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REIRRADIATION OF MIXED-OXIDE FUEL PINS AT INCREASED TEMPERATURES*

L. A. Lawrence
&
E. T. Weber

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1. INTRODUCTION

Mixed-oxide fuel pins from EBR-II irradiations were reirradiated in the General Electric Test Reactor (GETR) at higher temperatures than experienced in EBR-II to study effects of the increased operating temperatures on thermal/mechanical and chemical behavior.

The response of a mixed-oxide fuel pin to a power increase after having operated at a lower power for a significant portion of its lifetime is an area of performance evaluation where little information currently exists. Data are needed because of the following sources of power increases in an LMFBR. They include:

- Fuel Reloading Schemes
- Control Rod Movement
- Load Following
- Reactor Startup or Derated Operation

Increased power operation in fuel pins at significant burnups has been known to cause cladding rupture (1-4). Because of these possibilities and the current lack of appropriate data, the experiment I am going to describe this morning was conducted.

2. EXPERIMENT DESIGN

A series of fuel pins at different ^{235}U enrichments (heat ratings) and burnup levels were selected from EBR-II experimental subassemblies and returned to HEDL for nondestructive examination, modification, and remote encapsulation (SLIDE 1).

Capsules were irradiated in the GETR pool in a V-RAFT* to control fuel pin temperatures. Following irradiation, capsules were shipped to LASL for detailed examination.

The capsule assembly is shown schematically on the next slide (SLIDE 2). Capsules were of a standard design developed for fuel pin irradiations in GETR modified to facilitate the remote encapsulation. Capsules were equipped with thermocouples in contact with the cladding at three axial locations for monitoring and controlling irradiation conditions.

Fuel pins which were selected for reirradiation are summarized in the next slide (SLIDE 3). Fuel pins were selected from the PNL-3 and PNL-4 subassemblies at two burnup levels. The PNL-4 fuel pins operated in EBR-II at approximately twice the heat rating as did the PNL-3 fuel pins. In addition to the fuel pins selected for reirradiation, sibling pins were also obtained and examined to establish fuel pin conditions prior to irradiation in GETR.

Irradiation conditions in GETR are summarized on the next slide (SLIDE 4). All five fuel pins operated at essentially the same temperatures in GETR. Thus any differences observed following reirradiation were the result of the different irradiation conditions in EBR-II and not the result of differences in GETR irradiation conditions between the fuel pins.

Fuel pin temperatures during the reirradiation are compared to those during EBR-II irradiation in the next slide (SLIDE 5) for the high burnup, intermediate power (PNL-4) fuel pin (PNL-4-14/RCT-1A). Similar profiles were also calculated for the low burnup PNL-4 fuel pin (PNL-4-61/RCT-3). Peak fuel temperatures in GETR occurred at the top of the fuel column by design. This particular axial temperature profile was imposed on the fuel pins in order to maintain the peak cladding temperatures at the top of the fuel column similar to irradiation in EBR-II.

* Vertical-Radial Adjustable Facility Tube

Temperature profiles in the low power, low burnup fuel pin are shown in the next slide (SLIDE 6). Fuel pin temperatures in GETR are quite similar to the corresponding temperatures for the intermediate power pins (PNL-4) by design. Because of the lower heat ratings in EBR-II for the PNL-3 fuel pins the temperature increases experienced by these fuel pins in GETR were much greater.

In terms of these imposed temperature increases, I would like to briefly discuss the results of the fuel pin examinations and their implications.

3. RESULTS

3.1 CLADDING DIAMETER CHANGES DURING REIRRADIATION

Cladding diameter increases obtained from pre- and post-GETR profilometry data are shown on the next slide (SLIDE 7). In the case of the low power, moderate burnup EBR-II pins, cladding diameters exceeded the failure strain in both capsules. (RCT-4/RCT-5). The two low burnup fuel pins both showed a small decrease in diameter which corresponded somewhat to the power profile in EBR-II. For the moderate burnup, intermediate power pin (PNL-4-14) cladding diameter increases were ∿.6% permanent deformation. Cladding diameter increases in PNL-4-14 corresponded roughly to the calculated fuel center temperature increases. Fuel pin heat rating increases at the top of the pins in GETR at the peak power position are summarized in the next slide (SLIDE 8).

For power increases of up to ∿150% no deformation was observed in the low burnup fuel pins. Results indicate that any mechanical interaction which may have occurred in the low burnup pins was below the elastic limits for the cladding at those conditions. However, for power increases of ∿ 50% at a moderate burnup, permanent cladding deformation resulted and for a corresponding ∿170% increase cladding failure resulted.

