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TITLE

REACTOR HAZARDS REVIEW
ZERCONIUM RETUBING OF HANFORD REACTORS

ISSUED OCT 24 1967

AUTHOR

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February 15, 1960

REACTOR HAZARDS REVIEW
ZIRCONIUM RETUBING OF HANFORD REACTORS

R. NILSON

INTRODUCTION

The technology of producing satisfactory reactor-length zircaloy process tubes has now advanced to the point where serious consideration must be given to the possibility of retubing the Hanford reactors with zirconium tubes. One hundred smooth bore zircaloy tubes are to be installed in C-Reactor as early as the end of March 1960. A full pile conversion can be completed as early as the third quarter of FY-61.

The advantages of zircaloy tubes in the existing Hanford reactors has been adequately treated elsewhere.¹ The chief advantages of zirconium over aluminum are lower neutron absorption cross section, better corrosion resistance and great mechanical strength. The latter property permits the use of thinner-walled tubes, thereby enlarging the inside tube volume for increases in fuel size, coolant annuli, or both.

1. HW-54092, "The Economics of Zirconium Process Tubes", L. W. Lang (Secret), December 20, 1957.

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A reactor modification of this magnitude requires close scrutiny of all the factors pertaining to reactor safety. A reactor modification in itself should not worsen the situation with respect to safety; instead the status should be improved if possible. This report reviews all known factors of concern to reactor safety and how they are affected by the retubing modification. Of major interest are the changes in critical physics parameters, changes in the physical properties of the process tubes and changes in possible chemical reactions.

SUMMARY AND CONCLUSIONS

This report examines the pertinent features in the hazards analyses of the Hanford Reactors which may be affected by the substitution of zirconium tubes for the present aluminum process tubes. Resized I & E slugs, designed to preserve present pressure drops across the active zones and to minimize corrosion, are used as examples to compare the characteristics of the zirconium tubes reactor with the present.

The following statements summarize the conclusions reached:

1. The thinner walls of the zirconium process tubes allow sufficient fuel resizing so that it is possible to obtain a reactor lattice configuration which has a higher fuel-to-water ratio than at present. As a consequence, lattices closer to a configuration which is fail-safe* upon loss of coolant can be achieved. If from hydraulics or other considerations, it is desirable to resize fuel elements to decrease the fuel-to-water ratio, the changes in the pertinent physics factors are sufficiently small to pose no problems in the reactors' conforming to the present control criteria on nuclear safety.
2. The high melting point of zirconium should result in definite improvements in overall reactor safety, particularly in the loss-of-coolant accident to a single tube.
3. Zirconium tubes should decrease any hazard of a potential water-metal reaction in the Hanford reactors to below what is already considered an extremely low level of probability.
4. Reactor effluent will be no more (and probably less) radioactive with zirconium process tubes than with existent aluminum tubes. (Present effluent activities are sufficiently low to insure that radiation dosages to users of the Columbia River water are well below National limits for penetrating radiation.)

GENERAL REMARKS

A complete discussion of the Hanford reactors and associated hazards is, of course, out of place in a report of this scope. To assure the reader of adequate background information, he is referred to earlier reports² which cover the pertinent information in great detail.

* At Hanford, the term "fail-safe" describes a reactor lattice configuration that loses reactivity upon loss of coolant.

2. HW-44708 Vol. 1 & 2, "Hazards Summary Report - Projects CG-558 and CG-600, Reactor Plant Modifications", R. E. Trumble (Secret), March 6, 1957.

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However, it is well to briefly summarize the important features of the Hanford reactors, particularly, those aspects relating to the zirconium retubing modification and the hazards associated thereof. The present eight Hanford reactors are large, graphite-moderated, natural uranium reactors, cooled by light water in a once-through process. The present administrative power levels are 1900, 2100 and 4000 MW for the five old reactors (B, D, F, DR, H), C Reactor and the K Reactors, respectively. Aluminum process tubes pierce the reactors front to rear. Present fuel geometries are of the I & E type (internally and externally cooled) and the cladding is 2S aluminum. Twin ribs running parallel to the process tube axes support the slugs so coolant can pass on all sides of the fuel elements.

Control over the chain reaction is exercised by horizontal control rods which enter from one side of the reactor, perpendicular to the axis of the fuel channels. Emergency shut down control is effected by inserting gravity-accelerated safety rods or small boron-steel balls (Ball 3-X System) into vertical reactor channels. The fundamental nuclear and physical processes essential to control and safety such as coolant flow, coolant temperature, and neutron flux are continuously monitored by extensive instrumentation and associated circuitry. Automatic tripping assures reactor shutdown in the event of out-of-limit process variables.

The major hazards associated with any reactor naturally center around the inadvertent release of large amounts of radioactive fission products either to the surrounding countryside or to the confines of the reactor plant alone. The magnitude of the accidental release of fission products ranges from that resulting from a maximum credible accident (complete and permanent loss of coolant to the entire reactor) down to that from a one slug incident in which a small amount of radioactive material is released.

The accidents which must be considered in any hazards analysis are those with some probability (however small) of happening. The loss of coolant accident cannot be ruled out in spite of adequate backup protection in the water plant. An important factor in such an accident (which is unique to the present Hanford-type reactor) is, that under certain conditions, loss of coolant results in a more reactive lattice configuration. This condition imposes important requirements on the ability of the safety control systems. The systems must function properly and rapidly enough so that consequences of the accident are not increased significantly beyond the consequences of the disaster which are inevitable anyway. Thus, it is imperative to critically examine any changes resulting from the proposed zirconium-tube modification which may alter the situation with respect to the reactors' conformance to presently accepted nuclear control criteria governing safety control system response and strength.

