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RATE OF ALLOYING OF URANIUM ALLOYS WITH STAINLESS STEEL

(PART I. 1800 TO 2300°F)

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ABSTRACT

The rate of alloying between Type 304 stainless steel and metal fuels was investigated between 1800 and 2300°F. The alloying times were determined by experimental couples in vacuum and also by short fuel elements with a sodium or NaK bond between the fuel and the cladding. The fuels included unalloyed uranium, uranium-molybdenum alloys, and a Th - 7.6 wt % U alloy. Within the stated temperature range, unalloyed uranium alloys rapidly with the stainless steel, U - 10 Mo somewhat slower, and Th - 7.6 U the slowest of the fuels tested. The presence of a thin oxide film on the surface of a U - 10 Mo fuel wafer substantially lengthens the time required to form the low-melting iron-uranium eutectic, whereas this effect is minor with unalloyed uranium.

Additional work is in progress to study the alloying rates at lower temperatures.

I. INTRODUCTION

The Sodium Reactor Experiment (SRE) is one of several experimental reactors in the AEC program to develop high-temperature power reactors. The SRE is a graphite-moderated, sodium-cooled reactor with fuel elements made of seven-rod clusters. Each rod consists of twelve metal fuel slugs, 6-in. long by 0.750-in. diameter, in a stainless steel jacket 0.010-in. thick. The 0.010-in. annulus between the fuel slug and the jacket is filled with NaK for thermal bonding. A description of the design of the fuel elements is given by Parkins,[1] and a complete description of the SRE is given by Starr and Dickinson.[2]

Design SRE operational conditions are about 950°F outlet sodium temperature with a maximum fuel surface temperature of about 1000°F. Under continuous operation at higher temperatures, interalloying between the metallic fuels and the stainless jacket can proceed by solid state diffusion wherever the fuel slug happens to touch the jacket through the NaK bond. This interalloying can reduce the effective thickness of the jacket and weaken it. The reaction products are brittle. When operating at design conditions, where the surface temperature of the fuel does not exceed 1000°F, the diffusion rates are slow enough so that interalloying should not be a limiting factor in the life of the element. Operational experience has substantiated this assumption.

At higher temperatures, diffusion rates increase. Should the temperature exceed the melting point of the iron-uranium eutectic, 1340°F,[3] or, in the case of a thorium base fuel alloy, the melting point of the iron-thorium eutectic, 1580°F,[3] then the eutectic composition resulting from solid state diffusion will melt as it is formed. Once molten, jacket attack is rapid due to the larger area of contact and increased atom mobility in the liquid state. To determine the effect of eutectic formation on the life of SRE fuel elements, an engineering study was made of the rate of alloying between stainless steel and uranium-base or thorium-base alloys at temperatures above the respective eutectic melting points. This report covers the first phase of this study, in the temperature range of 1800 to 2300°F. No tests were made inpile, since Weil and Paine[4] have shown that irradiation has little effect on diffusion rates in the stainless steel-uranium system.

Diffusion rates have been established in the iron-uranium system[5] and the stainless steel-uranium system[4, 6, 7] by conventional diffusion-couple techniques. However, an SRE fuel rod does not conform to the requirements of such conventional diffusion couples in that intimate contact does not exist between the fuel and the cladding. Instead, they are separated by a NaK annulus. This experimental work was undertaken to evaluate interalloying rates as they may be affected by haphazard contact existing in an SRE fuel rod, and at temperatures higher than those of the reference design.

II. DISCUSSION OF MECHANISMS

A. URANIUM

The alloying action between unalloyed uranium or uranium-base alloys and stainless steel may be divided into three temperature ranges, which are: (1) below the eutectic melting point, (2) between the eutectic melting point and the melting point of the fuel, and (3) above the melting point of the fuel. In this discussion, the eutectic melting point is assumed to be 1340°F, the same as the iron-uranium binary eutectic,[3] although a U-SS eutectic melting point of 1370°F has been reported.[7] The melting point of uranium is taken as 2000°F, since the unalloyed uranium used in the test-work melted at 1980 to 2000°F. Hence, these temperature ranges become (1) below 1340°F, (2) 1340 to 2000°F, and (3) above 2000°F.

1. Reactions Below 1340°F

Loss of cladding integrity by melting cannot occur below 1340°F, the assumed melting point of the eutectic between uranium and stainless steel. It has been shown with conventional, intimately joined diffusion couples[4,6] that diffusion can occur to a significant fraction of the 0.010-in. cladding thickness below 1340°F. This alloy would then melt when heated sufficiently, causing quick penetration. However, the SRE fuel does not intimately contact the jacket, but instead may touch it haphazardly. The NaK thermal bond wets both the fuel and the jacket, preventing metal-to-metal contact unless considerable force (as might result from fuel swelling) is exerted. Diffusion of iron and uranium atoms across the NaK annulus is undoubtedly slower than in the usual intimately-joined diffusion couples. Hence, formation of iron-uranium alloys at normal operating conditions should not affect the expected service life of the SRE fuel element.

2. Reactions Between 1340 and 2000°F

In this temperature range, interalloying must proceed by solid state diffusion along a limited area of contact which may shift with time until a low-melting composition is reached. This low-melting alloy must contain between 68 and 98 wt % U if the balance is iron, depending on the temperature level, before melting will occur. The uranium-nickel eutectic, melting at 1370°F,[3] and the uranium-chromium eutectic, melting at 1580°F,[3] may influence both the composition range and melting-point of this low-melting composition. Once the alloy layer becomes fluid, the rate of eutectic formation and melting will accelerate. Hence, the life of an SRE fuel jacket in this temperature range is strongly configuration-sensitive; penetration will depend on the cleanliness of the surfaces as well as the intimacy and duration of contact at any given location.

The work of McIntosh and Bagley[7] emphasizes the strong influence of small temperature variations near the eutectic melting point. Their work indicates relatively rapid alloying between stainless steel and uranium above 1368°F, as indicated in Table I:

TABLE I

URANIUM-STAINLESS STEEL COMPATIBILITY

Test Temperature		Duration (hr)	Penetration
(°C)	(°F)		
760	1400	24	Complete
742	1368	72	0.005 in.
735	1355	168	Nil

Data from Reference 7. Original thickness of stainless steel 0.0625 in.

They estimate the eutectic melting point to be between 742 and 745°C (1368 to 1374°F), which is about 30°F higher than given by Rough and Bauer[3] for the iron-uranium binary.

3. Reactions Above 2000°F

Above the melting point of the uranium, jacket attack should be quite rapid. Molten uranium wets stainless steel and hence should flow rapidly along its surface. Not only does the area of contact rapidly increase, but atom mobility is greatly increased as the metal melts. Hence, penetration and gross alloying should proceed rapidly once the fuel melts.

