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METALLURGICAL EVALUATION OF FAILED BORAX-IV
REACTOR FUEL ELEMENTS

by

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ABSTRACT

The fuel elements for the Borax-IV boiling water reactor consisted of ThO_2 -6.36 w/o UO_2 pellets lead-bonded in X8001 aluminum alloy tube plates with silicon-bonded end closures. When the reactor was brought to power on February 19, 1958, after having been operated for approximately one year, over one-third of the fuel elements were found to have developed leaks, as evidenced by significant fission gas release into the process water. Since no fission breaks had been detected during the last previous operation of the reactor on December 5, 1957, it appeared that the leaks had developed during the $2\frac{1}{2}$ -month shutdown. A detailed metallurgical examination was made of two elements containing several failed tubes to determine the causes of failure and the amount of fission gas released from oxide pellets in unfailed tubes. It was found that the upper portion of each tube, where a void space had been intentionally left above the pellets, had collapsed under the reactor operating pressure. The reverse bending which occurred in the tube walls caused local cracking. The most probable cause for the leaks which developed during shutdown is considered to be corrosion in cracks and crevices of the collapsed tubing. The performance of the silicon-bonded end closures appeared to be quite adequate. Measurements and analyses of gas samples taken from unfailed tubes showed that the pellets released an average of 3.4 percent of the total fission gas yield, although they had operated at relatively low temperatures. The release is attributed to open porosity which existed in the pellets.

INTRODUCTION

The purpose of the Borax-IV reactor experiment was to obtain information on the safety and operating characteristics of a boiling water reactor with a long thermal time constant, as would be expected from oxide-fueled central station reactors.⁽¹⁾

The 0.013-in. annulus between the pellets and the tube wall was filled with lead, as shown in Figure 3. Figure 4 shows a complete fuel element consisting of six tube plates welded into a box. As can be seen in the photograph, one of the tubes is left open for insertion of a boron-steel poison rod. Only the 16 central fuel elements were modified to contain a poison rod. Fabrication of the fuel elements, which included a hitherto untried silicon-bonded end closure, has been described in detail previously.^(4,5)

21586

Figure 3. Cross Section of Portion of Borax-IV Tube Plate, Showing $\text{ThO}_2\text{-UO}_2$ Pellets Lead-bonded to the Aluminum Alloy Tube Wall

106-2851

Figure 4. Assembled Borax-IV Fuel Element. The hole in the second tube plate from the left is for insertion of a poison rod.

The reactor was first brought to criticality on December 3, 1956, at the Laboratory's Idaho site. It was operated until April 17, 1957, under atmospheric pressure, with water temperatures ranging from cold to boiling (93°C). Operation with a 59-element core at 300 psig and 216°C started in May 1957 and continued intermittently until December 5, 1957. During the period from December 3, 1956 to December 5, 1957, the calculated maximum burnup achieved in the core was 1960 Mwd/Ton of oxide.⁽⁶⁾ The maximum heat flux was 288,000 Btu/hr-ft². Fuel temperatures measured at reactor powers from 1 to 4 Mw⁽¹⁾ indicate that at full power (20 Mw) the maximum central fuel temperature was near 750°C. The pH of the water in the core generally ranged between values of 5 and 7. The specific resistance of the water generally ranged between 1×10^5 and 9×10^5 ohm-cm. The low values were usually caused by broken Calrod heaters, which permitted MgO to enter the water, or by specific additions, such as of boric acid.

Following the power run on December 5, 1957, the 59-element core was revised in order to increase the maximum power for continuation of stability studies. The boron steel poison rods were removed and 10 new elements were added to the periphery of the core.⁽⁷⁾

The reactor was started with the revised core on February 19, 1958. It was noted that the hotwell activity was approximately five times the maximum previously noted. After repairing two ruptured Calrod heaters, which were assumed to have caused the high water activity, another power run was attempted on February 25, 1958. High water activity again appeared. The principal source of activity was subsequently traced to cesium-138, indicating that a fuel element rupture had occurred.

