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Control-Rod Material Problems of Research Reactors

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[Editor's Note: Deterioration of a control rod has not thus far been known to have caused a serious reactor incident, either by the rod not scramming when needed (due to mechanical damage) or by loss of nuclear worth (due to transmutation of the poison material). Relatively minor problems have been troublesome in both power and research reactors, however, and designs have occasionally been changed to restore original performance. We therefore asked R. D. Martin to review his own experiences and those of others on the question of proper control-rod materials in research reactors.]

Abstract: *Control-rod material problems in research reactors have not caused any serious reactor accidents. However, repetition of poor designs (B_4C-powder-filled pool-reactor control rods) and insufficient mechanical testing of full-sized control rods (deformation of MTR and ORR aluminum-clad cadmium) have resulted in some problems that could have been avoided. The power-reactor operating experience with cracked boron–stainless steel control rods may be pertinent to research reactors operating in the megawatt regions. As research-reactor operating experience with various control-rod materials increases, an improved means of regularly disseminating operational-problem information is needed.*

The June and July 1968 issues of *Nuclear Applications*[1,2] contained articles that summarized control-rod material problems from the viewpoint of the power-reactor designer. A similar discussion of this topic by research-reactor designers is not available. Moreover, since in recent years the construction rate of new research reactors has not been comparable with that of the late 1950's and early 1960's, it is now more appropriate to summarize research-reactor control-rod material problems from the viewpoint of the operations supervisor.

Although these two viewpoints (design and operations) do not necessarily oppose each other, they do accent different aspects of reactor performance criteria. The designer seeks maximum nuclear performance (e.g., reactivity worth) of control rods, while the operations supervisor seeks maximum operational utility. The selection of the boron–stainless steel control rod of lower reactivity worth for swimming-pool reactors over the higher worth B_4C-powder-filled unit is an example of settling for less favorable nuclear characteristics in order to eliminate a number of potentially hazardous and/or operationally aggravating conditions. These conditions have included swelling, loss of poison by mechanical means, and power-level fluctuations caused by coolant-flow-induced vibration of the rods.

A discussion of research-reactor control-rod problems from an operations standpoint is not intended to provide operational-experience feedback to designers. Since the majority of research reactors are already in operation, with few new ones having been added in recent years, it is more important that the research-reactor supervisor be aware of conditions that may arise during the life of his facility. Probably this same situation will be true of power reactors in a few years, when designs become frozen and few modifications are made.

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To assure as thorough a coverage of the subject as possible, information gathering began with a Nuclear Safety Information Center computer printout on scram-mechanism failures and control-rod damage, continued with a conventional literature search, and concluded with a direct questionnaire to the operations supervisors of 84 research reactors.

The major control-rod materials in use in research reactors include cadmium and its alloys, boron and its compounds and alloys, and a group of materials I look upon as "exotics," including the oxides of dysprosium and europium. When a research-reactor supervisor thinks of a material like high-purity europium oxide powder, which costs $860/lb, the material is exotic unless it greatly outlasts $8/lb cadmium or is needed in much less quantity.

A division of research-reactor control-rod materials into three definite categories by material is not complete without some mention of the reactor type involved. Steady-state research reactors may be separated by high (>500 kw/liter), intermediate (10 to 500 kw/liter), or low (<10 kw/liter) core power density, and all pulse and fast-burst reactors may be placed together in a fourth category. The pulse and fast-burst reactor category can be quickly discussed because a literature search, as well as contacts with supervisors of these types of facilities, did not indicate any control-rod problems that could be classed primarily as material problems. The reported difficulties were primarily drive-mechanism problems, which all operators have had to face at one time or another. However, it must be kept in mind that the pulse reactors, as a group, have not accumulated many equivalent megawatt-hours of operating experience, and their apparent lack of material problems may be temporary.

The high power-density reactors (HFIR, ATR, and the original AARR design) present a different situation because they are advancing the state of the art, and, as such, their control needs are unique. Of these only the HFIR has operated very much; there have been control-plate bearing failures; the control plates have given excellent service, however.

In any discussions of the control-rod designs of low and intermediate power-density reactors, the primary differences center about the magnitude of the heat fluxes and hydraulic forces to which the control rods are subjected.