3.2 FUEL STRUCTURE CHANGES DURING REIRRADIATION

Postirradiation fuel structures were also found to be strongly dependent upon the prior EBR-II burnup. In the next slide (SLIDE 9) fuel structures before and after the power increase are compared at the two burnup levels for the two intermediate power pins (PNL-4).

Fuel structure changes for the low burnup fuel are consistent with behavior of fuel pins which had not been subjected to the prior low power irradiation. Structures are what would be predicted for fresh fuel pins at the imposed GETR irradiation conditions. In the case of the high burnup fuel, structures are significantly different from those expected from "steady-state" experience for a fuel pin at the GETR power levels at a burnup of 6.5 atom %.

There was a complete absence of any indications of pore migration, i.e. columnar grain growth and center void. The inner high temperature zone is replaced by a low density (~85%T.D.) porous structure more analogus to fuels subjected to transient heating. Fuel structures are shown for the fuel pins in somewhat more detail in the next slide (SLIDE 10).

Results of the power increases on fuel pin thermal/mechanical behavior are summarized in the last slide (SLIDE 11).

- Cladding strains produced by the power change are strongly dependent upon prior heat rating and burnup.

- Fuel structure changes in response to the power increase are also strongly dependent upon prior burnup.

It is well recognized that increases in fuel power level and temperatures can cause fuel structure changes and cladding hoop stresses due to the differential thermal expansion of fuel and cladding. The implication from the measured cladding diameter increases for these four pins, which operated at quite similar conditions in GETR, is that fuel thermal expansion effects alone cannot account for the differences in magnitude of cladding deformation between the low burnup and the high burnup pins. This suggests that fuel volume expansion induced by changes in fission gas distribution could account for the observed differences in cladding deformation. Fuel structure changes following the power increases provides supporting evidence for fuel volume expansion driven by fission gas redistribution.

4. CONCLUSION

Therefore, in conclusion, these results show that the cladding diameter changes resulting from the reirradiation are strongly dependent upon both prior burnup level and the magnitude of the temperature increase.

Results provide the initial rough outlines of boundaries within which mixed-oxide fuel pins can or cannot tolerate power increases after substantial prior burnup at lower powers.

