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DESIGN OF ABSORBER ASSEMBLIES WITH INTENTIONAL PELLET-CLADDING MECHANICAL INTERACTION

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DESIGN OF ABSORBER ASSEMBLIES WITH INTENTIONAL PELLET/CLADDING MECHANICAL INTERACTION

I. INTRODUCTION

Boron carbide is the internationally accepted absorber material for breeder reactor control elements, based on its worth, performance, and economic characteristics. One disadvantage of boron carbide, however, is that substantial quantities of helium gas are generated during irradiation. The formation of helium bubbles within the boron carbide causes swelling of the absorber pellets, which can be a major life-limiting phenomenon in absorber pin designs.

Accepted design practice has been to allow sufficient pellet-cladding gap to avoid gap closure during the intended element lifetime, based on empirical boron carbide swelling correlations. That is, circumferential pellet-cladding contact has been considered to constitute an end-of-life condition. To provide for extended element lifetimes, the pellet-cladding gap spacing has simply been increased to accommodate the anticipated absorber growth. Excessively large gaps can introduce undesirable performance characteristics in the absorber pin, such as very high operating temperatures and the potential for material relocation. Therefore, the degree to which this design approach can be applied is limited.

Improvements in absorber element performance characteristics and lifetime may be achievable by allowing mechanical interaction to occur between the absorber pellets and cladding. The risks involved with such a design criterion must be assessed prior to its acceptance. This effort included development of a computer program to facilitate evaluation of in-reactor Absorber Cladding Mechanical Interaction (ACMI). Predicted performance calculations for advanced absorber assembly designs employing ACMI are presented.

Before discussing intentional absorber cladding mechanical interaction, (ACMI), it is necessary to define this term. Mechanical interaction, as used here, is the intentional and uniform radial deformation of the cladding by the swelling of absorber material. Mechanical interaction is contrasted with localized deformation of the cladding which might result from pellet fracture and material relocation. The localized deformation process can produce failures at lower overall swelling values because of the concentration of strain. In absorber pins, mechanical interaction is expected to be a relatively slow event since transient reactor operations should not substantially enhance the swelling of the pellet into the cladding.

II. POTENTIAL IMPROVEMENTS FROM ACMI

Mechanical interaction offers several potential benefits in comparison to the conventional pellet-cladding contact approach. If ACMI can be justified, then designers will no longer be restricted to matching pellet-cladding gaps to predicted swelling values. Once it is established that the acceptance of ACMI and cladding deformation can lead to improved performance, it then becomes a matter of defining acceptable deformation limits.

A. Temperature

In the interest of reduced fabrication costs and enhanced absorber loading, the trend in absorber assembly design has been toward larger pin concepts. With the criterion of no pellet-cladding contact, however, these designs necessitate the incorporation of large pellet-cladding gaps to achieve desired swelling-limited lifetimes. The helium-filled gap around the absorber pellet acts as a heat transfer barrier, and serves to elevate boron carbide temperatures. Another design option gaining favor is the utilization of ^{10}B enriched boron carbide to increase reactivity worth. Heating rates in enriched boron carbide are greater, and the combination of high heating rates and large gaps may cause boron carbide operating temperatures to approach the melting point. Thus, some high enrichment absorber assembly designs may be excluded based on thermal considerations under conventional design criteria. If ACMI were permitted, however, initial pellet-cladding gaps could be made smaller, so that temperatures would be lower and high enrichment levels made tolerable from a thermal performance standpoint. Thus, application of ACMI is conducive to large diameter, high enrichment absorber pin designs.

B. Material Relocation

It is anticipated that large diameter pellets will be susceptible to fracture during irradiation; particularly, if enriched boron carbide pellets with their attendant large thermal gradients are employed. Swelling gradients within boron carbide pellets can also contribute to their fracture at higher burnup levels.(1) Fracture in this context refers to the separation of the pellets into small irregular pieces. The opportunity for material relocation following fracture is provided with large pellet-cladding gaps. If fracturing and relocation take place early in the life of an absorber pin, then the subsequent swelling can induce excessive localized strain in the cladding.

The type of crack pattern and size and shape of fractured pieces is important in determining the potential for material relocation. In Figure 1, two potential modes of relocation are depicted; internal, which has been observed in carbide fuel elements, and circumferential, which appears to be more detrimental. The internal relocation noted in carbide fuel pins has been cited as the cause of cladding failure. With circumferential relocation, it is easily seen how subsequent pellet swelling can result in localized cladding strains that are much greater than the average cladding distortion, and failure may well be expected in these high strain areas.

In addition to macroscopic cracking of the boron carbide pellets, microscopic cracking can take place between and in the crystallites.(2) Should the irradiated boron carbide be friable, then there is the possibility of small particles settling to the bottom of the pellet column where they could fill the pellet-cladding gap at the bottom. Pellet swelling is greatest at this location, and continued swelling after closure of the gap by powder buildup could deform the cladding past the design limits.

Problems associated with material relocation can effectively be eliminated by implementation of ACMI. By intentionally allowing mechanical interaction,