B. THORIUM-BASE ALLOYS

The mechanisms for thorium or thorium base alloys are similar to those for uranium and uranium-base alloys discussed in the preceding section, except that the equivalent temperatures are higher. Since the iron-thorium binary eutectic melts at 1580°F,[3] loss of jacket integrity by melting cannot occur below this temperature, which is assumed to be the approximate melting-point of the thorium-stainless steel eutectic. The thorium-nickel eutectic, melting at 1830°F, and the thorium-chromium eutectic, melting at 2260°F,[3] may influence this melting point. However, since thorium melts at a higher temperature than stainless steel, the integrity of the cladding might be lost (in the event of rapid heating) by tensile failure or melting of the cladding itself before eutectic-formation became significant. With slow heating rates, or temperature stabilization within the approximate range of 1580 to 2400°F, solid state diffusion between the fuel and cladding will occur in the same configuration-sensitive manner as for the uranium-fueled elements. When a low-melting composition is attained, liquification and rapid penetration of the cladding should follow in the same manner with either fuel.

Comparing thorium-fueled SRE fuel rods with those containing uranium, the thorium-fueled rods should withstand a longer exposure at the same temperature before losing cladding integrity, since the rate of diffusion and interalloying is undoubtedly slower than if the fuel rods contained uranium.

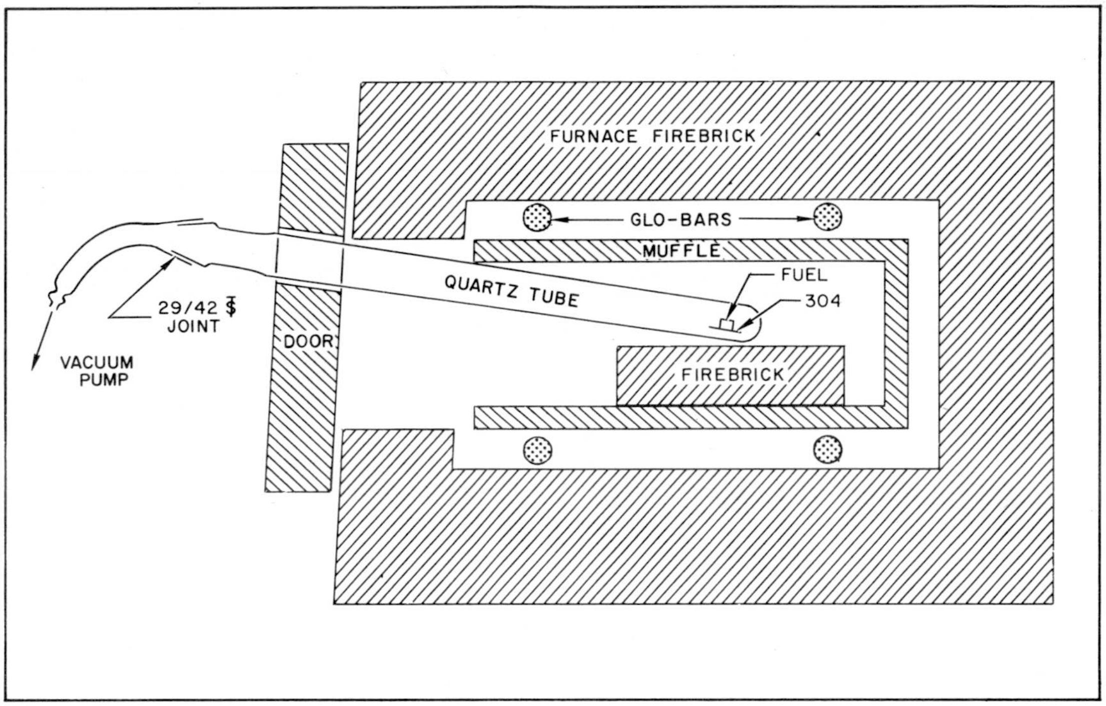


Figure 1. Apparatus for Quartz-Tube Technique

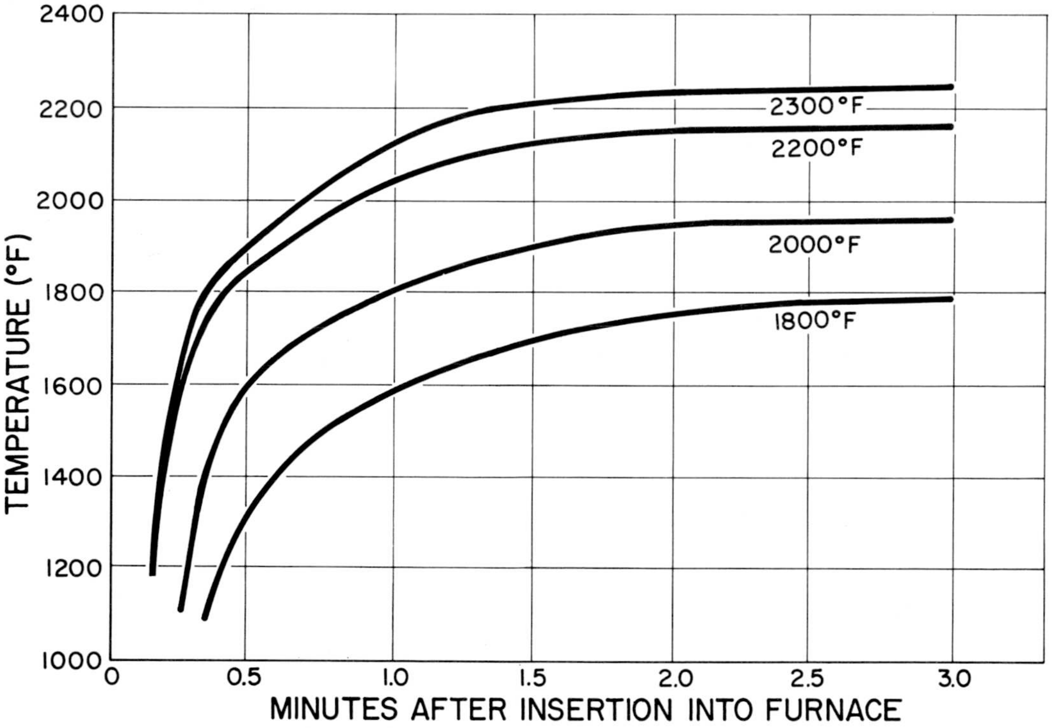


Figure 2. Heating Rates for Quartz-Tube Technique

III. EXPERIMENTAL

Two experimental techniques were used to measure the speed of alloying between stainless steel and the fuels. In the quartz-tube technique, a piece of the fuel is placed on a square of stainless steel inside a quartz tube. The tube is evacuated and then pushed through a hole in the door of a preheated furnace. Alloying and melting are observed visually. The apparatus is shown in Figure 1, and is described in detail in Appendix I. Heating-rate curves for the fuel/steel interface, determined according to the procedure described in Appendix III, are plotted in Figure 2.

The pressure-vessel technique was devised to avoid the surface oxidation obtained with the quartz-tube technique, and to more closely simulate an SRE fuel rod. A 0.010-in. wall stainless steel capsule was made up with a fuel wafer and sodium or NaK inside, under helium, to match the SRE fuel rod's radial geometry. This capsule was enclosed in a pressure vessel that had a thermocouple and pressure tube attached. The apparatus is shown in Figures 3 and 4, and described in detail in Appendix II. Penetration of the capsule was indicated by a sudden pressure surge or shorting of the thermocouple. Typical heating rate curves, recorded directly from the internal thermocouple, are plotted in Figure 5.

In both procedures, a stop watch was started when the specimen was put in the furnace, and stopped when it was pulled out. This actual time in the furnace is recorded in Tables I and II as "Time", and it does not include cooling time after removal from the furnace.

