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AN EVALUATION OF FIVE POSSIBLE HCR
SLEEVE MATERIALS FOR K REACTOR

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CG-PR-2, 1-28-94

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November 23, 1960

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E. R. Rudock
Reactor Modification Design
FACILITIES ENGINEERING SECTION

AN EVALUATION OF FIVE POSSIBLE HCR
SLEEVE MATERIALS FOR K REACTOR

INTRODUCTION

The graphite stacks of the K reactors have been distorted to the extent that steel balls from the ball 3X system have entered some of the horizontal control rod channels and have interfered with the proper operation of the control system. Although ball drops are infrequent*, the potential continuously exists for balls to enter the rod channels and to cause rods to malfunction. Removal of the balls from the channels requires a considerable amount of outage time. One possible method of eliminating this potential hazard and attendant recurring production loss would be to place stationary sleeves around the horizontal control rods. Liners or sleeves in the vertical ball and rod channels would prevent future leakage of balls into the moderator but would not eliminate the potential for balls already in the moderator to enter the horizontal control rod channels. For either horizontal or vertical liners it would be desirable to use an uncooled material which could withstand the reactor environment and which would not adversely affect the operation and production capacity of the reactor.

At the request of Reactor Modification Design, FES, the nuclear properties of five different materials have been reviewed to determine the maximum temperature which might be attained by each material when used as an uncooled sleeve, the effect each would have on the reactivity of the reactor, and the effect of each on the control capacity of the horizontal rod system. The five materials considered were: Inconel, a 300 series stainless steel, Zircaloy-2, aluminum oxide, and zirconium silicate. The mechanical and corrosion properties of these materials have not been considered.

SUMMARY

The results of this study are summarized in Table I. The metal sleeves were considered to be cylinders with an outside diameter of 3.5 inches; the wall thickness was varied as noted. The NPR process tube, which was an outside diameter of 3.25 inches and a wall thickness of 0.25 inches has been included for comparison. The ceramic sleeves were assumed to be rectangular with 0.15 inch walls as shown in H-1-24677 and were assumed to contain graphite saddle blocks as shown in H-1-24678. Heat generation was assumed to be 0.35 watts per gram in the ceramic and zircaloy, 0.25 watts per gram in the graphite, and 0.5 watts per gram in the Inconel and stainless. To estimate the range of temperatures which might be attained by an uncooled sleeve, graphite temperatures up to 700°C were assumed. Cooling was considered to

* Required by Process Standards to be dropped once a year to check ball hopper functionability.

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be to the stack (that is the rod was assumed to be withdrawn from the reactor). The production losses shown in Table I are those which are associated with the decreased conversion efficiency and increased cost of the enriched uranium required to compensate for the sleeves and do not include outage time nor capital costs required for the installation of the sleeves. All of the materials, excluding zircaloy-2, would be expected to withstand the reactor environment satisfactorily; the use of zircaloy-2 would depend on an assessment of the required physical and mechanical properties.

TABLE I
Summary of Results

	Wall Thickness (inches)	mk worth (20 sleeves)	Approximate production loss, \$/yr	Effect of Sleeves on HCR Strength	Maximum Estimated Temp. °C
Inconel	0.12	11.3	\$1,130,000	Large loss	805
	0.06	5.7	570,000	loss	755
	0.03	2.9	290,000	Small loss	730
Stainless steel	0.12	7.8	780,000	Large loss	790
	0.06	4.0	400,000	loss	745
	0.03	2.0	200,000	Small loss	725
Zircaloy-2	0.12	0.22	22,000	Small effect	790
	0.06	0.11	11,000	Small effect	745
	0.03	0.06	6,000	Small effect	725
NPR Process Tube	0.25	0.41	41,000	Small effect	830
Zirconium Silicate	0.15	0.17	17,000	Small loss	725
Aluminum Oxide	0.15	0.37	37,000	Small loss	740

DISCUSSION

A. Reactivity Effect of Sleeve Materials

The loss in reactivity caused by the installation of the various sleeves was estimated by assuming the material to be homogeneously distributed throughout the moderator and determining the change in thermal utilization of the lattice cell. In equation form the reactivity loss, ρ , is simply:

$$\rho = - \frac{\Sigma_p}{\Sigma_u + \Sigma_m}$$

where Σ_p is the flux-weighted macroscopic cross section of the sleeve material, Σ_u is the flux-weighted macroscopic cross section of the uranium and Σ_m is the flux-weighted macroscopic cross section of the graphite moderator, water and aluminum process tubes and cans combined. The flux weighting factors are based on cell calculations of the K reactor lattice. Since the sleeves were assumed to be located in the moderator or high flux region of the cell, the weighting factor used for the sleeve materials probably overestimates the effect of the more highly absorbing sleeves. Table II summarizes the values used in these calculations. The volume of the active zone was taken to be 6.098×10^7 cubic inches.