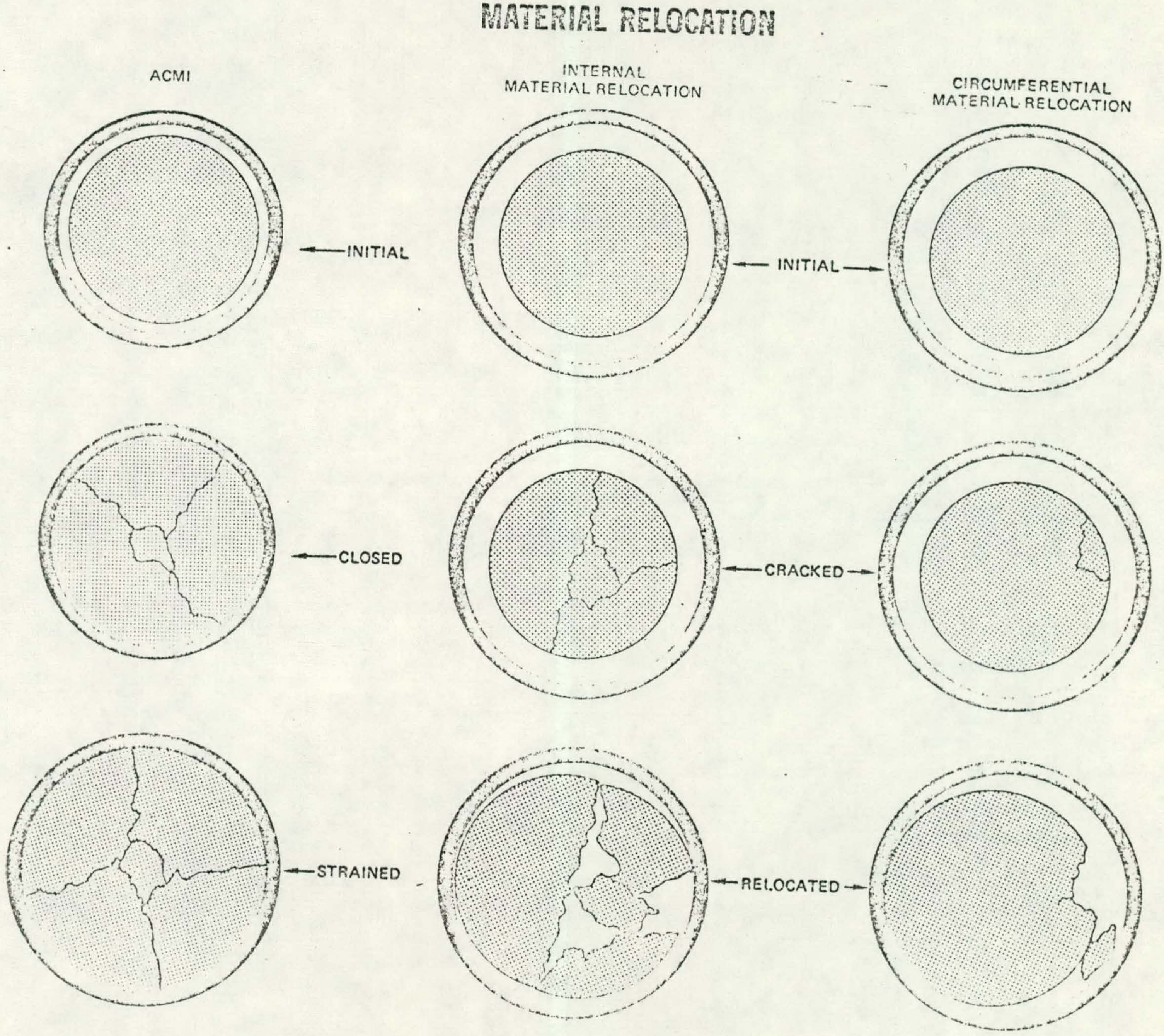

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FIGURE 1. A Schematic Representation of ACMI and Material Relocation that Would Cause Localized Deformation of the Cladding.

the gap between the pellet and cladding can be diminished such that the potential for material relocation will be decreased. As shown in Figure 1, a small gap provides little opportunity for material rearrangement. As the pellet fractures and swells, the growth is transmitted uniformly to the surrounding cladding. In the extreme case of zero initial pellet-cladding gap, the possibility of material relocation and rearrangement is essentially eliminated.

C. Longer Lifetimes

A major lifetime limiter in advanced absorber assembly designs is swelling of the boron carbide. The present design practice employed in ACMI analyses assumes that this swelling is unaffected by stress. If the swelling of boron carbide were to be reduced by application of a compressive stress, then designs based upon mechanical interaction would achieve greater swelling limited lifetimes than their unrestrained counterparts.

There are several indications that boron carbide swelling could be suppressed by existing compressive stresses, although definitive experimental verification has not been made. In Figure 2, metallographic cross sections of irradiated boron carbide show that internal cracks are formed at high burnup levels. The formation of these cracks produces additional internal volume, i.e., the crack opening displacement. Closure of these cracks by a compressive stress applied by the cladding could apparently provide additional compressibility.