Subsequent operation of the reactor during the spring of 1958 was for the purpose of evaluating the effect of operating a direct-cycle boiling water reactor with a fuel element defect⁽⁷⁾ and for locating defective elements in the core.⁽⁸⁾ The latter operation disclosed that 22 of the original 59 elements had developed cladding defects sufficiently large to release measurable amounts of fission products.

Two of the failed elements, Nos. 7 and 15, were shipped to the Metallurgy Division at the Argonne, Illinois, site for a detailed hot laboratory examination. The purposes of the examination were to determine the following:

- (1) cause and nature of cladding failures;
- (2) why the defective elements all apparently developed leaks during the shutdown period from December 5, 1957 to February 19, 1958;
- (3) performance of the silicon-bonded end closures; and
- (4) extent of fission gas release from the fuel in nondefective tubes.

DISASSEMBLY OF ELEMENTS

Figure 5 shows the fuel elements in the as-received condition. The ends of the fuel plates were damaged extensively. This condition was not caused by reactor operation, but is thought to have occurred during shipment of the fuel elements from the reactor. There was no excessive deposition of surface oxide, swelling or warpage in either fuel element. Figures 6 and 7 are end views of the elements.

106-3973

Figure 5. Borax-IV Fuel Elements Nos. 15 and 7 in the As-received Condition. The tops of the fuel elements are at the right.

23910

Figure 6. End View Looking at Bottom of Fuel Element No. 7

23912

Figure 7. End View Looking at Top of Fuel Element No. 15

Each fuel element was clamped in position on the bed of a mill and separated readily into its individual plates with a slitting saw. Figure 8 shows an element on the mill during the disassembly operation.

23905

Figure 8. Borax-IV Fuel Element in Position on Mill in Cave

In a test run using an unirradiated fuel element it was observed that galling would result if the feed rate was too rapid. Therefore, a slow feed rate was chosen for the actual cutting operation. No coolant was necessary during the disassembly. In all cases but one the fuel plates were separated from an element without disturbing the surfaces of each plate, thus making the visual examination more meaningful. One side of each plate had been stamped with a serial number during manufacture. This number was used to maintain identification of the disassembled plates.

In Figures 9, 10, 11 and 12 the condition of the fuel plate surfaces can be seen. A cursory examination indicated that, although areas of preferential corrosion were present, none were of sufficient depth to penetrate the cladding. Of more striking interest was the fact that all the fuel plates had collapsed to some extent in the gas space at the top of each tube above the fuel pellets. As shown in Figures 13 and 14, only one side of each tube had deformed in this manner. For any given plate the tubes were always collapsed from the same side. No preferential deposits of scale were evident. The plates were a hematite reddish color, indicating that iron oxides had formed film deposits on the aluminum.

LEAK TESTS

Each fuel plate was checked for cladding failure by placing it in a 5-in.-diameter glass tube filled with water and evacuating the air space above the system. Providing fission gases or air had remained in the tubes, cladding failures could be located readily as a source of bubbling (escape of gas) from the area of the plate that contained a defect.

The equipment used in bubble testing the fuel plates is shown in Figure 15. The glass tube is connected to a bottom plate and upper collar with O-ring seals. Three tie rods, 120 degrees apart, connect the bottom plate and upper collar, which contains the vacuum line and the air inlet valve. The bottom plate is provided with a drain line for lowering the water level inside the bubble tester. The fuel plate to be tested is inserted into the chamber after removing the top plate, which is also connected to the upper collar by an O-ring seal.

The results of the tests are listed in Table I, and the defects in the collapsed areas are circled in Figures 16, 17, 18, and 19. Seven areas were found where cladding failure had occurred. Five of the seven failures were located at the top of the plates in the collapsed free-space area. The remaining two leaks were at the bottom edge of the plates. The areas where failure had occurred did not appear to be excessively corroded. Based on the appearance of the bottom edge of the plates where two leaks were located, these leaks were not related to reactor operation but probably were caused by local damage that evidently resulted during shipment of the fuel elements.

