WSRC-TR-91-615

SUBSTITUTE SAFETY RODS PHYSICS OF OPERATION AND IRRADIATION (U)

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SUBSTITUTE SAFETY RODS
PHYSICS OF OPERATION AND
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SUBSTITUTE SAFETY RODS
PHYSICS OF OPERATION AND IRRADIATION (U)

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INTRODUCTION

Under certain assumed accidents, an SRS reactor may lose most of its bulk moderator while maintaining flow to fuel assemblies. If this occurs immediately after operation at power, components normally dependent on convective heat transfer to the moderator will heat up with the possibility of melting that component. One component at risk is the currently used cadmium safety rod. A substitute safety rod consisting solely of sintered B4C and stainless steel has been designed (Reference 1) which is capable of withstanding much higher temperatures. This memorandum provides the physics basis for the adequacy of the rod for reactor shutdown and provides a set of criteria for acceptance in the NTG tests.

This memorandum provides physics data for other aspects of operation. These include:

- * Heat production and helium production, along with related phenomena, resulting from inadvertent irradiation at power.
- * Gamma heat input under drained tank conditions
- * An equivalent rod design suitable for charge design and safety analyses.
- * Degradation under normal operation.
- * Thermal flux ripple in adjacent fuel due to axial striping of alternate B4C and steel pellets.
- * Possible effect on safety analyses.
- * Safety rod withdrawal during reactor startup.

SUMMARY

In this memorandum, all values are based on an operating power of 50% of traditional full power, i. e., 1200 Mw for the reactor. Down time is ignored. All of the computed temperatures, pressures and stresses are well within normal design bounds and are believed to be conservative insofar as

approximations and simplifications are concerned. The Nuclear Engineering and Materials Technology sections are expected to make more detailed and accurate estimates.

If a safety rod is inadvertently left in the reactor for a full year, well beyond the historical maximum period of 2 weeks, the temperature at the center will be about 600 deg C. The gas pressure will be about 510 psig resulting in a maximum hoop stress of 5300 psi, well below the yield stress of room temperature stainless steel. Diametral expansion from heating and helium formation is about 0.008 inches, or one-fourth of the clearance.

Under drained tank LOCA conditions, the temperature at the center will be about 17 deg C higher than the sheath. The gas pressure will be about 7.5 psig for a hoop stress of 60 psi.

Combining a one-year inadvertent irradiation with a drained-tank LOCA gives a maximum gas pressure of 570 psig with a limiting hoop stress of 4600 psi, a value still well below that for stainless steel at 600 deg C.

An axially uniform rod has been developed suitable for normal GLASS computations (Reference 2). This rod consists of a cylindrical steel sheath around a B4C rod. The rod diameter and the B-10 concentration were simultaneously varied to match reactivity worths of the striped rod at both start of cycle and at conditions approximating 75% burnup. The agreement is essentially exact for intermediate burnups and the model is expected to be accurate for much lighter and much heavier lattices as well. Under normal operation, the only conjectured mode of degradation is the neutron exposure of the bottom pellet in the cocked position. Helium accumulation will cause diametral swelling but this will be less than 0.0002 inch per year.

Axial flux and power variations due to the striped nature of the rods are completely washed out at the nearest fuel surface.

The shutdown worth of the rods exceeds that for the cadmium rods throughout the cycle. This is an advantage in all known accident scenarios involving safety rods.

The increased worth will impose tighter restrictions on startup due to larger flux increases following each withdrawal step, but the difference is minimal.

DISCUSSION

General Comments

For the B4C rods themselves, peak temperatures are of no concern. As a result axial peaking factors are ignored in this discussion. A power of 0.25 Mw/ft in adjacent Mk 22's is assumed over 12 feet of core for the purpose of computing burnup and helium gas generation, although the full 14 feet of active rod is assumed to be at the core temperature so far as gas pressurization gas is concerned. In addition, no credit is taken for radial and axial leakage of gamma rays. Not taking credit for the ends and gamma leakage partially offsets the axial peaking factor so far as internal temperatures of the rod are concerned. Gas pressure and hoop stress are only weakly dependent on rod temperature. They are much more sensitive to helium inventory.