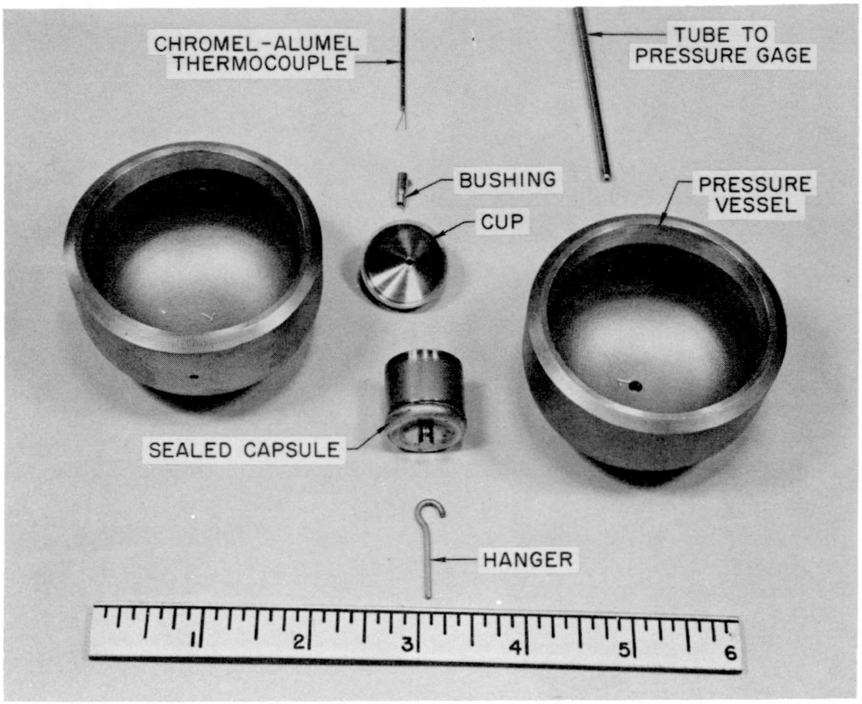


Figure 3. Apparatus for Pressure-Vessel Technique

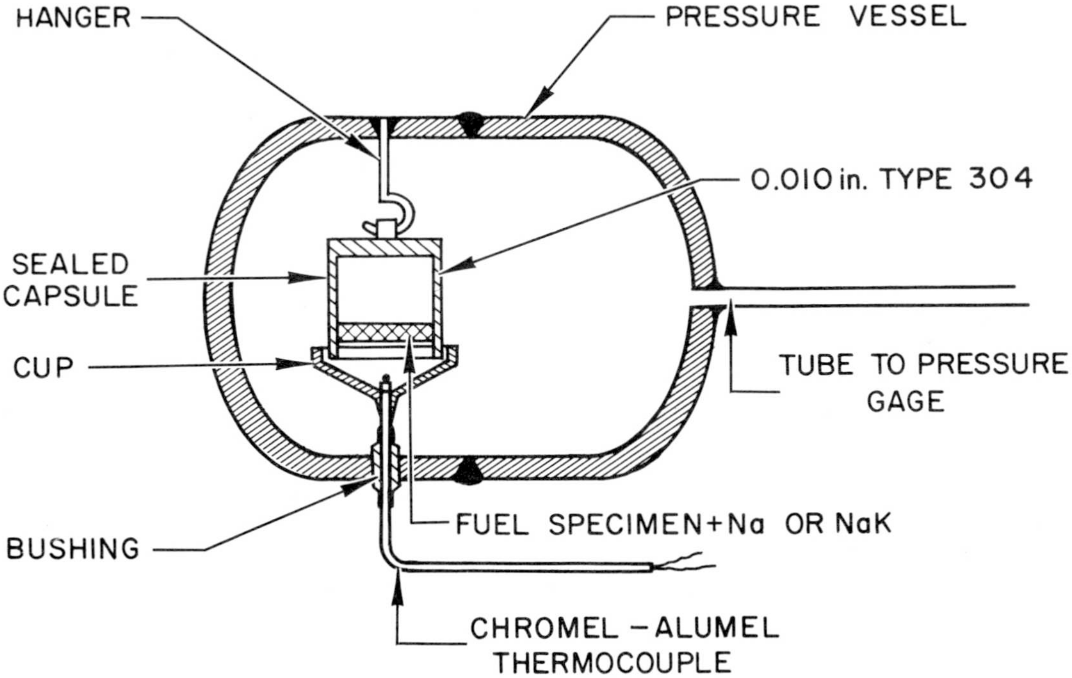


Figure 4. Cross Section of Pressure-Vessel Apparatus

TABLE II

EXPERIMENTAL RUNS AND RESULTS, QUARTZ-TUBE TECHNIQUE

Run No.	Specimen* Material	Furnace Temperature (°F)	Time (min)	Results and Comments
1	Th - 7.6 U	2000	4.38	No penetration, some alloying
4	Th - 7.6 U	2200	2.25	No penetration or alloying
2	Th - 7.6 U	2200	4.30	Parted, square hole
3	Th - 7.6 U	2300	2.00	Penetrated in several spots
5	Th - 7.6 U	2300	2.50	No penetration. One alloying spot
9	U - 3.5 Mo	2200	0.75	One tiny penetration spot
10	U - 3.5 Mo	2200	0.75	Same as Run 9. Good duplicate
11	U - 3.5 Mo	2200	0.83	Stainless steel penetrated, about 2/3 of specimen area
7	U - 3.5 Mo	2200	0.92	Parted. Stainless steel almost completely dissolved
12	Unalloyed U	1800	3.52	No penetration. Alloyed at interface
13	Unalloyed U	1800	3.98	Three small penetration spots
14	Unalloyed U	1800	5.10	More penetration than Run 13
15	Unalloyed U	1800	6.00	Slightly more penetration than Run 14
16	Unalloyed U	1800	10.02	Larger penetration, but no parting.
18	Unalloyed U	2000	2.23	About 90% of stainless steel melted through
17	Unalloyed U	2000	2.45	Parted, square hole
50	U - 10 Mo	1800	8.40	No alloying
52	U - 10 Mo	1800	8.65	Penetrated, one small spot
51	U - 10 Mo	1800	17.53	Penetrated, two places
44	U - 10 Mo	1800	22.25	Penetrated, one large spot
53	U - 10 Mo	1800	37.75	Penetrated, but not parted
56	U - 10 Mo	2000	2.05	No penetration, but firmly welded
57	U - 10 Mo	2000	3.00	Penetrated, two spots
58	U - 10 Mo	2000	3.00	Good duplicate of Run 57
54	U - 10 Mo	2000	2.90	Parted, square hole
60	U - 10 Mo	2000	5.72	Parted, square hole

* All alloy compositions in wt %.