106-4035

Figure 9. Fuel Plates from Borax-IV, Fuel Element No. 15. The plate numbers are given at the top; N refers to the numbered side and U the unnumbered side.

106-4036

Figure 10. Fuel Plates from Borax-IV, Fuel Element No. 15, Reverse of Sides in Figure 9. The plate numbers are given at the top; N refers to the numbered side and U the unnumbered side.

109-4079

Figure 11. Fuel Plates from Borax-IV, Fuel Element No. 7. The plate numbers are given at the top; N refers to the numbered side and U the unnumbered side.

106-4080

Figure 12. Fuel Plates from Borax-IV, Fuel Element No. 7, Reversed from Figure 11. The plate numbers are given at the top; N refers to the numbered side and U the unnumbered side.

23937 IX
Figure 13. Collapsed Tubes on One Side of Plate 674,
Element 7

23938

1X

Figure 14. Side of Plate 674 Opposite from that Shown in Figure 13. Note that no tube collapsing occurred on this side.

24290

Figure 15. Bubble Tester in Position in Cave.
A plate is shown submerged in
water.

Table I
RESULTS OF LEAK TESTING

Fuel Element No.	Plate No.	Remarks
7	844	No failures located.
7	598	No failures located.
7	674	No failures located.
7	504	No failures located.
7	585	Gas was observed escaping from the 5th tube from the left, $2\frac{5}{8}$ in. from the top of the plate at the aluminum insert. Other bubbles were noted on the 5th tube from the left, about $\frac{1}{2}$ in. from the bottom of the plate. The leaks were on the side of the plate having the collapsed tubes (see Figure 17).
7	802	Gas was observed escaping from the 4th tube from the left, about $1\frac{5}{8}$ in. from the top of the plate in the collapsed area (see Figure 16).
15	519	No failures located.
15	794	No failures located.
15	517	No failures located.
15	855	Bubbles were observed at the area where the cladding had been accidentally removed.
15	543	Two leaks were evident: one on the 3rd tube from the right, about $\frac{3}{4}$ in. from the top, and the other on the 4th tube from the right, about $\frac{3}{16}$ in. from the top. The leaks were on the side of the plate having the collapsed tubes (see Figure 18).
15	523	Gas was observed escaping from the 4th tube from the left near the top and the 3rd tube from the right near the bottom. Both leaks were near areas which had been mechanically damaged, probably during shipment. The leaks were on the side of the plate having the collapsed tubes (see Figure 19).

23936

1X

Figure 16. Fuel Plate 802 from Element No. 7.
The circle indicates area where leak
was observed.

23932

1X

Figure 17. Fuel Plate 585 from Element No. 7.
The circle indicates area where leak
was observed.

24249

1X

Figure 18. Fuel Plate 543 from Element No. 15.
The circles indicate areas where
leaks were observed.

24257

1X

Figure 19. Fuel Plate 523 from Element No. 15.
The circle indicates area where leak
was observed.

In testing plate 802 from the fuel element 7, a leak was located at the top of the element. The stream of escaping gas stopped eventually and all efforts to remove the water from the tube and to reproduce the bubbles failed. This indicates that the failures which were found do not represent necessarily all the leaks which may have been present, as the possibility of other defective tubes being filled with water certainly existed.

METALLOGRAPHIC EXAMINATION

The metallographic examination had two objectives: (1) to determine the cause of the defects revealed by leak testing, and (2) to investigate the soundness of the silicon-bonded end closures.

Transverse sections were taken near the suspected areas of tube 4 from plate 523, tubes 5 and 6 from plate 543, tube 5 from plate 585, and tube 4 from plate 802. Longitudinal sections were obtained from plate 855 in order to investigate the silicon-aluminum bond area. The samples were ground successively on 80-, 120-, 320-, and 600-grit silicon carbide paper. Polishing was performed on silk cloths impregnated with 3- and 1-micron diamond paste and on Selvyt using AB Magomet compound. This procedure was repeated until it could be determined whether or not there was present a crack which penetrated the aluminum cladding.

