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FACTORS AFFECTING THE SWELLING DURING DEGASSING OF COMPACTS CONTAINING URANIUM-ALUMINUM INTERMETALLICS DISPERSED IN ALUMINUM

A. K. Chakraborty, R. S. Crouse, and W. R. Martin

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MARCH 1970

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CONTENTS

Page

Abstract 1
Introduction 1
Experimental Procedures 3
Preparation of Dispersions 3
Dilatometer Measurements 4
Metallographic and Other Examinations 5
Results and Discussion 5
Effect of Fuel Concentration 6
Effect of Particle Size Distribution and Degassing Temperature 8
Influence of Steam on the Swelling Behavior 13
Effect of Ternary Alloy Additions 14
Zr-U-Al Alloys 14
Si-U-Al Alloys 18
Ge-U-Al Alloys 19
Sn-U-Al Alloys 20
Comparison of These Alloy Systems 20
Conclusions 22
Acknowledgments 23

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A. K. Chakraborty,[1] R. S. Crouse, and W. R. Martin

ABSTRACT

Swelling of dispersions of UAl_3 in aluminum was investigated by dilatometry, measurement of gas evolution, electrical conductivity, heating-stage metallographic examination, and electron-beam microprobe analysis. The swelling occurs in two stages. In the first, the swelling is gradual and believed to be due to adsorbed gases that are released from the surfaces of the aluminum and UAl_3 powder particles. After a varying "incubation time," the second stage of swelling at a greatly increased rate begins. This incubation period increases with increasing UAl_3 particle size and decreasing temperature. The second stage is due to the transformation of the UAl_3 to UAl_4 through reaction with the aluminum matrix.

The stability of UAl_3 containing either Si, Ge, Sn, or Zr was investigated. These results show silicon and germanium to be the most effective stabilizers within the range of approximately 5 to 6 wt %. Tin was effective at approximately 1.5 wt %, but higher concentrations were detrimental. Zirconium was ineffective for concentrations up to approximately 6 wt %, but a 14-wt-% alloy was stable.

INTRODUCTION

Dispersions of uranium-aluminum intermetallic compounds in aluminum in various proportions are being used or considered for fuel cores in several reactors, such as the Engineering Test Reactor, the Materials Testing Reactor, and the Advanced Test Reactor. Advantages of these intermetallics over U_3O_8 include higher thermal conductivity[2] and better

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[1]Present address, Argonne National Laboratory, Idaho Falls, Idaho.

[2]S. Nazare, G. Ondracek, and F. Thümmler, The Technology of UAl_3–Al Irradiation Test Plates, KFK-585 (April 1967).

compatibility with the matrix. In current fabrication techniques,[3,4] both intermetallic and oxide dispersion cores are generally degassed for 1 to 2 hr at 500 to 590°C before they are rolled into aluminum-clad fuel plates. Since the frame cavity must be accurately dimensioned to accept the core compact, unpredictable dimensional changes of the core compacts during degassing pose a serious problem.[4] Werner, Martin, and Erwin[5] reported a volume increase of 14.4% during degassing of compacts containing 51.1% UAl_3 dispersed in aluminum. The amount of swelling increases with the concentration of the intermetallic fuel and with the temperature of degassing. The reaction of UAl_3 with aluminum to form UAl_4 contributes to the instability of the compacts, although the volume change resulting from the reaction, as calculated from the densities of these compounds, is quite small.[5] A previous hot-stage metallographic study[6] showed that irregular shape change of the dispersed fuel particles during the transformation is a major contributor to the swelling. One purpose of this investigation was to gain a better understanding of factors that influence the swelling of these binary mixtures of UAl_3 and aluminum.

Picklesimer and Thurber[7] showed that a ternary addition to the intermetallic compound can suppress the transformation of UAl_3 to UAl_4. Thurber and Beaver[8] believed that any additional element can retard the

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[3]R. J. Beaver, J. W. Tackett, J. H. Erwin, G. M. Slaughter, and W. J. Kucera, Initial Development of HFIR Fuel Assemblies, ORNL-4108 (October 1967).

