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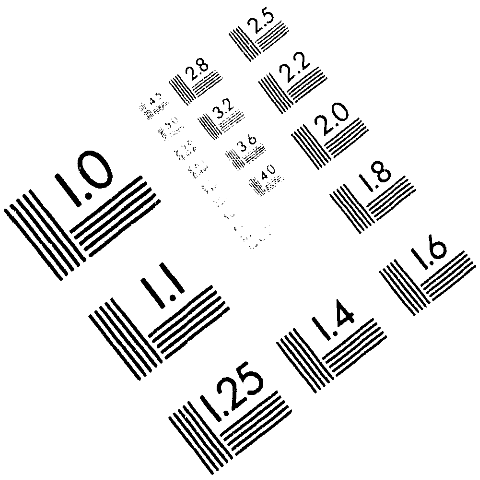

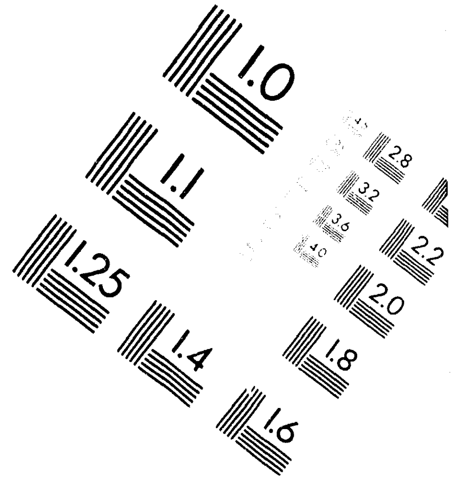

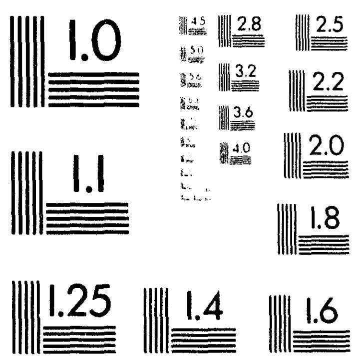

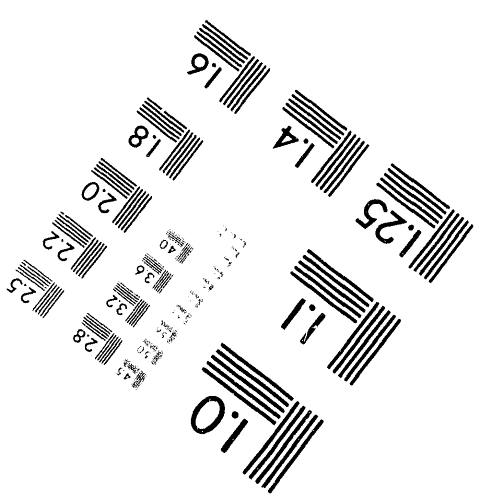

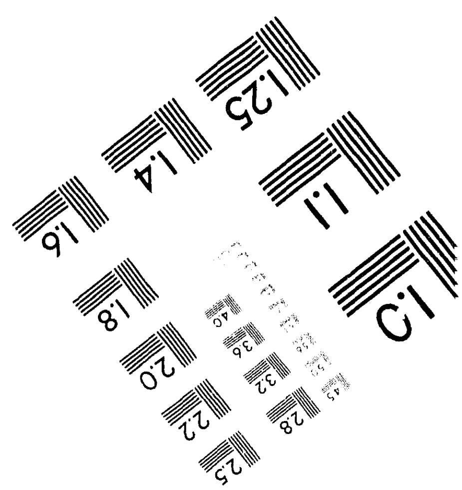

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HORIZONTAL CONTROL ROD CORROSION - KW REACTOR

AUTHOR

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HORIZONTAL CONTROL ROD CORROSION - KW REACTOR

by

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HORIZONTAL CONTROL ROD CORROSION - KW REACTOR

INTRODUCTION

On September 19, 1961, the #3 horizontal control rod at KW reactor was removed after an apparent failure of the wall separating the boron carbide powder from the coolant water.

The instrument indications that were interpreted as a rod failure include: high radiation alarms in the exhaust air, unexplained gain in reactivity, increasing coolant outlet temperature on #3 HCR, and high radiation readings of the outlet water from #3 HCR.