Examination of the tube failures indicated that the mechanism of cracking was similar in each circumstance. The reason for the collapsing of the tubing on only one side of the fuel plate can be easily seen in Figures 3 and 20 through 24. The collapsed wall was invariably thinner than the opposite wall. In some metallographic sections it was noted that the wall thickness varied around the circumference of the tube by a factor of three or more. Also, it was noted that the thinner sides of the tubes in a given tube plate were always on the same side of the plate. It can also be noted in Figures 20 through 24 that the greatest amount of deformation occurred at the juncture of the web and the tube. Reversed bending was most concentrated at this point. This is where all except one of the cracks was found.

Tube 4 from plate 523 (see Figure 20) gave no evidence of complete crack penetration; the grinding procedure apparently bypassed the appearance of the propagation of the crack completely through the cladding. Figure 20b illustrates a crack found at the left-hand side of the tube as shown in Figure 20a. Although this crack did not completely penetrate through the cladding, it is probably similar to the crack which actually did. A metallographic section of the crack which caused failure of tube 6 in plate 543 is shown in Figure 21. The opening of the crack appears to have been widened by the pulling away of the wall from the web due to the collapsing action. Tube 5 from plate 543 and tube 5 from plate 585 (see Figures 22 and 24) exhibited similar crack failures.

a. Cross Section of Entire Tube

28321

10X

b. Enlarged View of Outlined Area in Above Photograph, Showing Incipient Failure

28317

100X

Figure 20. Metallographic Sections of Tube 4, Plate 523

a. Cross Section of Entire Tube

28319

10X

b. Enlarged View of Outlined Area in Above Photograph, Showing Complete Crack Penetration

28323

50X

Figure 21. Metallographic Sections of Tube 6, Plate 543

a. Cross Section of Entire Tube

28318

10X

b. Enlarged View of Area Outlined in Above Photograph, Showing Complete Crack Penetration

28324

50X

Figure 22. Metallographic Sections of Tube 5, Plate 543

a. Cross Section of Entire Tube

28320

10X

b. Enlarged View of Area Outlined in Above Photograph, Showing Incipient Failure

28325

50X

Figure 23. Metallographic Sections of Tube 5, Plate 585

a. Cross Section of Entire Tube

28322

10X

b. Enlarged View of Area Outlined in Above Photograph, Showing Ductile Failure

28326

50X

Figure 24. Metallographic Sections of Tube 4, Plate 802

Both cracks occurred at the web-tube junction. However, in comparison with the crack in tube 6 from plate 543, shown in Figure 21, these cracks appear to have been widened by corrosive action, as evidenced by the marked local decrease in wall thickness. Tube 4 from plate 802 (see Figure 24) failed in an area other than the web-tubing junction. The failure appears to have been ductile and to have resulted from local elongation in the tube wall due to the collapsing of the cladding.

Figure 25 shows a metallographic section of a silicon-bonded end closure. Examination of this and other areas showed the presence of free silicon, not all of which was retained during metallographic polishing. The loss of silicon particles probably caused the voids shown in Figure 25. Although excess silicon was found at the bond interfaces, no cracking or separation was evident. This substantiates earlier observations that the two leaks noted in the end closures resulted from mechanical damage during handling.

27990

250X

Figure 25. Metallographic Section of Silicon-bonded End Closure in Plate 855, Showing Voids and Excess Silicon

FISSION GAS MEASUREMENTS

Five fuel plates were sectioned through the gas space at the top of each tube to determine the amount of fission gas released into the tubes from the fuel pellets. Gas samples were collected individually from tubes that contained significant quantities of total gas, and the amount of fission gas was determined by mass spectrometric analysis.