[4]J. H. Erwin, W. J. Werner, and M. M. Martin, Development and Fabrication of Instrumented-Plate Advanced Test Reactor Fuel Elements, ORNL-4268 (October 1968).

[5]W. J. Werner, M. M. Martin, and J. H. Erwin, Metals and Ceramics Div. Ann. Progr. Rept. June 30, 1966, ORNL-3970, pp. 107–109.

[6]J. L. Gregg, R. S. Crouse, and W. J. Werner, Swelling of UAl_3–Al Compacts, ORNL-4056 (January 1967).

[7]M. L. Picklesimer and W. C. Thurber, Method of Suppressing UAl_4 Formation in U-Al Alloys (to U.S. Atomic Energy Commission). U.S. Patent 2,950,188, Aug. 23, 1960.

[8]W. C. Thurber and R. J. Beaver, Development of Silicon Modified 48 wt % U-Al Alloys for Aluminum Plate-Type Fuel Elements, ORNL-2602 (Mar. 9, 1959).

peritectic reaction Al(liq) + $UAl_3 \rightarrow UAl_4$, and the most favorable additions are those that form an isotype compound like UX_3. Therefore, elements like Ga, Ge, In, Pb, Si, Sn, Ti, and Th, which form a compound UX_3 with $AuCu_3$ structure, should stabilize the UAl_3 compound.

Some ternary additions in uranium-aluminum alloys permit UAl_3 to coexist with aluminum during prolonged heating. For example, Petzow and Chakraborty[9] observed a stable two-phase region (UAl_3 + Al) in the U-Zr-Al system and found that UAl_3 could dissolve 16.9 at. % Zr. Miller and Bridges[10] also reported that such a two-phase region exists in equilibrium in the U-Al-Si system. Petzow and Exner[11] also predict that the solubility of the ternary elements in UAl_3 should depend on their atomic diameters. Aluminum atoms of the UAl_3 lattice should be most effectively replaced by elements with similar atomic radii, such as Si, Ge, or possibly Sn. Similarly, Ti, Zr, and Hf should replace atoms of uranium.

Since some of the phase diagrams are not adequately established, we needed to determine the stability of the UAl_3 phase as a function of concentration of ternary additives so we could select a ternary fuel composition that would be stable during fabrication.

EXPERIMENTAL PROCEDURES

Preparation of Dispersions

We investigated uranium-aluminum intermetallic prepared by two methods. In the first method we repeated the process of arc melting a given heat of U–23 wt % Al 12 times. Rapid cooling was used to minimize segregation. In the second method high-purity uranium powder and

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[9]C. Petzow, H. E. Exner, and A. K. Chakraborty, "Phase Equilibria in Aluminum-Uranium-Zirconium Alloys of the Partial System Aluminum-UAl_2-$ZrAl_2$," J. Nucl. Mater. 25, 1–15 (1968).

[10]E. C. Miller and W. H. Bridges, Met. Div. Quart. Progr. Rept. Oct. 31, 1950, ORNL-910, p. 28.

[11]G. Petzow and H. E. Exner, Aluminum-Rich Uranium Alloys, BMwF-FBK-67-88 (December 1967).

Alcoa 101 aluminum powder were mixed in the same proportions, blended 45 min, pressed in a graphite die, and then heated to 950°C for 3 hr under a pressure of 600 psi. X-ray diffraction showed that both products were principally UAl_3, with very little UAl_2 and no UAl_4. Only the powder metallurgy product showed some unreacted aluminum.

Materials prepared by both methods were ball-milled to powder. Various particle size fractions were blended with various proportions of −325-mesh aluminum. Since the storage history of the aluminum powder was uncertain, some was preheated 1 hr at 400°C under high vacuum. The mixtures were blended 1 hr in 5-g batches in bottles one-fourth to one-third full. The heat-treated powders were blended under argon and pressed immediately. Compacts were pressed at 22.5 tsi in a double-action die press. The die walls were lubricated with a solution of stearic acid in carbon tetrachloride. The pellets were 0.5 in. in diameter and nearly 0.5 in. in height; the exact height depended on the UAl_3 concentration.