For gas pressurization, three regions of free volume inside the rod are considered: 1) the annulus between pellets and sheath (144.6 cc), 2) the porosity in the 71% theoretical density B4C (243.8 cc), and the free space in the rod extension (359.6 cc). Expressed as volume fractions these are 0.193, 0.326, and 0.481 respectively. Each region has a different average temperature if the rod is heated by inadvertent insertion or by a drained-tank LOCA. For these computations the reference cold temperature and the temperature of the top extension is taken to be 310 deg K (37 deg C). The perfect gas law and conservation of mass are used to obtain an expression for R, the ratio of the hot absolute system pressure to that pressure were all regions at the reference 310 deg K. Using the volume fractions above and all temperatures in Kelvin, the expression is

$$1) \quad R * [(310 \text{ deg} / 310 \text{ deg}) * 0.481 + (310 \text{ deg} / T_{\text{porosity}}) * 0.326 + (310 \text{ deg} / T_{\text{annulus}}) * 0.193] = 1.000.$$

Inadvertent Insertion at Power

Isolated safety rods have on rare occasions failed to latch and remained in the reactor during startup. Their presence has been identified after power flattening by the power depression in the adjacent fuel assemblies. Two weeks is the longest known period before such rods were identified and removed. The concern with B4C rods arises primarily from the fact that neutron capture results in helium formation. The immediate effect of helium formation is particle-generated heat production. Long term and cumulative effects are swelling and pressure buildup. For an individual helium atom, which effect is produced depends on whether that atom is retained within the crystalline lattice or is released to the free gas space within the rod. For the SRS conditions the retention is expected to be about 75% (25% release) although pressures assuming 100% release (no retention) are also calculated. These represent an extreme upper bound on pressures and stresses.

The GLASS code was used to estimate the rate of helium production and gamma power deposition during inadvertent insertion. Separate cases were run for uniform rods of B4C and for stainless steel. Start of cycle conditions were assumed for the Mk22 lattice. In order to provide estimates of specific gamma power, both calculations were extended with the BURN/Gamma transport option of GLASS. The rate of B-10 burnup, i.e., helium formation, can be obtained in various ways from a GLASS printout. One straightforward way is to ratio the sum of the two-group B4C captures and fission events. This ratio was 0.12752. This ratio assumes a uniform B4C rod. It does not take into account the smaller amount of neutron self-shielding that would be seen in the striped rod. The difference can be estimated closely from data in TWOTRAN computations performed for uniform and striped rods in reference 1. From 10-Group cross sections for B4C and computed 10-Group fluxes, one gets a striped-to-uniform summed capture ratio of 1.351, . Combining this factor with the ratio above gives a specific B-10 capture-to-fission ratio in the B4C of 0.17228.

From this ratio and an assumed 201.7 Mev per fission and an effective particle energy of 2.342 MeV per B-10 capture we obtain the values of Table I.

Table I Heat input to Rods Inserted at Power (50% Traditional Power)

	Corrected for Striping		Continuous Rods		
	B4C	SS	B4C	SS	Avg
Alpha	2220 w/ft	-----	3000 w/ft	-----	3000 w/ft
Gamma	250 w/ft	975 w/ft	250 w/ft	975 w/ft	520 w/ft
Clad	450 w/ft	350 w/ft	-----	-----	-----

Volume averaging over B4C and stainless steel gives 2375 w/ft for the core and 410 watts per foot for the clad. The values of Table II extended for one year give a burnup fraction of 0.1325 for the B-10. If one assumes a 12 ft effective length, this results in $1.866E+24$ atoms, or 12.39 gms, of helium formed per year per rod. Using the gas volumes above gives added helium pressures of 28.4 atms (75% retention) and 113.6 atms (no retention) at a reference temperature of 310 deg K.

