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A. L. Pitner

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**Westinghouse
Hanford Company**

P.O. Box 1970
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LIQUID METAL REACTOR ABSORBER TECHNOLOGY

A. L. Pitner
Westinghouse Hanford Company
P.O. Box 1970
Richland, Washington 99352
(509) 376-9539

ABSTRACT

The selection of boron carbide as the reference liquid metal reactor absorber material is supported by results presented for irradiation performance, reactivity worth, compatibility, and benign failure consequences. Scram response requirements are met easily with current control rod configurations. The trend in absorber design development is toward larger sized pins with fewer pins per bundle, providing economic savings and improved hydraulic characteristics. Very long-life absorber designs appear to be attainable with the application of vented pin and sodium-bonded concepts.

I. DESIGN BASIS

Reactor control in a liquid metal reactor (LMR) is maintained by regulating the insertion level of a bank of neutron-absorbing control rods in the reactor core. Absorber assembly designs are similar to driver fuel designs in that wire-wrapped stainless steel pins are arranged in a bundle array contained inside of a stainless steel duct tube. In the case of absorber assemblies, however, two duct tubes are used. An inner duct with wear pads on the ends contains the absorber pin bundle that moves vertically inside a fixed outer duct. Also, because heat generation rates are lower in absorber pins than fuel pins, larger sized pins can be used. Figure 1 is a schematic representation of the absorber assembly for the Fast Flux Test Facility (FFTF).

The absorber assembly must perform in a manner consistent with the general requirements of the control rod system; that is, it must provide reliable reactivity control and rapid shutdown capability. In this context, it is necessary that the absorber assembly retain its required reactivity worth and vertical mobility throughout its prescribed design lifetime. Specific performance parameters associated with these design requirements