The possible reactor safety aspects of such a failure made it necessary to obtain a thorough examination of the rod and inner coolant tube. A complete borescope examination of the rod and partial visual examination of the inner coolant tube have recently been completed.

This document is intended to summarize the inspection results, discuss the safety and costs aspects of a horizontal rod failure, and suggest courses of action for the remaining rods at KE and KW reactors.

SUMMARY

Borescope examination of #3 HCR showed there was no failure of the wall separating the boron carbide powder from the coolant water.[1] There was considerable scale in the rod and one minor (1-2 mil) corrosion pit on the rod wall. The rod and coolant tube are 63-S aluminum.

Part of the inner coolant tube was examined with two severe corrosion pits observed at the "out-of-reactor" end of the tube. One of the pits had penetrated at least 60 mils into the 63 mil wall.

With the discovery of the severe localized corrosion attack on the inner coolant tube, the reactor safety aspects of such corrosion have been reviewed and are presented below:

Corrosion Penetration of Inner Coolant Tube

If corrosion penetration of the tube opened up a flow area greater than 0.2 square inch, enough of the coolant would by-pass the tip section that boiling and rod melting might occur if the rod were operating deep in the reactor.[2]

If a vapor lock occurs in the rod, the displacement of the water will cause a decrease in the poison strength of the rod. The pile reactivity increase accompanying a total vapor lock in a fully inserted rod would be about 30 cmk,[3] and would cause a power level increase of 200 MW[3] if no compensation is made

[1]Diagram in appendix.

[2]Calculation in appendix.

[3]Personal communication with R. A. Chitwood, Physicist, Pile Physics Unit, Operational Physics Sub-Section.

by inserting other horizontal rods. This power level increase would cause a 4 C increase in bulk outlet water temperature. If reactor bulk outlet temperature was at the 95 C limit prior to such an occurrence, the maximum surge to 99 C would still be one-half degree below the top of downcomer saturation temperature, so no downcomer damage would be expected. The local power effect could cause a rupture outbreak or may cause the tube outlet temperatures to exceed top-of-annulus boiling or trip-after-instability limits.

Once rod melting occurred, the water would break through the rod wall and pour into the graphite stack. Depending on the amount of water leak into the stack and the degree of dispersion of the boron carbide powder, a reactivity gain or loss could occur. The operator at the console might shut the reactor down due to the reactivity increase from the vapor lock, or, in any event, would shut the reactor down as soon as the melting occurred since the rod pressure would go to zero and annunciation would be received. It is unlikely that any safety compromise would occur.

The costs of such a rod failure may run up to $210,000 including outage costs, rod replacement, channel rehabilitation, and enrichment compensation costs.

Corrosion Penetration of Rod Inner Wall

If corrosion attack should occur on the rod inner wall (same alloy as the coolant tube), small amounts of boron carbide would be carried away in the water. The console operator would see any reactivity gains on several instruments, and could compensate with other rods. If two penetrations of the inner rod wall occurred, a small flow of water could pass through the boron carbide, but the losses would still be gradual. If by some remote occurrence all the boron carbide were lost from one of the two separate chambers, the pile reactivity increase would be 30 cmk.[4] This is equal to the increase predicted for the vapor lock condition discussed before, and would result in the same increase in power level and outlet temperature. Reactor safety should not be compromised.

The costs for a failure of this type would be $150,000 for the outage and $1,500 for replacement of the failed rod, making a total of $151,500.

Corrosion Prevention Recommendations

Recommendations have been received from R. B. Richman, Coolant Systems Development Unit,[5] that outline means of halting or slowing the corrosion attack. The recommendations include: 1) increase flow rates (velocity), 2) maintain shutdown flow equal to operating flow, 3) clean the rods of scale and treat with a sodium dichromate solution, 4) add dichromate to the system at any time that low flows are unavoidable. Richman also suggested examination of other control rods and the use of more corrosion resistant

[4]Personal communication with R. A. Chitwood, Physicist, Pile Physics Unit, Operational Physics Sub-Section.

[5]Letter, R. B. Richman to D. L. Renberger, March 5, 1962.