Cadmium

Cadmium can be regarded as the forerunner of all research-reactor control materials, having been used, in the form of metallic strips, in the first self-sustained fission chain reaction (CP-1). Since that time it has been used in research reactors primarily in sheet-metal form; however, some alloys containing cadmium have been used, primarily the 80% Ag–15% In–5% Cd ternary alloy. Although a preliminary evaluation of the suitability of high-temperature cadmium compounds as control-rod materials[3] has been made, at present no operating reactors use such cadmium compounds in control rods.

Metallic Cadmium

The majority of the problems with metallic cadmium result from low mechanical strength and lack of resistance to erosion and corrosion in flowing water. No reports of problems with metallic cadmium were found for gas-cooled research reactors.

The Aircraft Shield Test Reactor (ASTR) has unclad cadmium tubes[4] in its control rods. After severe pitting corrosion of control rods used to check out drive mechanisms was detected in a test tank filled with city water, the rods in the reactor were removed. Inspection of these reactor rods with a borescope showed evidence of less severe corrosion, but maximum pit depths of 0.015 in. in a cadmium thickness of 0.020 in. were measured. These unclad rods were replaced with stainless-steel-clad cadmium cylinders and later with Ag–In–Cd rods clad with 0.020-in. Inconel.[5]

The MTR, ORR, and many other reactors use a cadmium sheet covered with thin aluminum sheet and formed into a hollow square tube about 3 by 3 in. and 30 in. long. This tube, in which the cadmium is not bonded to the aluminum cladding, is mounted within the shim-rod assembly, which contains a fuel or reflector region, as well as the poison section. In both reactors the water flowing downward through the shim rods experiences a pressure drop over the length of the rod. However, any water that might leak through a faulty weld at the top of the poison section would uniformly pressurize the tube containing the cadmium to the pressure at the inlet end of the control rod. In both the MTR[6] and ORR,[7] the pressure difference created across the lower portion of the poison section under these conditions was sufficient to cause the tube to bulge inward and restrict coolant flow through the shim rod. This problem was solved by providing small holes through the cladding at the lower end to eliminate any differential pressures. Although some cadmium is now exposed to the primary coolant, cadmium corrosion rates have not been a serious problem. In fact, variations in the level of ^{115}Cd dissolved in the reactor coolant serve as an "early enough" preliminary indicator of cadmium corrosion problems.[8,9]

The control rods of the Westinghouse Test Reactor (WTR) were stainless-steel-clad cadmium[5] in the form of cylinders. During the design investigations for comparing aluminum and stainless-steel cladding material, it was found that, when the cadmium was heated to 630°F, the aluminum cladding would bulge outward, whereas the stainless-steel cladding would bulge inward. Since the outward bulge would have rendered the rods inoperable, stainless-steel cladding was chosen.

No information could be found in the literature about the reactivity-worth change or consequences if a control rod bulged, as in the MTR, ORR, or WTR experiences, or if boiling should suddenly occur within such a rod.

The NASA Plum Brook Reactor (PBR) also has cadmium as the poison material for its control rods. The cadmium is clad in stainless-steel sheet, and the resulting sandwich is riveted together and formed as a square tube somewhat similar to the MTR and ORR rods. The stainless steel in the original rod design was open at the ends. With this arrangement a small area of cadmium was exposed to the water coolant at the ends as well as at each rivet hole. Erosion and corrosion of the lower 6 in. of the cadmium were experienced when these rods were in service[10] owing to the contact between the cadmium and the cooling-water flow. It was thought that this erosion–corrosion effect might limit the effective lifetimes of the rods, but the rod lifetime has been found to be limited only by depletion of the ^{113}Cd isotope. The reactivity-worth change of the lower 6 in. of the rod would have been about the same even if the corrosion had not taken place.

Nevertheless, the ends of the stainless-steel sheets were welded shut to reduce the magnitude of the corrosion–erosion problem, but no modifications were made at the rivets. Effective shim-rod lifetimes are about as before, which is further evidence of the minor role of this corrosion in determining rod lifetime.*

*As a momentary aside to this topic, the PBR, ORR, and MTR all have beryllium followers on a number of their shim rods and have reported measurable bowing of the beryllium sections at fast-neutron doses of the order of 10^{21} to 10^{22} neutrons/cm^2. The ORR has also had similar bowing in aluminum follower sections and other aluminum components after exposures of approximately 10^{22} neutrons/cm^2 (Ref. 11).