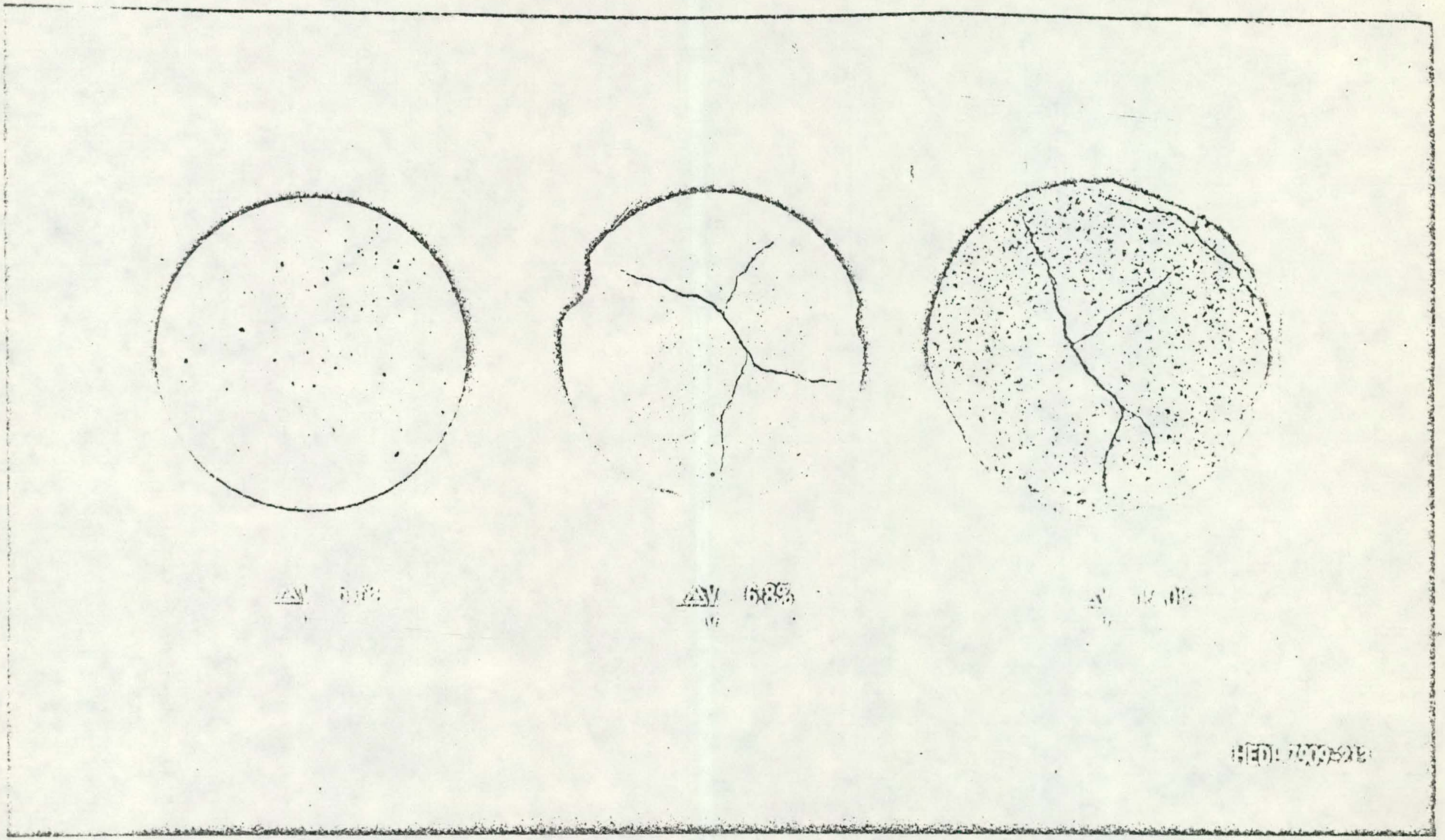

FIGURE 2. The Effect of Swelling on the Formation of Internal Macrocracks in Irradiated Boron Carbide. Neg. 7910610-1

The other source of reducing the cladding stress is the possible reduction of absorber pellet modulus. Irradiated boron carbide was found to be microcracked after irradiation to high burnup levels.(2) Microcracking in ceramics has been noted to dramatically reduce the modulus of polycrystalline materials.(3,4) Although no data are available to indicate the effect of irradiation on the modulus of boron carbide, some reduction might well be expected as microcracking becomes extensive.

A previous evaluation was performed to determine the influence of boron carbide modulus on deformation of the cladding.(5) That analysis considered an advanced absorber pin design with relatively thin cladding (0.025 in./ 0.064 cm). It was found that a substantial reduction in the modulus was required to significantly impact cladding deformation. While the nominal modulus of unirradiated boron carbide is > 300 GPa, a reduction to a value of 34 GPa resulted in only a 0.4% decrease in cladding strain. Thicker walled cladding designs would be more effective in restraining the boron carbide; however, it appears that large decreases in the modulus are required to notably affect ACMI predictions.

III. DESIGN OPTIONS

In the design of control or safety rods many features are considered, but the three major criteria are initial cost, reactivity worth, and lifetime. Changes which enhance one of these normally tend to adversely affect the others such that compromises are made to achieve the overall optimum design. Other performance parameters, such as pellet temperatures, are not really optimized, but must be within certain limits. Absorber cladding mechanical interaction, of and by itself, offers only small improvements in performance. The real value of ACMI is that it allows design changes to be made which yield significant gains in certain performance parameters, but does not require tradeoffs to be made with other performance parameters. In Table 1, a set of design changes, which are permitted by allowing mechanical interaction, are rated with respect to performance parameters.

The various design options listed in Table 1 were evaluated with respect to application to the FFTF advanced absorber assembly design, shown schematically in Figure 3. This design comprises 19 vented absorber pins arranged in a circular pattern inside of round duct tubes. The absorber pin cladding thickness is 0.025 in. (0.064 cm), and the boron carbide pellet diameter is 0.689 in. (1.750 cm). This design has the designation ADVAB-1.

TABLE I

POTENTIAL DESIGN IMPACT RESULTING FROM MECHANICAL INTERACTION

DESIGN CHANGES → DESIGN IMPACT ↓	NO CHANGE	REDUCE CLADDING O.D.	INCREASE PELLET DIA.	INCREASE ^{10}B REDUCE CLADDING O.D./PELLET DIA.
LONGER LIFE	☒	☒		☒
LOWER PELLET TEMP.		☒	☒	☒
HIGHER WORTH			☒	☒
LESS MATERIAL RELOCATION		☒	☒	☒