The loss of coolant to a single tube must also be examined. In this case, not enough coolant is lost to cause a nuclear excursion as is the case for the maximum credible accident. But, consideration should be given to any changes zirconium tubes might introduce with regard to restoration of coolant to the affected process channel. Inadvertent loss of control over the nuclear reaction must also be considered even though accidental excursions which could lead to gross release of fission products are considered very improbable in the Hanford reactors. Therefore, any way in which the proposed retubing modification affects the reactor operation insofar as an excursion probabilities are concerned should be evaluated.

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DESCRIPTION OF THE ZIRCONIUM TUBE MODIFICATION

To permit the most flexible use of zircalloy process tubes, smooth bore (ribless) tubes have been chosen. The nominal wall thickness of the zircalloy tubes is 40 mils compared to 62.5 mils for the present aluminum tubes. The dimensions are given in Table I for zirconium tubes of the same OD as the present aluminum tubes.

TABLE I

PROCESS TUBE SIZES - ALUMINUM VS. ZIRCONIUM
(All dimensions given in inches)

<u>Reactor</u>	<u>Present Aluminum</u>		<u>Zircalloy</u>	
	<u>I.D.^a</u>	<u>O.D.</u>	<u>I.D.</u>	<u>O.D.</u>
B,D,DR,F,H	1.604	1.729	1.650	1.729
C	1.640	1.764	1.681	1.764
KE, KW	1.680	1.806	1.726	1.806

a. Aluminum tubes are actually oval; ID represents average diameter.

The fact that the thinner wall zirconium tubes widen the present outer coolant annulus by about 22.5 mils opens the way for reactor production increases either by increasing coolant flow and power level or by increasing fuel size and conversion efficiency. The former course of action is not one of concern here since further modifications would be required to increase coolant flow rates and power levels. A separate hazards review would be required for increased power level cases and any conclusions reached there would be essentially independent of the tube material.

The fuel elements shown in Table II have been designed to maintain present pressure drops across the active reactor zones and to provide equal corrosion rates on both the internal and external aluminum clad surfaces of the I&E slugs. These fuel elements will therefore be used in the following discussion as representative of the initial charges for the zirconium tubed reactors. It must not be assumed, however, that these are the only size elements which can be charged. Assumptions involving higher coolant flow would dictate different sizes. But, as previously mentioned, this is a subject separable from the factors unique to the zirconium tube itself.

TABLE II

EXEMPLARY FUEL ELEMENT DIMENSIONS
(All dimensions given in inches)

<u>Reactor</u>	<u>Present Fuel Element</u>				<u>Zirconium Tube Fuel Element</u>			
	<u>Bare Uranium</u>		<u>Canned Element</u>		<u>Bare Uranium</u>		<u>Canned Element</u>	
	<u>I.D.</u>	<u>O.D.</u>	<u>I.D.</u>	<u>O.D.</u>	<u>I.D.</u>	<u>O.D.</u>	<u>I.D.</u>	<u>O.D.</u>
B,D,DR,F,H	0.416	1.356	0.310	1.445	0.476	1.390	0.370	1.480
C	0.481	1.370	0.375	1.460	0.486	1.410	0.380	1.500
KE,KW	0.491	1.370	0.385	1.460	0.526	1.440	0.420	1.530

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There exists an alternative to replacing the present aluminum tubes with zirconium tubes of the same OD. Serious study is being given to overboring the graphite channels in the Hanford reactors to allow retubing with larger diameter zirconium tubes. This alternative is a major undertaking and is now only in an embryonic stage of budget and feasibility study. The conclusions of this report apply only to the non-overbore tube replacement; the subject of overboring plus retubing requires a separate and more exhaustive report.

CHANGE IN PHYSICS PARAMETERS

The substitution of 40 mil thick zircaloy tubes for the present aluminum tubes has only one direct effect on the lattice physics of the reactor and that is a reduction in parasitic neutron absorption. However, there are attendant effects due to changes in the fuel or water volumes (or both), which are more significant.

Temperature Coefficients

The Hanford reactors experience the usual negative Doppler temperature effect. The magnitude of the coefficient is in the neighborhood of $2 \times 10^{-5}/\text{C}$. To a good approximation the metal coefficient is directly proportional to the amount of U^{238} in the reactor lattice cell. For the cases tabulated in Table II, the fuel volumes of the zirconium-tube fuel elements are slightly larger than the present designs resulting in a slightly more negative coefficient. In a wet Hanford reactor, the graphite temperature effect is positive. This is due to the lowering of the neutron temperature in the uranium by the neutron rethermalizing in the water surrounding the slug. Again, the differences in this coefficient over the normal operating temperature range are small between the aluminum and zirconium cases.

Of more importance, with respect to a hazards evaluation, are the temperature coefficients in the dry reactor. The metal coefficient is still negative, but of slightly larger magnitude due to the increased absorption of resonance neutrons in the dry, less-moderated lattice. The graphite coefficient is also negative in the green, dry pile. However, if there is sufficient plutonium in the fuel, the graphite coefficient is known to change sign and become positive at higher temperatures. We can only rely on theory to ascertain the magnitude and sign of the high exposure graphite temperature coefficient at high temperatures. These studies indicate that for a plutonium inventory corresponding to an average pile exposure of 400 MWD/T (which is higher than present average pile exposures) the graphite temperature coefficient approaches zero for graphite temperatures in the neighborhood of 1000-1100 C. (See Figure 1.) The differences between the dry pile coefficients for the present reactors and the exemplar zirconium cases, again, are small. (See Table III.)

Water Loss Reactivity Effect

Paramount in the hazards analyses associated with the maximum credible accident for the Hanford reactors is the effect of coolant loss on the reactivity. Two cases are of interest.

If coolant is lost in a shutdown reactor or one which is beginning a cold startup, there is insufficient energy to cause severe damage coincidental with or immediately following the accident. Of interest here is the maximum dry pile reactivity obtainable. The changes are listed in Table III.