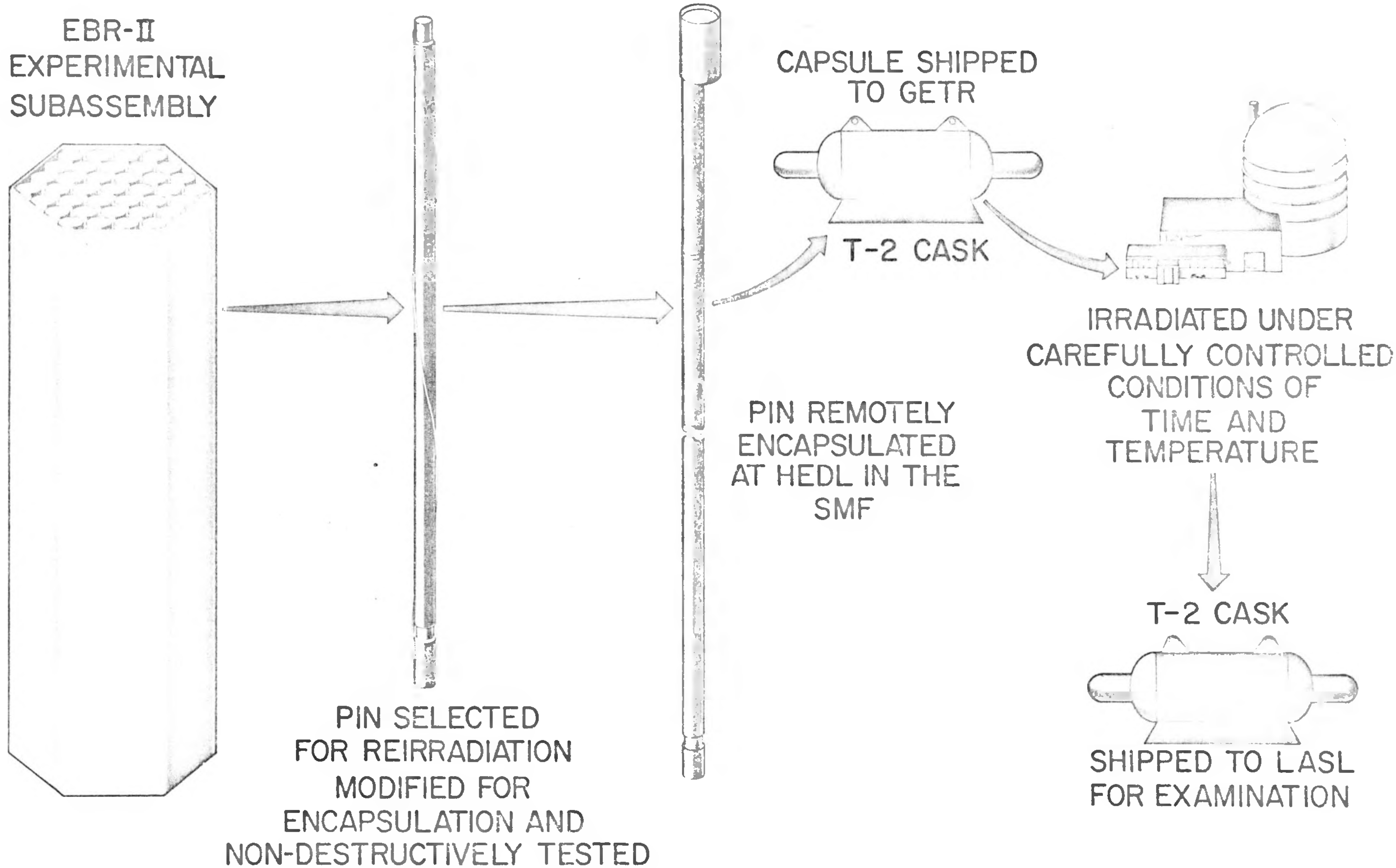
5. REFERENCES

1. S. Aas, "The Effects of Load-Following Operation on Fuel Rods", Nucl. Eng. Des. 33 (1975), 261.

2. Core Engineering, Fifty-first Quarterly Report, May-July, 1974, GEAP-10038051, August, 1974.

3. E. Rolstad, "A Mechanical Explanation of the Overpower Failures," Nucl. Tech. 25, January, 1975.

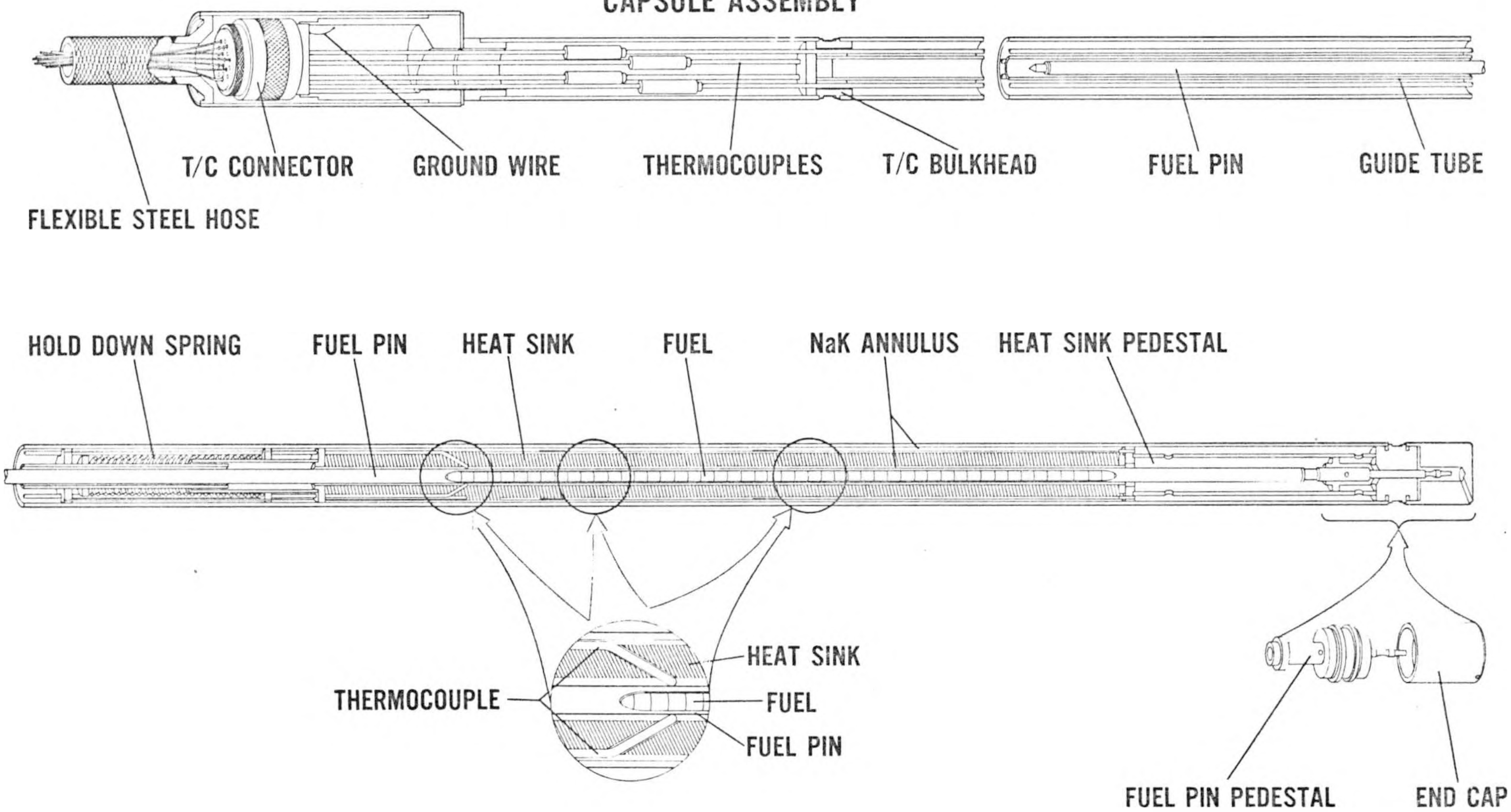
4. W. J. Penn, R. K. Lo, J. C. Wood, "CANDU Fuel-Power Ramp Performance Criteria," Trans. Am. Nucl. Soc., 22, 209, 1975.