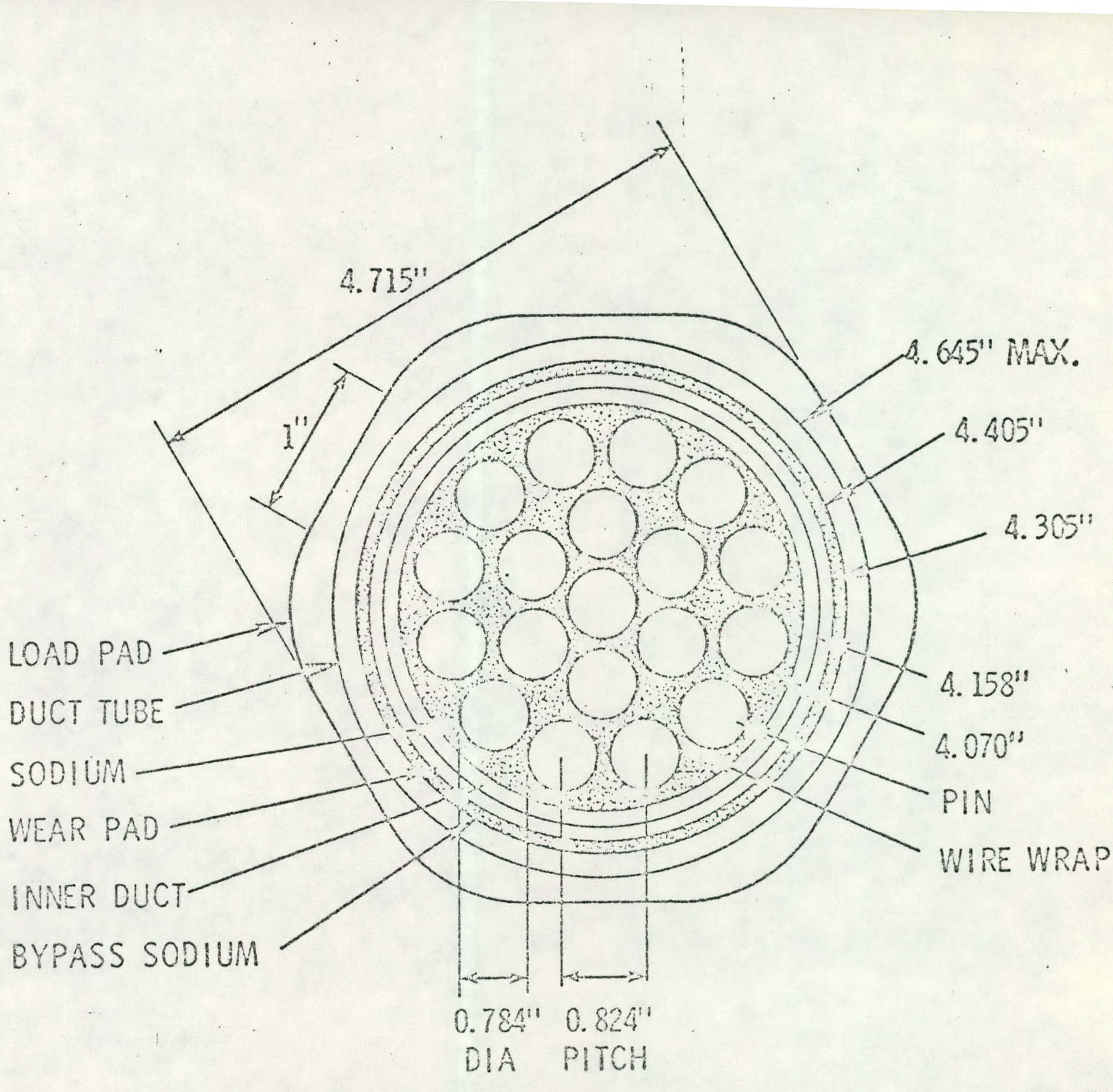

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FIGURE 3. Advanced Absorber Assembly Design Details.

With only a change in design criteria and no change in design, advantages of ACMI are very limited. Slightly longer lifetimes can be obtained by simply allowing the absorber assembly to remain in the reactor after the pellet-cladding gap has closed. However, soon after pellet contact occurs, the subsequent cladding expansion will result in pin bundle-duct interaction. In the ADVAB-1 design, the pin bundle-to-duct clearance is approximately 0.5%, and the lifetime would be extended from the present swelling-limited value of 920 full power days (FPD) to 1050 FPD before pin bundle-duct interaction occurred. Thus only one additional 100 FPD cycle of lifetime would be gained.

The second option considered is reducing the cladding outside diameter while maintaining all other dimensions the same, including cladding thickness and pellet diameter. The reduced pin diameter with this design modification extends pin bundle-duct interaction lifetime. The reduced pellet-cladding gap that results from this design change also lowers pellet operating temperatures, and lessens the potential for material relocation.

If the pellet diameter were increased, while retaining the same cladding geometry, a reduction in pellet temperature, higher reactivity worth, and less potential for material relocation would occur. However, without the benefit of a compressible absorber material this modification would result in a lower lifetime since the pin bundle-duct gap tolerance would close sooner. Hence, increasing the pellet diameter, even with mechanical interaction, continues to be a matter of trading off reactivity and lifetime.

Significant improvements in worth and lifetime could be achieved by reducing the pellet diameter and compensating for the loss in absorber volume by increasing the ^{10}B enrichment of the pellets. With conventional design techniques, the larger gaps associated with the smaller pellets would result in unacceptably high temperatures. With the adoption of the mechanical interaction design criteria, the gap could be reduced and lower temperatures could be achieved. With the smaller pellets, longer lifetimes can be achieved without pin bundle-duct contact occuring. Utilization of enriched boron carbide would increase the reactivity worth of the absorber assembly. Hence, the concept of a smaller diameter pellet with higher ^{10}B enrichment and mechanical interaction could potentially result in a design with longer life, reasonable pellet temperatures, and higher worth.

IV. CONROD CODE MODIFICATION

An important design tool in evaluating the performance of absorber elements is the CONROD computer code.(6) This code takes into account the varying nuclear environment as the control rod is withdrawn from the core during a normal reactor cycle, and calculates critical absorber element performance parameters. The computational logic for the code is illustrated by the flowchart in Figure 4. Once the control rod position and associated nuclear environment are determined, the code performs calculations for burnup, temperature, gas release, and swelling for the entire pellet column. Cumulative gas release is determined, and gas