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TABLE III
SIGNIFICANT PHYSICS PARAMETERS

<u>B,D,DR,F,H, Reactors</u>	<u>Example Slug Zirconium Tube</u>	<u>Present Slug Present Tube</u>
Doppler Coefficient (Dry)	$-2.0 \times 10^{-5}/C$	$-2.0 \times 10^{-5}/C$
Graphite Coefficient (Dry-Green) ^a	$-3.7 \times 10^{-5}/C$	$-3.7 \times 10^{-5}/C$
Graphite Coefficient (Dry-Ripe) ^b	$+1.6 \times 10^{-5}/C$	$+1.6 \times 10^{-5}/C$
$\Delta k/k$ on Coolant Loss (Cold)	+30 mk e	+28 mk
$\Delta k/k$ on Coolant Loss (Hot-Ripe) ^c	+14 mk	+13 mk
Change in Cold Dry Pile Reactivity ^d	+2 mk	---
 <u>C-Reactor</u>		
Doppler Coefficient (Dry)	$-2.1 \times 10^{-5}/C$	$-2.1 \times 10^{-5}/C$
Graphite Coefficient (Dry-Green) ^a	$-3.6 \times 10^{-5}/C$	$-3.8 \times 10^{-5}/C$
Graphite Coefficient (Dry-Ripe) ^b	$+1.6 \times 10^{-5}/C$	$+1.6 \times 10^{-5}/C$
$\Delta k/k$ on Coolant Loss (Cold)	+31 mk	+34 mk
$\Delta k/k$ on Coolant Loss (Hot-Ripe) ^c	+14 mk	+16 mk
Change in Cold Dry Pile Reactivity ^d	-2 mk	---
 <u>K-Reactors</u>		
Doppler Coefficient (Dry)	$-2.8 \times 10^{-5}/C$	$-2.6 \times 10^{-5}/C$
Graphite Coefficient (Dry-Green) ^a	$-3.9 \times 10^{-5}/C$	$-4.0 \times 10^{-5}/C$
Graphite Coefficient (Dry-Ripe) ^b	$+1.6 \times 10^{-5}/C$	$+1.6 \times 10^{-5}/C$
$\Delta k/k$ on Coolant Loss (Cold)	+18 mk	+25 mk
$\Delta k/k$ of Coolant Loss (Hot-Ripe) ^c	+1 mk	+6 mk
Change in Cold Dry Pile Reactivity ^d	-5 mk	---

-
- a. Average over temperature range 20-500 C
- b. Average over temperature range 20 -1000 C at 400 MWD/T average pile exposure.
- c. $T_g=450$ C, average pile exposure= 400 MWD/T. Values shown include 3 mk safety factor.
- d. Average pile exposure, 400 MWD/T. Entry represents gain in cold dry pile reactivity over that for present case.
- e. One mk = $10^{-3}\%$ k

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Of greater importance than the cold pile reactivity changes upon loss of coolant is the magnitude of the reactivity jump if water is lost during equilibrium operation. The water loss reactivity function is the dominant factor in the excursion following this type of accident. Fast insertion of safety rods and the negative Doppler coefficient are both required to turn the excursion. For the old pile and C pile zirconium-tubed cases under discussion, the gain in k-excess in the hot, ripe pile is only slightly different than for the present piles. In the particular K reactor case under consideration, a substantial reduction in the reactivity jump is incurred. The pertinent parameters are summarized in Table III.

Other Factors

Factors such as long term gains, xenon inventory and control and safety rod strengths are also dependent on the particular fuel element. However, changes in these factors are so minor for the cases being considered that they have negligible effect on the hazards analyses.

CHANGE IN PHYSICAL PROPERTIES

In addition to the changes in the nuclear characteristics of the reactor one must consider any changes in physical properties introduced by the zirconium tubes. The primary differences are a considerably higher melting point for the tube material, new chemical reactions, and better corrosion resistance.

Higher Melting Point

Aluminum melts at 660 C, zirconium at 1850 C. The low melting point of aluminum guarantees an earlier, permanently subcritical reactor following the maximum credible accident (permanent loss of coolant). The sequence of events is as follows. After loss of coolant, fission product heat is sufficient to raise the temperature of the reactor block beyond the melting point of aluminum resulting in either aluminum melting or the formation of the alloy UAl_3 depending on the rate of heating. Beyond this point continued energy release raises the temperature beyond the melting point of uranium (1133 C) and UAl_3 (1350C) and the gravity flow of molten uranium or UAl_3 through the lattice renders the reactor grossly subcritical. Tests reported in Reference 3, indicate as high as a 70 mk loss in reactivity when uranium fuel columns were redistributed in a manner simulating melting and flowing.

The nature of a meltdown in a zirconium tubed reactor is more difficult to assess. At present, laboratory meltdown tests are being conducted at Hanford to determine the mechanisms involved when the temperature of aluminum-clad uranium fuel elements is raised above the melting point of uranium. Two tests have been made at this time and the results are as follows:

Test 1:

Four one inch aluminum-clad uranium slugs resting in 24 inch sections of semi-circular ribbed Zr-2 process tubing were induction-heated to the melting

3. HW-50284, "Total Control Requirement - Hanford Piles" J. H. Brown, (Secret), May 21, 1957.

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point of uranium. The experiment was performed in a helium atmosphere. The following sequence of events and results were observed: When the temperature of the slug cladding reached the melting point of aluminum, the aluminum cladding quickly melted and puddled on the bottom of the process tube. Upon reaching the uranium melting point, the uranium flowed along the bottom of the process tube. The contact of molten uranium with molten aluminum resulted in a momentary increase in brightness at the contact zone. Power input to the assembly was held high enough to maintain the uranium in a molten state for periods of about 10 and 20 minutes for the tests. Following power cut-off, the helium bleed was continued until the test material was cool enough to remove for inspection. Maximum temperature of the uranium was of the order of 1200 C. Inspection after the test showed that there had been no penetration of the Zr-2 tube. Examination of a polished and etched section showed that very little U-Zr alloy formation occurred during the tests

Test 2:

The second series of meltdown tests is still in progress. In order to achieve higher temperatures with available induction heating equipment, it has been necessary to employ reduced scale fuel slugs and simulated process tube sections. The assembly has been heated to 1400-1450 C (uranium surface temperature as monitored by optical pyrometer) and held for about 30 minutes. After this contact period, there was no positive visual indication of penetration of the melt through the Zr-2. Upon removal of the boat, it was found that sufficient gross interaction between the U-Al alloy and Zr-2 had occurred to render the residual Zr-2 very fragile. There was some indication of a skull formation (comprised presumably of U, Al and Zr) which effectively contained the melt.