[redacted]

material for fabrication of any new horizontal rods.

Rod Replacement Recommendations

Failure no. 7

Records show the outlet temperature of #3 rod was 52.8 C ten days before its failure.[6] It had the second highest outlet temperature of the 20 horizontal rods, with only five other rods having outlet temperatures greater than 40 C. The reactor physicist indicates the same six horizontal rods are usually run deep (more than 75 per cent into the reactor), and so would all have similar temperature history. A check of the temperature data on March 3, 1962, confirms the consistent position and outlet temperatures of these six rods.

Since the #3 rod was observed to have high corrosion and it is known that the corrosion rate increases with temperature,[7] it would be advisable to replace rods with similar operating history at an early date (provided, of course, the rod has not been replaced in the past year or two). The cost of replacing a single rod is only $1,500, and when compared with the possible outage costs of $150,000 or channel rehabilitation and enrichment costs of $59,000, it is clear that early replacement is advisable.

The following table shows the rods with similar high temperature history.

Rod Number	Type	Recommended for Replacement
2	Full	Yes
3	40%	No - replaced 9/19/61
10	60%	Yes
11	40%	No - replaced early in 1961.
18	60%	Yes
19	Full	Yes

In summary, two full poison rods (2 and 19) and two 60 per cent rods (10 and 18) should be replaced as soon as possible, with a total estimated cost of $6,000.

Applying the same reasoning to the KE reactor, rods 9 and 19 should be replaced as soon as possible. The number 19 rod is a full poison rod and 9 is a 60 per cent. Total cost of replacement is $3,000.

Failure Detection Recommendations

In addition to the above recommendations, the following items are suggested for improving failure detection: 1) a filtered sample of the outlet water should be taken periodically to detect boron carbide, 2) methods of in-pile testing of the rods for corrosion be studied (for example, the inner coolant tube could be probologged), 3) pressure test the rods that operated deep in

[6] See temperature data in appendix.
[7] Personal communication with R. B. Richman, Coolant Systems Development Unit.

the reactor on any outage following an increased water collection rate, and 4) make routine comparisons of heat generation and rod worth to detect loss of the boron carbide.

DISCUSSION

Rod Failure Indications

On September 19, 1961, high radiation alarms were received from the exhaust air system. One and one-half hours later a gain in reactivity was experienced that was not explainable by control rod actions. The exit temperature of #3 HCR was observed to be at 60 C and increasing about 0.1 C every three to four minutes. A radiation survey of rod outlet water showed #3 rod at 900 mr compared to 150-250 mr for the other rods.

From the above observations it was believed that the rod had an internal rupture and the boron carbide was washing out into the coolant water. The reactor was then shut down and the rod removed and placed in a shielding cave.

Examination of #3 HCR

The inner coolant tube was removed and the rod borescoped. No penetration into the boron carbide cavity was found, but the examination was hampered by large amounts of scale and crud. (Some of this "crud" was analyzed and no boron was present.)[8] The rod was then cleaned with a 45-minute soak of Turco 4306-C, then back-flushed with water. Extremely dirty water and many chunks of scale came out of the rod during the flush. A second borescope attempt was then made but was halted when water was encountered in the rod. The rod was then cleaned with a wire brush, the water emptied and a third borescope made. This final borescope allowed good examination of the rod and no penetration into the boron carbide cavity was found. The rod inner wall was in good condition with only a possible 1-2 mil corrosion pit. Considerable scale was still present near the tip end, but did not hamper the examination.

The full length of the inner coolant tube was not examined due to the danger of contaminating the area with the highly radioactive scale.

In lieu of a full inspection, a four-inch sample was cut from each end of the coolant tube and sent to Component Testing for examination. The sample from the "out-of-reactor" end of the tube had an isolated corrosion pit that had penetrated at least 60 mils into the 63 mil wall. The pit was about 1/4 inch in diameter and was on the outside of the tube. The remainder of the four-inch sample was in very good condition with no uniform or pitting type corrosion apparent.

Subsequent examination of the tube on either side of the corroded location showed another isolated corrosion pit 1-1/2 feet away that measured 40 mils in depth.

---

[8] Spectrochemical Analysis Report of crud from #3 HCR, KW Reactor - February 13, 1962.