The 5-Mw MIT reactor control rods (hollow cylindrical cadmium sandwiched between aluminum cladding; similar to the WTR design) have not given any difficulty other than that it is necessary to wait about 2 days for the "hot" end of the cadmium to decay prior to replacement of a control rod without using special shielding. During operation the ends reside in a core region that has an unperturbed thermal-neutron flux of approximately 10^{14} neutrons/(cm^2)(sec).

There were no reports of the consequences to reactor control capability if the cladding separates from the cadmium, provides an insulating gap, and causes melting and subsequent loss of reactivity worth.

However, an evaluation was made of the rate of attack on aluminum by molten cadmium under various thermal and physical conditions.[12] The conclusion was that the attack of aluminum by molten cadmium at 400 to 600°C is slow (<12 mils/day) and that an aluminum wall temperature of 160°C will cause the cadmium to resolidify and halt its attack on the aluminum cladding. This predicted behavior was confirmed by postirradiation examination of a cadmium control rod that was inadvertently inserted for a full cycle of high-flux operation [flux level 4.8×10^{14} neutrons/(cm^2)(sec)]. The examination revealed that the cadmium had separated from the cladding, probably because of thermal cycling during irradiation. The cadmium had locally melted and resolidified, but it had neither altered the exterior dimensions nor affected the integrity of the control rod.

Since the test rod was not discovered until after shutdown of the reactor, it may be reasonable to conclude that melting of the cadmium had little effect on the worth of the control rod.

Cadmium Alloys

One of the first sets of control rods used at the Bulk Shielding Reactor (BSR) at ORNL consisted of a mixture of lead with 17 wt.% cadmium, which was poured, while molten, into an oval aluminum shell. Unfortunately much of the early BSR history is difficult to trace in the open literature. Between the startup of the reactor in 1950 and the first Geneva Conference in 1955, control-rod types had been changed three times, but the reasons for the changes are not wholly clear. It can be inferred[13] that the cadmium–lead rod may have had a significantly lower reactivity worth than the boron carbide-powder-filled aluminum shell which eventually was its replacement and which has since been supplanted[14] by boron–stainless steel rods.

The 80% Ag–15% In–5% Cd ternary alloy was originally investigated as a possible substitute material for hafnium in the Naval Reactors Program[1] and has been used successfully in operational experience in power reactors, notably Yankee. The use of this alloy in research-reactor control rods appears to be limited thus far to the PULSTAR systems and the Sandia Engineering Reactor (SER). At both SER and Yankee, the rods were plated with nickel to prevent the escape of the chemically active silver ions to the primary water system and subsequent plateout on primary system components.[10,15] The center SER control blade is cruciform in shape, and plating was difficult. However, experience at SER and at Western New York Research Center's PULSTAR has been satisfactory.

Power-reactor experience at Yankee, although admittedly involving a more severe thermal environment than that of most research reactors, has not shown similar satisfactory results from the nickel plating.[15] However, Inconel cladding has yielded satisfactory results.[16]

Boron

The use of boron as boron carbide powder, boron steels, and boral for control-rod materials has produced a number of unusual operations experiences. Where cadmium control-rod difficulties have primarily been corrosion and cladding deformation, the boron-based control rods have swelled, cracked, warped, corroded, and elongated.

Boron Carbide

Boron carbide-powder-filled oval aluminum or stainless-steel shells used as control rods in pool-type research reactors have repeatedly had to be replaced because of poor mechanical design that resulted in distortion caused by swelling or off-gassing. Although the following is not a complete list, such swelling and off-gassing have been observed at:

Reactor	Date
Oak Ridge National Laboratory's BSR	February 1957
University of Michigan's FNR	August 1960
Babcock & Wilcox's LPR	October 1960
University of Virginia's UVR	December 1960
Naval Research Laboratory's NRR	June 1961
University of Missouri's (Rolla) UMRR	September 1964

One important aspect of these failures, besides the direct safety considerations, is that the first failure occurred on Feb. 15, 1957 (see above), when only three or four other swimming-pool-type reactors with B_4C shim safety rods were in operation.[17] However, more than 30 of the 60 or more pool reactors built after 1957 were originally equipped with control rods of this same basic design. In contrast to a general lack of operational feedback[18] to reactor designers, the continued use of faulty design in an operating facility, and in the initial cores of some 30 new facilities, appears to be a case of both operators and designers failing to act on available information.

