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BLISTERS IN BDF-TYPE CONTROL RODS
FINAL SUMMARY REPORT
ENGINEERING

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BLISTERS IN BDF-TYPE CONTROL RODS

FINAL SUMMARY REPORT

ENGINEERING

August 30, 1965

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August 30, 1965

BLISTERS IN BDF-TYPE CONTROL RODS
FINAL SUMMARY REPORT
ENGINEERING

- Ref: 1) HW-84116, "Blisters in BDF-Type Control Rods, An Interim Report", G. W. Riedeman, September 16, 1964, Confidential-Undocumented.
- 2) HW-84116 A, "Blisters in BDF-Type Control Rods, Second Interim Report", G. W. Riedeman, May 25, 1965, Confidential-Undocumented.
- 3) HW-84116 B, "Blisters in BDF-Type Control Rods, Final Summary Report, Processing", G. W. Riedeman, June 29, 1965, Secret.

The first two referenced reports present observations from post-mortem examinations of several blistered control rod sections; the third put down ten points distilled from these observations of importance to reactor operation. Part I of this report contains comments on the engineering aspects of this type of rod's performance; Part II covers the behavior of boron-carbide in aluminum poison rings.

The scope of this report defies a concise abstract. In lieu of an abstract, the following topical outline will both indicate the subjects covered and show how these subjects are organized.

Part I Engineering Aspects

Blister Formation
Temperature Effects
Cooling Effects
Drive Connections
Housing Effects
Housing Materials
Radiation Effects

Part II The Behavior of Boron Carbide-Aluminum Poisons

Swelling
Swelling Rates
Restraint
Material Behavior

Part III Conclusion

I. ENGINEERING ASPECTS

Blister Formation

The original reason for undertaking the work leading to these reports was to find the cause for blisters, or localized swollen areas, that had been

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found on some troublesome control rods upon their being removed from service. The work ultimately uncovered data of far greater scope, but its original justification still requires satisfaction.

Blisters are not a prime phenomena, that is they are the end result of two other causes that are, engineering-wise, more noteworthy than blisters, per se. There appear to be two distinct types of blister: Those that form at the ends of a poison column and those that appear to lie at channel inflections. The ones at poison column ends are filled with decomposed or crushed poison rings. The ones at channel inflections are largely open and appear to be buckles in the rod housing.

Poison rings swell markedly during irradiation. Because these rings are threaded on cooled aluminum cooling tubes which retain their strength throughout rod life, they are longitudinally restrained and break up at restraining points at the column ends. As they crush and continue to expand, debris forces the housing to "blister". These blisters are solidly filled with ring debris.

In contrast, those blisters that form at other places appear to be much less symmetrical; maximum bulging on one rod face usually does not lie exactly opposite the bulge on the other face. Sometimes only one side bulges; sometimes one side bulges while the other forms a depression. All these observations added to the fact that very little ring degradation lies beneath these blisters indicate a bending, or buckling, phenomenon.

Most recorded blister measurements came from number 2 half rod removed from 105-B in July, 1963. This particular rod had four blisters, one at each end of the poison column and two about two feet apart back six feet from the rod tip. The two center blisters appeared very similar and to be of the buckling variety; the end blisters also appeared similar and of the debris-filled type. One end (reference 1) and both center blisters (reference 2) were cut open to see the nature and extent of their decline.

Blisters thickened this rod about three-sixteenths inch (0.150-0.180 inch) although general rod swelling accounted for about one-eighth inch of this measurement. Both type blisters thickened the housing about equally; neither caused any significant widening.

Another item - a descendant of general poison ring swelling - that contributed to the ease with which blisters formed was the extreme softness of the rod housing. This particular housing operated at 600° to 700°F where it had a yield strength of only about 2000 psi; it would deform plastically under almost no bending stress and would be able to restrain only the slightest swelling pressures from within. These temperature effects will be covered in more detail in the next section on temperature.

With this understanding of blister morphology, one can be quite certain that blisters form slowly, requiring months or years from first being

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noticed to presenting insuperable sticking problems. As long as they will pass through a standard, 0.250 inch enlarged bushing, they harbor no danger of blowing open and spewing poison and water into the reactor core.

Temperature Effects

In the past, we were content to rely upon calculated rod component temperatures because these calculations indicated an adequate safety margin and no direct measurement technique had been developed. Had the rods retained their original dimensions and assembly tolerances, this approach would have been entirely adequate. They didn't, and it wasn't.

Two new methods were employed to fix typical rod housing temperatures by measuring or evaluating changes in housing properties that are time and temperature dependent. Both methods yielded about the same result: operating temperatures had reached 600° to 700°F. Over some blisters, temperatures may have exceeded 750°F.