One can definitely assume that the zirconium tubes will contain the uranium melt for some time beyond the time the assembly reached 1450 C. Subsequent tests are planned at higher temperatures (up to 1650 C) and for holding periods of sufficient length to establish the presence of high melting phases which can act as melt containers. The additional tests should also identify roughly the temperature level when rapid Zr-U-Al interaction occurs. The phenomena under investigation are complex, involving heat transfer, diffusion, intermetallic compound formation and melting. The reactivity effects associated with the various possible physical effects during the meltdown must also be known in order to assure that the no adverse reactivity changes occur in the meltdown accident which would increase the consequences of the accident. Two effects are immediately obvious which must be considered.

1. The fact that the zirconium tube will contain the melt for sometime beyond uranium melting produces only a partial redistribution of the fuel in the reactor. The puddling of the uranium or UAl_3 in the bottom of the process tube has been demonstrated experimentally to result in a negative reactivity change. The same test referred to earlier⁽³⁾ showed a 5 mk loss for a complete pile of slumped slugs. Therefore the temporary containment of molten uranium or UAl_3 provides a lower reactivity configuration.
2. If one assumes that the zirconium tube will actually contain the melt up until the zirconium tube itself melts at 1850 C (which is unlikely). then careful attention must be given to the effect of possible release of volatile, residual fission product poisons or removal of

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safety control elements from the pile by melting before sufficient uranium redistribution can take place. The evidence of skull formation, which effectively contained the melt in the melting tests previously discussed, gives some assurance of xenon containment beyond the time the uranium has melted. The boron-steel materials which comprise the present vertical safety systems will melt at approximately 1450 C, a temperature above uranium melting but considerably below zirconium melting. It has been demonstrated analytically, however, that loss of xenon or loss of control poison at a fast enough rate to achieve a prompt critical state in the reactor would be extremely difficult to achieve. Discussion on this subject is amplified later in this report.

Water-Metal Reactions

Chemical reactions between water or steam and reactor component metals have never been considered an important source of energy in the Hanford reactors by the very nature of the very limited amount of H₂O available. However, a brief review of possible metal-H₂O reactions is warranted.

The following reactions are of interest.

It is our opinion that both the probability and the consequences of H₂O-metal reactions are reduced if zirconium tubes are substituted for the present aluminum process tubes. The following facts support this conclusion:

- 1) A large specific area (reacting surface per unit weight) of the reactant metals is precluded until after the metal melts. At such temperatures the molecular density of any steam present in the reactor would be relatively low.
- 2) Substantially higher temperatures are necessary for the Zr-H₂O reaction. Thus, less oxidizer (steam) would undoubtedly be present in the reactor atmosphere.
- 3) Volumewise, there would be less reactive metal in the reactor with the thinner walled zirconium tubes.
- 4) The energy release per unit volume of metal of the Zr-H₂O reaction is less than that from either the Al-H₂O or U-H₂O reactions.
- 5) The Zr-H₂O reaction produces less hydrogen per unit volume of reactant metal.

Thus as far as metal-H₂O reactions are concerned, a smaller probability of reaction will exist with zirconium tubes in the reactor than with the present aluminum tubes. In addition, the fact that many of the conditions necessary for metal-H₂O

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reactions are highly improbable in the Hanford reactors, leads to the conclusion that zirconium process tubes will further decrease any metal-H₂O reaction hazard below an already low probability level.

Corrosion Resistance

The excellent resistance of zirconium to corrosion makes it ideally suited to long-life usage in reactors. There are other factors associated with the good corrosion resistance which are somewhat more obscure, but which nevertheless have the potential of improving reactor safety.

1. Increased Water Volume Due to Tube Corrosion

It has already been pointed out that in the present overmoderated Hanford reactors an increase in the water-to-fuel volume ratio worsens the lattice as far as fail-safeness on loss of coolant is concerned. In other words, if the coolant volume is increased without a compensating increase in uranium volume in the Hanford reactors, any gain in reactivity experienced with water loss is increased.

It has been computed that the pile-average outer coolant annulus is widened about three mils by aluminum tube corrosion.⁽⁵⁾ This figure is obtained by averaging the observed corrosion along the process tubes and making reasonable assumptions on the average life of the tubes in the reactor. At the present power levels and fuel sizes, the increase in coolant volume caused by corrosion is not large enough to seriously limit the reactor operation with respect to the safety control criteria. However, for much higher power levels or re-designed fuel elements, this factor would become more important in assessing the reactors' conformance to the criteria.

Zirconium tubes guarantee, by virtue of their good corrosion resistance, a uniform coolant annulus throughout the life of the tube, eliminating any concern for inadvertent water volume increases.

2. Radioactivity of Reactor Effluent⁽⁶⁾

The overall operation of the Hanford Irradiation Processing Department is controlled so that the concentration of biologically-dangerous, radioactive isotopes in the reactor effluent water is sufficiently low to insure that radiation dosages to users of the Columbia River Water are well below National limits for penetrating radiation.