The sample cut from the "in-reactor" end of the tube had heavy scale present, but was cleaned and found to be free of corrosion.

About 75 per cent of the inner coolant tube has not been examined, there may be more corrosion pits or even locations of complete penetration.

Looking back at the rod failure indication in light of the visual examination results, the following events could have occurred:

1. There may have been a penetration of the inner coolant tube with boiling present in the tip section. The boiling action could have loosened scale from the rod wall, causing the high radiation readings on the outlet hose.

2. Scale from the rod wall could have partially plugged the outlet orifice.

Possible Rod Failure Mechanisms with Associated Hazards and Costs

Corrosion Penetration of the Inner Coolant Tube

This type failure could be costly since a short circuit of the coolant to the tip would occur with possible boiling and rod melting.

Calculations[9] show that a 1/2-inch diameter penetration in the inner coolant tube would reduce flow to the tip enough to allow boiling in a fully inserted long rod. Once boiling started, a vapor lock could occur that would allow the rod to boil dry.

If a vapor lock occurs in the rod, the displacement of the water will decrease the poison strength of the rod. The pile reactivity increase accompanying a total vapor lock in a fully inserted rod would be about 30 cmk[10] and would cause a power level increase of 200 MW,[10] if no compensation is made by inserting other horizontal rods. This power level increase would cause a 4 C increase in bulk outlet water temperature. If reactor bulk outlet temperature was at the 95 C limit prior to such an occurrence, the maximum surge to 99 C would still be one-half degree below the top of downcomer saturation temperature, so no downcomer damage would be expected. The local power effect could cause a rupture outbreak or may cause the tube outlet temperatures to exceed top-of-annulus boiling or trip-after-instability limits. Once rod melting occurred, the water would break through the rod wall and pour into the graphite stack.

Depending on the amount of water leak into the stack and the degree of boron carbide dispersion, a reactivity gain or loss could occur.

The operator at the console would shut the reactor down as soon as the melting occurred, as the rod pressure annunciator would sound when the outlet pressure went to zero. It is unlikely that any safety compromise would occur.

---

[9] See appendix.

[10] Personal communication with R. A. Chitwood, Physicist, Pile Physics Unit, Operational Physics Sub-Section.

Costs associated with such a failure would be:

1.	Removal and replacement of failed rod	$ 1,500
2.	Loss of production due to outage[11]	150,000
3.	Channel rehabilitation[12] (at a later outage)	50,000
4.	Enrichment compensation for boron carbide scattered in bottom on channel[13]	9,000
	TOTAL	$210,500

Corrosion Penetration of the Rod Inner Wall

Since both the inner coolant tube and the rod inner wall are of 63-S aluminum, the same corrosion pitting observed on the tube may also occur on the rod wall and penetrate to the boron carbide powder. Once this penetration occurred, water would fill the voids in the carbon carbide powder and pass on through the magnesia packing and out the weep hole. The water from the weep hole would collect in the inner rod room thimble and may eventually run back into the plenum and down into the drip legs. Free hydrogen and oxygen would be formed as soon as the water contacts the boron carbide,[14] but should escape through the penetration back into the coolant or out of the weep hole. Small amounts of ~~carbon~~ boron carbide would be carried away in the coolant water, but even if a series of penetrations occurred, the amount carried away should be small enough that the operator at the console can compensate for a reactivity gain. If by some remote occurrence, all the boron carbide were lost from one of the two separate chambers, the pile reactivity increase would be 30 cmk.[15] This is equal to the increase predicted for loss of water to a rod due to a vapor lock. The consequences of such an increase were discussed in the previous section, "Corrosion Penetration of Inner Coolant Tube."

The costs associated with corrosion penetration of the rod inner wall would be about $151,500, including $1500 for a new HCR and $150,000 outage costs.

Detection of Rod Failure

Penetration of Rod Inner Wall With Boron Carbide Being Carried Away by the Water

Presently there are three methods of monitoring the status of the rod coolant water, but none of these would detect this type failure.

[11] Assumes $50/gram, 78 per cent production efficiency, bulk limited operation.

[12] Based on overbore and VSR rehabilitation experience, the cost of cleaning out an HCR channel may be $20,000 to $50,000.