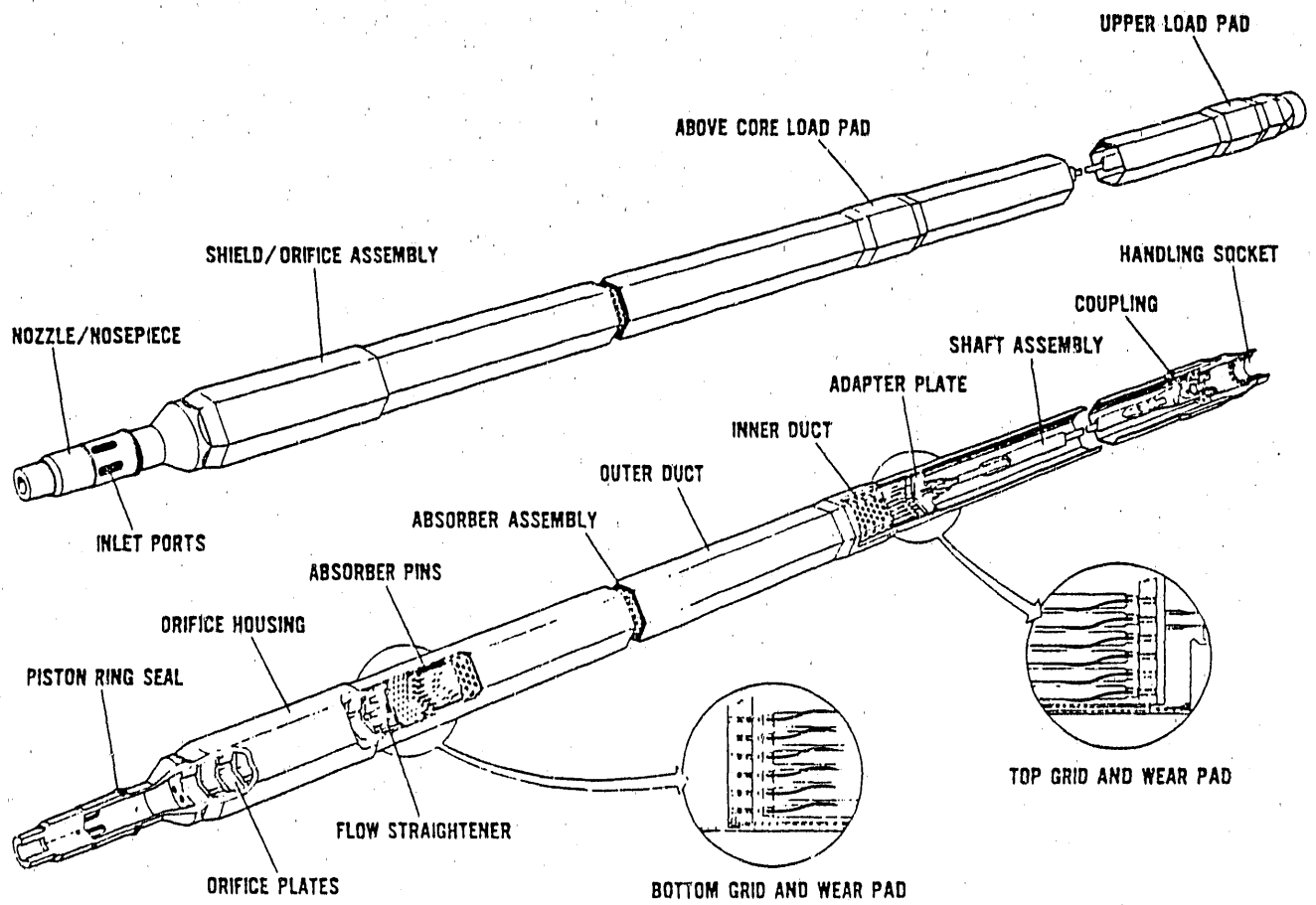


FIGURE 1. FFTF Control Rod Absorber Assembly.

include absorber material worth, absorber pin integrity or benign failure consequences, irradiation-induced component distortions, and scram insertion rates.

II. ABSORBER MATERIAL SELECTION

Boron carbide (B_4C) has been established as the reference absorber material in the international LMR community. Its initial selection was based on its relatively high neutron absorption cross section in a fast flux spectrum, its commercial availability at reasonable cost, and its low radioactivity after irradiation. Other materials were considered also; Table 1 presents the relative reactivity worths of the various absorber candidates. It is seen that B_4C has comparable or greater worth than the other candidates and, in addition, can be enriched in boron-10 (^{10}B) content from 20% natural up to 90% to increase reactivity worth. The other materials have been dismissed from consideration as a result of availability, cost, or high decay heat. The good irradiation performance displayed by B_4C in LMR control rod applications has confirmed its proper selection.

Table 1

Relative Reactivity Worth of Absorber Materials
in an FFTF Control Rod.

<u>Absorber Material</u>	<u>Relative Worth</u>
Boron carbide (B_4C -natural)	1.00
Europium sesquioxide (Eu_2O_3)	0.98
Eu_2O_3 -Tungsten cermet (10% W)	0.91
Europium hexaboride (EuB_6)	1.13
Tantalum (Ta)	0.75
Rhenium (Re)*	-1.3

*Not available in sufficient quantities for control rod applications.

Neutron capture in B_4C occurs through the $^{10}B(n,\alpha)^7Li$ reaction; thus, helium gas is generated during irradiation of B_4C . The reaction products and the incident neutron flux produce structural damage in the B_4C matrix, which influences the rate of helium release, pellet swelling, and various other

thermal-physical properties. Irradiation performance of B_4C was extensively characterized using representative burnup and temperature conditions for LMR control rod applications.

III. DEVELOPMENT TESTING

Once B_4C was selected as the reference absorber material for the FFTF control rods, numerous B_4C irradiation tests were conducted to support control rod design activities. In addition to obtaining basic irradiation performance data to verify the FFTF absorber pin design, a number of material variable effects were investigated to determine which characteristics provided the better in-reactor behavior. This information was then applied in establishing specification requirements for B_4C pellet procurement.