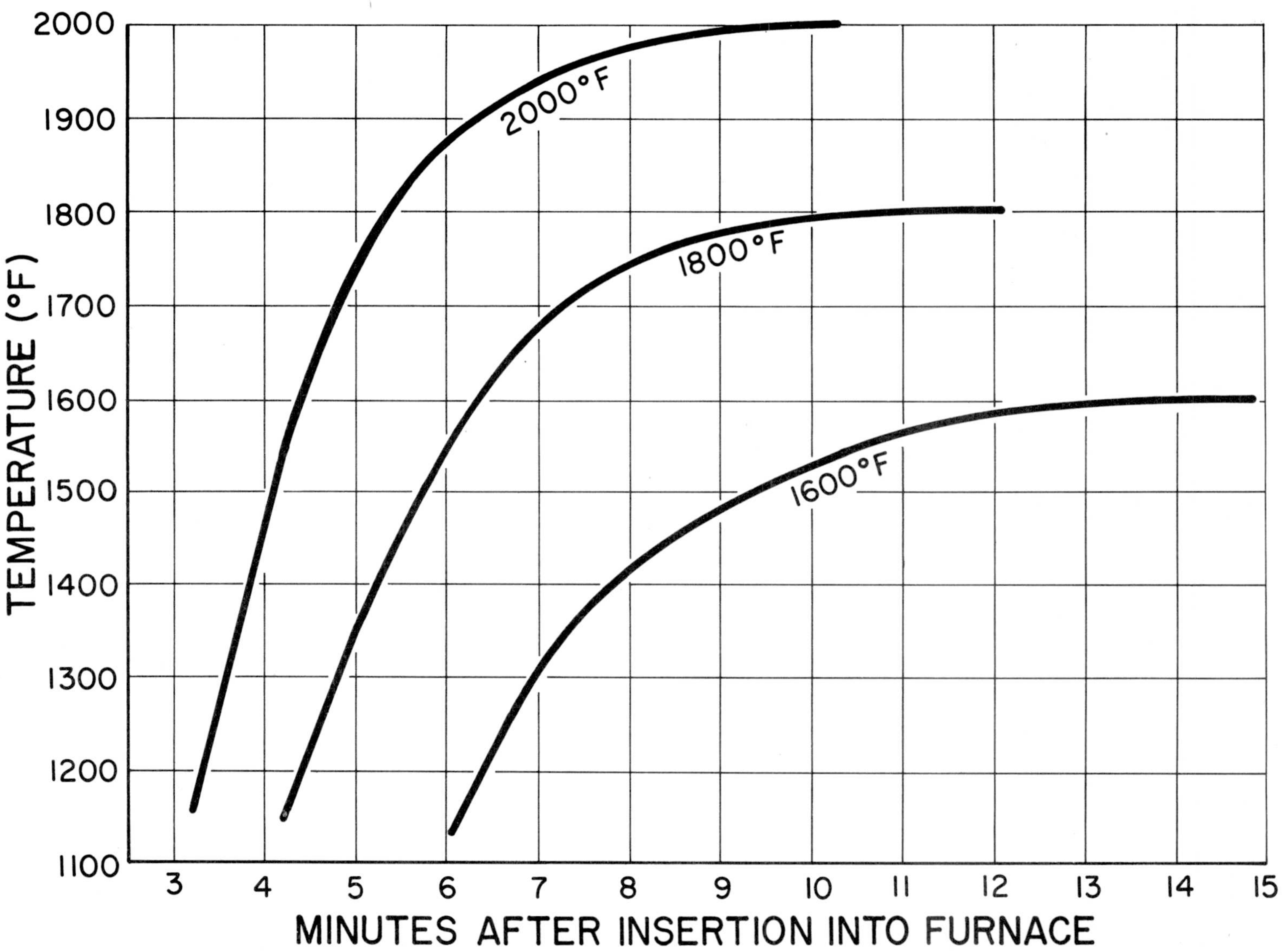


Figure 5. Typical Heating Rates for Pressure-Vessel Technique

IV. MATERIALS

The stainless steel used for these experiments was cut from welded Type 304 stainless steel tubing, 0.790-in. diameter, manufactured for use in the SRE. Nominal wall thickness was 0.010-in; actual thickness varied from 0.0100 to 0.0105-in. Other pieces of stainless steel were machined from AISI Type 304 bar stock. Surface preparation is described in Appendixes I and II.

Fuel materials included unalloyed uranium, U - 3.5 wt% Mo, U - 10 wt% Mo, and Th - 7.6 wt % U. All samples were cut from castings that had been vacuum induction melted by the Fuel Element Development Group at AI. Where possible, specimens were machined from fuel slugs made for use in the SRE.

The sodium and NaK were reactor grade metals. The NaK was the eutectic composition, containing 77% potassium and 23% sodium.

V. RESULTS

Approximately 65 runs were made. Many of these are listed in Table II for the quartz-tube technique and in Table III for the pressure-vessel technique. The degree of alloying is grouped into three catagories: no penetration, penetrated, and parted. Penetration is defined as the melting of a hole through the cladding, varying in size from a small pinhole to a large opening. Parting is defined as sufficient penetration so that the jacket would separate into two parts; this separation may be aided by increased tensile stresses in the remaining cladding. Photographs of typical penetrated specimens are shown in Figures 6 and 7, and typical parted specimens are shown in Figure 8.

To compare the results of the two techniques, the quantity "time-at-temperature" has been arbitrarily defined as the number of minutes the specimen was within 25°F of the highest temperature attained during each run. Selected results for uranium fuels are compared in Table IV, and thorium-base fuels in Table V, on the basis of time-at-temperature.

There is some scatter in the data, which is to be expected in these configuration-sensitive tests. There is sufficient agreement in the data, however, to

TABLE III
EXPERIMENTAL RUNS AND RESULTS, PRESSURE VESSEL TECHNIQUE

Run No.	Fuel Material*	Bond	Furnace Temperature (°F)	Time	Penetration		Results
					Temperature (°F)	Time	
25	Unalloyed U	Na	1800	14.33	1787	12.57	Penetrated
31	Unalloyed U	NaK	1800	14.78	1786	9.83	Penetrated
32	Th - 7.6 U	Na	1800	25.07	1790	25+	Failed while cooling
35	Unalloyed U	Na	1900	9.15	1820	8.05	Penetrated
36	Unalloyed U	NaK	1900	10.00	1772	6.80	Penetrated
29	Unalloyed U	Na	2000	11.25	1955	7.63	Parted
30	Unalloyed U	Na	2000	9.50	1925	7.03	Parted
33	Th - 7.6 U	Na	2000	8.58	1892	6.87	Penetrated
34	Th - 7.6 U	Na	2000	18.10	1978	16.53	Penetrated

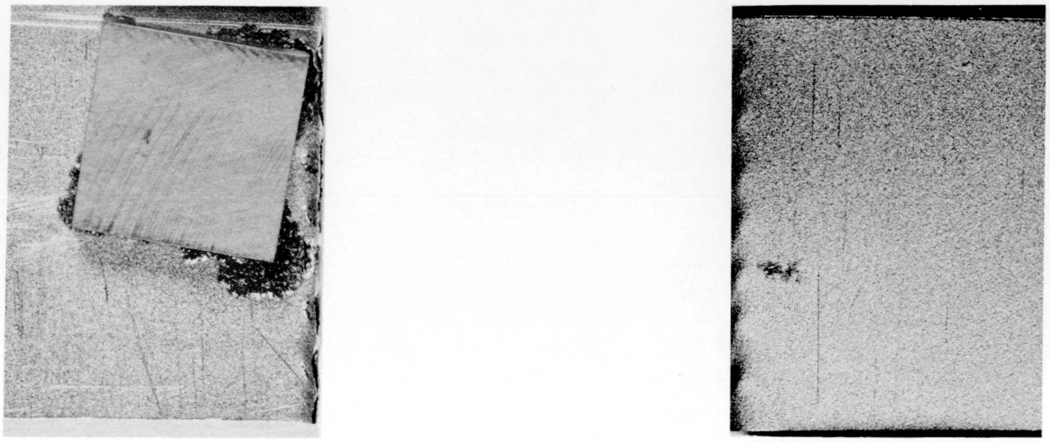
*All alloy compositions in wt %.