[13] Assumes 30 cmk poison, with 6 E^2 tubes compensation at cost of $1500/tube year. This $9,000 cost would probably continue ten to fifteen years.

[14] MMPP-110-2, "Deformation of Ford Nuclear Reactor Shim-Safety Rods, December, 1960.

[15] Personal communication with R. A. Chitwood, Physicist, Pile Physics Unit, Operational Physcis Sub-Section.

1. Rod Outlet Pressure

The pressure just upstream of the outlet orifice is monitored continuously and is indicated by a Panellit gauge set to give high and low trip annunciation upon reduction of flow to eight gpm. Reactor shutdown is required when such annunciation is recieved and verified.

The boron carbide carried away in the water should have no effect on the pressure readings and would go undetected by this monitoring system.

2. Rod Outlet Temperature

This variable is read out once an hour by a manual potentiometer. The maximum rod temperature is then recorded with the other hourly readings. Increasing the frequency of data recording or even a continuous printout would not be of value since the power generation varies with flux level and rod position, and both of these change fairly often during routine operation.

3. Rod Outlet Water Activity

One chamber is located near the rod outlet downcomer, but the B_4C will not be more radioactive than the water or the scale that would flake off the inside of the rod, so no failure would be detected.

Penetration of Inner Coolant Tube

Penetration of the inner coolant tube would allow some water to by-pass the tip section, but the total flow through the system would remain essentially unchanged unless rod wall melting occurred. The potential for detecting this type failure by one of the three monitoring systems is discussed below:

1. Rod Outlet Pressures

Since this pressure is monitored at the outlet of the overall rod-hose system, only real flow changes to this point would be detected.

A short circuit in the cooling tube would not significantly affect the overall pressure drop in the system[16] and therefore no detectable flow change would occur and no change of the pressure at the outlet orifice. Only if a vapor lock resulted in considerable back pressure would the failure be detected before the rod melted.

Once the rod melted, the pressure at the orifice would drop to zero and annunciation would be received.

2. Rod Outlet Temperature

A short circuit of the flow might not result in any change in temper-

[16] See Appendix, Section E.

ature at the point of measurement since it is more than 50 feet from the point of water and vapor mixing. Minor fluctuations in temperature would not be noticed on the present readout system.

3. Rod Outlet Water Activity

   A short circuit in the flow stream would not have any effect on the outlet activity.

Corrosion Control Methods

Recommendations for corrosion control were requested and received from R. B. Richman, Coolant Systems Development Unit, HLO. Five specific recommendations were received and are presented below with comments on each added by the writer of this document.

1. Maintain continuous and increased flow of water through the control rod cooling channels.

   Maintaining continuous flow during shutdown equal to the operating flow would require piping modifications. Some possibilities are:

   a. Using water from the crosstie.

   b. Using filtered water--would have to provide for dichromate addition.

   The increased flow possibilities are not promising for the following reasons: Maximum allowable supply pressure on the HCR's is 150 psi. Present supply is 126 psi resulting in about 12.75 gpm average flow per rod. Increasing the supply pressure to 150 psi and removing the two outlet orifices would increase the average flow to 15.2 gpm with the velocity increasing from 3 fps to 3.8 fps* in the annulus. Richman suggests velocity increases from two to four times present velocity would be necessary to halt the corrosion.

2. "Clean existing flow channels and treat with a sodium dichromate solution."

   This can be done and should be actively pursued. One possible problem may be the loosening of large amounts of scale that could later break loose and plug the outlet orifice.

3. "After the initial treatment, add dichromate to the system at any time that low flows are unavoidable."

   This should be possible and would be superior to attempts at increasing the flow during shutdown.

*See calculation in appendix.

[redacted]

4. "Examine any other control rods that are removed during the next several months."

   KE has recently removed an HCR that could be examined. Processing Operations should devise a method of cleaning the highly radioactive scale from the inner coolant tube so it can be visually examined along its entire length to determine the extent of corrosion attack.

5. "Consider the use of alclad tubing for fabrication of any new rod cooling systems that are installed."

   This is being investigated by Reactor Modification Design as part of a design program for new K reactor horizontal rods.