Testing was performed in thermal reactors (to extend the thermal reactor database to FFTF temperature regimes), spectrum-hardened thermal reactor environments, and fast flux reactors. Some of the tests were instrumented to permit continuous monitoring of temperatures and gas release quantities. The early fast reactor testing was performed in the Experimental Breeder Reactor-II (EBR-II), but several tests were also irradiated in the FFTF once it became operational. In all, a total of 435 individual test pins or capsules were irradiated in 24 separate reactor experiments.

Based on observed irradiation performance, baseline fabrication specifications were defined for what was termed "reference" B_4C . Acceptable irradiation behavior was achieved with the following material parameters for the B_4C pellets: average grain size $<15 \mu m$, a pellet density of $92 \pm 2\%$ TD, and stoichiometry of B:C ratio = 4.00 ± 0.15 . Irradiation performance of this material is described in Section IV.

Compatibility testing was performed to establish reaction rates between B_4C and cladding candidates. Testing was performed at temperatures ranging from $600^\circ C$ to $1000^\circ C$ for times of up to 8600 hours. The results showed that in the temperature ranges representative of normal operating conditions, reaction rates were insignificantly low. No distinction could be made between

the various cladding alloy materials, which included stainless steel, Inconel^a, Hastelloy^b, and nimonic alloy. Reaction rates observed between components in irradiation tests agreed with out-of-reactor test results, indicating that interaction rates were not accelerated under irradiation conditions. When sodium bonding between the B₄C and cladding material was used, reaction rates were nominally doubled but remained acceptably low for normal temperature levels.

The susceptibility of irradiated B₄C to erosion by flowing sodium was investigated to determine the consequences of a breached absorber pin. Both in-reactor and ex-reactor tests were conducted. Even with large defects machined in the cladding, the B₄C loss was restricted to the pellet surface in the vicinity of the defect and was very limited. In a loop test conducted in which high-burnup B₄C pellets (100 x 10²⁰ captures/cm³) were exposed to 538 °C sodium flowing at 1.5 m/s, the total quantity of B₄C lost through 2.5-mm-wide slot defects was less than 4% of the local pellet volume after 50 days of test duration. The material that was washed out was very small in particle size (approximately grain-sized) and would not be harmful to reactor components.

Testing of vented pin concepts has been pursued. While gas release fractions from B₄C are generally quite low, it is anticipated that future LMRs will use control rods that must withstand higher operating temperatures and higher burnup levels. Gas release volumes under these circumstances will be appreciable and probably require that the absorber pins be vented to avoid excessive gas pressure buildup. Both laboratory and in-reactor vent testing have been conducted on various types of vents, including porous sintered metal plugs, capillary tubes (restricted flow area), ceramic fiber vents, and diving bell configurations (standpipe operating on a pressure balance principle). An original objective was to develop a vent design that would release the helium gas without allowing any sodium ingress to the absorber pin. As discussed in Section IV, however, sodium ingress has not been found to be detrimental to integral absorber pin irradiation performance based on experience to date.

^aInconel is a trademark of Huntington Alloys Inc., a Division of International Nickel Inc., Huntington, West Virginia.

^bHastelloy is a trademark of the Cabot Corporation, Kokomo, Indiana.

IV. IN-REACTOR PERFORMANCE

Boron carbide pellet and absorber pin irradiation data have been obtained for burnup levels approaching 200×10^{20} captures/cm³ and irradiation temperatures ranging from 500 °C to more than 1800 °C. Also, information on integral absorber assembly performance has been obtained from experience gained while operating the FFTF control rod system. Discussions of the various aspects of in-reactor performance of absorber assemblies and their components follow.

A. Helium Release

For lack of better data, early absorber assembly design efforts assumed high gas release fractions, and absorber pins were designed to accommodate high gas pressures. Test data have since shown that helium release quantities from B₄C under irradiation are substantially less than first anticipated. A helium release correlation was developed from irradiation test data that presents helium release quantity as a function of burnup and temperature. The correlation projects increasing fractional gas release at higher burnups ($>100 \times 10^{20}$ captures/cm³) and higher temperatures (>1500 °C), but generally indicates gas release fractions of 10% or less for conditions below these levels. Helium release accordingly becomes limiting in sealed pin designs only when very high burnup and/or temperature conditions are encountered.