The primary source of radioisotopes in effluent water is impurities in process water, either impurities in the river water or chemicals added in the water treatment process. In the case of aluminum tubes, experience has shown that corrosion accounts for a small fraction of the activity density in effluent water for the radioisotopes of concern. With zirconium, the products of corrosion would be even less.

5. Private Communication from N. R. Miller

6. HW-63853, "The Effect of Zirconium Process Tubes on Radioactivity in Reactor Effluent Water", A. B. Greninger (Confidential) February 9, 1960.

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The impurities in process water do not pass through the reactor with the water. The abundance of radioisotopes in the effluent would be much less if the impurities did pass directly through. Instead a film forms on the walls of the process tubes. The parent elements stick to the film perhaps are an integral part of it, are irradiated and released. The nature of the film surface is a function of the materials carried in the process water rather than the underlying metal. Therefore, changing the tube material from aluminum to zirconium should not cause a significant change in the activity density of radioisotopes in reactor effluent water. Radioanalyses of effluent water from individual zirconium tubes which are now in service support these theories.

If any corrosion of zirconium, (however slight) does add to the activity of effluent water discharged to the river, an increase in the activity densities of Zr^{95} and Zr^{97} would be expected in effluent from zirconium tubes. Measurements of the amounts of these isotopes in several effluent samples from zirconium process tubes showed that there is no more than that measured in the effluent from aluminum tubes.

ACCIDENT ANALYSES

Excursion Possibilities

Excursions as in the Hanford reactors during normal operation or during startup are considered to be very unlikely. The three potential excursion areas are 1) insufficient turnaround control 2) lapses of control because of inadvertent flushing of supplementary poison and 3) startup accidents. Any changes in the reactor transients, however slight, which would affect turnaround, startup or other pertinent reactor operating characteristics would be taken into account in revising the Process Standards. Rod withdrawal rates, for example, are determined on the basis of maintaining an adequate degree of safety no matter what the type of loading.

The amount of supplementary poison required in the zirconium-tubed reactor loadings may be more or less than now depending on the exact nature of the final fuel element design. In no case would significant changes in the supplementary poison requirements be required. Thus, any increase in the frequency or amount of poison flushing would be slight. Supplementary poison removal is normally covered by procedures requiring prior insertion of control and reduction in power level. In the event procedure does break down and a poison column is flushed entirely at once, the pile power rise would be limited by the negative Doppler effect. The reactor would be automatically scrammed before saturation temperature was reached in the downcomer and considerably below any burnout conditions could be reached in any fissile-metal bearing tubes. The worst credible result of the incident would be an increase in slug rupture potential which is not considered a safety-related problem.

Single Tube Meltdown

The single tube accident, one in which coolant is lost to a single process channel, has always been considered as a reactor accident at Hanford of very low or extremely low probability with small to moderate consequences as far as fission product release is concerned. See for example the minutes of the ACRS meetings of May and June of 1958.⁽⁷⁾

7. HW-56764, "Meeting with Advisory Committee on Reactor Safeguards, Hanford-June 5 and 6, 1958 and Summary of May 9, 1958 Meeting", R. L. Dickeman, (Secret) July 14, 1958.

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It has been recently estimated that about 40 percent of the K Reactors' fuel channels and about 30 percent of the channels in the six older reactors are subject to tube and fuel meltdown on complete and instantaneous failure of their front hydraulic connectors. Further study indicates that with zirconium tubes in the reactor, none of the channels would be subject to tube melting during the course of this type of incident.

This conclusion is based on recent calculations⁽⁸⁾ which show that six to eleven hours, at present power levels, and 2.2 to 6.5 hours, at levels 40 to 50 percent above current levels, are required for uranium melting for such an accident even though coolant is completely expelled in less than two seconds after water loss.

The experiments referred to earlier have shown that little or no zirconium-uranium alloying takes place at temperatures just above the melting point of uranium and that channel flow would not be blocked by the products formed by aluminum jacket melting or U-Al diffusion. Other laboratory tests indicate that reverse flow rates attainable with present rear header pressures are sufficient to arrest the temperature rise in the tube well below the uranium melting temperature considering the time sequence of events of Reference 8. With aluminum tubes such positive assurance cannot be given since reverse flow may very likely be cut off either by tube melting or excessive blockage by U-Al diffusion after the process tubes reached the melting point of aluminum.

Maximum Credible Accident

Of most concern is the effect zirconium tubes may have on the consequences following a maximum credible accident (complete and permanent loss of coolant). The changes in the pertinent physical, chemical and nuclear characteristics of the Hanford reactors introduced by the zirconium retubing modifications have already been discussed.

The operation of the Hanford reactors are governed by requiring conformance to two important control criteria. The so called Speed of Control Criterion deals with the consequences of a loss of coolant accident during equilibrium reactor operation. It dictates the requirements on the speed of the vertical safety rod system. In very general terms the criterion is stated as follows:

Speed of Control Criterion. The operation of the Hanford reactors shall be such that in the event of a power excursion resulting from any credible combination of events including complete and permanent loss of coolant, the response of the reactor safety control system shall be sufficient to insure that no energy state will develop while the reactor is supercritical during the excursion which would significantly increase the consequences of the accident.

The presently-adopted and accepted interpretation of the criterion which has been formulated from comprehensive studies⁽⁹⁾ and is subject to continual review⁽¹⁰⁾ is as follows: The surface temperature of the fuel element shall not be permitted to reach the melting point of uranium during the excursion.

8. HW-62494, "An Analysis of the Time-Sequence of Events Following a Complete Loss of Cooling Water to a Hanford Reactor", W. F. Ekern et al, November 5, 1959 (Secret).
9. HW-53694, "Review of the Speed of Control Criterion", J. H. Brown, November 22, 1957, (Secret).
10. HW-63157, "Parametric Analysis of Hanford Speed of Control Criterion", J. C. Peden, R. E. Tiller and R. Nilson. To be issued.