To obtain the hot pressures via Equation 1, it is necessary to first estimate the temperatures of the annular region and that of the B4C (porosity). The average core power density of 2375 w/ft converts to a surface heat density of 2.93 cal/sq cm/sec. The computation for the annulus is somewhat complicated by the fact that thermal conductivity for helium varies strongly (increasing) with temperature. The conductivity is closely given by the expansion:

$$2) \quad H = 6.77E-05 + 1.127E-06*T - 4.949E-10*T^2 + 1.491E-13*T^3$$

with the conductivity H given in units of cal/cm/sec/deg K and the temperature T given in cal/cm/sec/deg K. Using this expression, one obtains a delta T of 326 deg C across the gap. Using a temperature of 60 deg C for the moderator and clad gives an average annulus temperature of 496 deg K and a surface temperature of 659 deg K. Shaffer's method (Reference 3) was used to estimate the temperature in the carbide. The surface-to-center temperature for a uniform rod with a constant and uniform heat input per unit volume is given by the expression

$$3) \quad \Delta T(\text{deg C}) = (\text{watts/cm}) / (4 * \pi * H(\text{w/cm/deg C}))$$

where the quantity (watts/cm) is the linear power density for the pellet. This is 106 watts/cm for the B4C pellet considered alone. Figures are

included in reference 4 from which the thermal conductivity can be estimated for the conditions here. Values are 0.055 and 0.040 watts/cm/deg K for 2 weeks and one year exposure. These give ΔT 's of 153 and 211 deg C for the surface-to-center temperature difference. Taking the average value to be the average of these values gives a porosity temperature of 765 deg K.

Applying these temperatures to Equation 1 above gives a hot-to-cold pressure ratio of 1.362 or a hot-gas pressure of 514 psig for 25% helium retention and 2040 psig for no retention. Under these conditions the limiting hoop stress is also the maximum stress. This occurs at the counter-bored sections at the top and bottom where the diametral wall thickness is 0.081 inch. Hoop stresses are 4590 psi for the expected 25% retention and 18,200 psi assuming no retention.

Diametral swelling after one year of inadvertent insertion is estimated to be 0.0079 inches. This value is derived from the computed 13.25% per year burnup and the volume coefficient of expansion of 0.225% per percent burnup given in reference 3. The thermal linear expansion at 765 deg K is about 0.22% for a diametral change of 0.0018 inch.

Gamma Heat Input During Drained Tank Conditions

The gamma redistribution within the supercell is documented in reference 5. The essential results from this document for the B4C rods are summarized in Table II below. Values given are deposited gamma heat as a percent of total gamma power within a supercell of six Mk 22 fuel assemblies, one fully loaded control-rod cluster and one safety rod within a thimble. The effect of the rod striping was not explicitly included. The effect of striping is bounded by two limiting cases: 1) homogenizing B4C and SS and 2) volume weighted averaging of B4C and SS computed separately. The results indicate that the rod heat input for the summed core and clad has a power input 11% to 15% lower than for the cadmium rod. The reduction in part is due to differences in gamma self-shielding but arises primarily from the lower average atomic mass number of materials in the B4C rod. Preliminary calculations by the Nuclear Engineering Section suggest that the reduction is more than enough to offset local temperature peaking expected for the B4C rod that is not observed for the cadmium rods. These are due to the axial striping and the loose fit of the pellets within the sheath. The latter permits azimuthal variations from eccentric positioning of the pellets, the worst condition being if a string of pellets, the clad, and the thimble are all tangent at the same azimuthal angle.

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Table II Comparison of Heat Input to Cd and B4C Safety Rods
(Reference 4)

New Rod Average			New Rod Components		
Region	Cd Rods	Homog	Wt'd Avg	B4C	SS
Core	1.322%	0.986%	0.912%	0.412%	1.712%
Clad	0.453	0.589	0.596	0.624	0.550
Thimble	0.311	0.315	0.316	0.325	0.302
Rod Total	1.775	1.575	1.508	1.036	2.262
Total	2.086	1.890	1.834	1.361	2.564