B. Swelling / Pellet-Cladding Interaction

The high gas retention level displayed by B₄C under irradiation is responsible for substantial swelling behavior. A swelling correlation has been developed from the database used to derive the helium release correlation. While the correlation indicates that the swelling rate depends somewhat on both burnup and temperature, a basic swelling rate of about 0.5% diameter increase per 10^{20} captures/cm³ is projected. This swelling rate is consistent with that reported in foreign test programs.^{1,2}

Inasmuch as the B₄C swelling rate is greater than that of the cladding, the pellet-cladding gap eventually closes with increasing irradiation

exposure. Continued B_4C swelling then results in mechanical interaction between the pellets and cladding. This pellet-cladding interaction (PCI) can result in cladding strain, as shown in Figure 2. Here, the profilometry trace of an absorber pin from a test control rod in FFTF shows the general irradiation-induced swelling profile of the 316 stainless steel cladding (plenum region) with PCI spikes superimposed on this profile in the pellet stack region. The maximum PCI occurs at the bottom of the absorber stack where the burnup is greatest in normal control rod operation with the rod being continually withdrawn during the course of each reactor cycle. The actual spike locations correspond to pellet ends where B_4C swelling is slightly greater due to the higher density in these regions that results from the hot-pressing pellet fabrication process. The absorber pin incurred over 1% PCI strain above the swelling dilation of the cladding and did not fail. In fact, no PCI-type failures have been incurred in absorber pins where the maximum PCI strain was less than 2%. The Soviet Union has reported pin failures when PCI strain extended into the 2% to 4% range, as discussed in Section IV.E.

C. Physical Integrity

Irradiation causes deterioration in the physical integrity of B_4C pellets, with the degree of structural degradation most severe at lower irradiation temperatures (<650 °C). Pellets irradiated in sealed (helium atmosphere) pins to burnup levels of 80×10^{20} captures/cm³ or less, however, typically have been recovered intact. There is evidence that the presence of sodium may accelerate the structural degradation during irradiation. Boron carbide pellets are frequently found to be cracked and fragmented after irradiation to high burnup levels. However, this type of pellet fragmentation (with or without the presence of sodium) has not been observed to cause any degradation in absorber pin performance. The pellet fragments are generally constrained to their proper position in the absorber pin by the cladding, and such behavior is not considered detrimental to overall absorber pin performance.