Specific Recommendations

Process Engineering concurs with the recommendations presented by Coolant Systems Development and suggested these further steps be considered:

1. The rod that normally run deep (with resulting high outlet temperatures) should be replaced at an early date. Since the galvanic type corrosion is temperature dependent[17] and the #3 HCR was a high heat generation rod, it would be desirable to replace other rods with the same operating experience, as soon as possible. Some of the rods replaced should be inspected to determine their condition. Rods recommended for replacement are:

KW Reactor		KE Reactor	
Rod No.	Type	Rod No.	Type
2	Full poison		
10	60% poison	9	60% poison
~~18~~	~~60% poison~~	19	Full poison
19	Full poison		

2. At the present time, it appears that there are no available methods of monitoring severe corrosion on the inner coolant tube. A probolog type inspection of the rods should be considered and evaluated.

3. Several methods are available for detecting a corrosion penetration of the rod inner wall, but at present, such monitoring is not being done. Some methods suggested are:

   a. Take filtered samples of the rod outlet water and have them analyzed for boron content.

   b. Any time the water collection in the reactor increases, pressure test of the hottest rods should be scheduled on the next outage.

*Personal communication with R. B. Richman.

c. Periodic comparisons of heat generation versus cmk worth of the rod should be made. Any time the heat generation rate falls below that expected, partial loss of the boron carbide may be suspected and the rod should be pressure tested.

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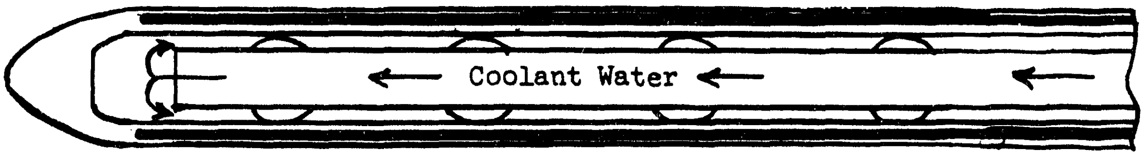
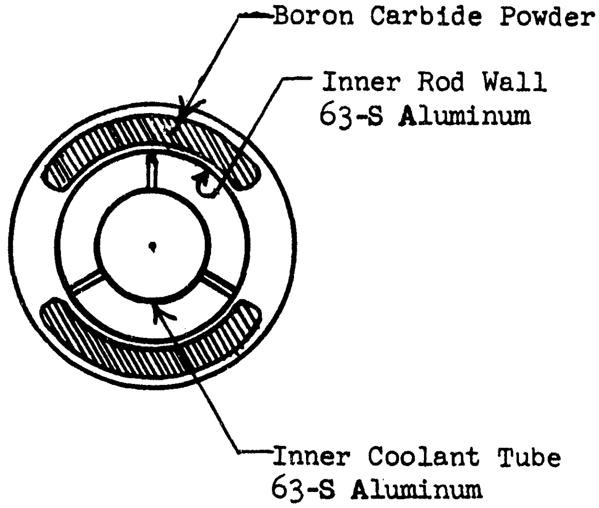
APPENDIX

A Diagram of horizontal control rod





B. Pressure drop through HCR

1. Inner coolant tube - O.D. = 1.000"
   W.T. = 0.063"
   I.D. = .874" - .073 ft.
   Flow area = .00417 ft^2

Flow	Velocity	Re	Friction Factor	Head Loss
12 gpm	6.4 ft/sec.	4.35×10^4	.021	8.25 ft.
4 gpm	2.1 ft/sec.	1.45×10^4	.028	1.23 ft.

2. Annulus - O.D. = 1.625"
   I.D. = 1.000"
   Flow area = .00895 ft^2
   Hydraulic radius = .013 ft.

Flow	Velocity	Re	Friction Factor	Head Loss
12 gpm	3 ft/sec.	1.47×10^4	.042	5.1 ft.
4 gpm	1 ft/sec.	4.92×10^3	.048	0.65 ft.

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C. Calculation of flow and velocity increase available by increasing supply pressure and removing the outlet orifices.