The first method merely evaluates changes in the nature of the age hardening precipitate of the housing alloy, 6063-T834 aluminum. These precipitates agglomerate and diffuse in recognizable patterns characteristic of specific operating temperatures.

The second method relates a change in a measurable mechanical property, in this case - hardness, to a parameter containing both time and temperature. By measuring hardness and knowing the rod's service life, the operating temperature can be estimated.

Neither method is very precise, but both yielded similar values and lend each other credence. One-hundred degree ranges are about maximum precision.

Separately and independently, J. D. Agar constructed a heat transfer model of a BDF-type control rod in which he looked for variables with a strong influence upon sheath temperatures.⁽¹⁾ Although his work was finished before the real extent of swelling was recognized, he confirmed that gaps between the rod's internal parts were one of the more important parameters. As gaps increased, housing temperatures increased. His analysis stopped at gaps of 0.020 inch, where housing temperature had reached 650°F at full power; he offered an estimate of 200° to 300° below graphite temperature as a limit for larger gaps - 750° to 850°F for graphite at 1050°F. Significantly, these calculations further corroborate temperature estimates from metallographic and hardness tests. Conversely, the fact that observed temperatures fell close to calculated values testifies to the validity of Agar's heat transfer model and analytical technique.

(1) Old File HCR Operating Temperatures, J. D. Agar, October 10, 1963, HW-79209, Secret.

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Cooling Effects

Because housing temperatures are so sensitive to radial gaps within the rod assembly, the general design philosophy which places boron poisons outside of the coolant cannot avoid continually increasing rod temperatures as the rod ages. Boron swells as it absorbs neutrons and will inevitably pull away from the cooling tubes, creating barriers to effective heat removal. Placing cooling tubes inside boron poison elements is the wrong approach to keeping rods cool. The behavior of BDF rod designs quite clearly demonstrates this problem.

Drive Connections

BDF-type rods depend upon their housings to carry all loads associated with rod movement. The drives connect to the housings, and the housings contact all seals, bushings, and channel distortions that can impede rod movement. When housing temperatures reach 400° to 500°F, which they do after perhaps two years, the housing becomes the weakest part of the assembly. Cooling tubes do not soften because they seldom exceed 150°F and will carry a much higher load than will the hotter housing. The problem with this arrangement was demonstrated recently when attempts to pull a stuck half rod broke the housing and allowed the cooling tubes to pull away from their connection in the drive rack. Although this rod has not been examined closely, the cooling tubes are retracted and cooling could not help but be impaired or worse.

Because of this kind of situation, the major driving part of the rod assembly should have enough strength to make it the strongest member at whatever temperatures it may reach. A member far removed from the coolant will require a material with high temperature strength (certainly not aluminum). The cooling tubes themselves would do very well because they stay at coolant temperatures (aluminum will do very well).

Housing Effects

Some BDF control rod channels contain vertical inflections that bend more sharply than the control rods can naturally accommodate and, as a result, apply bending stresses to the rod. These stresses load the top and bottom rod surfaces alternately in tension and compression and, when the metal is in its weakened state, will cause plastic yielding. Yielding in tension increases the housing length at that surface. When the stresses reverse, the added length will pucker and buckle and raise the housing away from the underlying poison. This sort of sequence most likely caused the two center blisters in the 2-B rod.

Softened housings are not an absolute pre-requisite to raising blisters of this kind; any unbonded rod cladding will have the same problem if bending forces can cause plastic deformation, particularly by bending over a fulcrum. It is apparently common practice to define rod bending requirements

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in terms of a minimum radius necessary to pass a channel inflection. Doing so assumes uniform bending stresses along an appreciable length of rod and uniform temperature along the rod housing. In a practical sense, neither of these assumptions may be true. First, in order to apply any appreciable bending moment, the rod must be bent forcibly across a fulcrum which may be either at the channel top or bottom. Second, particularly at this fulcrum, the housing will be in very strong contact with the graphite and, if not directly cooled, will be appreciably hotter than at nearby areas. Agar's report⁽¹⁾ also evaluated the effect of graphite to housing contact coefficients and found them to have great influence upon housing temperature - as the coefficient rose from 100 to 1000 BTU/hr-ft²-°F, housing temperatures increased about 140° F. (The relationship is far from linear; temperature changes at lower coefficients are much more rapid than at higher ones. See Agar's report for details.) Metals lose strength as temperature rises; the housing will be weakest at this fulcrum and will absorb most of the bending forces in this small area. Plastic deformation and buckling may well occur even though the radius of curvature analysis may indicate stresses below yield.