Uranium alloys with various proportions of Zr, Si, Sn, and Ge were prepared by arc melting six times in argon. The alloys were crushed to fine powders and hydrided at 550°C for several hours for further refinement. After chemical analysis the hydrided alloys were mixed with hydrided uranium powder to obtain the desired additive concentrations. The particle size distribution of the mixtures was 90% −325 mesh. These powders were then mixed with Alcoa 101 aluminum powder, blended, cold pressed, and sintered in a graphite die for 2 hr at 1000°C and 600 psi. The proportions were so chosen that the product contained 26% Al.

These intermetallic fuel materials were examined by metallography and x-ray diffraction to identify the phases present. They were then crushed to powders in a glove box and mixed with 60 wt % Alcoa 101 aluminum powder. The mixtures were blended 45 min and cold pressed at 22.5 tsi to compacts 0.5 in. in diameter × 0.5 in. high.

Dilatometer Measurements

The change in length of the pellets was measured, and the pressure of the system was recorded as a function of time at temperature. The

pellet was placed in a quartz tube in contact with a thermocouple to measure its approximate temperature. A clamshell furnace anchored to an adjustable jack and mounted on rollers was used to heat the pellets rapidly. The dilatometer chamber and quartz tube were evacuated to 10^{-5} torr. The furnace was positioned with its hottest zone surrounding the pellet, and the system was simultaneously isolated from the vacuum pump. When the specimen thermocouple reached the test temperature, we began measuring the change in length with the dilatometer and the gas evolution with a pressure gage.

Metallographic and Other Examinations

Room-temperature metallographic observations were carried out by standard techniques. Different etchants were used[12] to distinguish different intermetallic compounds. High-temperature metallography was done with a Reichert heating-stage microscope by procedure described elsewhere.[6] Local concentrations of aluminum and uranium were determined with an electron-beam microprobe.

Electrical resistivity was measured on pellets 1 in. long × 0.25 in. in diameter made by the procedure described above. The potential drop between two razor blades contacting the specimen, 2 cm apart, was measured with a Kelvin bridge. Specimens with different particle size fractions were heat treated at 600°C. After the pellets were cooled very quickly, the resistivity measurements were made at room temperature.

RESULTS AND DISCUSSION

To consider separately many of the swelling variables investigated, we have separated our results and discussions into four separate areas. These are: (1) effect of fuel concentration, (2) effect of particle size distribution and degassing temperature, (3) influence of steam on the swelling behavior, and (4) effect of ternary alloy additions.

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[12] R. F. Hills, "Some Observations on the Identification of Compounds in the System Uranium-Aluminum," J. Inst. Metals 86, 438–441 (1957).

Effect of Fuel Concentration

Figure 1 shows the change in length during degassing for 1 hr at 600°C of 0.5-in. pellets containing different concentrations of UAl_3. The swelling increased with the intermetallic content for the range of concentrations investigated.

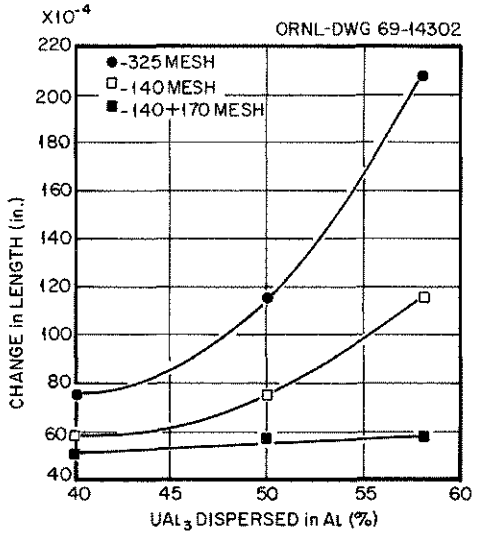

Fig. 1. Change in Length of Pellets Containing Different Concentrations of Arc-Melted UAl_3 During Isothermal Degassing at 600°C for 1 hr.