The ORNL-BSR experience with B_4C control-rod problems is extensive.[41] In September 1959, a second rod was removed because of dimensional changes. In May 1960 another of the rods was found to be off-gassing, indicating a leak in the rod shell. After dimensional checks were made, the rod was returned to service and used without incident until January 1967. Binding of this rod occurred 2 months after uprating to 2 Mw (no off-gassing had been observed), and the rod was discarded.

The continued use of this known defective rod for almost 7 years seems unusual in the light of a relatively rapid failure of a different rod which occurred at the BSR during this same period. In 1965 the rod jammed in the core after it had satisfactorily passed a dimensional inspection only 27 days earlier. The day before, rod drop times had been normal. The FNR staff reviewed the various possible failure mechanisms and concluded that leakage of water into the shell was the only credible explanation for formation of internal pressure causing the distortion.[19,20] However, actual inleakage has not been observed.

In the NRR failure[21] a gas mixture with a hydrogen-to-oxygen ratio of 3:1 was detected. Information regarding the production of high-purity B_4C showed that free-hydrogen entrapment in the B_4C matrix is a production problem. This was assumed to be the reason for the high hydrogen-to-oxygen atomic ratio.

In the case of the UMRR,[22] the use of a stronger stainless-steel shell (0.065 in. thick) compared with the more common aluminum shell did not prevent the swelling. Moreover, the exposure in the reactor had only been 2.45 Mw-hr at less than 100 kw, which suggests that the rod may have had either some moisture or a leak prior to installation.

The chances of a control rod jamming because of this type of swelling are increased somewhat because of the design of the control elements in which the rod moves. The physical clearances provided in the control-element guides of pool reactors for control-rod movement are greatest at the ends of the oval cross section (where the shell is strongest) and smallest at the flat portion of the oval (where the shell is weakest, and where the maximum shell dimensional change occurred under internal pressure).

Sometime during the late 1950's, it became conventional to provide a cadmium liner in these B_4C-filled shells. It is not clear from the open literature exactly when or why, but presumably it was done to provide a poison backup in the event the B_4C powder was lost from a shim safety rod. In 1961 a malfunction led to the replacement of one of the B_4C shim safety rods at the Industrial Radiation Laboratory reactor. When the replaced unit had "cooled" enough to allow handling, the B_4C powder was removed from the shell, but the cadmium liner was left in place. A subsequent reactivity-comparison test[23] did not detect any difference in reactivity worth between the water-filled cadmium liner and the B_4C-powder-filled cadmium liner.

One reactor did experience a situation in which powder was lost from a B_4C unit. In 1964, two of the three control rods at the Ohio State University (OSU) reactor could not be lifted by the electromagnets.[24] These rods had not jammed in their control-element guides, but rather the support shafts connecting control rod and magnet armature had broken. Most probably the shaft failure occurred because of inadequate shock-absorber action and an extremely small effective shaft cross-sectional area (0.013 sq in.). As in the case of a number of pool reactors, these control rods had lead ballast rods within the control-rod shell to increase the weight of the B_4C assembly. Unfortunately the lead ballast rods were not attached to the upper portion of the control rod with its supporting shaft, small though it was. Therefore the entire deceleration force produced by the lead ballast tubes following a rod drop was borne by the end plug, which was attached to the aluminum shell by a thin weld. During the inspection to find the cause of the failure of the rods to withdraw, "dirt" was noticed on the pool floor. The inspection revealed that one of the end plugs had been pounded out of the bottom of the shell by the ballast tubes, and the dirt on the pool floor was the B_4C from the lower 6 to 7 in. of the B_4C rod.

It was later concluded that the remaining B_4C had not been released because it had earlier solidified in the shell because water had leaked into the shell through galvanic-corrosion pinholes where stainless-steel screws fastened the positioning end boxes to the side plates of the control-rod fuel elements.

Another materials problem of the B_4C rods is shown by the need to provide them with these lead ballast rods. Since compacted B_4C has a density of approximately 2 g/cm^3, these rods tend to be relatively light. This has caused operators of a number of forced-convection-cooled pool reactors to report[25] instrument noise from flow-induced shim-rod vibration. At a number of reactors, some type of constraint has been successfully installed within the rod guide channels to limit the amplitude of vibration. There is evidence[26] to show that heavier assemblies (e.g., boron–stainless steel shim rods) are not subject to this vibration for the low coolant flow rates used in most pool reactors.