Housing Materials

Traditionally, control rod housings have been of an aluminum alloy primarily because many aluminums harbor very low induced radioactivity, at least in comparison to most other handy materials. There is no other reason to use aluminum. There are stronger materials, more corrosion resistant materials, materials less likely to score and gall, and materials just as easy to fabricate. All these other materials, until recently, have fallen before the spectre of high induced radiation. So, control rod designers were faced with choosing the best of a bad lot. In trying to emulate those mechanically more desirable materials without sacrificing aluminum's tenuous advantage, the designers settled upon alloy 6063, which could be produced in the shapes necessary, which could develop reasonably high strengths when cold worked and heat treated, which contained few alloying or impurity elements, and which was a commercially available product.

If design dimensions and internal component clearance had remained as at assembly, housing temperatures would have remained much nearer coolant temperature. And the effort devoted toward choosing an alloy and special fabrication scheme to obtain as high strength as possible would have been successful. As it was, however, the boron-carbide-aluminum poison rings swelled and ultimately forced housing temperatures into a no-man's land for any aluminum alloy, regardless of composition or heat treatment. At operating temperatures of 600°F and above, 6063 alloy is no better than pure aluminum (1100 alloy); both have a tensile strength of about 3000 psi. For comparison, alloy 6063 and 1100 have mechanical properties nominally so:

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	<u>6063 T834</u>	<u>1100 H-18</u>
Tensile Strength		
Room temperature	36,000 psi	24,000 psi
600°F	3,000	2,500
On return to room temperature	13,000	13,000
Yield Strength		
Room temperature	33,000 psi	22,000 psi
600°F	2,500	1,500
On return to room temperature	7,000	5,000
Elongation (a measure of ductility)		
Room temperature	9%	15%
600°F	80	80
On return to room temperature	About 25	45
Hardness (BHN ₅₀₀)		
Room temperature	About 90	44
600°F	*	*
On return to room temperature	25	23

* Too low to measure; probably less than BHN₅₀₀ 5.

The interesting point here is that once a housing has operated at 600°F, from then on it is mechanically indistinguishable from 1100. We have had many rods operating at this temperature without undue trouble before they noticeably blister. Which raises the question, is high housing strength really necessary? Apparently not. One might ask about added strength for unusual maintenance demands. These demands usually come about because of rod sticking or binding. Sticking, at least in the smaller reactors, is caused most often by swelling; when a rod has swelled enough to stick, it is already softened and any cold work or age strengthening will have long disappeared. Even though the housings retain their original strength for their early life, they do not benefit from this strength when they need it most - when swelling starts to create "unusual maintenance demands". As long as we talk aluminum, housing strength is not very important.

However, should materials other than aluminum - materials with a temperature tolerance accepting a 600° to 700°F environment - become more popular, then housing strength assumes a new dimension. Then, strength will be there when it is needed most.

Now, where the housing is directly cooled, the situation improves, but some problems still remain. With coolant keeping housing temperatures below 250°F, aluminum will retain its original strength indefinitely. The 105-C control rods benefit from direct cooling and, except where a rod has lost inlet water, show no evidence of softening. On the negative side, once inlet water is lost, the rod will immediately soften to near annealed properties. Guaranteeing that a control rod would never lose coolant over its service life would be difficult. Even when cooled, aluminum is not without probable fault.

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Save only for the problem of induced radioactivity, aluminum is at best a marginal material for control rod structural components. It may well be that the induced radioactivity of some other materials may not prove so important in light of the price we pay by adhering to aluminum.

Radiation Effects

The only observable radiation effect was swelling of the poison rings. It is true that the housings may have sustained some damage, but if so, it was so masked by thermal effects that it was not identifiable. The cooling tubes probably hardened under the fast neutron exposure of more than 10^{21} nvt, but since cooling tubes gave no problems and we know aluminum does not suffer too badly at these exposures (from process tube examinations ⁽²⁾), no attempt to measure their properties appeared necessary.

Radiation effects on poison rings are described in the following section.

II. THE BEHAVIOR OF BORON CARBIDE-ALUMINUM POISONS

Swelling

Boron swells as it absorbs neutrons. Of boron's two natural isotopes, boron¹⁰ and boron¹¹, only boron¹⁰ has sufficient cross section to act as a poison; natural boron contains about 20 percent boron¹⁰. Natural boron's cross section averages about 760 barns; boron¹⁰ is 3840 barns; boron¹¹ is less than 0.05 barns.