In addition, seven runs were made with U – 10 Mo fuel, NaK-bonded to the stainless steel jacket. These data are not considered reliable for reasons discussed in the text.

reach the conclusions presented in Table VI. Reproducibility was surprisingly good, as demonstrated in Runs 9 and 10, 13 to 15, and 57 and 58.

Seven runs were made by the pressure-vessel technique with NaK-bonded U - 10 Mo fuel wafers. No alloying occurred in six of these runs, even after 85 min at 1800°F or 38 min at 1900°F. Lack of alloying is ascribed to excessive oxide contamination during fabrication of these fuel elements. Metallographic examination of the U - 10 Mo wafer after the run showed a thin dark film on its surface. X-ray analysis of the film showed it to be mostly uranium oxide. This film was not as dark as the films on some of the unalloyed uranium wafers which did alloy with the jacket. The oxide layer on the U - 10 Mo fuel apparently is a much more effective diffusion barrier than one on unalloyed uranium, even though the thickness may have been somewhat greater in the latter case.

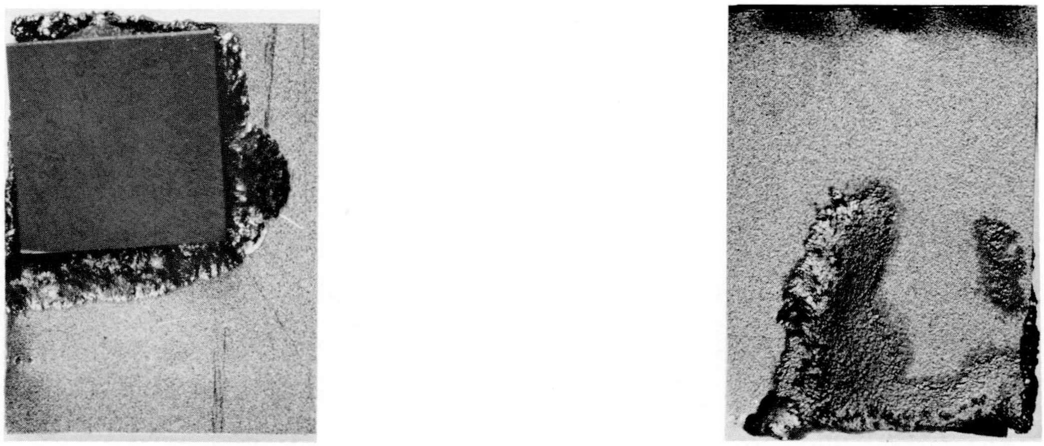
RUN 10 – 0.75 MINUTES



3X
TOP VIEW

3X
BOTTOM VIEW

RUN 11 – 0.83 MINUTES



3X
TOP VIEW

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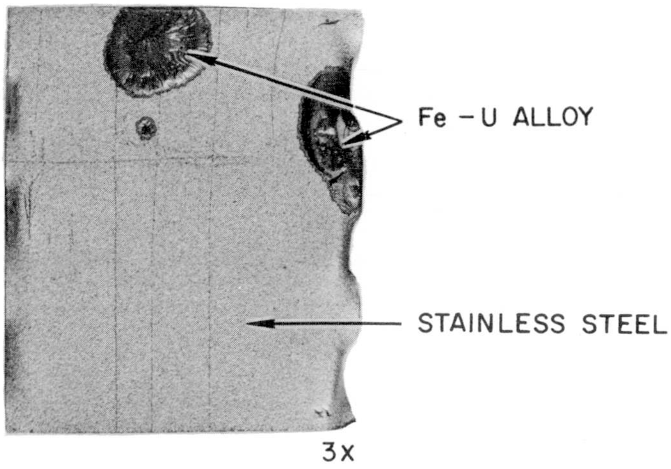
BOTTOM VIEW