However, not all experiences with B_4C rods have been unsatisfactory. Several pool-reactor supervisors have reported trouble-free service lives for such units.[10] Moreover, the experience with B_4C in power-reactor control rods has been satisfactory.

The majority of the B_4C power-reactor control rods are fabricated in a cruciform shape with B_4C-packed tubes held in position with suitable end fixtures.[27] The use of the smaller tubes provides a structurally stronger shell than an oval or boxlike structure. Moreover, powder-loss hazards are minimized, e.g., by locating steel balls at even intervals along the B_4C-loaded tubes and swaging them into place or by using B_4C pellets. Thus a corrosion or mechanical tube failure will only release the powder between adjacent balls. The balls are not fully sealed in place, and thus the helium from the (n,α) reaction is free to migrate to a void space provided at the top of each tube. Rods of this type have operated more than 11,000 hr in Dresden 1 with no observable problems or reports of water leakage into the tubes. Perhaps a more significant observation would be that, despite a more severe environment, better fabrication and testing prevent corrosion-induced swelling. The design is based on initial water and helium impurities that give (for 700°F operation) an internal pressure of 278 psi (Ref. 28).

A somewhat similar design of a hot-pressed B_4C ring within concentric tubes was to be used on the EGCR.[29] In this instance the stainless-steel tubes were copper plated to prevent $Ni-B_4C$ interaction at high temperatures. Unfortunately the cancellation of the EGCR project prevented any operating experience with this design.

Boron Steel

The use of boron–stainless steel (B–SS) for control rods in research-reactor applications has been primarily in the control rods for the air-cooled graphite research reactors (e.g., carbon steel at the ORNL Graphite Reactor and the Brookhaven Graphite Research Reactor), some of the power-reactor prototypes (e.g., HWCTR), and replacements for the B_4C control rods of pool reactors. From the research-reactor standpoint, there have been no reported material difficulties with the B–SS units other than the lower reactivity worth[22,30] compared with B_4C. The B–SS rods generally have a worth of about 80% of that of a B_4C rod in the same core location, even for high natural-boron contents (1 to 2 wt.%). Similar reactivity-comparison results have been reported[31] at power reactors.

These stainless-steel alloys are more nearly always boron dispersions in a metal matrix; and, since the boron has a tendency to form nickel borides and some boron carbide, the formation of nickel borides depletes the nickel content of the stainless steel. This partial depletion of nickel content may explain the rust observed on the FNR control rods, which are 1.5 wt.% boron.

Although research reactors have had generally good experience with B–SS rods, other than the low worth and rust already noted, some of the power-reactor experience should be noted as an indication of potential difficulties. Power-reactor experience with B–SS shim rods has not been good when accumulated thermal-neutron exposures exceed 10^{20} neutrons/cm^2. The Elk River, BONUS, Indian Point, Dresden, and Pathfinder stations have all observed cracking of the B–SS control rods. In the case of Indian Point, 35-sq in. pieces of B–SS had broken away from the rods.[32] In this design the stainless-steel blade tips were riveted to the B–SS poison section. Differential expansion resulted in a sinusoidal deformation of the transition section, with the node points at the rivet plates joining the two sections.

Detailed inspection of the Dresden 2% B-SS control-rod blades in 1961 after 60 full-power days revealed cracks in all blades examined. The cracks started at the edge of the weld zone and penetrated up to 1 in. into the blade.[28]

At BONUS, because of experience that involved a piece of a control rod falling off during a rod inspection, B–SS rods are limited to an exposure of 3×10^{20} neutrons/cm^2. Replacement hafnium rods have been ordered.[33]

Many of the instances of cracking in B–SS rods have occurred at points in the rod where mechanical work (welding, punching, riveting, forming, etc.) had been done. However, attempts[34] by the designers of Pathfinder to heat-treat the rods and thus relieve work-induced stresses were not successful; cracks occurred near fabrication welds after 18 months of operation.[35]

If the BONUS rod-exposure limit of 3×10^{20} neutrons/cm^2 is appropriate for similar B–SS rods used in pool research reactors, and if an approximate rod-tip surface neutron flux of 1.5×10^{12} neutrons/(cm^2)(sec) per megawatt of power (as measured at the FNR midplane) is generally applicable to these reactors, these rods would have a useful lifetime of approximately 60,000 Mw-hr, or approximately 10 years at a power of 1 Mw with a full-power on-line factor of 0.8. Research reactors with power levels in excess of 1 Mw may experience problems similar to those reported for power reactors with B–SS control rods.