Present conditions

Supply Pressure = 126 psi (control room)
Exit Pressure = 26 psi (control room)
Delta Pressure = 100 psi
Average Rod Flow= -12.75 gpm
Annulus Velocity= 3 ft. per second

$$(\text{Flow})^{1.85} = K \text{ (Delta Pressure)}$$
$$K = 1.12$$

Proposed conditions

$$(\text{Flow})^{1.85} = 1.12\ (150-13)$$

150 psi - maximum allowable supply
13 psi - static leg at zero outlet pressure

Flow = 15.2 gpm
Annulus velocity = 3.8 ft/sec.

Maximum outlet temperature would be lowered by 8 C, but velocity increase of only 0.8 ft/sec. would not be significant from the corrosion standpoint.

D. Calculation of effect of leak in inner coolant tube.

At 12 gpm flow, the head loss from inlet to the tube to outlet of the annulus is 13.5 feet of water.

Assuming loss of one velocity head,

$$\text{Loss} = \frac{V^2}{2g}$$

$$\text{Velocity} = \sqrt{13.5(64.4)} = 29.5 \text{ ft/sec.}$$

For a 1/2-inch hole in the tube (0.2 in^2), by trial and error, the flow through the hole is 7.7 gpm and through the rod tip is 4.7 gpm.

Assuming a 150 kw maximum heat generation in any rod, and a 65 psi absolute pressure in the rod, the saturation temperature of 298 F would be exceeded if the flow through the tip section is about 4 gpm.

E. Since the pressure drop in the rod is only 5-6 psi, a complete short circuit of flow so that none passed through the rod tip would not significantly affect the total flow. The pressure drop through the rest of the system is 95 psi and is the major flow controlling factor.

[redacted]

FIGURE-1

REACTIVITY INCREASE DUE TO LOSS OF BORON CARBIDE FROM A HORIZONTAL ROD--K REACTORS.

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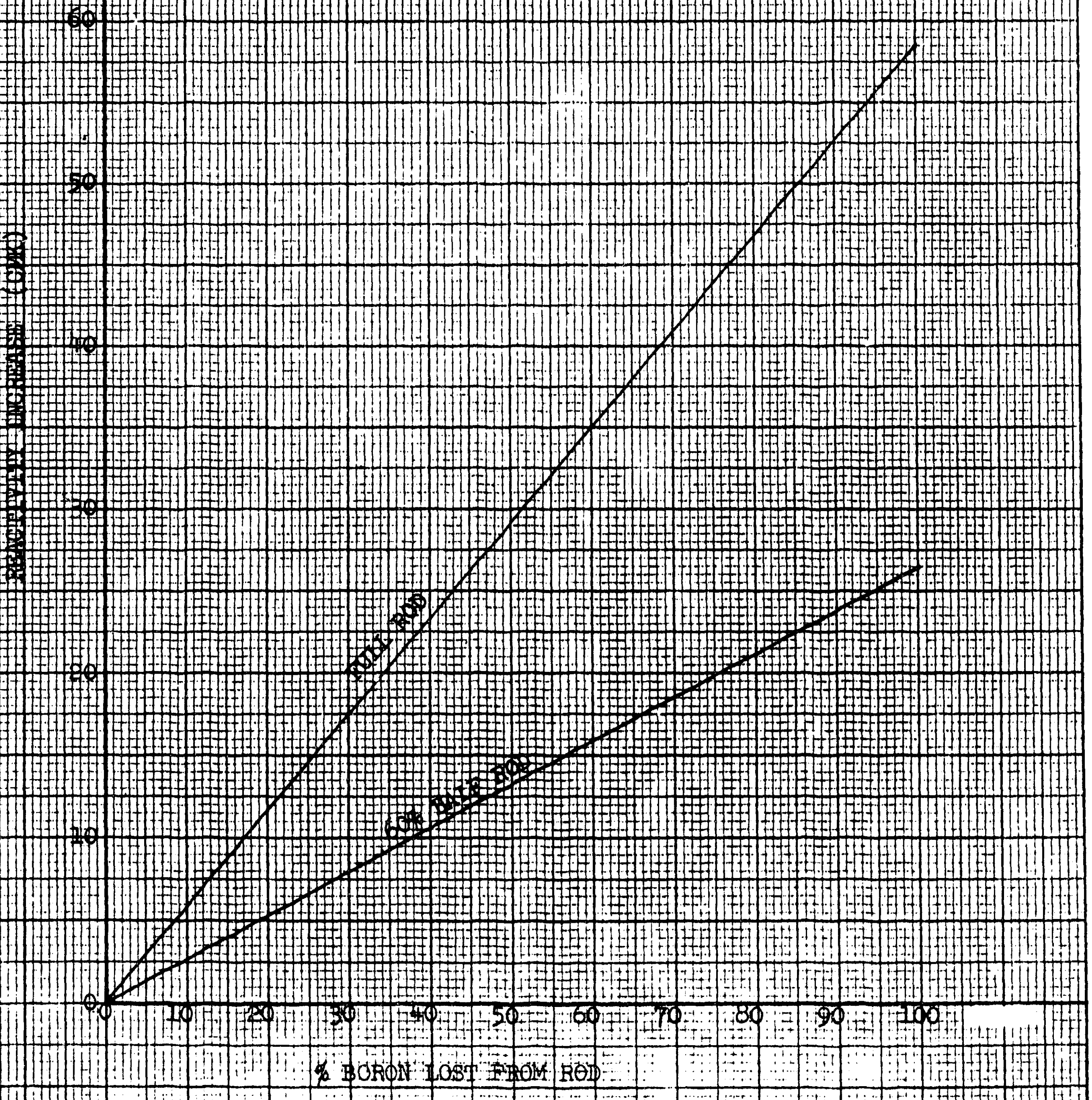