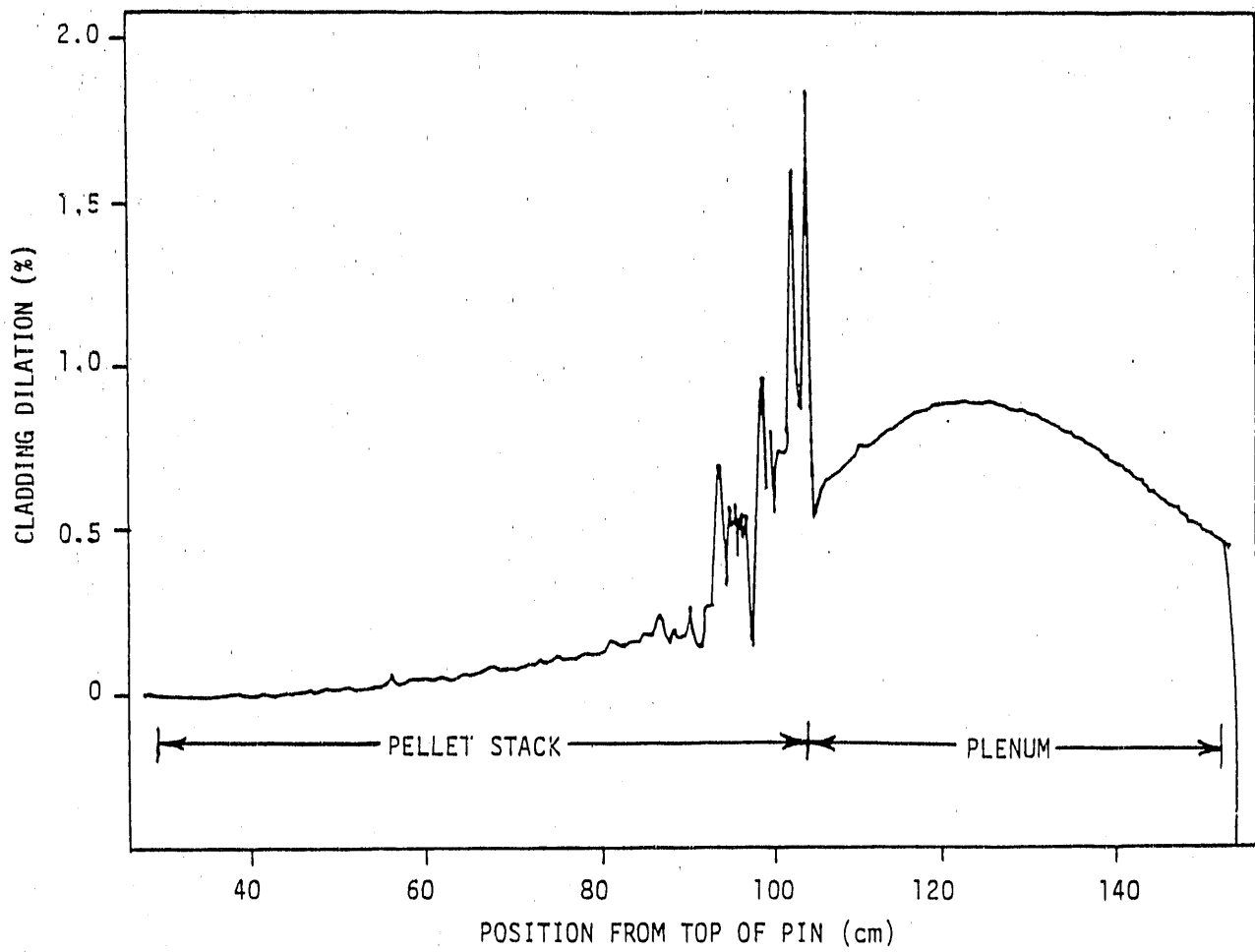


FIGURE 2. Pellet-Cladding Interaction in Absorber Pin.

D. Vent Performance

More than 100 vented absorber pins have been irradiated, and all the pins tested vented helium successfully. Vent types investigated included capillary, porous plug, and diving bell vents. On occasion the diving bell concept was combined with one of the other flow-restrictor type vents. Both top- and bottom-mounted vents were tested. While all types of vents successfully released the helium from the absorber pin, some sodium ingress was also allowed by all types at one time or another. Bottom-mounted vents were most effective in suppressing sodium ingress to the absorber pin. The concentration of sodium ingress was always heaviest toward the bottom of the absorber stack, making pellet recovery in this region difficult due to sodium bonding between the pellets and cladding. Otherwise, no detrimental effects of sodium ingress were noted. The sodium appears to penetrate and weaken the B_4C pellets, but basically they remain intact and contained in their proper position within the cladding.

E. Failure Experience

There has been limited experience with absorber pin failures. No failures have occurred in any FFTF control rods or test assemblies. The Soviet Union has reported absorber pin failures in the BOR-60 reactor from PCI when cladding strain levels were in the 2% to 4% range. The failures were in the form of longitudinal cracks in the cladding, which was similar to 316 stainless steel except for molybdenum content. No significant loss of B_4C from the absorber pins was noted.

One other occasion of PCI-type failure was incurred in an EBR-II absorber test. The failures were considered somewhat atypical because of the unique B_4C pellets used in the test. The pellets had been subjected to a non-normal tumbling treatment during fabrication in an effort to remove sharp corners. This treatment caused subsequent spallation of chips from the pellet surfaces that relocated in the pellet-cladding gap. As the bulk B_4C pellets swelled with irradiation exposure, small dimples formed in the cladding at the

locations of these wedged chips. In some instances, an approximately 0.75-cm-long crack was formed across the dimple. While these breaches allowed substantial sodium ingress into the absorber pins, there was no evidence of material loss from any pin.