Figure 6. Quartz-Tube Specimens in Furnace at 2200°F

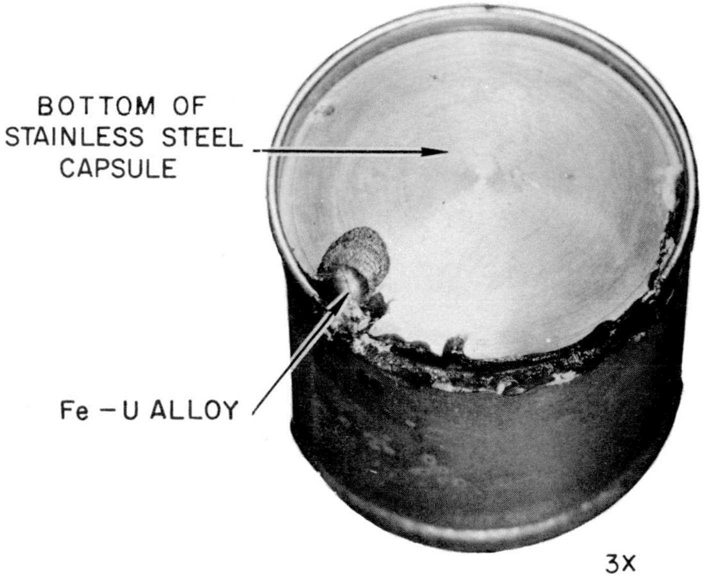
QUARTZ - TUBE TECHNIQUE



BOTTOM VIEW

RUN 16: URANIUM ON
STAINLESS STEEL HELD
7.92 MINUTES AT 1775-1800°F

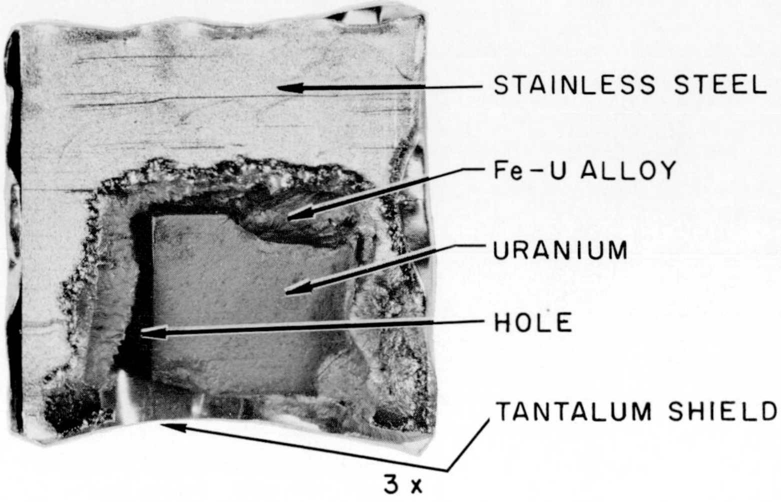
PRESSURE - VESSEL TECHNIQUE



RUN 25: SODIUM - BONDED
URANIUM HELD 3.0 MINUTES
AT 1780 - 1804 °F

Figure 7. Typical "Penetrated" Specimen

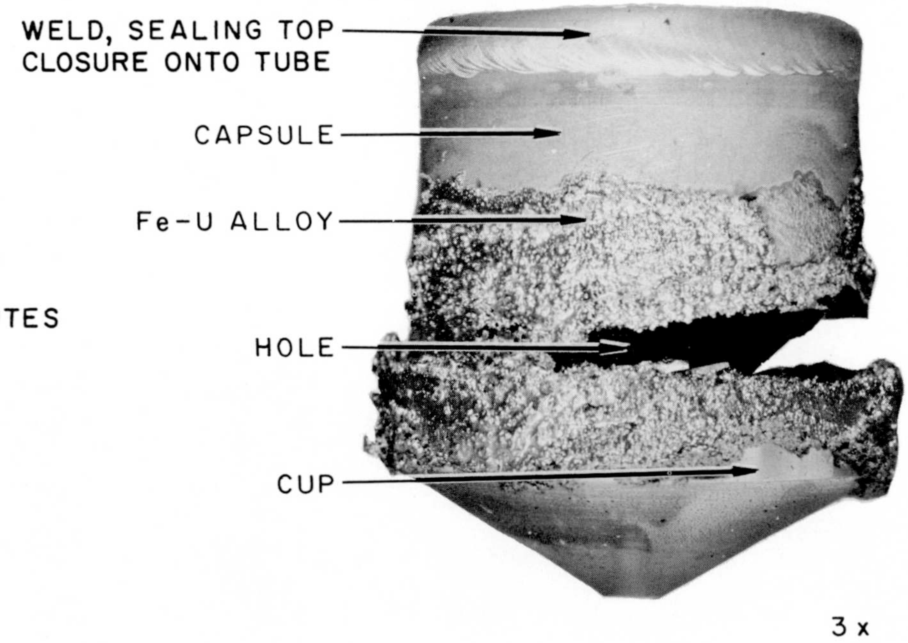
QUARTZ - TUBE TECHNIQUE



RUN 17: URANIUM ON
STAINLESS STEEL HELD
0.50 MINUTES AT 1945 - 1960°F

TOP VIEW

PRESSURE - VESSEL TECHNIQUE



RUN 29: SODIUM-BONDED
URANIUM HELD 3.62 MINUTES
AT 1955 - 1981°F

SIDE VIEW

Figure 8. Typical "Parted" Specimen

TABLE IV

COMPARISON OF DATA FOR URANIUM-BASE FUELS

Run No.	Method[*]	Fuel[†]	Temperature (°F)		Time, at Temperature (min)	Remarks
			Furnace	Top[§]		
12	Q. T.	U	1800	1800	1.42	Alloyed, not penetrated
31	P. V.	U	1800	1786	6.0	Penetrated in 1.05 min
25	P. V.	U	1800	1804	3.0	Penetrated in 1.25 min
13	Q. T.	U	1800	1800	1.88	Penetrated
16	Q. T.	U	1800	1800	7.92	Penetrated, not parted
36	P. V.	U	1900	1857	1.75	Penetrated at 1772°F
35	P. V.	U	1900	1848	0.82	Penetrated at 1820°F
30	P. V.	U	2000	1962	2.15	Penetrated at 1925° and parted at end
29	P. V.	U	2000	1981	3.62	Penetrated at 1965° and parted at end
18	Q. T.	U	2000	1960	0.28	Parted
17	Q. T.	U	2000	1960	0.50	Parted
9	Q. T.	U - 3.5 Mo	2200	1960	0.06[**]	Penetrated
10	Q. T.	U - 3.5 Mo	2200	1960	0.06[**]	Penetrated
11	Q. T.	U - 3.5 Mo	2200	1990	0.06[**]	Large penetration
7	Q. T.	U - 3.5 Mo	2200	2020	0.06[**]	Parted
50	Q. T.	U - 10 Mo	1800	1800	6.6	No alloying
52	Q. T.	U - 10 Mo	1800	1800	6.8	Penetrated, small spot
44	Q. T.	U - 10 Mo	1800	1800	20.0	Penetrated, large spot
53	Q. T.	U - 10 Mo	1800	1800	36.0	Penetrated, but not parted
56	Q. T.	U - 10 Mo	2000	2000	0.5	Alloyed, not penetrated
55	Q. T.	U - 10 Mo	2000	2000	1.0	Penetrated
59	Q. T.	U - 10 Mo	2000	2000	2.4	Penetrated, big spots
54	Q. T.	U - 10 Mo	2000	2000	1.4	Parted, square hole
60	Q. T.	U - 10 Mo	2000	2000	4.3	Parted, square hole

[*] Q.T. = quartz-tube technique; P.V. = pressure vessel technique.

[†] Fuel compositions in wt %.

[§] Top temperatures listed are the same as furnace temperatures for Q.T. runs since individual temperatures are not measured in this technique.

[**] Time and temperature estimated from heating rate curves in Figure 2.

TABLE V

COMPARISON OF DATA FOR THORIUM-BASE FUELS

Run No.	Method*	Fuel†	Time at Temperature (min)	Top Temperature (°F)	Results
32	P. V.	Th - 7.6 U	14.1	1790	Penetrated on cooling
33	P. V.	Th - 7.6 U	1.4	1927	Penetrated at 1892°F
1	Q. T.	Th - 7.6 U	2.9	2000§	No penetration
34	P. V.	Th - 7.6 U	9.0	1980	Penetrated after 7.4 min at temperature
4	Q. T.	Th - 7.6 U	0.50	2200§	No penetration
2	Q. T.	Th - 7.6 U	3.1	2200§	Parted
5	Q. T.	Th - 7.6 U	0.85	2300§	No penetration
3	Q. T.	Th - 7.6 U	0.90	2300§	Penetrated

* P.V. = pressure-vessel technique; Q.T. = quartz-tube technique
† All compositions in wt %.
§ Nominal temperature. Individual temperatures not recorded in quartz-tube technique.

TABLE VI

SUMMARY OF RESULTS

Nominal Temperature (°F)	Approximate Minutes for Penetration	Approximate Minutes for Parting
	A. URANIUM	
1800	1	over 8
1900	under 1	over 2
2000	few seconds	under 0.5
	B. URANIUM - 10 wt % MOLYBDENUM	
1800	6.8	over 35
2000	0.5 to 1	2 to 4
	C. THORIUM - 7.6 wt % URANIUM	
1800	14	-
2000	6 to 9	-
2200	over 1	3
2300	0.8 to 1	-

Penetration and parting times are for 0.010 in. thick, Type 304 stainless steel.
The number of minutes given is for "Time at Temperature," as defined under Results.

VI. DISCUSSION OF RESULTS

A. URANIUM

The uranium (and the U - 3.5 Mo alloy) used in this work, melted between 1980 and 2000°F, and rapid penetration and parting were observed at or above this temperature. When the test temperature was 1800°F, penetration required about a minute, but parting did not occur with additional exposures up to seven minutes. This unexpected result is illustrated by Run 31. In this particular run, the fuel capsule was held some five minutes at 1800°F after penetration occurred. As may be seen in Figure 9, the uranium was alloyed to a depth of about 0.075-in. and the stainless steel thinned appreciably. The jacket was pentrated in an area not included in these photomicrographs, and the stainless was consumed at that spot in a manner similar to that depicted in Figure 7 for Run 16. Thus, it appears that the progression from penetration to parting is not as rapid as had been anticipated, but instead remains dependent on diffusion mechanisms and close physical proximity.