To estimate internal temperature variations, we assume prior operation at 50% of traditional power or 1.5 Mw/ft fission power in the six Mk 22 assemblies in the supercell. The temperature is constantly varying through the accident, reaching a peak safety-rod temperature after about 1000 seconds. From reference 8 the total decay gamma power at this time is about 1.0% of the original fission power. Using the Table II power fraction for the homogenized core of 0.986%, one obtains a linear power density of 4.85 w/cm and a surface density of 0.766 w/sq cm. The conductivity of B4C depends on temperature and burnup and can be estimated closely from data given in reference 5. For no burnup and 600 deg C, $H = 0.10$ w/cm/deg C. This results in a surface-to-center temperature rise of 4 deg C. Allowing a full year of inadvertent exposure would decrease the conductivity and thus increase the temperature difference to 7 deg C.

For pressures and stresses we again need to estimate the temperatures in the three free gas regions. To estimate these temperatures we assume a priori that the average sheath temperature is 600 deg C. We assume again that conductivity in helium is the sole method of heat transfer across the annulus. With the thermal conductivity given by Equation 2 above the thermal conductivity at an average annular temperature of 879.6 deg K is 0.000777 cal/cm/sec/deg K to give an annular temperature ΔT of 12.8 deg C and a porosity temperature of 889.5 deg K. Inserting these temperatures into Equation 1 above gives a value of 1.509 for the ratio of hot-to-cold pressures. Values of hot pressures and hoop stresses in the sheath are given in Table III for various assumed irradiation times.

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Table III Gas Pressures and Hoop Stresses in a B4C Safety Rod During a LOCA Following Inadvertent Irradiation

75% Retention				No Retention		
Irrad. Time	Pcold	Phot	Hoop Str.	Pcold	Phot	Hoop Str.
0.0	0.0 psig	7.5 psig	60 psi	0.0 psig	7.5 psig	60 psi
2 Wk.	14.3	29.1	234	57.3	94	755
3 Mo.	93.4	148	1190	373	570	4590
1 Yr.	373	570	4590	1490	2260	18200

In this table the limiting hoop stress occurs in the hot middle region of the rod rather than in the cool counter-bored top and bottom. At 600 deg C the irradiated stainless steel has lost enough tensile strength to more than offset the difference in wall thickness. All but the highest value are well below the yield point of irradiated stainless steel at 600 deg C.

Equivalent Rod for Production GLASS Computations

Various applications such as safety analyses and charge design require GLASS computations involving safety-rods under various operating conditions. Since the striped rod is not amenable to GLASS which allows no axial variation, it is desirable to have a model which is and one that closely matches the nuclear properties of a striped rod over a wide range of conditions. The most sensitive factor affecting safety rod worth is the neutron spectrum. A model was selected which keeps the same 0.795" diameter for the steel clad and has a central core of B4C. The partition diameter and the B4C concentration were varied to provide an exact match to the striped rod worth at conditions of 0.0% and 75% burnup of a Mark 22 lattice. The derived values also gave a close fit at 50% burnup. The equivalent-rod specifications are:

SS Sheath	0.940" OD	0.836" ID	0.0848 at/bcm Fe
Clad	0.795" OD	0.650" ID	0.0848 at/bcm Fe
B4C Core	0.650" D	0.0328 at/bcm C	0.0213 at/bcm B-10

A cross section of the equivalent rod along with material specifications is given in Figure 1. The data for generating equivalent rods can be used to evaluate worth and worth relative to cadmium as a function of burnup. The results are shown in Figure 2. The reason for plotting burnup in terms of the inverse of the remaining U-235 content is that this results in a near-linear relation. As seen from Figure 2, the ratio of worths decreases with burnup, but the absolute worth of both B4C and cadmium rods increases. The difference in worth is nearly constant over this range. The small decrease indicates that an extremely light lattice would be required before the worth of the cadmium rod exceeds that of the B4C rod.

Thermal Flux Ripple at Fuel Tube

The thermal neutron flux ripple due to striping could be of concern when the rod is inadvertently inserted at power. The ripple was computed using the TWOTRAN code. Well before reaching the nearest fuel surface, this ripple has died out and is within the convergence band of the TWOTRAN computation (about 0.1% variation in flux).