EBR-II EXPERIMENTAL SUBASSEMBLY
PIN SELECTED FOR REIRRADIATION MODIFIED FOR ENCAPSULATION AND NON-DESTRUCTIVELY TESTED
PIN REMOTELY ENCAPSULATED AT HEDL IN THE SMF
CAPSULE SHIPPED TO GETR
T-2 CASK
IRRADIATED UNDER CAREFULLY CONTROLLED CONDITIONS OF TIME AND TEMPERATURE
T-2 CASK
SHIPPED TO LASL FOR EXAMINATION

GETR REIRRADIATION TESTS

OF MIXED OXIDE FUEL PINS IRRADIATED IN EBR-II

CAPSULE ASSEMBLY



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SLIDE 2

REIRRADIATION OF EBR-II PINS IN GETR

SUMMARY OF CAPSULES AND FUEL PINS

EBR-II HEAT RATING PRIOR TO REIRRADIATION	EBR-II BURNUP PRIOR TO REIRRADIATION		
		LOW BURNUP PNL-3 (2.1 at. %) PNL-4 (2.4 at. %)	MODERATE BURNUP PNL-3 (4.7 at. %) PNL-4 (6.4 at. %)
	LOW POWER 170 - 188 w/cm 5.2 - 5.7 kw/ft	RCT-2 (PNL-3-41) SIBLING: PNL-3-26	RCT-4 (PNL-3-14) RCT-5 (PNL-3-16) SIBLING: PNL-3-15
	INTERMEDIATE POWER 274 - 294 w/cm 8.4 - 8.9 kw/ft	PCT-3 (PNL-4-61) SIBLING: PNL-4-60	RCT-1A (PNL-4-14) SIBLING: PNL-4-12