One intentional gas pressure-induced failure was experienced in an absorber test pin.³ In an instrumented EBR-II test, a core-length pin was fabricated with a very restricted plenum volume to promote high pressurization as the irradiation progressed. Failure was incurred after 33 days of irradiation. Figure 3 shows the pressure measurement response in the surrounding enclosure chamber. The helium was released in a gradual manner during a period of about 20 minutes. Postirradiation examination revealed a narrow 0.5-cm-long crack on the exterior of the cladding. Only a pinhole-type penetration visible at a magnification of 1000X was found on the internal surface of the cladding, which was consistent with the slow release of gas observed during the rupture event.

F. Duct Bowing

The flux and thermal gradients across an absorber assembly can cause bowing of the pin bundle and outer duct as irradiation proceeds. If the relative bowing of these two components becomes severe enough, interference to the vertical travel of the movable pin bundle may be encountered. Analytical evaluations to project bowing behavior are performed in a conservative manner, using worst-case swelling and creep correlations along with misalignment conditions that result in the most potential for bundle-to-duct interference. No observations of degraded scram performance have ever been noted in the operation of the FFTF, with some assemblies having resided in the same location/orientation for up to 600 equivalent full-power days (EFPD). A technique is available to minimize duct bowing effects. Rotation of the assembly by 180 degrees relative to core center after some period of exposure is effective in reversing bowing trends and, in effect, serves to straighten the ducts again with continued irradiation.