Boral

Although boral has seldom been used as a control-rod material for research reactors, the limited experience has been satisfactory. The University of Missouri's (Columbia) 10-Mw research reactor (currently operating at 5 Mw) uses boral in the shape of segments of a cylinder. This reactor has a reflector-controlled flux-trap core. The only material difficulty[10] so far has been occasional pinhole corrosion of the cladding that covers the B_4C–Al core, which is routinely corrected by peening the pinholes closed.

Another research reactor that uses boral has not had any difficulties thus far in its operation. The University of Kansas adopted a new design[10] after swelling difficulties were experienced with its original set of rods. The new design was a series of boral plates welded, in picture-frame fashion, into an aluminum channel. The original control rod, two boral plates with a lead plate between them, was clad with 0.035-in. aluminum sheet. Leakage of water into the shell caused the thin aluminum cladding to bulge (apparently from a radiolysis pressure), thus restricting movement of the rod through its guide channel.

Boral samples ¼ in. thick were exposed in the ORNL Graphite Reactor (0.020-in. aluminum-clad 52 wt.% B_4C samples) for 14 months and received an accumulated exposure of 2.6×10^{19} neutrons/cm^2 with no physical evidence of significant damage.[36] However, boral has been used primarily at low core power-density facilities. With operation of the University of Missouri reactor having begun, significant thermal-neutron exposures of boral rods will be accumulated. It will be interesting to observe the performance of this material at exposures greater than 10^{20} neutrons/cm^2.

One occurrence involving boral may be of interest, even though not in a reactor. The shipping cask used by the National Lead Company for irradiated fuel elements from the Canadian NRU reactor has baskets of boral clad in $\frac{1}{16}$-in. stainless-steel sheet. During a fuel shipment a portion of the cladding deformed. It was hypothesized[37] that water leaked into the basket structure during underwater loading, and the internal cask temperatures (maximum between 400 and 450°F after draining) caused steam formation of the water between the cladding and the boral with consequent cladding deformation. However, when one stainless-steel-clad section was removed in order to inspect the boral, a raised blister was evident on the boral itself. The boral used on the NRU fuel cask was not edge sealed, because of the use of the stainless-steel cladding, but the raised section of the boral was not located at an edge area. The cause of the blister formation has not been determined.

In contrast to this experience, the boral that is edge sealed in the National Lead Company's cask for MTR-type fuel has never exceeded a temperature of 350°F, and there have been no swelling problems.

Exotic Materials

The operational experiences with research-reactor control rods containing exotic materials, such as europium and dysprosium, are easy to summarize. Both materials have given satisfactory service from a materials standpoint. No material difficulties with control rods have been reported for either the HFBR or the HFIR. Most of the HFIR control-plate problems have been with the bearings used on the plates rather than with the plates themselves. After reactions of europium and silicon observed in early tests were eliminated, use of europium in the SM-1 has been satisfactory.[38]

The ATR, not yet in operation, is a fourth facility that will use such material in its control drums.

Summary and Conclusions

Control-rod material problems in research reactors have not caused any serious reactor accidents.[39] However, the operational difficulties encountered at research reactors because of control-rod material problems have been numerous and varied. They result from (1) insufficient knowledge of materials behavior (e.g., B–SS embrittlement and failure behavior at stress concentration points), (2) unnecessary repetition of bad designs (e.g., pool reactor B_4C-powder-filled rods), and (3) insufficient component-testing programs (e.g., bulging of cadmium cladding).

From the research-reactor control-rod material problems summarized here, it appears that reactors with low and intermediate power densities should use cadmium as their primary neutron absorber. Cadmium, when placed in a cladding suitable from the standpoints of mechanical strength and materials compatibility, has offered the fewest problems of any material for which there is operational experience. The high rate of burnup of the ^{113}Cd isotope tends to limit the lifetime of cadmium rods, and thus the use of cadmium rods is avoided for neutron exposures above the 10^{22} neutrons/cm^2 range, where changes in material properties are so little understood.