HEDL 7604-40-25

SLIDE 3

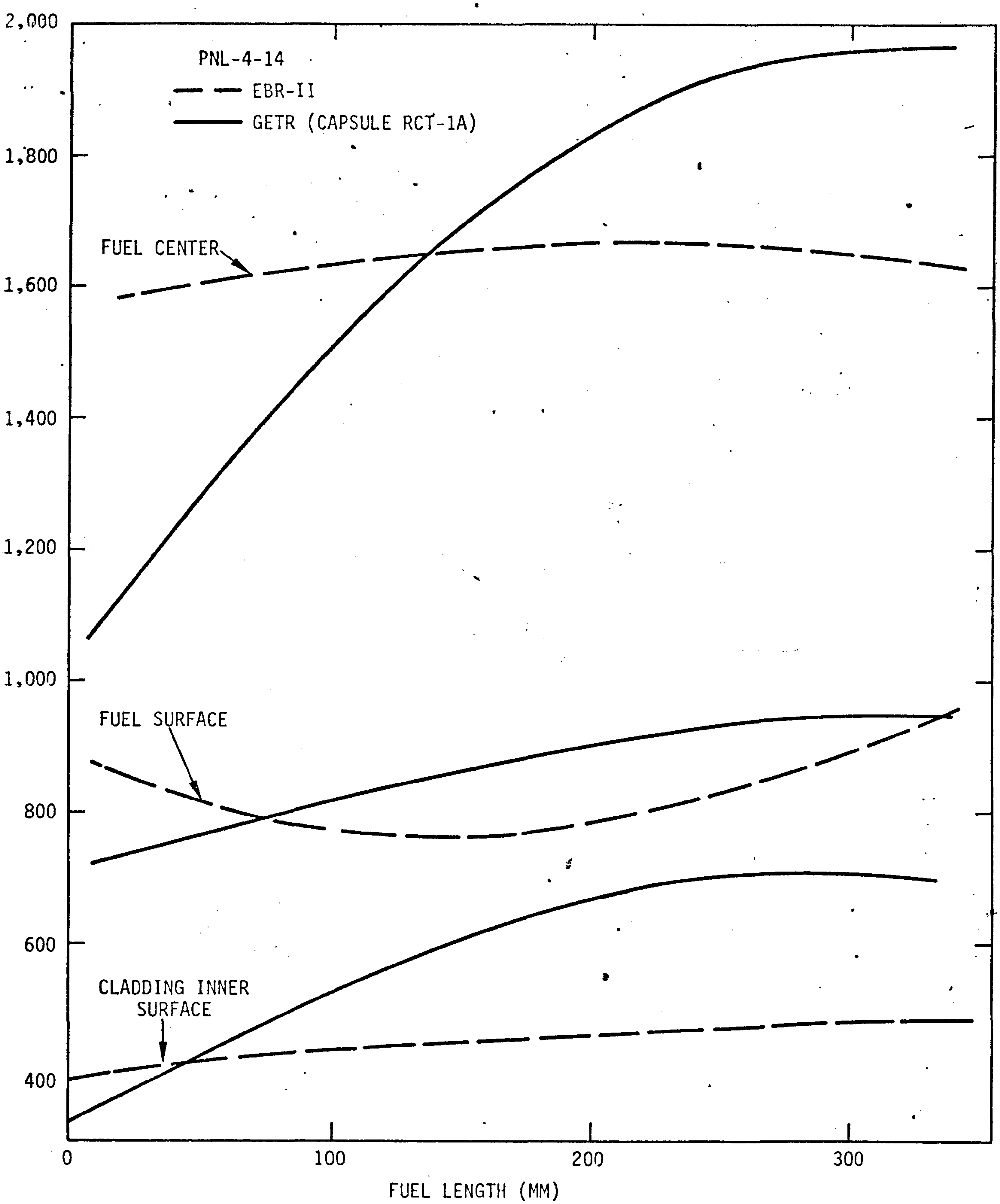
TEST CONDITIONS

TEST VEHICLE	MARK-VII-V-RAFT
INITIAL CHARGING SCHEME	0 TO 66% FULL POWER IN 4 STEPS AT 15 MIN. EACH
	66% TO 100% FULL POWER IN 9 STEPS OF 4 HOURS EACH
IRRADIATION TIME	650 HOURS AT FULL POWER (~ .6 AT% PEAK BURNUP)
PEAK HEAT RATING	365 W/CM (11.1 KW/FT)

(ΔT EQUIVALENT TO A ~ 295 W/CM (9 KW/FT) FAST FLUX)

IRRADIATION TEMPERATURES

THERMOCOUPLE CONTROL POINT	636°C
CONTROLLING RANGE	± 6°C
MAXIMUM CLADDING ID TEMPERATURE	730°C
UNCERTAINTY IN CLADDING ID TEMPERATURE (1σ)	~ ± 15°C