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TABLE II
Summary of Reactivity Calculations

	Volume Cubic Inches	Volume Percent	Σ 2200 cm-1	Flux Weighting	Σ eff cm-1	Reactivity loss - mk
Graphite	5.61×10^7	92.00	0.000273	1.7	4.27×10^4	
Aluminum	6.84×10^5	1.12	0.01384	1.45	2.25	
Water	6.82×10^5	1.12	0.0221	1.45	3.59	
Uranium	1.42×10^6	2.32	0.3672	1.0	85.19	
Inconel	1.11×10^4	.018	0.392	1.5	1.07	11.3
	5.64×10^3	.0092	0.392	1.5	0.541	5.7
	2.84×10^3	.0047	0.392	1.5	0.278	2.9
Stainless	1.11×10^4	.018	0.274	1.5	0.748	7.8
	5.64×10^3	.0092	0.274	1.5	0.378	4.0
	2.84×10^3	.0047	0.274	1.5	0.195	2.0
Zircaloy-2	1.11×10^4	.018	0.0078	1.5	2.13×10^6	.22
	5.64×10^3	.0092	0.0078	1.5	1.08	.11
	2.84×10^3	.0047	0.0078	1.5	0.54	.06
NPR Tube	2.05×10^4	.0336	0.0078	1.5	3.93	.41
ZrSiO	1.55×10^4	.025	0.00422	1.5	1.60	.17
Al2O3	1.55×10^4	.025	0.00924	1.5	3.50	.37

B. Effect of Sleeves on Control Rod Strength

The strength of a control rod is a complex function of its size and the size of the opening in which it is placed; it is also dependent on the neutron absorption properties of the rod as a function of incident neutron energy and the neutron energy spectrum in which it is placed. Because of the difficulty and time required to make a detailed analysis of the effect of each of the many postulated sleeves on the strength of the existing control rods, a first order approximation of this effect has been made by considering only the relative transmission of thermal neutrons through the various sleeves. For these calculations the method of Wachspress (1) was used in which the fraction of incident neutrons which penetrate a thin slab of material is given by:

$$T = 1 - 2\xi_t f(\xi_t) + \xi_s f(\xi_t) E$$

where T is the probability that an incident neutron will pass through a slab prior to reflection or absorption, ξ is the product of the macroscopic cross section and the slab thickness (the subscript t signifies total cross section values and the subscript s is for scattering cross section values), the f function is a self shielding factor for slab geometry which is

(1) E. L. Wachspress "Thin Regions in Diffusion Theory Calculations", NSE, 3, 186-200 (1958).

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graphed in reference 1, and E is the probability that a neutron will escape from the slab prior to being absorbed and is given by:

$$E = f(\xi_t) / \left\{ 1 - \frac{\Sigma_t}{\Sigma_t} [1 - f(\xi_t)] \right\}$$

The base condition was taken as the present case which includes the graphite saddle blocks which form the sliding surface for the rods. Removal of these blocks would increase the rod strength by 21% based on the method employed. This value is obviously an overestimate of the actual effect which would result. Materials such as graphite which have relatively large scattering cross sections and essentially no absorption cross sections reflect a large fraction of the incident neutrons. However, these neutrons are not absorbed and have a high probability of being reflected toward the rod again and again. Thus, the above transmission equation will overestimate the effect of removing or adding sleeve materials which are primarily scattering media but should realistically estimate the effect of materials with significant absorption cross sections. Table III presents the data used in estimating the effect of the sleeves on the rod strength and the conclusions which were reached.