Degradation Under Normal Operation

In normal operation little degradation occurs. Normal operation involves two stages: at power and shut down. The cumulative exposure during the shutdown transient and the exposure to shutdown fluxes is negligible. At power, the safety rods are positioned so that the tip of the rod is at the top poison plate. The flux drops off very rapidly with elevation upwards from the poison plate through the top shield, so that the bottom pellet is the only one of concern.

Combinations of GLASS and TWOTRAN computations were used to estimate the helium formation in the bottom pellet. GLASS was used to generate 10-group cross sections for the top shield, a mixture of equal volumes of H₂O and steel Raschig rings. The TWOTRAN model was of a single cell with reflecting radial boundaries. It extended from midcore (reflecting boundary) up into the shield (vacuum boundary). The material of the inner region, 5.000 inches in diameter, for all regions above the core was taken to be that of the top lattice region, i.e., a mixture of D₂O and aluminum. The outer region was taken to be core material (core), top lattice material (fuel top ends), steel (poison plate), D₂O (moderator flow region) and mixed Raschig rings (shield). The tip of the rod was taken to be exactly at the lower edge of the poison plate. This places the bottom of the bottom B4C pellet just above the bottom of the top shield.

The estimate of neutron capture at the bottom of the last pellet was made by comparing neutron fluxes at the edge of the cell at the bottom pellet elevation to that in the core. B4C slugs were not included in the computations i.e., only the unperturbed fluxes at the slug locations were calculated. The 10-group fluxes were weighted by the group cross sections and averaged to give an absorption ratio of 0.0326, i.e., the maximum swelling rate should be 3.26% of that computed for inadvertent irradiation in the core. The 0.0079 inch per year swelling computed for the core thus gives a swelling rate of 0.00026 inch per year at the rod tip. Total helium production is not enough to alter the initial fill pressure.

Effect on Safety Analyses

Increased rod worth can have the effect of increasing axial peaking factors during assumed accidents. The increased peaking factor however is always more than offset by a reduction in average power. Other members of the Reactor Physics group were consulted and no one was found who could conjecture an accident sequence in which increased safety rod worth would lead to higher powers at any time or at any point in the reactor during safety-rod insertion or residence. This is tacitly assumed in safety analyses that assume minimum worth (due to uncertainties in rod worth or to differences in operating conditions). There are no known safety analyses involving safety rod insertion or residence where maximum worth is assumed. Nonetheless, the Reactor Safety Analysis group plans to investigate each assumed accident involving safety rods to make sure there are no exceptions. A separate memo presenting the views of SCS on the suitability of the B4C rods has been published by R. L. Webb (Reference 6).

Safety Rod Withdrawal on Approach to Power

Increased safety-rod worth does have a small negative impact on approach to power. This is because safety rods are withdrawn in preprogrammed groups and at fixed withdrawal rates. Hence higher rod worths equate to greater reactivity addition rates and hence to larger power increases from each withdrawal step. Rods are initially withdrawn in gangs of six and finally in pairs. Operating procedures require that the flux no more than double on any step. Exceeding this limit is defined as going critical on the safety rods.

The effect is most pronounced on the withdrawal of the final pair. The reactivity worth of the final pair of cadmium rods is 0.14% in reactivity.

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Assuming a maximum credible worth of 1.5 times that of the cadmium rod, the B4C rod gives a worth of 0.21% in reactivity. Margin of Control (MOC) is defined as shutdown reactivity of the lattice immediately following removal of the last safety rod. Based on point reactor kinetics the restriction on flux doubling means that the limiting value for MOC is the worth of the last pair of rods withdrawn. A MOC less than this is defined as "going critical on the safeties". For the K-14 charge, the computed minimum MOC is 2.60% in reactivity (Reference 7). This means that the higher worth rods reduce the allowed margin of error in the MOC from 2.46% down to 2.39% in K, a negligible reduction.

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Fig 2 Worth Dependence on Spectrum

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