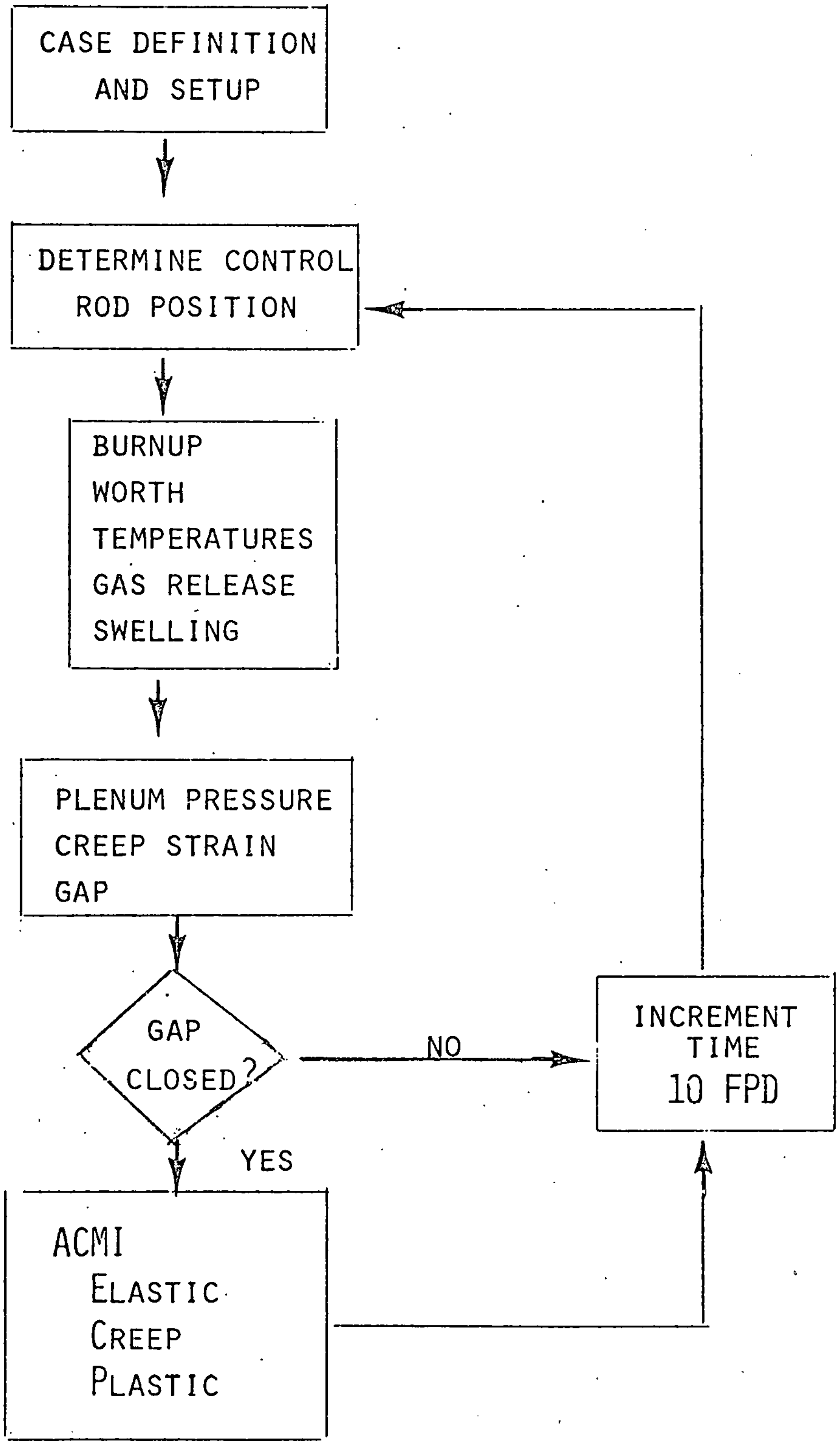

FIGURE 4. CONROD Computational Logic

pressure-induced cladding strain is calculated. The remaining pellet-cladding gap is also computed at each time step. If the gap has not closed at any point along the pellet column, time is incremented by 10 FPD and the calculation sequence is repeated. If gap closure has occurred after any time increment, then computation is redirected to a subprogram for calculating ACMI.

As the pellet swells into the cladding, there are several displacement contributors which accommodate the mechanical, radial mismatch. Initially, elastic strains are built up in both the pellet (compressive) and cladding (tensile), which sum up to the total radial mismatch caused by the pellet swelling. As time progresses, the stresses imposed on the cladding result in an irreversible creep strain. If the stress level rises above the yield strength, plastic strains contribute to the displacement. These strains yield permanent radial displacements to the inside diameter of the cladding. This reduces the radial mismatch and the elastic strains and stresses diminish.

The elastic strains and stresses are computed incrementally. During each time increment, plastic strain and creep strain predictions are based upon the stress during that time increment. In the next time increment, the computation of cladding stress acknowledges the permanent deformation that occurred during previous time steps. An equilibrium is established between the swelling rate of the B_4C and the creep strain rate in the cladding. The creep strain rate basically dictates the level of stress in the cladding.

V. PERFORMANCE PREDICTIONS WITH ACMI

The normal operating mode for control rods is steady withdrawal from approximately half-in to nearly full-out positions during the course of each reactor cycle. As a consequence, the bottom pellet in the absorber column receives the greatest exposure and exhibits the highest swelling. ACMI calculations in the CONROD code apply, therefore, to the bottom pellet location.

Analyses were performed for the ADVAB-1 design employing a modified cladding material. This alloy is mechanically similar to AISI Type 316 stainless steel, which is the reference FFTF cladding material, but displays very low swelling under irradiation. The pellet-cladding diametral gap for an ADVAB-1 pin that avoids mechanical interaction throughout its lifetime is 0.045 in./0.114 cm (6.5%). In Figure 5, predicted cladding stress history is presented for two alternate gap sizes: 0.005 in./0.013 cm (0.7%) and 0.030 in./0.076 cm (4.4%).

With the smaller gap option, pellet-cladding contact occurs during the first cycle and cladding stresses begin to increase. The stress rises immediately to over 50,000 psi (345 MPa) at the beginning of the next cycle. It then declines to less than 35,000 psi (241 MPa) by the end of that cycle. During each full reactor cycle (100 FPD), the control rods are withdrawn from the initial, half-in position to the final, full-out position; consequently, the neutron capture rate and boron carbide swelling rate at the bottom pellet decline during that period. The reduction in cladding stress during each cycle reflects this reduction in the cladding strain rate. When the control rods are reinserted at the beginning of a cycle, the increased boron carbide swelling rate causes cladding stress to rise rapidly.