TABLE III
Effect of Sleeves on Control Rod Strength

Sleeve	Thickness cm	Cross Sections			Probabilities			Estimated Effect on Control Strength
		Σ_s (cm ⁻¹)	Σ_a	$f(\xi_t)$	E escape	R reflec- tion	T trans- mission	
Graphite saddle	2.11	.385	.385	.43	1.0	0.35	.65	Base
Inconel	0.30	1.255	1.65	.58	.852	.186	.666	Large Reduction
	0.15			.70	.921	.121	.800	Significant Reduction
Stainless	0.076			.80	.943	.072	.871	Small
	0.30	.833	1.16	.63	.876	.146	.730	Large Reduction
	.15			.76	.930	.094	.836	Small Reduction
Zircaloy	.076			.86	.963	.055	.908	Small
	.30	.335	.343	.83	.996	.083	.913	Small
	.15			.92	.998	.046	.952	Small
NPR tube	.076			.97	.999	.024	.975	Small
	.635			.72	.991	.152	.838	Small
Zirconium silicate	.38	.271	.275	.83	.996	.085	.911	Small
Aluminum oxide	.38	.329	.338	.80	.994	.099	.895	Small

It is concluded that Inconel or stainless sleeves which are more than about 0.030 inches thick would reduce the rod strength more than would be desirable and in some cases more than could be tolerated from the operating standpoint. None of the other sleeve materials or arrangements should affect the strength of the control system significantly. These conclusions are based on the relative escape probabilities of the sleeve materials in addition to the relative transmission factors.

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C. Maximum Sleeve Temperatures

A control rod sleeve would generate heat because of the nuclear radiation which it would absorb. If a liquid or gaseous coolant were not used to remove this energy from the sleeve, the temperature of the sleeve would rise until the energy could be dissipated to its surroundings. The maximum temperature which the sleeve would attain would be dependent on the heat generation rate, the efficiency of the heat removal process, and the temperature of the surroundings. The following assumptions were made:

1. The HCR was assumed to be withdrawn from the reactor so that no internal cooling would take place.
2. Only equilibrium conditions were considered.
3. There would be no heat transfer by conduction either through the contact points with the graphite or through the gas.
4. Sleeves with 1/8 inch clearance or less between the sleeve and graphite would prevent convective cooling currents. In the case in which convective cooling was possible (5% of the NPR process tube heat was removed by convection) the convective heat transfer medium was considered to be helium.
5. The view factor for radiation was considered to be unity in every case. In order that the range of temperatures which the sleeves might attain could be estimated, calculations were made for the adjacent graphite at both 400°C and 700°C. These temperatures are not necessarily the upper and lower limit of the graphite which might surround the sleeve but should bracket the range which would exist most of the time. The physical constants of the materials which were used are in Table IV.

TABLE IV
Physical Constants and Temperatures of Sleeve Materials

Material	Thickness (mils)	Density g/cc	Heat gen watt/gm	Volume* Cu. Ft.	Transfer Area	Emissivity	700. °C	400 °C
Inconel	30	8.5	0.5	0.069	27.4	0.50	730	480
	60			.133			755	535
	120			.265			805	620
Stainless	30	8.0		.069		0.55	725	470
	60			.133			745	520
	120			.265			790	605
Zircaloy	30	6.6	0.35	.069		0.31	725	470
	60			.133			745	520
	120			.265			790	605
NPR tube	250			.420	25.6		830	680
Zr-Si	**	2.95	0.35	.370	37.6	0.92-8	725	485
Al-O	**	3.6	0.35	.370		0.63	740	505
Graphite	**	1.6	0.25	.600	—	0.98	—	—

* Volume and Transfer area are given for a sleeve length of thirty feet.

** Ceramic sleeve and graphite saddle block dimensions used are those given in prints H-1-24677 and H-1-24678.

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D. Conclusions

From the standpoint of the nuclear properties of the materials considered in this report, either zircaloy or one of the ceramics would be the best choice for the sleeve material.. Inconel and stainless should not be considered in thicknesses greater than about 30 mils because of their effect on the control system. The physical properties of these materials at the temperatures calculated should be considered in the design of a rod sleeve. For example, it is known that zircaloy loses much of its strength and is subject to rapid corrosion processes at elevated temperatures.

An evaluation of the physical properties of these materials and the acceptability of operation at the expected temperatures has been made by M. C. Fraser and is reported in a letter to E. R. Rudock dated November 28, 1960..

W. L. BunchJ. D. Ogar

Reactor Design Analysis

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