Figure 2 shows the change in length as a function of time at 600°C for pellets containing various proportions of the intermetallic compounds from which we can resolve two stages of swelling. These specimens were pressed from powders that had not been heat treated, so adsorbed gases, principally water vapor, had not been removed from the powder surface. Pellets pressed from aluminum powder alone showed different behavior than those containing the intermetallic. After an initial rapid change in length, the expansion slowed down.

The pellets containing the intermetallic at first showed a similar behavior, except that the initial expansion was much less. However, after the initial period of swelling a second stage of swelling is observed in the compacts containing the intermetallic. The first-stage swelling is nearly complete in 10 to 20 min at 600°C. This observation

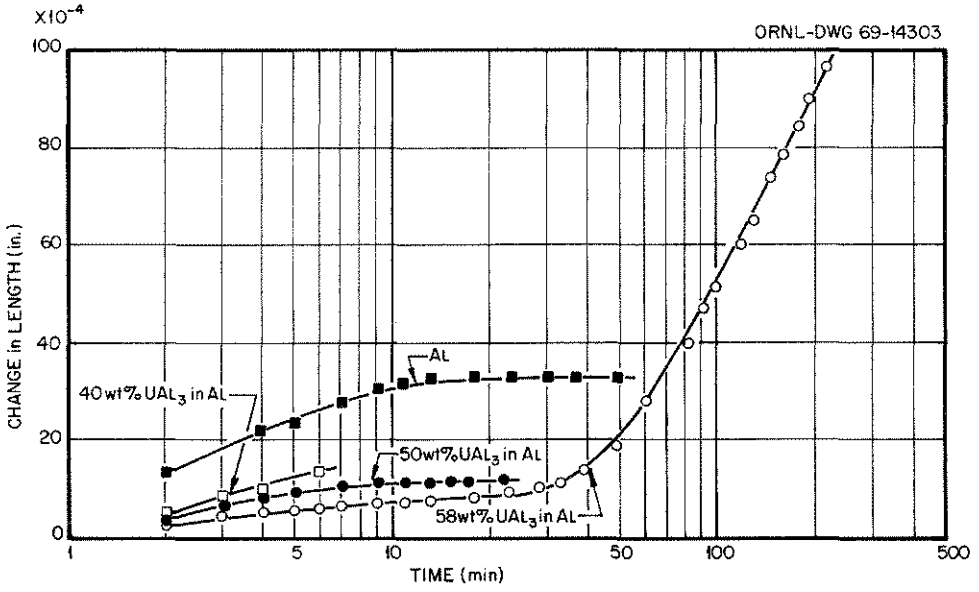

Fig. 2. Change in Length of Pressed Aluminum Powder and Dispersions of 100-μm-diam Intermetallic in Different Proportions at 600°C. The UAl_3 powders were prepared from arc-cast buttons, and neither fuel nor aluminum powders were degassed before compaction.

indicates that the aluminum powder is primarily responsible for the initial stage of swelling. The adsorbed gases on the aluminum powder apparently play a dominant role in swelling of the highly compacted material. At elevated temperatures these gases desorb and expand to decrease the contact between the particles, pushing them apart and thus increasing the volume of the compact. The initial volume increase of both pure aluminum and the intermetallic dispersions can be explained by this effect. The effect should increase with decreasing porosity, and hence higher compacting pressure should lead to a greater volume increase. Pines, Sirenko, and Sukhinin[13] observed this in their experiments on the sintering of copper powder.

Increasing the concentration of the intermetallic also increased the time before the onset of rapid swelling. We have no satisfactory explanation for this.

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[13]B. Ya. Pines, A. F. Sirenko, and N. I. Sukhinin, "Sintering of Inorganic Solids. III. Sintering of Mixtures Containing Low-Melting Components," Zh. Tekn. Fiz. 27, 1893–1903 (1957).