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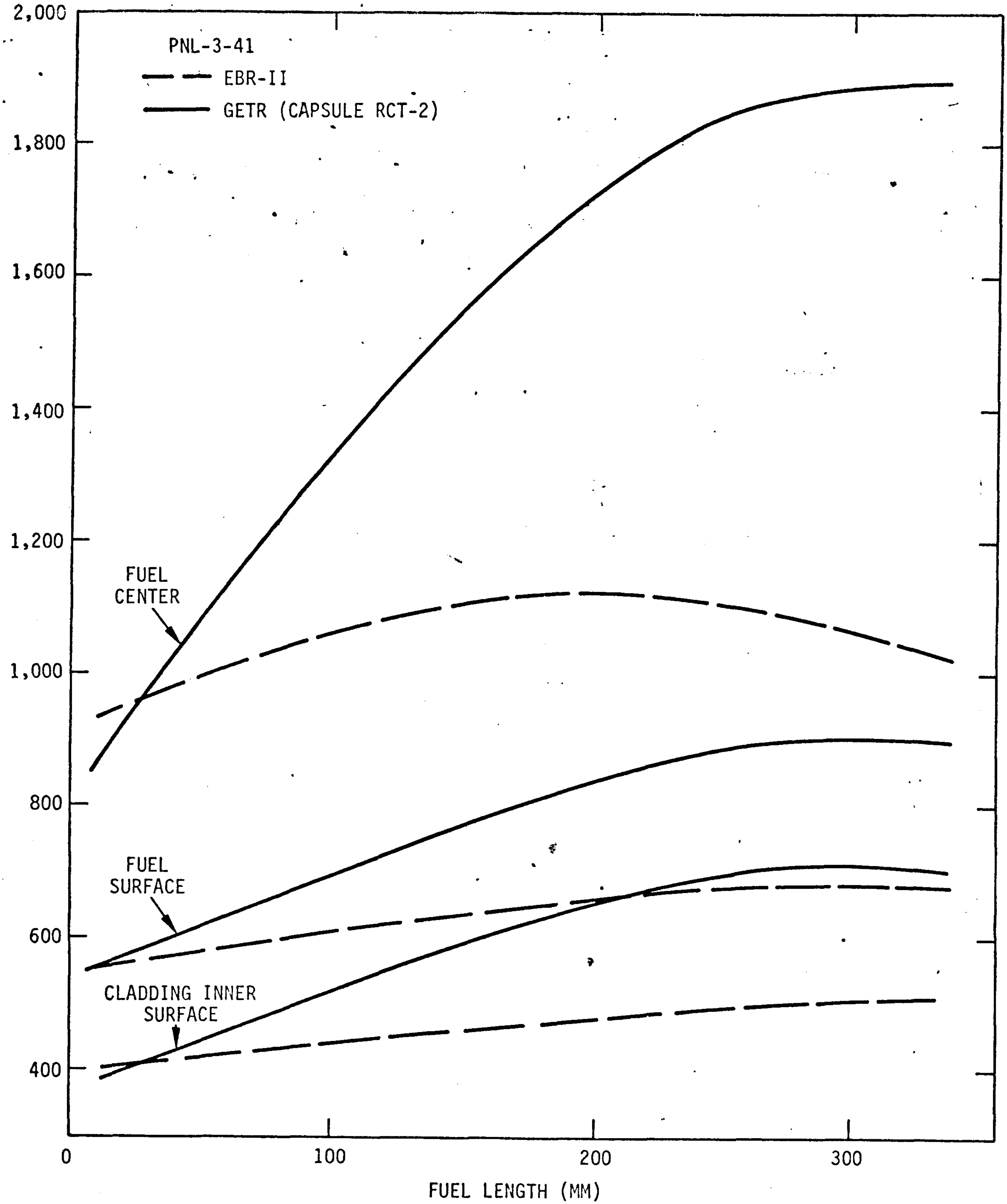
SLIDE 5



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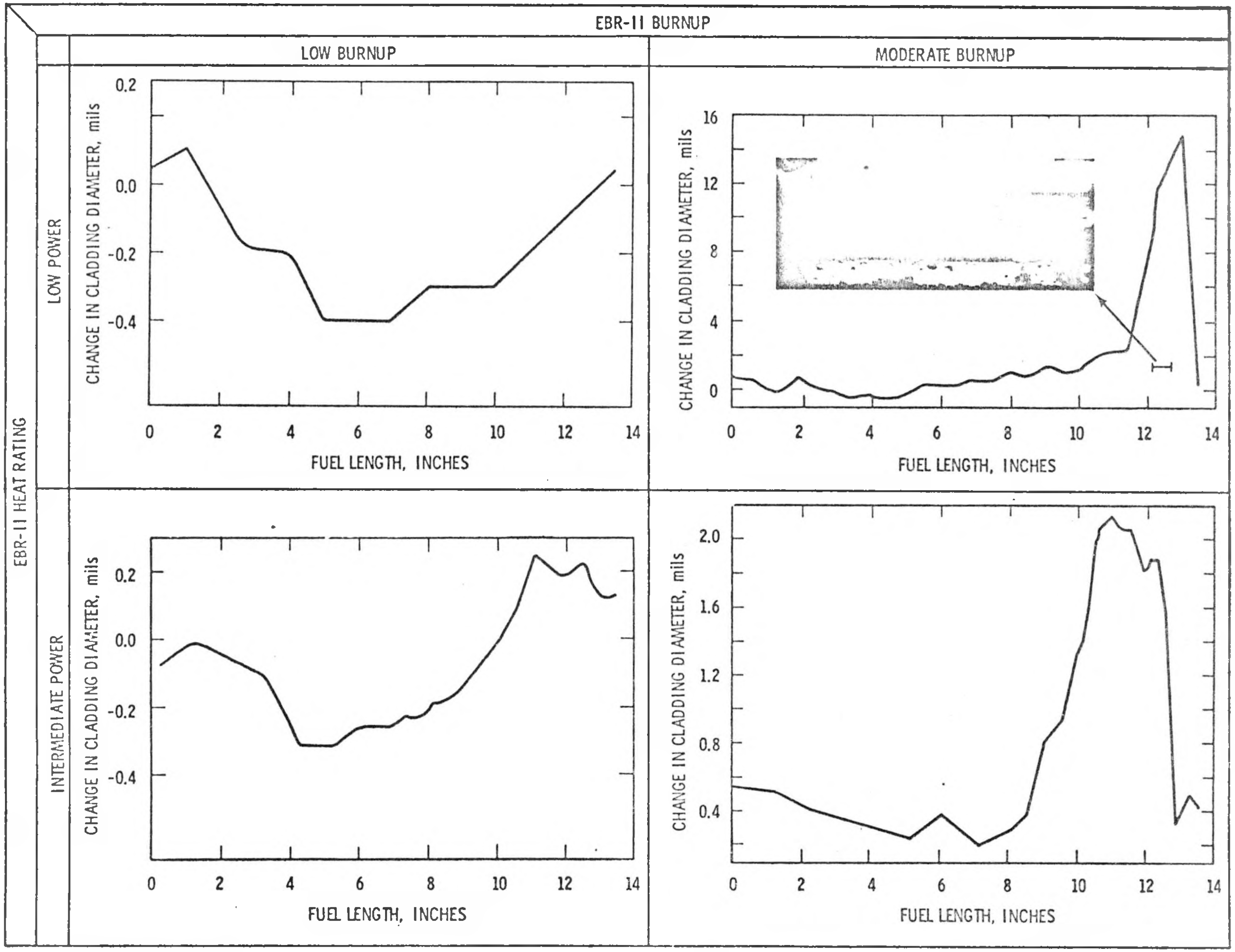
SLIDE 6