B. URANIUM-MOLYBDENUM ALLOYS

As shown in Tables I and III, a few runs were made with a U - 3.5 Mo alloy. No significant difference was noted from unalloyed uranium, and no further runs were made with this alloy.

On the other hand, a significant difference in alloying rates was noted when 10 wt % Mo was added to U. As the first fuel loading for the Hallam Nuclear Power Facility is expected to be U - 10 Mo, this alloy was investigated more completely than U - 3.5 Mo. As may be seen from Table VI, much longer times for both penetration and parting are required at 1800 and 2000°F for U - 10 Mo than for U. The results in Table VI for U - 10 Mo are based on data obtained by the quartz-tube technique under a vacuum of 3 to 8 x 10^{-5} mm Hg. The data for all the other alloys by the quartz-tube technique were obtained without a diffusion pump in the vacuum system, where the pressure probably ranged from 0.5 to 3 x 10^{-3} mm Hg. This difference in vacuum quality requirements is worthy of comment.

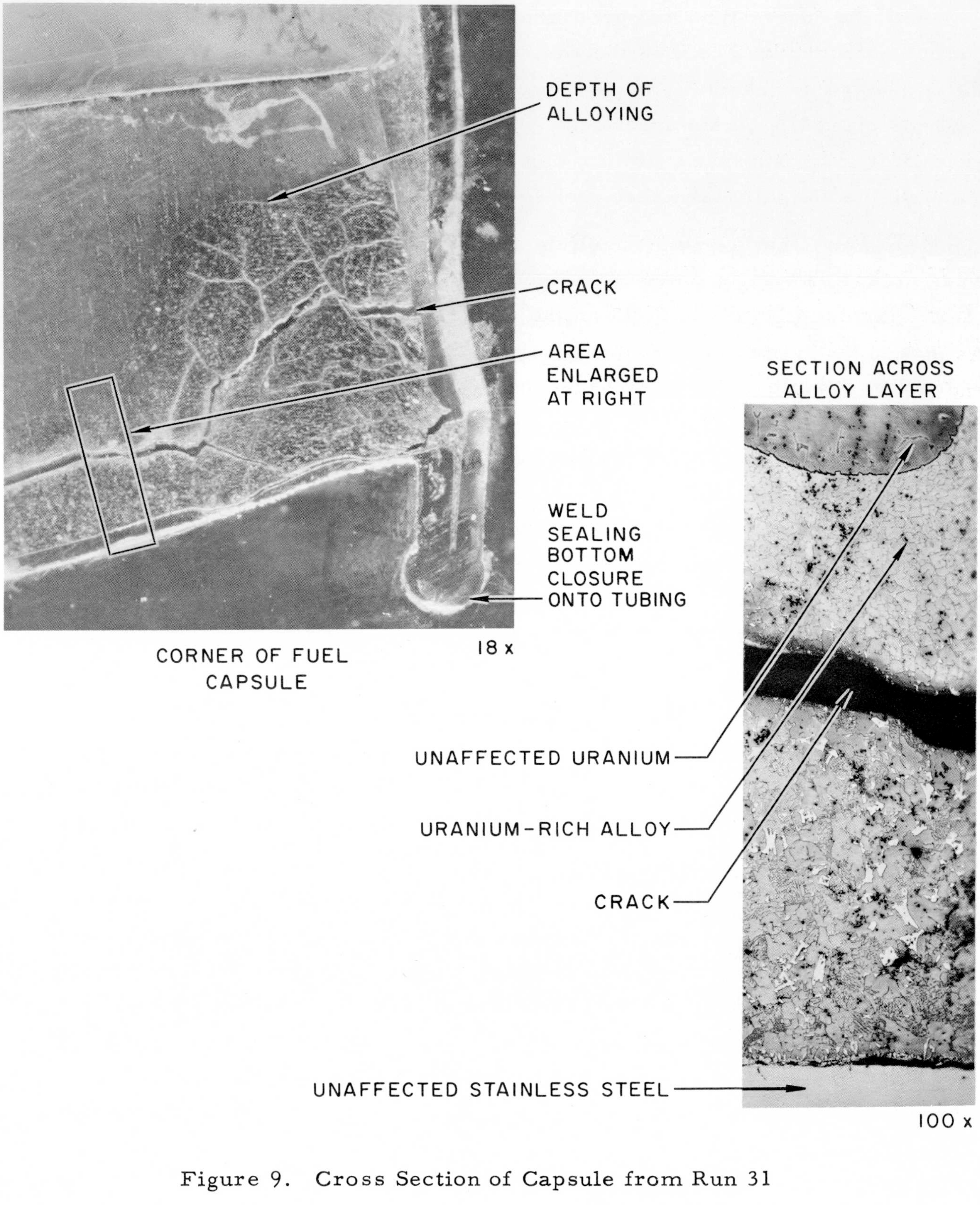


Figure 9. Cross Section of Capsule from Run 31

Both the quartz-tube and pressure-vessel techniques were used with good but not extraordinary care in the runs with unalloyed U. Quartz-tube runs with the two-stage mechanical pump continuously evacuating the tube resulted in badly oxidized U - 10 Mo specimens which did not alloy with the stainless steel even after long exposures. Improving the vacuum with a cold-trapped diffusion pump yielded slightly tarnished fuel specimens and the data reported herein.

Similarly, the U - 10 Mo fuel elements for the pressure-vessel technique were encapsulated in a glove box wherein, over a period of a few minutes, a visible tarnish film would form on the surface of the NaK. This level of oxygen content in the helium glove-box atmosphere is typical for the loading and welding of the fuel capsules used in this test work. Yet, six of the seven runs were made with U - 10 Mo by the pressure-vessel technique resulted in no alloying. When these fuel wafers were inspected after the run, films varying from medium to dark grey were found on them. Metallographic inspection showed the film varied in thickness, but did not exceed about 0.0003 in. This thin film apparently has a powerful inhibiting effect on the interdiffusion of uranium and stainless steel. No attempt was made to fabricate additional fuel elements with the extraordinary care necessary to achieve an absolute minimum of oxygen contamination.

The effectiveness of the thin oxide film in delaying loss of cladding integrity at temperatures approaching the melting point of the U - 10 Mo fuel suggests its use in reactor fuel elements. An oxide film 0.0005 in. thick would increase the metal fuel temperature only 15 to 20°F, a small price to pay for the insurance offered.

C. THORIUM - 7.6 wt % URANIUM

The Th - 7.6 wt % U fuel alloyed with the stainless steel more slowly than the uranium-base alloys, as was expected. The very rapid penetration observed with unalloyed uranium at 2000 and 2200°F did not occur in any of the runs made with thorium fuels, since none were made close to the melting point of either the fuel or the stainless steel.