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In order to determine if the reactor operation conforms to the criterion the spatially-independent reactor kinetic equations are solved by analog means(10, 11). The calculation must take into account all the reactivity, temperature and power level variations which occur after the coolant is lost. Important factors which must be considered are the boilout function, the vertical safety rod trip and insertion functions, the water loss reactivity effect, the Doppler coefficient, heating and heat transfer functions and the necessary prompt and delayed neutron fractions and mean lifetimes.

Under reasonable assumptions and with built-in safety factors, the calculations provide for each reactor a speed of control limit curve. The curves are shown in Figures 2 through 5. The ordinate of the graphs is the equilibrium pile power level in MW when water is lost. The abscissa represents the worth of the water, i.e. the dry pile-wet pile reactivity difference. The interpretation of the curves is as follows. Operation to the left and below the limit curve represents "safe" operation, i.e. no uranium melting will occur during an excursion due to water loss. The present reactor positions and the zirconium-tube reactor positions are shown with respect to each curve. The differences in the limit curves among the various reactors stem from differences in VSR insertion times, VSR strengths and Doppler coefficients. For the K Reactors, the present Speed of Control position and the expected position for the zirconium-tubed K Reactor fall outside the portion of the graph shown. It is obvious, for the cases considered, that operation is well within the limit curves for all reactors with either the present slugs or the zirconium-tube reactor designs.

The reactivity worth of the water is markedly a function of fuel element size and shape, water volume, exposure and neutron temperature. Therefore, it must be pointed out that a simple vertical extrapolation to the limiting power level is not valid. Accompanying power level increases of any magnitude, would be higher graphite temperatures and perhaps altered fuel sizes both of which would change the water worth on loss of coolant.

The second control criterion governing the operation of the Hanford reactors is the Total Control Criterion.

Total Control Criterion. The operation of the Hanford reactors shall be such that in the event of any credible combination of events, the total control strength shall be sufficient to insure that no reactivity state would develop which would significantly increase the consequences of the accident.

With respect to the maximum credible accident, the presently adopted and approved interpretation of the criterion(3, 12) is that no reactivity state must develop in the dry reactor (after the scram and any excursion which may have accompanied the accident) which would decrease the probability of restoring coolant to the reactor, i.e. a delayed neutron critical state is not permitted until after a significant number of process tubes have been rendered useless as coolant channels. (A prompt critical state is never permitted).

11. HW-52339, "Speed of Control in Hanford Reactors", J. C. Peden and J. H. Brown, September 16, 1957 (Secret).
12. HW 54188, "Total Control Problem - Hanford Reactors", J. H. Brown, December 16, 1957 (Secret).

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The evaluation of any possible effects introduced by the presence of zirconium tubes which may alter the present reactor conformances to the total control criterion requires a very detailed examination of the expected sequence of events in the course of the meltdown disaster. It is most effective to choose particular representative examples and compare both the aluminum and zirconium-tube reactors. Three cases are of importance. Each presents slightly different problems with respect to adequacy of total control strength and together they cover all possibilities. The three cases are: 1) loss of coolant during equilibrium pile operation, 2) loss of coolant during a startup after a minimum outage, and 3) loss of coolant during an extended outage.

For the discussion, a BDF type reactor is assumed with an equilibrium power level of 1750 MW. The fuel has been irradiated to an average exposure of 400 MWD/T. The following further assumptions are made:

1. Uniformly loaded pile.
2. Present OIIN I&E fuel element for the aluminum-tubed case. See Tables I and II for dimensions.
3. Exemplar I&E slug described earlier for the zirconium-tubed case. See Tables I and II for dimensions.
4. Temperature coefficients as given in Table III and Figure 1.
5. Water loss reactivity gains as given in Table III except that the actual theoretical hot pile values are used. The values in Table III include an arbitrary 3 mk additive factor for conservatism in applying the speed of control criterion curves.
6. VSR worth is 37 mk.
7. VSR plus Ball 3X worth is 51 mk.
8. Any HCR or supplementary poison in the reactor is assumed shadowed by the vertical systems so that poison worth of the horizontal systems is reduced to .3 normal value when both systems are in reactor.
9. HCR worth is 15 mk (unshadowed).
10. Equilibrium lattice k_{eff} is 1.038. Equilibrium xenon is 26 mk; equilibrium rods and poison is 12 mk.
11. Equilibrium average graphite temperature is 450 C for 1750 MW.
12. Equilibrium average uranium temperature is 213 C for 1750 MW.

Loss of Coolant at Equilibrium

The reactor is at full power operation when coolant is lost. The rods and ball 3X system enter in time to prevent uranium melting. The jump in the hot ripe pile reactivity is 10 mk for the present aluminum-tubes reactor (henceforth abbreviated Al-T) and 11 mk for the zirconium tubed reactor (Zr-T). The equilibrium rods and poison (shadowed as mentioned in the assumptions) make the worth of the added vertical system in the reactor 43 mk.

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Unlike the single-tube accident, the loss of coolant at equilibrium to the entire reactor or a large part of the reactor can drive the reactor to a high power, supercritical state during which time fuel jackets may be melted. At the present administrative power levels, the excursion is terminated well before any possibility of uranium melting. The temperature rises accompanying the excursion proceed at high enough rates to preclude the formation of much UAl_3 by intermetallic diffusion if temperatures exceed the melting point of aluminum. Thus, it is expected that the process channels would not be blocked completely or rendered useless for emergency cooling until fission product heating in the subcritical reactor melted the process tubes.