Figure 3 shows photomicrographs of dispersed −140 +170-mesh particles taken on the hot-stage microscope after different periods at 600°C. In (a) several grains have started to transform by 10 min, even though the sample has not yet reached the second stage of swelling. In (b) the transformation is nearly complete. Note the void space around the transformed particles; Castleman[14] has similarly observed voids at higher temperatures near the Al-UAl_3 interface. Also, a strain and evidence of recrystallization can be seen in the aluminum matrix, as observed earlier by Gregg et al.[15] Comparing with (a) shows that particles are tending to fragment as they transform; this increases the surface area of the particles.

Effect of Particle Size Distribution and Degassing Temperature

Figures 4 and 5 show the swelling of compacts containing 58% UAl_3 having different particle sizes when heated in vacuum at various temperatures. In these experiments the blended powders had been vacuum annealed at 400°C for 1 hr before pressing to decrease the initial swelling shown in Fig. 2. This treatment removed adsorbed water vapor but did not decompose the hydrated aluminum oxide[16] on the surface of the aluminum powder. The second-stage swelling of the compacts with finer UAl_3 occurs sooner as shown in Fig. 4 at 550 and 600°C. Comparing the curves in Fig. 5 shows that the onset of rapid swelling is reduced by lowering the temperature. In fact, this transition is not reached at 500°C within 300 min. Two factors contribute to this particular size effect. Decreasing the particle size of the UAl_3 increases the area of contact with aluminum per unit volume of fuel. Smaller particles also decrease the average distance aluminum atoms must diffuse to complete the conversion of UAl_3 to UAl_4.

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[14] L. S. Castleman, "Layer Growth During Interdiffusion in the Al-U Alloy Systems," J. Nucl. Mater. 3(1), 1–15 (1961).

[15] J. L. Gregg, R. S. Crouse, and W. J. Werner, Swelling of UAl_3–Al Compacts, ORNL-4056 (January 1967).

[16] J. A. Dromsky, A Study of the Dispersion Strengthened Al or SAP Type Alloys, Ph.D. Thesis, Rensselaer Polytechnical Institute (1963).