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F. Horizontal Rod Heat Generation

September 9, 1961

Pile Power Level - 3200
Inlet Temperature- 18.8 C
Rod Supply Pressure - 120 psi

Rod	Type	Percent Out	Outlet Temp. °C	Delta Temp. °C	Flow GPM	Power KW	CMK
1		70	28.2	9.4	12.5	31	45
2		24.5	45.0	26.2	13.4	92	119
3	60%	8.1	52.8	34.0	12.4	111	64
4		84.8	23.8	5.0	12.4	16	18
5		100	19.8	---	12.2	---	---
6		100	19.8	---	11.4	---	---
7		87.5	23.0	4.2	11.2	12	8
8		100	19.8	---	10.0	---	---
9		67	31.8	13.0	11.8	40	38
10	60%	20.5	43.0	24.2	13.0	82	69
11	40%	18.0	43.4	24.6	14.0	90	46
12		100	19.8	---	10.4	---	---
13		100	19.8	---	11.0	---	---
14		100	19.8	---	11.0	---	---
15		12.1	32.6	13.8	12.6	46	78
16		88.4	22.0	3.2	12.4	10	13
17		89.0	21.8	3.0	12.6	10	12
18	60%	17.2	46.5	27.7	13.4	98	69
19		16.3	54.3	35.5	13.0	122	125
20		50.2	38.5	19.7	13.0	67	84

March 3, 1962

Pile Power Level - 4400
Tube Power - 10 High Natural 1710
Inlet Temperature - 2.7 C
Rod Supply Pressure - 130 psi

1		70	13.6	10.9	13.1	38	45
2		27	35.0	32.3	13.0	111	116
3	40%	16	34.3	31.6	13.0	108	46
4		73	14.5	11.8	12.6	39	38
5		---	3.8	---	13.4	---	---
6		80	8.9	6.2	12.3	20	15
7		94	5.1	2.4	12.3	8	4
8		---	3.7	---	12.6	---	---
9		67	16.2	13.5	12.4	44	38
10	60%	21	32.8	30.1	13.0	103	69

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F. Horizontal Rod Heat Generation (cont.)

Rod	Type	Percent Out	Outlet Temp. °C	Delta Temp. °C	Flow GPM	Power KW	CMK
11	40%	12	32.4	29.7	13.5	106	46
12		---	3.8	---	11.5	---	---
13		---	3.8	---	12.1	---	---
14		---	3.8	---	11.8	---	---
15		66	15.8	13.1	13.0	45	31
16		72	13.4	10.7	13.2	37	40
17		87	6.4	3.7	13.0	13	14
18	60%	21	36.2	33.5	13.3	114	69
19		20	41.0	38.3	13.0	131	123
20		54	23.2	20.5	12.7	69	78

DATE
FILMED
6/17/94

END