The recent calculations reported in Reference 8 indicate that aluminum process tube melting from fission product and delayed neutron fission heating will occur sometime less than an hour at power levels near the present limit of 1900 MW for the old reactors. This figure is somewhat longer than earlier results quoted in Reference 9, due to refinements and improvements made in the heat generation calculations. However, times even as long as an hour after the accident may be insufficient to implement repair of damage severe enough to cause rapid loss of coolant to the reactor.

The same calculations show that uranium melting takes place six to eleven hours after the loss of coolant. Presumably, the melting of zirconium or interaction with uranium or aluminum would take place even later. Thus, in the case of the zirconium-tubed reactor, a significantly longer time may be available to restore cooling to the reactor and avert the considerable consequences of a complete meltdown.

The possibility of restoring water to a reactor which may have reached temperatures so that molten metals are present introduces the possibilities of metal-water reactions. But, the most important conditions for violent metal-water reactions are not very probable (as discussed earlier in this report) even for the case of water being sprayed on molten aluminum or uranium. In addition, considerable low-melting reactant material would be eliminated from the reactor by the replacement of aluminum process tubes with zirconium. The ultimate decision to restore coolant must be made at the time that it has become possible to do so. It does appear that any risk of possible metal-water reactions may be considerably less than the known risks of permitting the reactor to melt down.

After the accident, the Al-T reactor would be 33 mk subcritical and the Zr-T reactor 32 mk subcritical. As fission product and delayed neutron heating heat the pile to the temperature of uranium melting (1133 C) the following reactivity variations take place, assuming eleven hours to achieve uranium melting.

1. Xenon buildup by decay of iodine backlog is 34 mk, decreasing pile reactivity by 34 mk.
2. The metal temperature coefficient contributes 18 mk negative reactivity.
3. The graphite temperature coefficient contributes 18 mk positive reactivity.

Thus, the Al-T and Zr-T reactors are 67 and 66 mk subcritical just prior to uranium melting. The worth of the xenon is now 60 mk which if released would make the reactor still subcritical. In the Al-T reactor, progression beyond uranium melting should result in nearly simultaneous xenon escape and uranium redistribution leaving the reactor still grossly subcritical (-77 mk). In the Zr-T reactor, we must assume that complete physical rearrangement of uranium is checked by the high-melting zirconium tubes.

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Reference 13 described experiments made on the release of krypton from thin samples of uranium. The results would lead to the conclusion that during the hours required to reach the melting temperature of uranium, very little of the xenon would escape; it would be released essentially at the same time the uranium melts. Melting and puddling of the fuel in the zirconium tubes would then occur simultaneously with xenon release. The negative reactivity change due to slumping would partially compensate the loss of xenon poison. (A less pessimistic assumption would be that skull formation would contain the melt and also the xenon.) If we assume, however, total xenon escape accompanied by uranium slumping, the net reactivity in the Zr-T reactor would still be subcritical by 11 mk.

At or near the melting point of steel, the control elements in the pile would melt. Melting would take place first in the center of the reactor. Thus, any movement of liquid-metal poison would not be solely vertical, but, very likely, partly horizontal. Spreading of nuclear poison in the graphite stack would result in a very large loss in reactivity. To remain as conservative as possible, it is assumed that the control poison would eventually flow out of the active zone of the reactor and effect a supercritical state.

If it is assumed that the control poison could be removed from the reactor at the high rate of 2.5 mk/min. representing loss of the entire 51 mk in only 20 minutes, it is theoretically possible to show that a prompt critical state cannot be achieved. Analog calculations have been made under the following assumptions! at time zero, an entire uranium-graphite complex is at a sufficiently high temperature so that there is perfect thermal coupling between uranium and graphite. The reactor is just critical and the fission power is 10^{-3} watts. The reactor then starts gaining reactivity at the specified rate of 2.5 mk/min. The fission power increases up through the region of appreciable heat generation in about 125 seconds (power equal to 1 MW). A negative metal temperature coefficient of $-2.5 \times 10^{-5}/^{\circ}\text{C}$ is assumed operative and is sufficient to turn the transient short of a prompt critical state. It is very likely that upon achieving a supercritical state in the reactor, the renewal of appreciable fission power would hasten melting of the zirconium tubes to permit uranium flow coincident with poison flow. This would return the reactor to subcriticality and permanent poisoning.

The loss of all control poison in this case would result in a 55 mk gain in reactivity which is less than the poison worth or uranium redistribution. Thus, if all controls and poisons can leave the reactor (which is very unlikely) and the uranium has flowed into the cracks of the graphite stack, the eventual reactivity status would be subcritical.

If a critical state is allowed beyond uranium melting and permanent poisoning of the reactor is prevented until after the melting point of zirconium, an estimate of the increase in fission product in the pile is necessary to assure that no appreciable increase has been permitted. As stated in Reference 3, the total heat release required to produce melting of the uranium pile inventory is about 10 MWD, an insignificant fraction of the 100,000 to 400,000 MWD generated in the reactor previously. The additional energy required to raise the entire uranium-zirconium-graphite complex from 1133 C to 1850 C (where one can well assume uranium redistribution had occurred) is less than 20 MWD. Most of this energy is required to heat the graphite. Thus, the zirconium by virtue of its proximity to the heat source would melt occur early in the excursion, and

13. "The Diffusion of Fission Krypton from Metallic Uranium", M. B. Reynolds, Nuclear Science and Engineering, 1, (1956)

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the reactor would be driven subcritical well before much of the 20 MWD energy release could occur. Thus, it can be concluded that, even under the the worst assumptions, the consequences of the accident will not be significantly worsened by the presence of zirconium tubes.

Loss of Coolant Shortly After a Minimum Outage

Startup from a minimum outage can occur with essentially no horizontal rod in the reactor and no supplementary poison charged. Loss of coolant from this state could result in a xenon-free reactor containing no horizontal rod. Minimum startups are now rather rare in the Hanford reactors, so the probability that the reactor is undergoing such a startup if water is lost is extremely low.