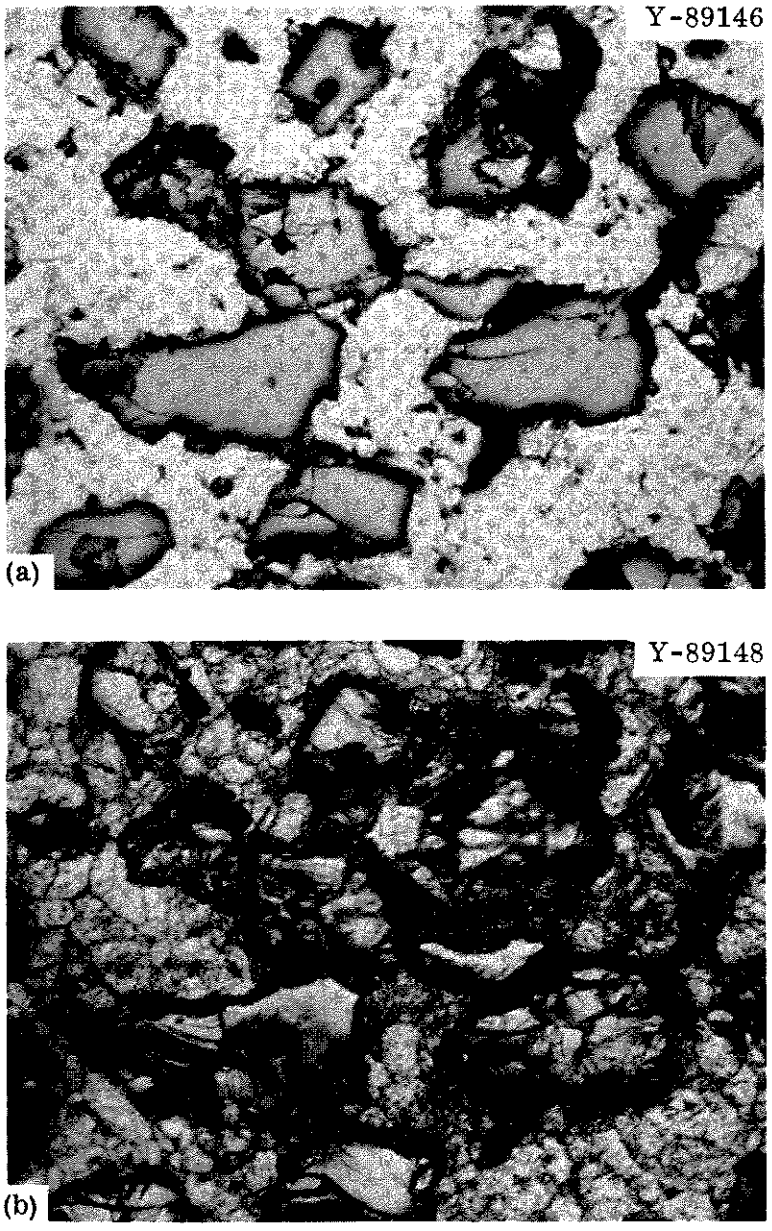

Fig. 3. Microstructure of Dispersion of −140 +170-Mesh Intermetallic as Observed on the Heating Stage During Transformation at 600°C. 200×. (a) After 10 min. (b) Same area after 1 hr.