Although it is true that research-reactor experience with B–SS rods has been satisfactory thus far, the lower reactivity worth and the poor power-reactor operational experience make these rods appear to be a poor choice compared with cadmium rods.

Information Availability

Throughout the writing of this article, I had reservations about the ability of anyone to obtain complete information on control-rod material problems. Much of the information used in this article was based on a survey[10] of facility supervisors. Letters were sent to the operations supervisors of 84 research reactors, and only 38 replies were received. Twenty-three indicated that no control-rod material problems had been experienced, and the experiences related in the other 15 replies have been summarized. To those who replied to my inquiry, both reactor supervisors and AEC officials, I wish to take this opportunity to offer my thanks for their assistance.

When gathering data for this kind of article, the author deals in a "sensitive" area with respect to research-reactor operation, albeit one in which there is limited operational information in open literature. Many design reports for power-reactor rods are available, but similar reports for research reactors are almost nonexistent. The sensitivity of this subject results from an understandable reluctance of the reactor supervisor to document troubles that have occurred with his reactor's primary safety mechanisms—the control rods. This is akin to "washing your dirty linen in public!"

When a reluctance to admit to such problems is coupled with the regulatory system that includes inspections to detect items of noncompliance with the terms of an operating license, the operator tends to become a Philadelphia lawyer when recounting adverse experiences. It is unfortunate that the AEC's compliance inspectors, who are in a position to disseminate* the experience gained at various facilities, must be looked upon primarily as law-enforcement officers. Nevertheless, as long as their primary responsibility is the enforcement of compliance, individual attempts on the part of compliance inspectors to disseminate information can meet with only limited success.

Often the limitation in gathering a representative number of experiences for review and publication is the operations supervisors themselves. Their responsibility is to evaluate problems when they arise (complying with AEC notification requirements), to effect as quick a solution as possible, and to get the facility back into operation. This sequence of events does not involve the writing down of the history and the details of the cause and the remedy in a form suitable for publication. A freewheeling discussion among interested and experienced parties in congenial circumstances leads to freer, and often more honest, exchanges of ideas and experiences than the use of paper and pen.

The professional society meetings, such as the biennial Operations Division meeting of the American Nuclear Society, have a useful function in that they serve along with the society journals as a medium for publication, but they require excessive preparation time and occur too infrequently for the information to be current. A more suitable arrangement would be for operations supervisors from between 5 and 10 operationally similar facilities to privately arrange to meet on a semiannual basis. No formal preparation of reports would be required, and a transcript or other minutes of the meeting would be made only if all participants agreed. This might be one way to enable groups of operations supervisors to meet and discuss problems openly with freedom from both national publicity and concern over repercussions from regulatory agencies.†

Perhaps the editors of *Nuclear Safety* will one day promote a study of the decision-making process used by an operations supervisor when he is confronted with the task of making a facility change based on the experiences of another. An understanding of the complexities of having to weigh the factors of costs, lost time in licensing matters, and engineering time against the potential improvement in safety or operational efficiency might help to explain some of the recurrence of control-rod problems that has been experienced in research reactors.

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*[Editor's Note: In an earlier article of *Nuclear Safety*,[40] P. A. Morris (then Director of AEC's Compliance Division) suggested that compliance inspectors could aid in dissemination of reactor safety information.]

†[As Mr. Martin indicates, a communications problem surely exists; for an additional discussion, see the introduction to the article on safety-related occurrences that were reported in 1966 [*Nuclear Safety*, 9(3): 249-252 (May–June 1968)]. However, it seems that regularly scheduled meetings such as are suggested here, although undoubtedly very useful to the few participants, would merely delay an eventual solution to the general problem of effective communication. A better solution might be (1) to require records of both any unusual event or situation and the steps that were taken to prevent or alleviate it and (2) to make the records readily available to other members of the nuclear community who have a legitimate use for the information. Computer-storage techniques are presently available (for example, the Selective Dissemination of Information programs of the Nuclear Safety Information Center and of others) which make feasible the rapid communication of pertinent information to selected members of the nuclear community.—E. N. Cramer, *Editor*]

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