As boron¹⁰ absorbs a neutron, it transmutes to lithium⁷ and emits an alpha particle which quickly picks up a stray electron and forms an atom of helium. Lithium⁷ is only one-fifth as dense as boron¹⁰, and an atom of lithium⁷ requires slightly more than three times the volume of a boron¹⁰ atom. The helium is a gas and the volume it requires is difficult to calculate or measure. Nevertheless, the combination of these less dense transmutation products distorts and enlarges the original boron structure and causes swelling.

BDF-type poison elements are ring shaped, bonded mixtures of natural boron carbide and aluminum powders, one weight boron carbide to two of aluminum.

Upon finding control rods swelled as much as they had, it appeared worthwhile to measure the amount of swelling and compare this value to those already documented. Samples from one rod were available, number 2-B (July, 1963 retirement), for this test. This rod had absorbed 4.4×10^{21} neutrons per cubic centimeter of poison⁽³⁾ and was in service eight years. Boron¹⁰ burnup was about 70 percent.

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- (2) "Mechanical Properties, Irradiated Reactor Process Tubing", J. R. Young, to be published shortly, Secret.
 - (3) Calculated from data in "Cumulative Exposure, HCR #2-105-B", C. E. Bowers, October 7, 1964, HW-84403, Secret.

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Swelling was measured in two ways, by measuring poison ring dimensional changes and by measuring changes in density. Both methods gave similar results. Ring dimensions were available at two locations on the 2-B rod, near the far rod tip and near the center of the twelve-foot poison column. Density measurements were possible only at the latter location. The following table shows these measurements.

TABLE I
POISON RING VOLUME CHANGES

	By Dimensions		By Density
	Rod Tip	Poison Column	Center
Inner Ring	Plus 23%	Plus 10.3%	Plus 13.0%
Outer Rings	Plus 11.5%	Plus 8.2%	Plus 10.1%

With the exception of the rod tip inner ring, all these values average plus 10.6% $\pm$ 2.4% which is quite close considering that these data did not come from controlled irradiation experiments. As for the 23 percent increase in the rod tip inner ring, the sample was very difficult to measure accurately and, because of the sample's thin wall, small diameter measurement errors make large volume errors.* It would be relatively easy to rationalize the data into line, but doing so would serve small purpose in view of the other data's consistency.

One other concession was made which applies to all measured volume changes. Because of very strong axial restraint in the poison column, axial swelling was largely thwarted, and volume changes would be reflected as a change in cross section area. Actually, measurements of ring thickness would indicate some axial compression, but new ring thickness varied considerably and before and after comparisons are not too valid. It is also difficult to conjure up a mechanism that would apply the active axial compressive force necessary to thin all of the rings visible in all our photographs. Nevertheless, axial compression may have occurred by some unknown means, and if so, these swelling figures will require some correction downward. Evaluating this phenomenon is not possible with existing data.

Swelling Rates

Now that figures for cumulative swelling are on hand, establishing a swelling rate is the natural next step. Because of the similarity of all except one

* See Reference 1, HW-84116, page 12, for the picture from which these measurements came.

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volume increases, using the average value of 10.6 percent will simplify this step.

Swelling is directly related to rod exposure; however, over a period of several years, it could as well be quoted in terms of service time as short term operating fluctuations average out. For convenience, several different relationships will be presented so that those who would use this information will hopefully find something in terms near to their needs.

From the literature, one finds few comments about the constancy of boron's swelling rate with time, exposure, or any other parameter. Those few comments indicate swelling proceeds at a rather slow rate for an appreciable period and then increases.⁽⁴⁾ Hanford operating experience tends to support this rate variation in that few problems occur for the first three or four years of a rod's service. Unfortunately, all we can do here is to acknowledge that a rate variation probably occurs and present the data as a "linear swelling rate". For all practical purposes, this figure should probably suffice.

Another confusing factor is that neutrons do not absorb uniformly throughout a poison element. A new poison ring absorbs more than 99.9 percent of all incident neutrons in the first millimeter where this same piece after six years absorbs only little more than half the neutrons in this same millimeter. It is very difficult to accommodate this phenomenon in a simple measure of swelling rate, and consequently, we again will acknowledge the existence of this variation and rely upon the simple assumption of an isotropic, or uniform, absorption characteristic.