The thorium-uranium phase diagram of Bentle[8] shows a region of αTh + L_1 (called δ + L_1 Reference 3) from about 2000 to about 2315°F, for the Th - 7.6 wt% uranium alloy. Calculations show about 5% liquid phase in equilibrium with α-thorium at 2000°F, decreasing to zero at about 2300°F. This may explain the apparent anomalous behavior in Run 33, in that some of the liquid phase formed and touched the stainless steel through the sodium bond causing rapid penetration. In general, the formation of a small amount of liquid phase (as indicated by the equilibrium diagram) within the thorium-uranium fuel specimen did not seem to affect the penetration rate.

VII. CONCLUSIONS

Should the interface between the stainless steel jacket and the unalloyed uranium fuel in an SRE fuel element reach 2000°F, rapid penetration of the jacket will occur. The jacket will part after a few seconds. At 1800°F, the jacket will maintain its integrity about a minute. Under normal operating conditions, where the interface temperature is about 1000°F, SRE operational experience has shown that formation of a eutectic composition is too slow to affect the anticipated life the the element.

When the fuel is U - 10 Mo, the 0.010-in. thick stainless steel jacket will be penetrated in a little less than a minute after reaching 2000°F and will part about two minutes later. Should the element remain at 1800°F, the data indicate that it should not be penetrated in less than six minutes. However, a thin oxide film on the U - 10 Mo fuel surface will substantially lengthen these times. A film thickness of less than 0.0005-in. should be effective As with unalloyed uranium, eutectic composition formation at 1000°F should be no problem.

Thorium-fueled elements will not be damaged by eutectic-composition-formation as quickly as uranium-fueled elements. The iron-thorium eutectic melts at a higher temperature. The anticipated life should be over 10 min at 1800°F, decreasing to about 1 min at 2300°F. As with uranium fuels, the life of a thorium-fueled element operating at normal temperatures should not be affected by eutectic-composition-formation.

APPENDIX I
QUARTZ-TUBE APPARATUS

The apparatus for the quartz-tube technique is shown in Figure 1. Fuel specimens were nominally 1/8-in. thick and 3/8-in. square. One face was machined to a 32 rms finish or better. The specimens were degreased and electropolished to clean them, and stored in a vacuum dessicator to prevent oxidation. The Type 304 stainless steel squares were cut from 0.010-in. SRE tubing, flattened and cleaned. They were about 3/4-in. square.

Not shown in Figure 1 is the support for the stainless steel squares. This support was necessary to increase the ease of handling the apparatus, and to prevent contamination of the quartz tube in case of melt-through. A piece of 0.005-in. thick tantalum sheet, about 7/8 by 1-1/4 in., was shaped like part of a cylinder to conform to the inside of the quartz tube, and the edges bent in to clamp the stainless steel in place. This shield may be seen under the specimen from Run 17, in Figure 8.

The quartz-tube was evacuated thoroughly before it was inserted into the furnace. A Welch Model 1397 two-stage pump was used for this purpose. However, it was found necessary to add a 2-in. diffusion pump and a cold trap to the evacuation train for the U - 10 Mo tests. With this addition, a vacuum of 5×10^{-5} mm Hg or better was attained before beginning each test.

APPENDIX II

PRESSURE-VESSEL APPARATUS

The apparatus for the pressure vessel technique is shown in Figures 3 and 4. It consists of a fuel capsule of the same dimensions as an SRE fuel rod except for length, and an outer pressure vessel.

The fuel capsule was made with Type 304 stainless steel. A piece of SRE tubing, 0.790-in. outside diameter by 0.010-in. wall, was cut to 0.70-in. lengths. Bottom end caps were machined from bar stock to 0.010-in. thickness, with a weld-lip about 0.04-in. long. The bottom end cap was welded to the tube by the tungsten-electrode, inert gas process (TIG) and leak checked. The fuel wafers were machined to 0.750-in. diameter by 0.125-in. thick with a 32 rms finish and degreased. They were cleaned by electropolishing immediately prior to loading. The capsule was loaded with the fuel wafer, about 0.3 g of Na or NaK added, and the top cap TIG-welded on in a glove box wherein the NaK would show a visible oxide layer in 10 to 15 min. The completed capsule was helium leak-checked prior to assembly into the pressure vessel.

The pressure vessel around the fuel capsule was necessary for two reasons. It prevented a fire and/or contamination of the furnace after the capsule was penetrated. Secondly, the helium inside the pressure vessel was maintained at 4 to 8 atmospheres pressure, depending on the test temperature and the resultant vapor pressure of the Na or NaK, to prevent distortion of the capsule's bottom end cap. The pressure vessel was made by butt-welding two commercially-available weld caps together. These 2-in. Schedule-40 weld caps were of Type 347 stainless steel, since Type 347 is considerably stronger than Type 304 stainless steel at 1800 or 2000°F. The required parts were TIG-welded into each weld cap and leak checked prior to welding the two caps together, and this final weld was again leak checked.

Before each run, the pressure vessel was evacuated and refilled with helium about six to ten times, through the pressure-gage tube. The pressure of the helium after the final filling was between 5 and 25 psig, depending on the test temperature and whether the fuel was bonded with Na or NaK. After connecting the thermocouple leads, the pressure vessel was placed in the preheated Glo-Bar furnace and the recorder chart was started at the time of insertion. The pressure gage readings were noted alongside the temperature on the recorder chart. Also, an ohmmeter was connected between one of the thermocouple wires and the thermocouple sheath. The ohmmeter read about 0.3 to 0.9 meg until penetration occurred, with release of the Na or NaK from the capsule. This Na or NaK would collect in the cup directly below the capsule, and short the bare thermocouple bead to the sheath. Thus, at penetration, the ohmmeter indicated a short, the ohmmeter voltage was impressed on the thermocouple causing the recorder to go offscale, and the pressure gage indicated a pressure increase. Although the time and temperature of penetration is accurately indicated, there was no way of determining whether parting had occurred until the pressure vessel was opened after the run. Generally, the pressure vessel was not removed from the furnace for several minutes after penetration, to see whether parting would occur in the additional time.

The same large Glo-Bar furnace was used for this technique as was used for the quartz-tube technique. The relatively large mass of preheated firebrick helped increase the heating rate, and the 35 kw power input quickly brought the furnace back to the desired temperature after closing the door.

APPENDIX III

HEATING RATE DETERMINATIONS

Heating rates for specimens tested by the pressure-vessel technique were measured by the bare thermocouple located directly below the capsule. The thermocouple output was fed to a recorder having a chart speed of 4 in./min and a 1/4-sec full-scale pen travel. The records of each run made by the pressure-vessel technique were plotted together and then averaged for each temperature. The resulting curves are shown in Figure 5.

The heating rates for the quartz-tube technique were determined indirectly. A chromel-alumel thermocouple, made of 0.005-in. wires, was welded to the center of a 3/4-in. square of the 0.010-in. thick stainless steel. A dummy fuel specimen was made of stainless steel and centered on top of the thermocouple. A small slot was milled in the bottom of the fuel specimen to fit the thermocouple wires. A special Pyrex fitting, with thermocouple wires sealed in, was fitted to the end of the quartz tube to connect it to the mechanical vacuum pump. Thus, the heating rate of the interface between the "fuel" and the stainless steel was recorded at least four times for each temperature. The curves obtained in this way were averaged and are plotted in Figure 2.

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