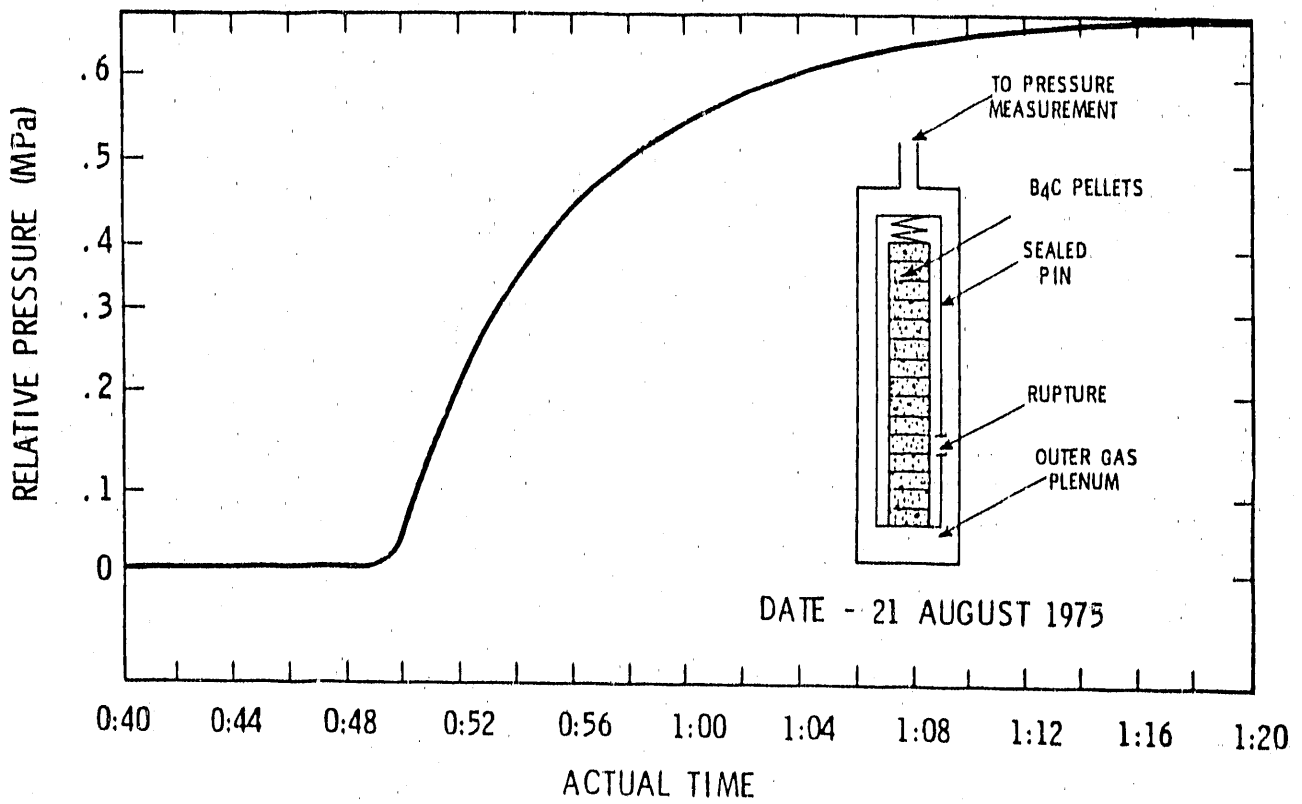


FIGURE 3. Gas Release Response to Cladding Rupture.

G. Scram Performance

The scram response requirement for FFTF control rods is that the assembly reach the 3/4 core insertion level in 835 ms or less. At this point the dashpot mechanism becomes active to decelerate the pin bundle to achieve an acceptable impact velocity. The reference 61-pin bundle assembly for FFTF easily meets this criterion with average scram times of about 620 ms. The trend in absorber design evolution is toward larger pin sizes, which requires fewer pins to fill the assembly. These designs have reduced hydraulic resistance, which translates into faster scram times. A 19-pin absorber bundle design tested in FFIF displayed scram times of about 400 ms.

V. DESIGN EVOLUTION

Because of the paucity of irradiation performance data, the initial absorber design for the FFTF (Series 1) was necessarily conservative in nature. Small-diameter pins (1.2 cm) with thick-walled cladding were used to accommodate the anticipated high gas pressures that might develop from helium release during the 300 EFPD design lifetime for the Series 1 absorbers. As more test data became available, it was apparent that B_4C pellet swelling was more limiting than gas release. This permitted the application of larger diameter pins with relatively thinner cladding. Accordingly, pellet-cladding gaps were sized to accommodate the B_4C swelling projected for the design lifetimes. The Series 3 absorber assembly design for the FFTF control rods employs 19 sealed pins that are 2.1 cm in diameter. The design lifetime for the Series 3 absorbers is 900 EFPD.

The absorber designs in the various countries with LMR programs have interestingly enough evolved toward basically similar concepts. While tantalum and europia absorber materials were applied to some degree in early absorber designs, they have generally been supplanted by B_4C because of its superior performance attributes in LMR applications. Pin sizes have also evolved toward a common dimension. Initially, pin diameters ranged from about 1 cm to nearly 5 cm; the current standard pin diameter is about 2.5 cm. The number of pins per assembly may vary between absorber designs depending on the

lattice pitch of the reactor core. The B_4C pellet density is generally around 90% TD, with ^{10}B enrichment set as needed to meet reactivity worth requirements.

While both sealed and vented absorber pins are used in current LMR absorber designs, it is a general consensus that vented pins will be required for extended lifetime absorbers. Large-pin absorber designs with lifetimes of 1200 EFPD or greater are envisioned for future LMRs. Test data with burnups to $\sim 300 \times 10^{20}$ captures/cm³ are required to support these advanced designs. Sodium ingress at these high exposure levels is expected to be substantial even in vented pins that were originally helium-bonded; therefore, demonstration of long-lifetime capability of sodium-bonded or weeper-type vented absorber pins should be pursued. Duct and cladding materials with commensurate high-exposure capability must also be identified.

IV. CONCLUSION

The selection of B_4C as a fast-reactor control rod material has proved to be a wise choice, and B_4C is now internationally accepted as the reference LMR absorber material. Extensive irradiation testing has verified its good in-reactor performance. Its commercial availability, relatively good reactivity worth in an LMR spectrum and enrichment capability to increase worth, compatibility with sodium and cladding materials, and benign failure consequences are all creditable attributes of B_4C . Very long absorber lifetimes appear to be attainable with application of vented and sodium-bonded pin concepts.

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