The sectioning operation was performed in the vacuum chamber shown in Figures 26 and 27. The chamber was of welded aluminum construction with a solid aluminum cover which sat on a flat, neoprene rubber gasket. The window in the cover was made of nonbrowning cerium-stabilized glass which, combined with a mirror, allowed visual control of the sectioning. Cutting was done with a 3-in.-diameter fine-toothed circular saw driven by a $\frac{1}{8}$ -hp motor from outside the chamber. A vacuum-tight seal was maintained on the drive shaft by a double quad-ring compression seal. The fuel plate was rigidly clamped to a lateral traverse and fed to the stationary saw one tube at a time. The feed was hand controlled from outside the chamber through a worm gear drive arrangement.

A schematic diagram of the out-of-cell gas collection and measurement apparatus is shown in Figure 28. Three pressure-measuring instruments were incorporated into the system: a dial gage with a range of 0-50 mm Hg, and two tilting McLeod gages with ranges of 0-1 mm and 0-10 mm. The volume of the out-of-cell system was calibrated to be a total of $1235 \text{ cm}^3 \pm 2\%$. The cutting chamber volume was $27,550 \text{ cm}^3 \pm 3\%$.

Sectioning of the fuel plate was begun when the static pressure in the entire system was 10 microns Hg or less. This required a minimum 12-hour evacuation period after the fuel plate was put in the chamber. One tube was then cut and the released gas allowed to expand into the whole system. After equilibrium had been reached, the pressure was measured with a suitable gage. The gas was then statically adsorbed into an activated charcoal trap which was cooled to liquid nitrogen temperature. Experimental trials showed that all fission gases and air could be trapped out in this manner in about four hours. The unadsorbed gas remaining in the system after adsorption was the helium filler gas, which is not adsorbable on charcoal at this temperature. The charcoal traps were later desorbed and the gas analyzed by mass spectrometric techniques.

The results of the gas release measurements and the mass spectrometric analysis are given in Table II. Of the total 39 tubes that were sectioned, seven were known to be leakers as shown by previous bubble testing. Twenty other tubes contained amounts of gas ranging between 0.14 cm^3 and 0.89 cm^3 at STP. These were considered insignificant compared with the amounts in the twelve remaining tubes, which ranged between 1.23 cm^3 and 7.18 cm^3 at STP.

27915

Figure 26. Vacuum Chamber for Gas Collection from Borax-IV Fuel Plates

27916

Figure 27. Vacuum Chamber Showing Borax-IV Fuel Plate in Cutting Position

106-5559

Figure 28. Diagram of Apparatus for Collection of Fission Gas

Table II
GAS RELEASE MEASUREMENTS

Plate No.	Tube No.	Total Gas Released, cm^3 at STP	Xe, cm^3 at STP	Kr, cm^3 at STP	Total Fission Gas, cm^3 at STP	Release of Fission Gas, %
585	1	0.41				
585	2	3.33	0.090	0.009	0.099	3.02
585	3	0.21				
585	4	0.24				
585	5(a)	0.14				
585	6	0.14				
585	7	0.20				
585	8	0.17				
802	1	3.10	0.039	0.039(b)		
802	2	0.24				
802	3	3.59	0.080	0.011	0.091	2.78
802	4(a)	0.07				
801	5	0.14				
802	6	0.14				
802	7	0.20				
802	8	0.17				
523	1	0.34				
523	2	0.34				
523	3	7.18	0.168	0.020	0.188	5.74
523	4(a)	0.31				
523	5	0.48				
523	6(a)	0.31				
523	7	3.85	0.041	0.005	0.046	1.40
523	8	3.18	0.149	0.021	0.170	5.19
543	1	0.38				
543	2	0.31				
543	3	0.30				
543	4	2.38	Sample lost			
543	5(a)	0.17				
543	6(a)	0.14				
543	7	0.27				
543	8	0.89				
855	1	1.23	0.055	0.007(c)	0.062	1.89
855	2	2.83	0.041	0.005(c)	0.046	1.40
855	3	2.99	0.019	0.019(b)		
855	5	3.12	0.162	0.019	0.181	5.53
855	6	2.94	0.108	0.013(c)	0.121	3.69
855	7	0.58	0.064	0.064(b)		
855	8(a)					

(a) Known leakers from bubble tests.