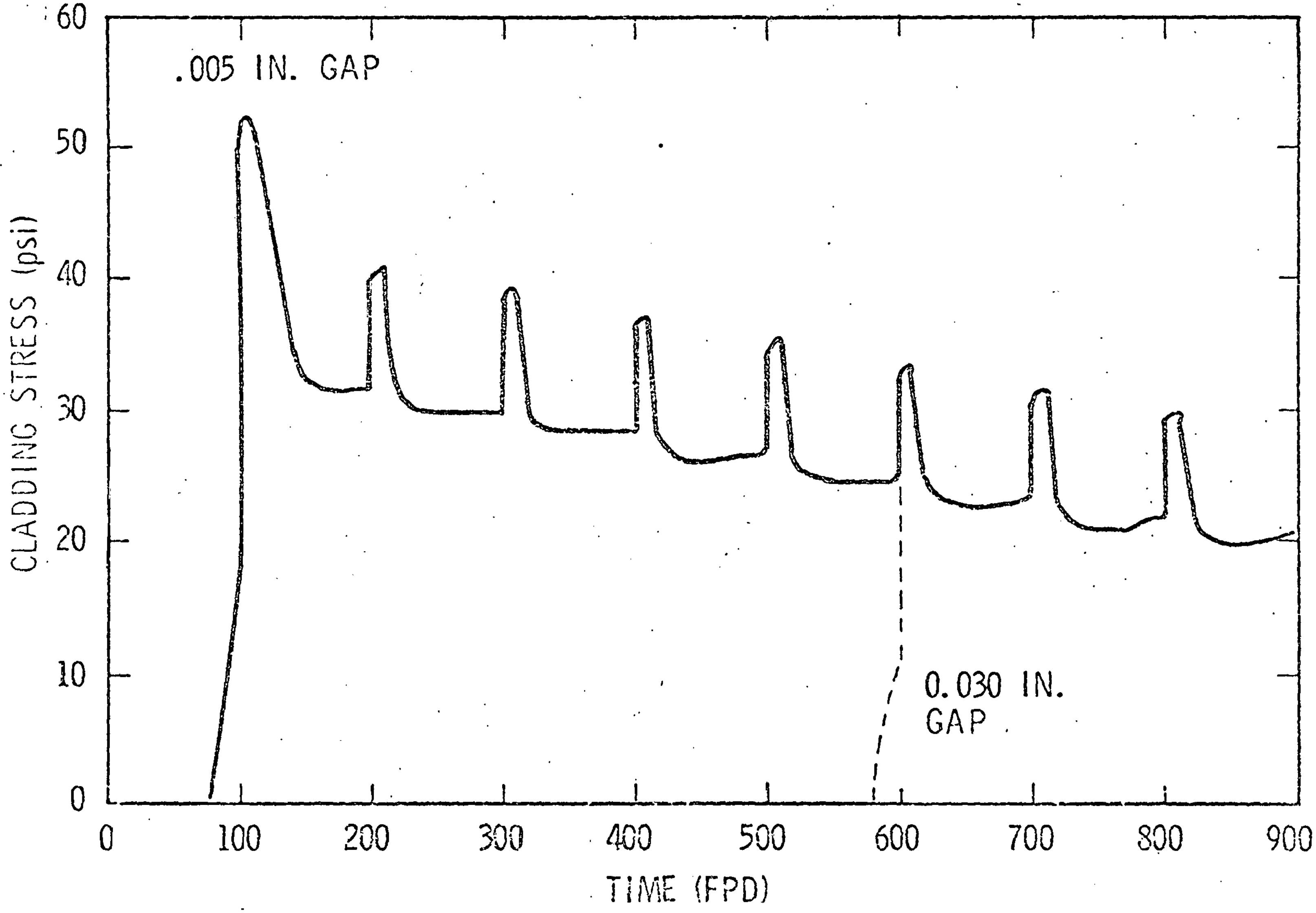

FIGURE 5. CONRCD Predictions of the Stresses Resulting from Mechanical Interaction. Two Pellet-Cladding Gaps (0.005 in/0.72% and 0.030 in/4.4%) are Compared. Neg. 7910109-1

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During the 100 to 900 FPD period in Figure 5, there is an overall reduction in the cladding stress. This overall reduction in stress results from depletion of the ^{10}B atoms in the boron carbide; consequently, lower neutron capture and swelling rates are obtained in the later cycles.

By increasing the starting gap to 0.030 in./0.076 cm (4.4%), the predicted occurrence of pellet-cladding contact is delayed until almost 600 FPD. After contact, the stresses are similar to those produced by smaller gap designs since the predicted boron carbide swelling rate and alloy creep coefficients are independent of stress history.

During a shutdown of the FFTF reactor, the system cools to approximately 400°F (204°C), which causes the cladding and pellets to contract. Because the cladding alloy has a greater thermal expansion coefficient than boron carbide, the cladding contracts more than the pellets in ADVAB-1. The cladding stress increases because of this additional strain. Plastic strain in the modified CONROD code is computed only if the yield stress is exceeded. For the modified alloy in Figure 5, the cladding stress at the 100 FPD cooldown is 121,000 psi (834 MPa). The amount of plastic strain incurred is only 0.008%; thus a slight amount of yielding took place during the initial cooldown to 400°F (204°C). Subsequent cooldown events produced lower stresses, i.e., less than 90,000 psi (621 MPa), and no further plastic yielding occurred.

In the ADVAB-1 design, the mechanical mismatch between the pellet and cladding is accommodated primarily by elastic and creep strains. Elastic strains are set by the level of stress in the cladding and generally accounted for less than 0.27% strain. For the case with a 0.005 in./0.013 cm (0.72%) gap, the creep strain is so large in comparison to this, that the creep strain can be considered equivalent to the swelling induced mismatch.

In Figure 6, the creep strains caused by mechanical interaction for the modified alloy are displayed for several gap sizes. The smaller the gap size, the earlier pellet-cladding contact will occur. The lower swelling rates (and hence creep strain rates) at higher exposures can be seen in these curves. Also the temperature and burnup variations within each cycle are shown in Figure 6 as slight changes in slope at the beginning of each 100 FPD cycle.

It is seen that sizable cladding strains may be attained through the implementation of ACMI. The obvious question that arises is to determine what practical levels of cladding strain may be permissible from the standpoint of ACMI. The strains associated with mechanical interaction can potentially lead to cladding breach. For the sake of perspective, it is worthwhile to review the consequences of a breached absorber pin. In both out-of-reactor loop tests and in-reactor irradiation tests (EBR-II) it was found(7) that only a minimal amount of boron carbide erosion occurred, and that was restricted to a region near machined-in cladding flaws. Consequently, the risk does not appear to be severe even in the case of an actual breach occurring. In any case, designs will be based on a no-breach criterion.