From reference (3) on page 8, we find the 2-B control rod absorbed 1.8×10^{25} neutrons. The rod was in service almost exactly eight years. From these two measures of age, the "linear isotropic swelling rate" would be:

-
- (4) These comments are best typified on page 54 of the "Technical Progress Report, Pressurized Water Reactor (PWR) Project for the Period October 24, 1961, to December 23, 1961", December 23, 1961, WAPD-MRP-95, Unclassified. This report quotes a rate in B_4C of 0.15% $\Delta V/10^{20}$ depletions of B_{10}/cc up to 90×10^{20} depletions/cc when breakaway occurs. This rate is low. 90×10^{20} depletions/cc is about 40% burnup of all B_{10} atoms in undiluted, natural B_4C . Had this poison been used in the Hanford 2-B half rod, approximately sixteen years would be required for this exposure to accumulate. Though not defined, "breakaway" probably denotes massive granulation of the poison. Apparently, Hanford poisons, B_4C in aluminum, do not suffer this effect.

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Linear Isotropic Swelling Rates

1. 0.24% $\Delta V/10^{20}$ depletions of B_{10}/cc
2. 1.3% $\Delta V/year$
3. 1.4% $\Delta V/10^{21}$ environmental nvt
4. 0.22% $\Delta V/10^{20}$ housing thermal nvt
5. 2.0% $\Delta V/10^{21}$ average reactor thermal nvt
6. Each neutron absorbed adds 2.4×10^{-23} cc to system

Conversion techniques are in the Appendix.

Number two refers specifically to conditions imposed by a small Hanford reactor upon a control half rod; the other values are of more general applications.

Number one is one of the more common ways to express swelling rates and comes simply from dividing the measured change in volume by the number of boron¹⁰ depletions per cubic centimeter.

Numbers three, four, and five are employed occasionally where the available exposure data is in these particular terms.

Number six is new in this report and is so simple in its meaning it seems strange that something like it has never been used before. For those of us only casually acquainted with the mathematical manipulations of nuclear quantities, swelling data portrayed in this manner illustrates quite clearly just what we must contend with. It says exactly what number one says, but in a much less obscure way.

For comparison, the following list shows already documented swelling rates converted to units of numbers one and six. The experiments leading to these values differed greatly. Some were capsule irradiations; some irradiated discs or strips. Some samples were clad; others were not. Some used natural boron; some used high percentage boron¹⁰. Some were long exposures; others were short. In spite of this variety, the rates are generally quite consistent. Our value falls close to the over-all average.

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Summary of Reported Swelling Rates

<u>Data Source and Reference</u>	<u>% $\Delta V/10^{20}$ Depletions of B_{10}/cc</u>	<u>cc/Neutron Absorbed (x 10^{-23})</u>
1. Hanford Measurement	0.24	2.4
2. Westinghouse (A)	0.33 (1)	3.3
3. British Unpublished (B)	0.41 (1) 0.24 - 0.40 (1) 0.065 - 0.17 (2) 0.083 - 0.11 (2) 0.15 - 0.18 (1)	2.4 - 4.0 0.65 - 1.7 0.83 - 1.1 1.5 - 1.8
4. General Electric APED (C)	0.13 0.13 0.35 0.33	1.3 1.3 3.5 3.3
5. Westinghouse (D)	0.15	1.5
6. BMI (E)	0.0 (2)	0.0
7. KAPL (F)	0.21	2.1
8. Harwell (G)	0.07 0.091 0.21 0.27 0.357 0.333	0.7 0.91 2.1 2.7 3.57 3.33
9. General Electric APED (H)	0.23 (1) 0.30 (1) 0.23 (1) 0.17 (2) 0.16 (2) 0.19 (2)	2.3 3.0 2.3 1.7 1.6 1.9
10. Westinghouse (I)	0.84 (3) 1.2 (3) 0.36 0.48 0.24 0.48 0.82 (3)	8.4 12.0 3.6 4.8 2.4 4.8 8.2

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NOTES

- (1) Unclad samples.
- (2) Clad samples.
- (3) Boron in pure iron. Rates for this material appear always greater than other matrices or forms of boron (e.g. B_4C).

REFERENCES

- (A) "Irradiation Behavior of Austenitic Stainless-Steel Burnable Poisons", R. G. Gray, et al, August, 1962, WAPD-262.
- (B) "Reactor Materials", Volume 6 #1, February, 1963, page 65.
- (C) "Investigation of B_4C -Ni Electro Dispersions for Control Rod Applications", H. E. Williamson, et al, November 3, 1961, GEAP-3831.
- (D) "Technical Progress Report, Pressurized Water Reactor (PWR) Project for the Report Period October 24, 1961, to December 23, 1961", December 23, 1961, WAPD-MRP-95.
- (E) "Zircaloy Cladding or Niobium 10 W/O Zirconium Matrix Dispersions", S. J. Paprocki, et al, BMI-1447.
- (F) "Materials Development Operation Progress Report, December, 1963, to February, 1964", KAPL-2200-11.
- (G) "Metallurgy Division Progress Report, March 1 to August 31, 1961", AERE PR M-1.
- (H) "Investigation of B_4C -Ni Electro Dispersions for Control Rod Applications", Transactions, American Nuclear Society, Volume 4, page 90, H. E. Williamson, et al.
- (I) "Irradiation Behavior of Boron¹⁰ Iron Base Alloys", Transactions, American Nuclear Society, Volume 4, page 338, W. Yeniscavich, et al.