(b) Percentages not accurately determined in analysis.

(c) Calculated from average xenon-to-krypton ratio of 8.3 to 1.

Only the latter samples, with a few exceptions, were collected for analysis. Slight radioactivity was present in several of the gas samples collected from the group of twenty tubes which contained the smaller amounts of gas. The average error over the range of values for the volumetric measurements was $\pm 7\%$.

Due to leakage of air into the charcoal collection traps before aliquot samples were taken for analysis, the fission gases constituted only a very small percentage of the total gas present. In a few cases, this was below the limit that could be accurately determined. The amounts of xenon and krypton shown in the table are based on the total volume of the diluted sample and its percentage composition obtained from the mass spectrometric analysis. In cases for which only the amount of krypton was below the lower limit of accurate resolution, the value given in the table was determined from the experimentally measured average xenon to krypton release ratio of 8.3:1.

The percentage release of gas from the fuel is based on an average burnup of 980 Mwd/Ton of oxide (2.91×10^{19} fissions/cc) and a corresponding fission gas yield of xenon and krypton of 3.275 cm^3 per tube at STP. The average release for the nine samples that contained measureable quantities of fission gas was 3.4 percent of the total yield.

The gas spaces in four tubes of plate 802 were found to contain lead. The collapsed sections of the aluminum tubes were compressed into the lead. The lead evidently became molten and flowed into the gas space during final end closure bonding of the tube plate.

DISCUSSION OF RESULTS

As mentioned earlier, all leaks which were believed to have occurred during reactor operation and which could be located were found to be situated in the collapsed areas of the tubes. The collapsing of the tubes was evidently accelerated by the nonuniform wall thickness that occurred during extrusion of the tube plates.

The postirradiation examination of the failed elements did not furnish a clear answer as to why the elements performed satisfactorily (i.e., without leaks) during reactor operations in 1957, but were found to have developed numerous leaks when reactor operation was resumed $2\frac{1}{2}$ months later on February 19, 1958. It is evident that all of the tube collapsing must have occurred during reactor operation which preceded the $2\frac{1}{2}$ -month shutdown. Yet, the collapsing itself did not immediately result in leaks, as indicated by the lack of fission product activity in the reactor water system during reactor operation just preceding the $2\frac{1}{2}$ -month shutdown. It appears that some other failure mechanism was active during the shutdown period, and that this

mechanism combined with the tube collapsing which had already occurred to cause the extensive amount of leaks that were observed after reactor startup on February 19, 1958.

Two mechanisms which could have caused the leaks during the shutdown period are (1) overstressing of the cladding incident to reloading of the core and removal of the poison rods from the 16 central fuel elements, and (2) corrosion in the stagnant water in the reactor vessel in which the elements were submerged.

The first possibility, that of mechanical damage, seems unlikely. It is believed that the end fittings attached to the fuel elements would have largely prevented damage due to handling. This would be particularly true for the four tube plates inside the assembled fuel element.

Corrosion is believed to be a more probable cause of the leaks developing during shutdown. Aluminum alloys have been observed to corrode at abnormally high rates in cold, stagnant water in the absence of oxygen.⁽⁹⁾ Furthermore, as long as the system is oxygen-deficient, this type of corrosion is accompanied by a rise in pH, so that the process is accelerated. The bottom of a crack or crevice would furnish an ideal site for this phenomenon, since oxygen could diffuse only slowly to the bottom of the crack. Although no regular readings of water quality were taken after the December 5 shutdown, the reactor records show that the reactor vessel was filled during the shutdown with one-megohm water which had a pH of 6.5.⁽⁶⁾ Nevertheless, it seems likely that high pH conditions could have existed in localized areas, such as in the cracks in the cladding, which would not have been detected by normal water sampling procedures.