Present Process Standards require that sufficient control poison be in the reactor at all times during an outage or during a startup to guarantee a subcritical dry pile up until the time that the process tubes are rendered useless as coolant channels. Residual xenon is counted as part of the total poison in such a manner that if water is lost now, there will be sufficient xenon plus other poisons in the reactor to guarantee subcriticality until process tubes are destroyed at the calculated later time.

A minimum startup in a BDF type reactor, 25 hours after a shutdown, is assumed interrupted by loss of coolant. All HCR's are out of the pile and are assumed inoperable after the accident. The graphite is still cold, but the uranium is assumed hot. The loss of coolant adds 28 mk to the Al-T reactor and 30 mk to the Zr-T reactor. No excursion occurs and the reactor is scrammed. The worth of the vertical system is 51 mk in this case since no horizontal rod is in the pile. Since the reactor is assumed just critical at the time of the accident, the reactivity status after coolant loss and scram is 23 and 21 mk subcritical for the Al-T and Zr-T reactors, respectively.

The residual xenon is 34 mk and is decaying off. At the time uranium melting can take place after the accident (assumed 22 hours later), the xenon has decayed to 9 mk, thereby increasing the reactivity status by 25 mk. At the same time the metal and graphite heating contributions to 1133 C are - 18 and + 16 mk respectively. Thus, just prior to uranium melting the reactivity status would be 0 and +2 mk for the Al-T and Zr-T reactors, respectively. The just critical state of the Al-T is of course within the total control criterion. The +2 mk supercritical status of the zirconium-tube case only indicates that this much more supplementary poison would have had to be in the reactor during the startup if the time of uranium melting were chosen as the point beyond which a delayed critical state would be allowed. This would delay startup slightly and incur a minor economic penalty.

The Al-T reactor is permanently poisoned by the physical rearrangement of the fuel. The events in the Zr-T reactor are similar to that described under the previous section. The 9 mk of remaining xenon may escape; the initial slumping of the fuel in the zirconium channels takes place with an assumed 5 mk loss. If xenon loss puts the pile on a rising period, the rate of loss would be so slow that achieving a prompt critical state would be precluded. Also if, on the other hand, the pile remains subcritical until the steel control elements melt and begin to flow out of the reactor, prompt criticality is again averted by the built-in reactivity damping of the Doppler coefficient. Meltdown in either case is hastened by a supercritical state and permanent subcriticality is eventually achieved. A xenon-free, control-free, dry pile with maximum fuel redistribution would be subcritical at the melting point of uranium. The reactivity behavior after the melting temperature of uranium has been reached in the reactor is somewhat obscure.

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The temperature coefficients above uranium melting temperatures are not well-known, but a few simple considerations can be mentioned.

The negative Doppler effect is a result of uranium lumping. If the uranium in the reactor at temperatures beyond 1200 C is in the form of very thin sheets or small molten globules, insufficient self-shielding of resonance energy neutrons may eliminate any Doppler effect entirely. Thus, in the absence of measurements in this range, one should not count on a negative prompt coefficient beyond the time the uranium has flowed into the graphite stack.

The positive f-coefficient in a heterogeneous graphite reactor stems primarily from the fact that as temperatures are raised, the neutron diffusion length is increased, resulting in a spatially-flatter neutron flux distribution in the lattice. Thus, the thermal utilization of a heterogeneous lattice approaches that for a homogeneous reactor which is not temperature dependent (except for small deviations from the $1/v$ law). If the physical rearrangement of uranium is sufficient to simulate a homogeneous or nearly homogeneous reactor then the f-coefficient will vanish.

The theoretical η -coefficient, for a 400 MWD/T average exposure is positive at 1000 C. The coefficient becomes negative beyond this temperature. The effect of slumping or redistribution of uranium in the lattice should have a negligible effect on η , even though, by the melting process, a homogenization of a previously non-uniform spatial distribution of fissionable isotopes would result. Stuart⁽¹⁴⁾ and Neumann⁽¹⁵⁾ have both showed that for irradiated fuel rods of very high exposure (containing very pronounced non-uniform isotope distributions) any effect on η which can be attributed to the isotopic distribution is negligible.

The leakage of thermal neutrons from the reactor will increase as the pile temperature increases due to the inverse energy dependences of the absorption cross section of most of the reactor components. The cessation of the effect on resonance neutron absorption by Doppler broadening after uranium redistribution would also increase the neutron lifetime resulting in slightly greater leakage probability.

Thus, the most probable reactivity variations with temperature expected to exist in the hot reactor beyond the time when physical rearrangement of uranium and total loss of control poison (if possible) had taken place, would be the negative reactivity effect of increased neutron leakage. Once the reactor is rendered subcritical by the high temperature melting and rearrangement of materials, a chain-reaction could never again be achieved by natural means. Eventual cooling of the meltdown pile could not introduce any positive reactivity effects of sufficient magnitude to regain a critical reactor.

Loss of Coolant During A Long Outage

There is essentially zero xenon inventory in the reactors 70 - 80 hours after a shutdown. Thus, if water is lost during such a shutdown, the maximum amount of poison would be required to comply with the total control criterion. Assuming

14. HW-35211, "Re: Temperature Coefficients of High Exposure Reactors", G. W. Stuart, February, 1955 (Secret).
15. HW-35722, "Effect on η of Radial Distribution of Isotopes in Irradiated Fuel Rods", H. Neumann, March 10, 1955 (Secret).

all rods in place and sufficient poison to guarantee a subcritical cold dry reactor, loss of water in the reactor will make the reactor just subcritical. The reactivity variations to the melting point of uranium are only the metal and graphite temperature coefficient contributions of -22 and +16 mk, respectively. The sequence of events following uranium melting are then identical to the minimum outage case except that the xenon has been replaced by other poison material of more permanent nature.

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