GETR HIGH TEMPERATURE REIRRADIATION TESTS

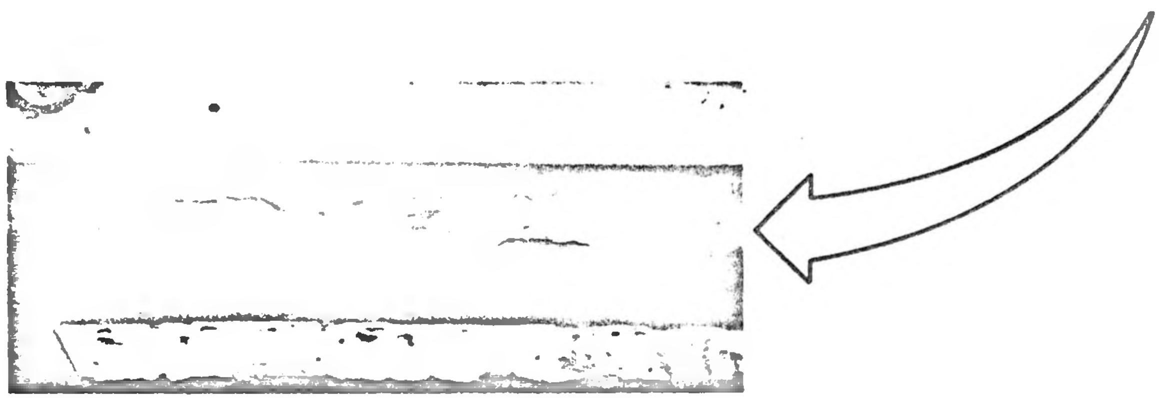
EFFECTS OF POWER INCREASE ON CLADDING DIAMETERS



GETR REIRRADIATION TESTS

HEAT RATING INCREASES IN GETR

FUEL PIN (CAPSULE)	EBR-II BURNUP, ATOM %	HEAT RATING, kw/ft			CLADDING BEHAVIOR
		EBR-II	GETR	INCREASE IN GETR	
PNL-4-61 (RCT-3)	2.5	7.2	11.1	3.9 (55%)	NO DEFORMATION
PNL-4-14 (RCT-1A)	6.4	7.6	11.1	3.5 (46%)	~0.6% PERMANENT DEFORMATION
PNL-3-41 (RCT-2)	2.2	4.6	11.1	6.6 (143%)	NO DEFORMATION
PNL-3-14 (RCT-4)	4.7	4.1	11.1	7.0 (170%)	FAILURE