The performance of the silicon-bonded end closures was, as far as could be determined, quite adequate for reactor operating conditions. The two leaks that were found at the lower edge of plates 523 and 585 were in areas where mechanical damage had occurred, evidently during shipment. The bubble test was not sufficiently precise to determine whether the leaks were through the bond itself or through defects in the cladding.

By comparing the results obtained for gas release from tubes known to have leaked and the twenty tubes that contained small volumes of gas, it appears that these twenty tubes had leaks which were not detected by the bubble-test method. Several of the gas samples from these tubes were slightly radioactive, indicating that fission gas still remained in the tubes. This gas probably diffused from the fuel, then through imperfections in the lead bond, and then between the lead-aluminum interface under the one atmosphere pressure gradient during gas sampling. The movement of gas in the lead-aluminum interface was shown to be possible when the end tube of plate 855 was inadvertently cut during disassembly. Upon bubble testing a large evolution of gas took place from the cut area. When sectioned for gas release, this tube released the smallest volume of gas of any tube tested.

The volume of total gas released from the nondefective tubes was slightly larger than was expected. The volume of the gas space above the fuel pellets was approximately 1.7 cm^3 . This gas space was filled with helium during fabrication as a means of leak testing the end closures after bonding. The helium was simultaneously blown into all eight tubes while the end of the tube plate was cold pressed to form a gastight seal.⁽⁴⁾ It is conceivable that the gas trapped within the void space was under a pressure greater than one atmosphere. The average release of gas from eleven tubes excluding Tube 3, Plate 523, was 2.96 cm^3 . Tube 3, Plate 523, released 7.18 cm^3 of gas. The mass spectrographic analysis indicated that this tube contained abnormally high percentages of water vapor and carbon dioxide. It is believed that these gases may have been entrapped during fabrication.

The release of fission gas from the fuel, in terms of percent of the total yield, ranged from 1.40 percent to 5.74 percent, with an average of 3.40 percent. The extent to which the lead influenced the release of gas from the fuel was probably dependent upon its integrity. The fact that fission gas could migrate through solidified lead was shown in those gas samples from defective tubes that were radioactive. The amount of gas that was drawn from the fuel under vacuum was not determined but is believed to be of the order of 0.01 cm^3 , or 0.3 percent of the gas formed. It was not possible to separate this gas from the fission gas released by thermal diffusion. The amounts of fission gas release shown in Table II are therefore believed to be slightly higher than for solely thermal diffusion.

The release of fission gas is attributed primarily to the low bulk density of the oxide fuel pellets (82.3% of theoretical). Observations on UO_2 pellets of this density have shown that almost all the void space consists of open porosity.⁽¹⁰⁾ In dense UO_2 pellets the 750°C maximum central fuel temperature which was present in the Borax-IV elements would not be expected to cause fission gas release rates of the magnitude observed.⁽¹¹⁾

The experimental release ratio for xenon to krypton of 8.3:1 is higher than the reported yield ratio of 5.52:1 for U^{235} fission.⁽¹²⁾ Also, it has been reported by Booth and Rymer⁽¹³⁾ that there is no significant difference in the diffusion rates of xenon and krypton in UO_2 . However, other recent work at this Laboratory has substantiated the higher xenon-to-krypton release ratio from $\text{ThO}_2\text{-UO}_2$ pellets.⁽¹⁴⁾

CONCLUSIONS

1. The primary cause of failure of the Borax-IV fuel elements was collapse and overstressing of the unfueled portion of the aluminum alloy tube plates.
2. Corrosion in cracks or crevices of the collapsed tubing appeared to be the most probable cause for the leaks which developed during shutdown.
3. The performance of the silicon-bonded end closures appeared to be quite adequate for at least normal reactor operation.
4. The amount of fission gas released from the oxide fuel was significant, and is attributed to the relatively large amount of open porosity in the pellets.

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