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Restraint

From the preceding list, comparing those values marked for notes (1) and (2) would indicate that cladding has a demonstrable effect upon swelling rates, reducing them by one-third to one-half. In the case reported from General Electric Company APED (item 9 in the list), the cladding consisted of only 0.002 inch of nickel plate on small discs of B_4C suspended in a nickel matrix. The discs were 3/8 inch diameter by 0.040 inch thick. Such a clad certainly cannot be considered massive restraint; it would appear that fairly slight restraint can have an important bearing upon the swelling rate.

From Hanford BDF-type control rod experience, only one element of restraint appears to have been active, axial restraint by the cooling tubes. Diametral swelling appears to have proceeded relatively unhindered. As assembled and after any period of normal operation where the tube temperature never exceeds 200°F (around 100°C), these three tubes can withstand a total force of nominally 14,700 pounds before breaking. This force would produce a compressive stress of 9,740 psi in the poison rings. (Should the cooling tube become annealed by, for example, a loss of inlet cooling water, these values would reduce by about two-thirds.) To reach these values, the tubes would have to stretch about 10 percent, or 17 inches over the fourteen-foot poison column of a half rod. At one-half inch elongation, the applied force would be nominally 13,500 pounds with a corresponding poison column compressive stress of 8,930 psi. This force and stress will increase linearly from zero to one-half inch elongation and will not plastically deform the tubes. Above one-half inch (or 0.0033 in/in), the elongation is predominantly plastic and the tubes will not return to their original length once the load is removed.

The values in the preceding paragraph are maximum nominal limits that define the basic BDF-type half rod system. It does not appear that stresses of even the lower value of 8,930 psi ever occur in the poison rings because of their apparent willingness to take their swelling in another direction, diametrically. The breakup of rings at either end of the poison column to raise blisters affords another measure of relief. A better measure of the swelling forces that could build up would be in the poison rings' creep properties, but unfortunately, these data are hard to come by without wildly extrapolating data from marginally related materials. Because of too many interfering actions, no decent creep data can be distilled from the BDF-type rod examinations. Poison rings do, however, appear to creep easily at stresses below 8,930 psi at temperatures over 400°F.

Material Behavior

Poison rings consist of one-third boron carbide particles suspended in two-thirds aluminum matrix. At present, two manufacturing methods have been used to form this mixture into poison rings; both methods are similar but

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the products differ appreciably. The basic process in both instances combines powders of aluminum and boron carbide and subsequently compacts and sinters these mixtures into rings. The first method compacts the powders cold into the proper shape and then hot presses the "green" parts in a furnace to make finished rings. The second method combines these steps - compacting, heating, and pressing - in one operation. As one would expect, the latter method produces a much more dense product, 2.4 compared to about 2.1 grams per cubic centimeter.

The second method has been employed only for very recent ring purchases and no control rods using these rings have accumulated very high exposure or have been removed from service. The observations described here relate to rings of the earlier vintage. The difference in behavior between these two generations may be great.

Boron carbide-aluminum poison rings do not behave as one would expect of a product consisting mostly of metallic aluminum. Aluminum melts and collapses around 1200°F, the poison rings do not. In fact, the poison rings have still not lost their shape at more than 1500°F - 300°F over the matrix' melting point. Over 1200°F, the rings begin to "bleed" slightly as small pockets of aluminum near the surface do melt and escape, but the ring remains substantially intact. At 1500°F, the rings will still support small compressive loads of a few psi.

This observation leads to two interesting items.

First, even though a control rod loses all cooling and both housing and cooling tubes melt, the poison will not. The molten aluminum would fall away from the rings and run into escape points in the rod channel; the rings would essentially remain in the channel. Some few pieces may wash away with the molten aluminum, but the bulk would remain in the channel where it could be removed with the other debris. Little irretrievable poison would remain in the core.

