERSION CHART FOR EURATOM PROGRAM FUEL RODS

$\int_{T_s}^{T_{\mathcal{C}}} KdT$ vs CLAD SURFACE HEAT FLUX

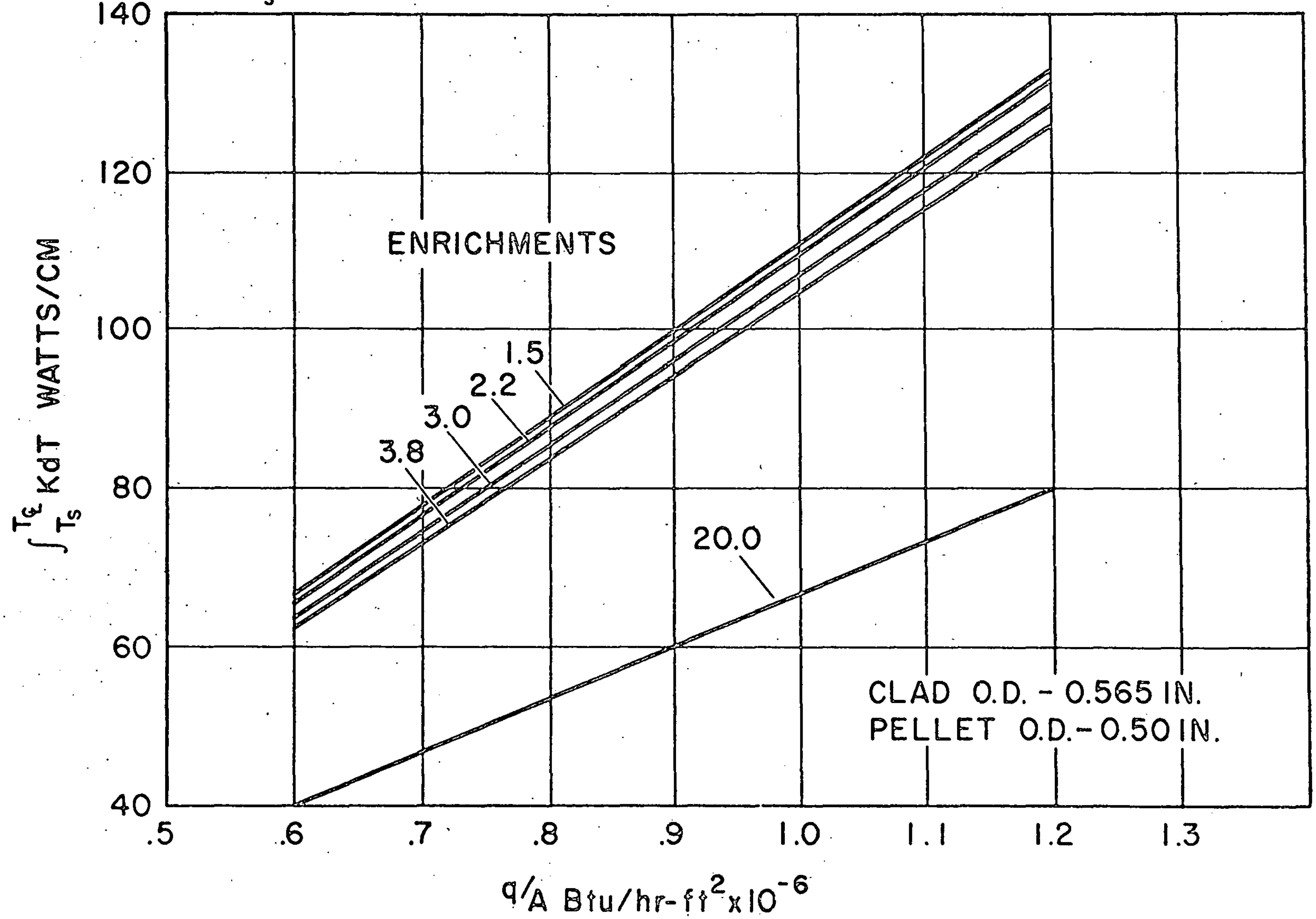


FIG. 19