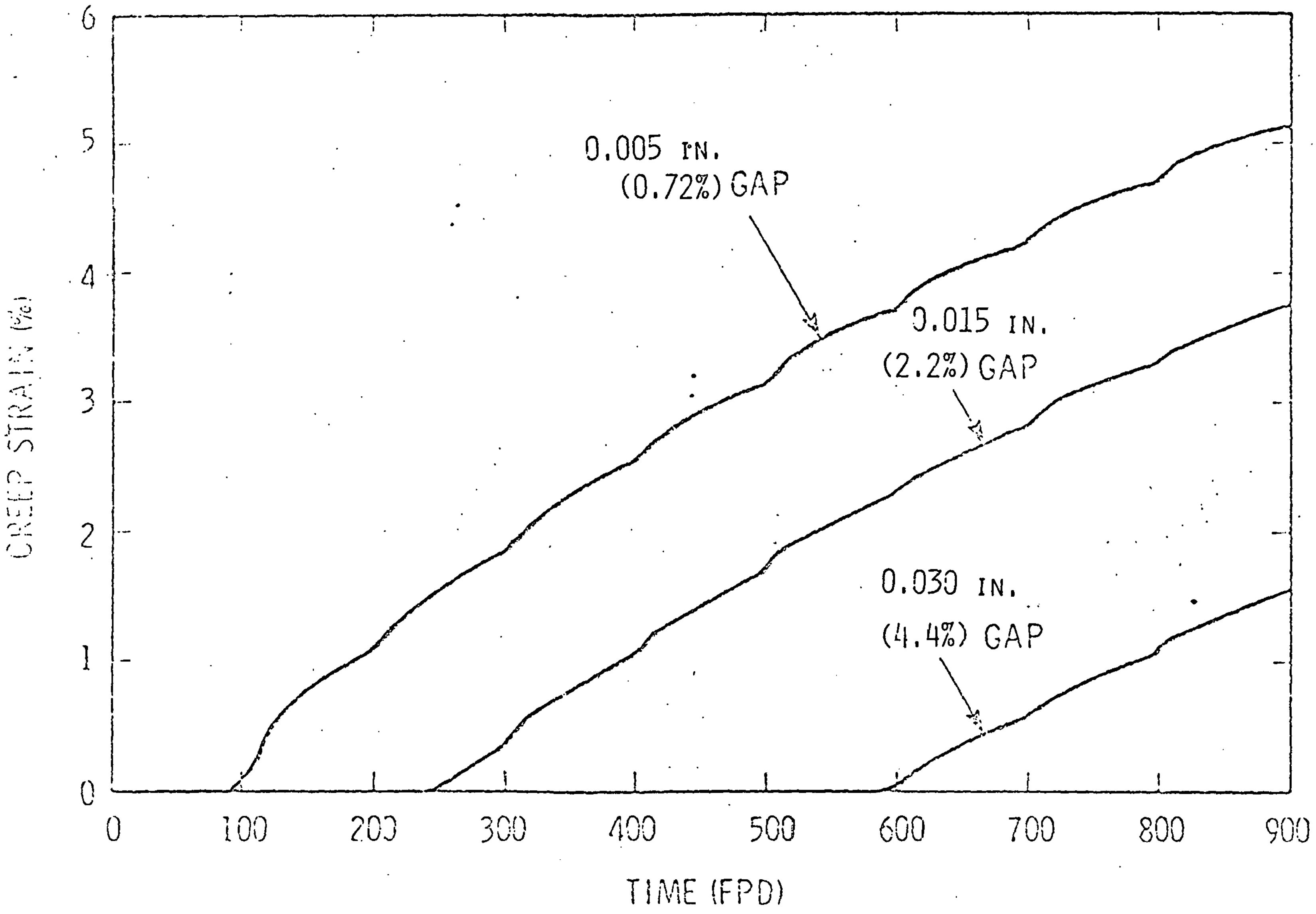

FIGURE 6. CONROD Predictions of the Stresses Resulting from Mechanical Interaction in ADVAE-1. Three Pellet-Cladding Gaps (0.005 in/0.72%, 0.015 in/2.2% and 0.030 in/4.4%) are Compared. Neg. 7912404-1

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VI. STRAIN LIMITS

The question of the swelling limited lifetime in a particular design which accepts mechanical interaction is practically reduced to the establishment of a strain limit for the cladding. Other factors, such as pin bundle duct interaction, can be attacked by specific design modification. The most logical approach to establishing a limit for cladding strain is to allow experimental absorber pins to continue under irradiation after pellet-clad contact has occurred. ACMI for absorber pins in both the U.S. and abroad has been reported. Experimental results determined by postirradiation characterization of absorber and carbide fuel pins give an indication of the extent of deformation possible, and also the expected consequences of rupture. Table III presents a review of irradiation experience of cladding interaction.

An irradiation experiment was conducted in EBR-II employing B_4C powder in 304 stainless steel tubes.(8) The powder mixture was composed of particle sizes from -325 to 10 mesh (U. S. Series) and vibration compacted to a density of 80% T.D. within the tubes. After the boron carbide achieved a burnup of $\sim 7 \times 10^{20}$ captures/cm^3, the cladding diameter was enlarged by 0.5%. The cladding operating temperature of approximately 675°C is higher than that typically found in absorber elements. Gas pressure measurements confirmed that no ruptures had taken place during irradiation.

Hot-pressed B_4C pellets were irradiated in EBR-II and allowed to swell into 316 SS cladding.(5) Several different test configurations were used such that different B_4C swelling values and cladding operating temperatures

TABLE III

CLADDING INTERACTION EXPERIENCE

EXPERIMENT	MATERIAL/ CLADDING	CLADDING TEMP (°C)	RUPTURE	STRAIN (%)	
				AVG	PEAK
EBR-II/HEDL	B_4C/304	650-750	NO	0.5	—
EBR-II/HEDL	B_4C/316	750	NO	0.97	1.8
EBR-II/HEDL	B_4C/316	650	NO	0.54	1.8
EBR-II/HEDL	B_4C/316	650	NO	0.46	1.6
EBR-II/HEDL	B_4C/316	425	NO	0.82	1.3
EBR-II/HEDL	B_4C	425	NO	0.50	0.67
BOR60/USSR	OX16H15M3B	520	NO	0 TO 2%	—
			YES	2% TO 4%	—

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were obtained. Profilometry measurements revealed that the cladding strains varied substantially with axial position. As shown in Figure 7, peaks in cladding diameter coincided with the ends of the absorber pellets. This "bambooing" or "hour-glassing" of the pellets was also observed in fuel, where it was attributed to the difference between plane strain and plane stress conditions at the center and edge of the pellets, respectively.(9) Density gradients were considered a potential contributor, since the higher density regions at the top and bottom of the pellets would be expected to swell more.(5) Cladding temperatures in this experiment ranged from 425°C to 750°C; the latter being far above typical absorber pin cladding temperatures. In the five irradiated pins, cladding strains were observed to average from 0.46% to 0.97%. Peak cladding strains were as high as 1.8%. Gas pressure measurements verified that none of the pins were breached.