Second, rather than melting and collapsing as would metallic aluminum, these rings retain their shape at temperatures well over aluminum's melting point. Indeed, the metallic aluminum in the part does melt, but the aluminum oxide distributed through the matrix prevents collapse. This characteristic is typical of special powdered aluminum products commonly called SAP (Sintered Aluminum Powders), PMP (Powdered Metallurgical Products), or APMP (Aluminum PMP). However, though the manufacturing methods for rings and SAP parts are quite similar, the starting powders are quite different. SAP powders range in size from 0.1 to 1.0 micron (4 to 40 millionths of an inch - 0.000004" to 0.00004") thickness. Powders from which rings came were 100 to 1000 times larger, appearing to be about 0.005" (about 100 microns) thick or larger. Aluminum powders oxidize where exposed to air to a more-or-less constant maximum depth, regardless of particle size. The finer powders have higher surface to volume ratios and contain a higher over-all percentage of oxide. Typical values are 20 percent oxide for 0.1 micron powders, 2 percent oxide for 1 micron powders. Ring powders, as large as their grains appeared,

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should have contained only an insignificant amount of oxide. Apparently, this reasoning is not entirely valid as the rings behaved as though they contained appreciable oxide.

On carrying the SAP analogy a little further, one can reach some understanding of the properties of these poison rings. There are two better known SAP compositions, one referred to specifically as SAP which contains 10-13 percent oxide, the other referred to as M-257 which contains 6-8 percent oxide. Other than oxide content, the two materials are chemically similar. The powders' oxide coatings form an oxide network when the powders are compacted and hot pressed that strongly supports the metallic aluminum particles held inside. This effect is particularly noticeable at elevated temperatures. For comparison, 6063-T6 aluminum will hold about 7000 psi for 1000 hours at 400°F before failure; SAP will hold 22,000 psi and M-257 will hold 15,900 psi under the same conditions. At 900°F, SAP will hold 7,800 psi for 1000 hours, M-257 will hold likewise 6,400 psi.⁽⁵⁾ At 900°F, there are no reportable data for 6063 aluminum, but the value would probably not exceed 1000 psi.

Another characteristic of SAP materials that appears applicable to boron carbide-aluminum poison rings is a very low ductility at high temperatures. In fact, ductility decreases as temperature rises, a characteristic completely contradictory to virtually all other wrought aluminum alloys. Poison rings crack and shatter very easily while in service. It is true that radiation damage may account for some of this cracking, but were the rings more like aluminum, the ductility at operating temperatures of 400°F or more should accommodate the rings' swelling without failure. Elongation of annealed 1100 aluminum at 400°F is about 75 percent, 6063 is about 40 percent, SAP is about 8 percent, M-257 is about 14 percent. At room temperatures, these values are, 1100-O-45 percent, 6063-T-6-18 percent, SAP-10 percent, M-257-16 percent. The poison rings fail brittly at all temperatures below at least 900°F, i.e. without any elongation. As temperatures approach the melting point of aluminum, the rings fail in a mush fashion and have a consistency reminiscent of dentists' amalgam. SAP and M-257 behave similarly.

The similarity between SAP-type products and poison rings appears clear. Accepting this similarity should open the door to improved boron carbide-aluminum parts, be they rings or whatever, by absorbing the rather well developed SAP technology into the business of making nuclear poisons. Accepting this similarity should also lead to more sophisticated use of these poisons by designing systems that will specifically accommodate the idiosyncracies of a material that only vaguely resembles a metal.

(5) "Reactor Handbook, Second Edition, Volume 1", 'Materials', Chapter 19, pages 482-501.

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III. CONCLUSION

This report concludes this series on BDF-type control rods. The behavior of these rods can now be predicted with some certainty, and the strange quirks they have shown from time to time no longer appear quite so strange. Though the faults are many and cover virtually the gamut of contributing technologies, the rods have provided a substantial measure of performance. Rather than being interpreted as an indictment of dissatisfaction, these data and analyses should more properly broaden our understanding of the materials and assemblies that make up a control rod. They should provide an advance station from which new generations of rod designs can spring. To this end, these documents are dedicated.

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APPENDIX

CALCULATIONS OF SWELLING RATES

1. From Bowers (3) rod absorbed 1.8×10^{25} neutrons

Rod contains 249 in³ poison

or 4100 cm³ poison

$$\frac{1.8 \times 10^{25}}{4100} = 44 \times 10^{20} \text{ neutrons absorbed per cm}^3$$

Rod swelled 10.6%

$$\frac{10.6}{44} = 0.24\% \Delta V/10^{20} \text{ depletions of } B_{10}/\text{cm}^3$$

2. Rod swelled 10.6%

Rod was 8 years old

$$\frac{10.6}{8} = 1.3\% \Delta V/\text{year}$$

3. From Bowers (3) environmental nvt was 7.6×10^{21} n/cm²

Rod swelled 10.6%

$$\frac{10.6}{7.6} = 1.4\% \Delta V/10^{21} \text{ environmental nvt}$$

Environmental nvt is best described as the exposure in the reactor volume directly influenced by the poison when in-place but with the poison out.