CONVERSION CHART FOR EURATOM PROGRAM FUEL RODS

$\int_{T_0}^{T_{\mathcal{C}}} K\,dT$ vs CLAD SURFACE HEAT FLUX

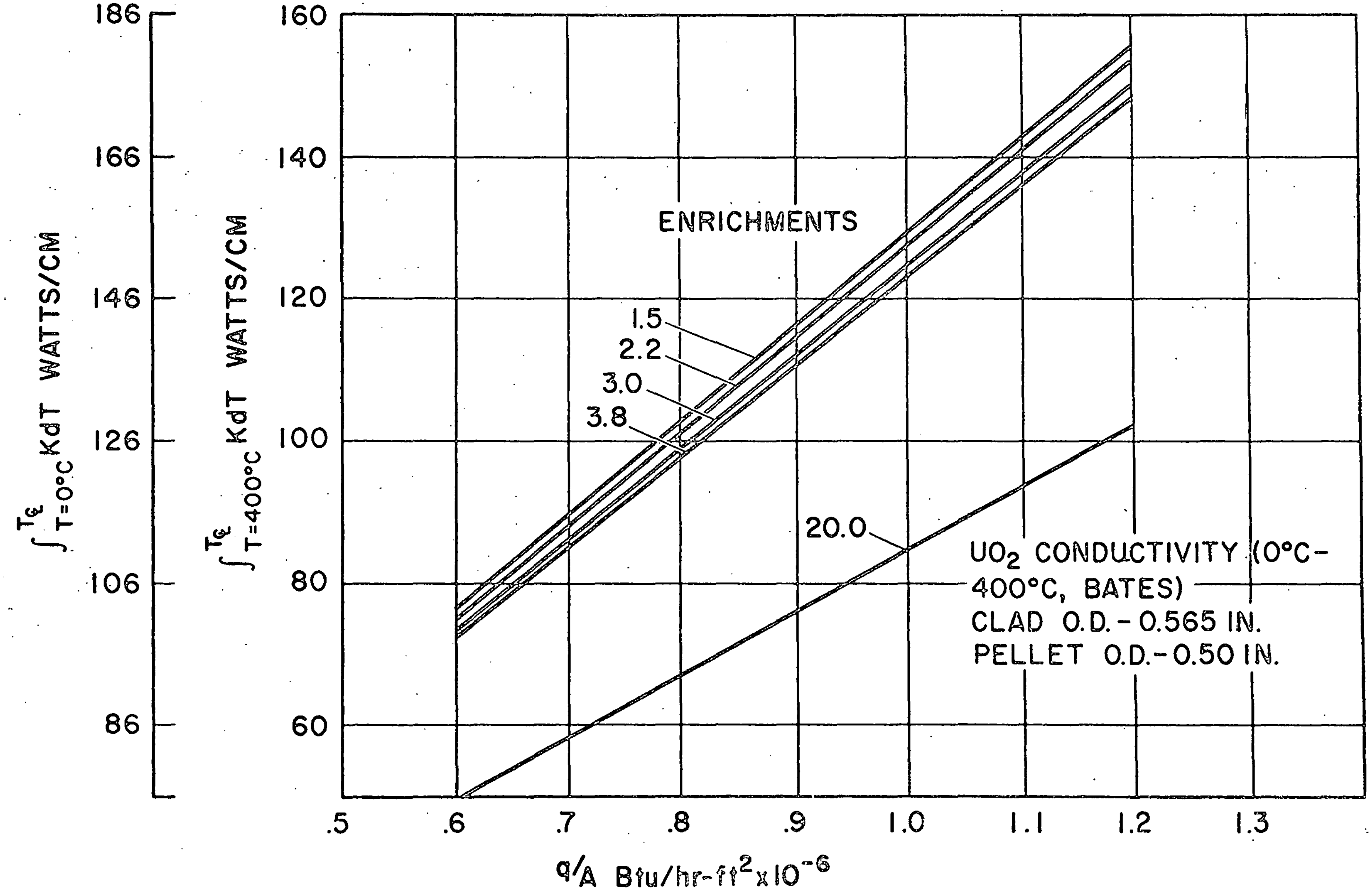


FIG. 20