The only report of failures due to mechanical interaction between boron carbide and cladding was made in 1973 by the Russians.(10) Control and safety rods from the BOR-60 reactor with expected cladding temperatures of 520°C were examined after 20 to 36 x 10^{20} captures/cm^3. Peripheral absorber pins with 2 to 4% cladding deformation were observed to have longitudinal cracks caused by pellet swelling and mechanical interaction. The cladding was composed of an alloy similar to 316 stainless steel in composition, except for molybdenum content. Absorber pins with less than 2% cladding deformation did not rupture. Some of the absorber elements with more than 2% deformation did, but no significant loss of absorber material was noted.

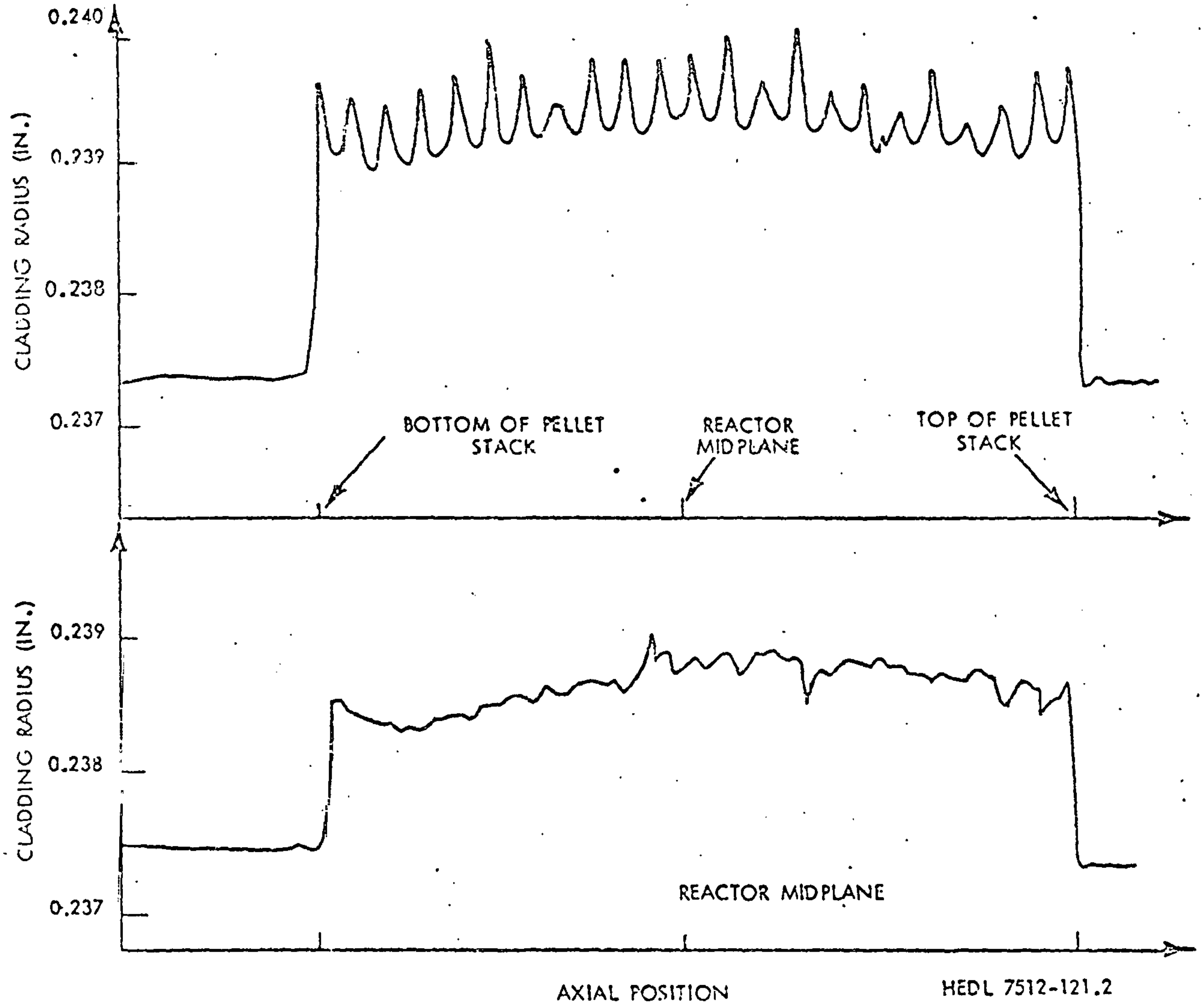

FIGURE 7. Profilometry of the Diameter of Two Pins that Were Irradiated in EBR-II. Experimental Cladding Deformation was Caused by Mechanical Interaction Between the Boron Carbide Pellets and the Cladding.

Additional data on in-reactor strain of 20% CW AISI 316 stainless steel was obtained in an EBR-II fuel experiment.(11) In this test, prototypic FFTF mixed oxide (UO_2-PuO_2) fuel pins were irradiated to fluences up to 11×10^{22} n/cm^2 ($E > 0.1$ MeV) at cladding temperatures near 490°C. These pins sustained nearly 4% diametral strain without cladding breach.

Thus it appears possible to achieve significant strains from mechanical interaction and still maintain the integrity of the cladding. Alternate cladding materials may tolerate even greater strains without failure than observed experimentally to date. Final verification will require actual in-reactor testing under mandrel loading conditions representative of ACMI.

VII. CONCLUSIONS

A number of improvements in absorber assembly performance characteristics can be achieved through implementation of absorber cladding mechanical interaction (ACMI). Benefits include lower operating temperatures, less potential for material relocation, longer lifetime, and increased reactivity worth. Analyses indicate that substantial cladding strains may be attainable without significant risk of breach. However, actual in-reactor testing of ACMI in absorber elements will be required before design criteria can be revised to accept ACMI.

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