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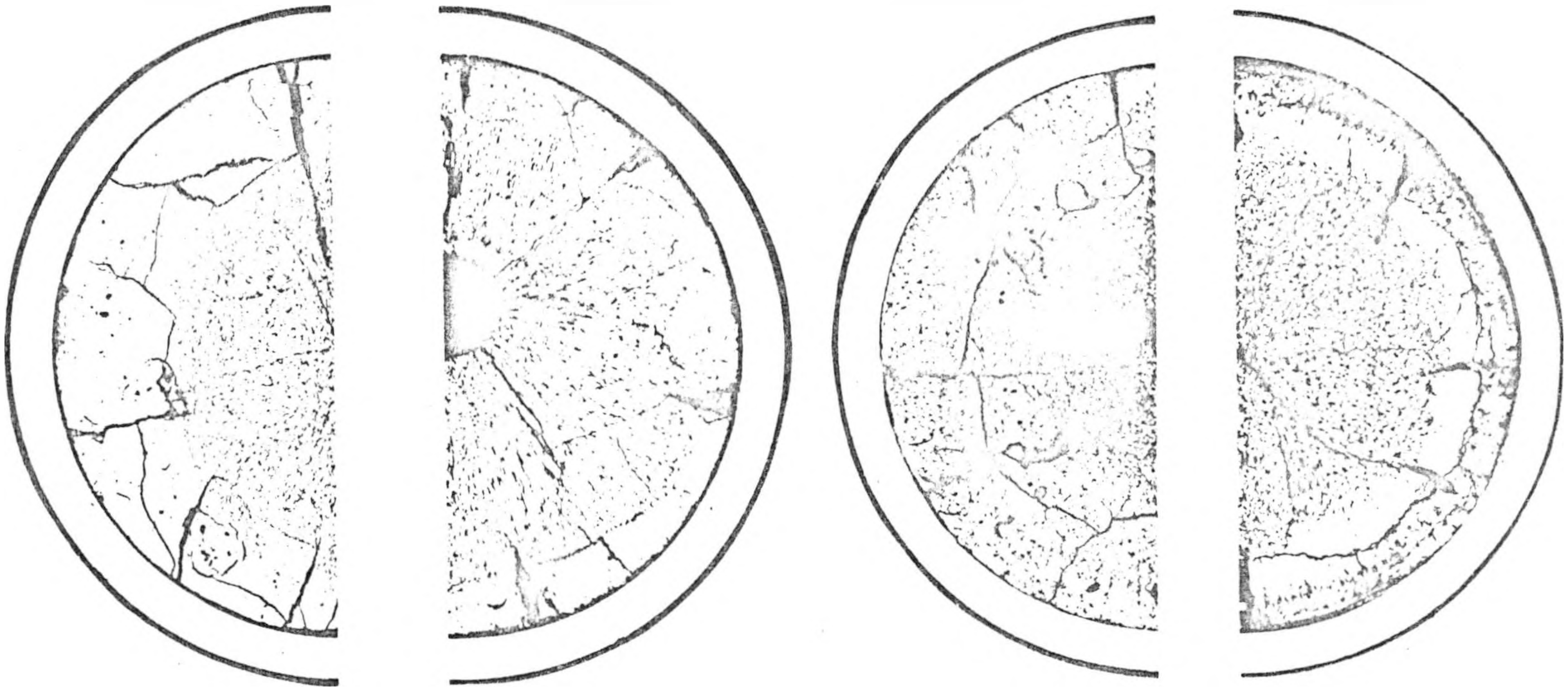
SLIDE 8

GETR HIGH TEMPERATURE REIRRADIATION TESTS

EFFECTS OF POWER INCREASE ON FUEL STRUCTURES

BEFORE POWER CHANGE | AFTER POWER CHANGE | BEFORE POWER CHANGE | AFTER POWER CHANGE



BURNUP: ~30,000 MWd/MTM BURNUP: ~65,000 MWd/MTM

FUEL CENTER TEMPERATURES BEFORE POWER CHANGE ~1600°C

FUEL CENTER TEMPERATURES AFTER POWER CHANGE ~2000°C

HEDL 7604-40-30

SLIDE 9

GETR HIGH TEMPERATURE REIRRADIATION TESTS

EFFECTS OF BURNUP ON FUEL RESTRUCTURING FOLLOWING A POWER INCREASE

LOW BURNUP (~2.5 atom %)

MODERATE BURNUP (~6.4 atom %)

SUMMARY OF RESULTS

- CLADDING STRAINS PRODUCED BY POWER CHANGES STRONGLY DEPENDENT UPON PRIOR HEAT RATING AND BURNUP:

  LOW BURNUP - NO STRAIN

  INTERMEDIATE BURNUP - CLADDING STRAIN
  - FAILURE

- FUEL STRUCTURES DURING POWER CHANGES STRONGLY DEPENDENT UPON PRIOR BURNUP:

  LOW BURNUP - TYPICAL OF START-OF-LIFE

  INTERMEDIATE BURNUP - INFLUENCED BY PRESENCE OF FISSION PRODUCTS