4. From Bowers (3) rod absorbed 1.8×10^{25} neutrons. Assuming neutrons entered the rod uniformly over the whole rod surface, the accumulated neutron movement through unit housing area would be

$$\frac{\text{Total neutrons absorbed}}{\text{Active rod surface area}}$$

The active rod surface area is 7650 cm², so

$$\frac{1.8 \times 10^{25}}{7.65 \times 10^3} = 2.4 \times 10^{21} \frac{\text{neutrons}}{\text{cm}^2}$$

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This movement (neutron current) is one-half the flux level at the rod surface. (*)

$$(2.4 \times 10^{21})(2) = 4.8 \times 10^{21} \text{ thermal nvt at rod housing}$$

(This nvt value could be used to calculate induced radioactivity in the rod housing)

Rod swelled 10.6%

$$\frac{10.6}{48} = 0.22\% \Delta V/10^{20} \text{ housing thermal nvt}$$

(*) This relationship comes from diffusion theory. See Glasstone, S., "Principles of Nuclear Reactor Engineering", Van Nostrand, 1955, pages 137 to 139.

The net neutron current through a given area is equal to the difference between the currents flowing in either direction. The definition of these neutron currents is

$$J^+ = \frac{\phi}{4} - \frac{D}{2} \frac{d\phi}{dx}$$

$$J^- = \frac{\phi}{4} + \frac{D}{2} \frac{d\phi}{dx}$$

where J^+ is the current one way

J^- is the current the other way

D is the diffusion constant

ϕ is the flux

$\frac{d\phi}{dx}$ is the flux gradient.

$$J_{\text{net}} = J^+ - J^- = \left[\frac{\phi}{4} - \frac{D}{2} \frac{d\phi}{dx} \right] - \left[\frac{\phi}{4} + \frac{D}{2} \frac{d\phi}{dx} \right]$$

$$J_{\text{net}} = -D \frac{d\phi}{dx}$$

In a perfect poison, neutrons flow only one way. So, one current is zero.

$$J^- = 0 = \frac{\phi}{4} + \frac{D}{2} \frac{d\phi}{dx}$$

$$\frac{\phi}{4} = - \frac{D}{2} \frac{d\phi}{dx}$$

$$D \frac{d\phi}{dx} = - \frac{\phi}{2}$$

$$J_{\text{net}} = -D \frac{d\phi}{dx} = \frac{\phi}{2}$$

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At the poison surface, the neutron current flowing into the poison is one-half the neutron flux level.

5. Average reactor thermal nvt comes simply from accumulating average reactor flux for the operating time of interest.

Average reactor thermal flux assumed 2.5×10^{13} nv

Time = 8 years - 2.5×10^8 seconds

$$2.5 \times 10^{13} \times 2.5 \times 10^8 = 6.25 \times 10^{21} \text{ nvt}$$

Assuming 85% TOE

$$6.25 \times .85 \times 10^{21} = 5.3 \times 10^{21} \text{ nvt}$$

Rod swelled 10.6%

$$\frac{10.6}{5.3} = 2.0 \text{ o/o } \Delta V/10^{21} \text{ average reactor thermal nvt}$$

6. Starting with 0.24% $\Delta V/10^{20}$ depletions B_{10}/cm^3 from Appendix point 1, the manipulation goes as follows:

Volume change is 0.24% for every 10^{20} depletions per cm^3 .

In one cm^3 , volume changes 0.0024 cm^3 for each 10^{20} depletions, so, for one depletion, volume changes $0.0024 \times 10^{-20} \text{ cm}^3$,

or $2.4 \times 10^{-23} \text{ cm}^3$ adds to the system for each depletion (absorption).

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FOOTNOTE REFERENCES

- (1) "Old Pile HCR Operating Temperatures", J. D. Agar, October 10, 1963, HW-79209, Secret.
- (2) "Mechanical Properties, Irradiated Reactor Process Tubing", J. R. Young, to be published shortly, Secret.
- (3) "Cumulative Exposure, HCR #2-105-B", C. E. Bowers, October 7, 1964, HW-84403, Secret.
- (4) "Technical Progress Report, Pressurized Water Reactor (PWR) Project for the Period October 24, 1961, to December 23, 1961", December 23, 1961, WAPD-MRP-95, Unclassified.
- (5) "Reactor Handbook, Second Edition, Volume 1", 'Materials', Chapter 19, pages 482-501.

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