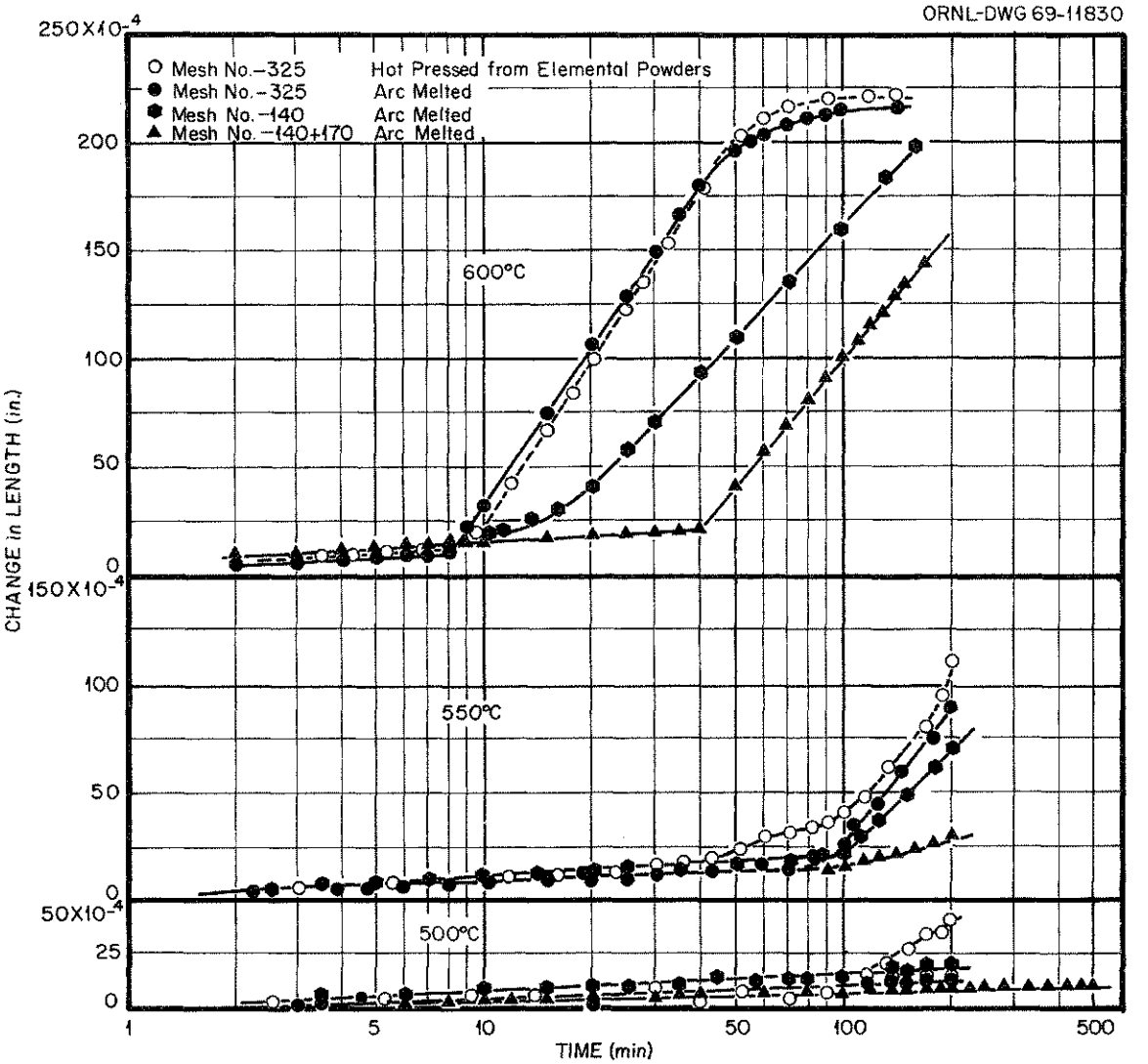

Fig. 4. Effect of Particle Size on Swelling of Compacts Containing 58% UAl_3 at Three Temperatures.

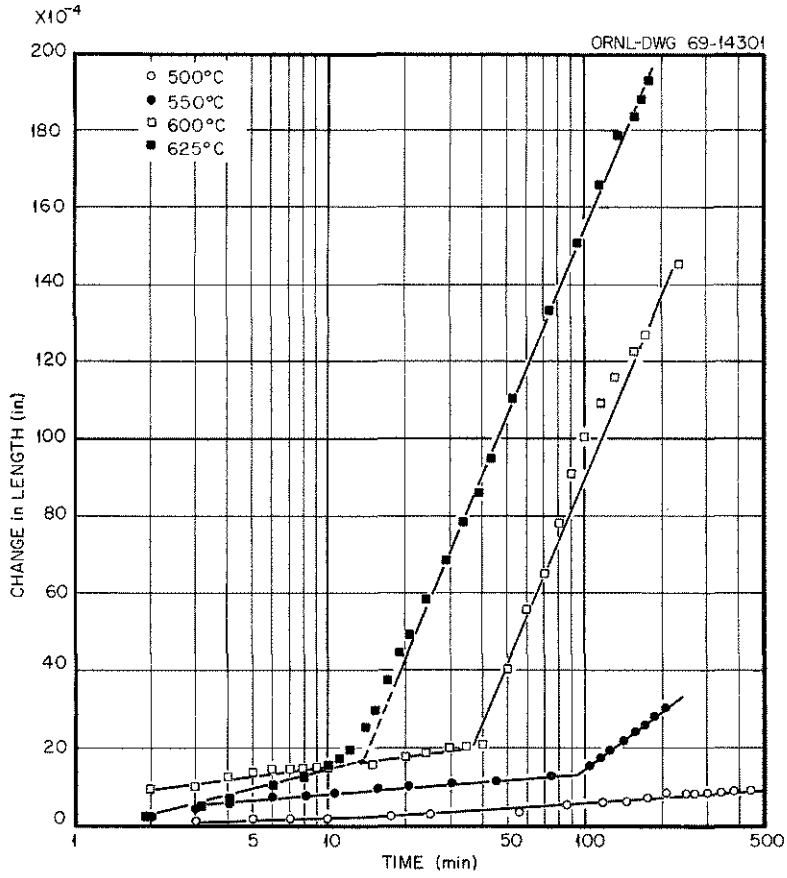

Fig. 5. Effect of Temperature on Swelling of Compacts Containing 58% −140 +170-Mesh UAl_3.

Figure 6 shows the change in pressure as the pellets containing different particle sizes of the intermetallics were heated in an evacuated apparatus at 600°C. For these experiments, the pellets reached 600°C in about 7 min. It is evident that gases are evolved even below 600°C. The pressure increases in a manner similar to the length of the pellets. The gas evolution from the finely divided particles begins earlier and reaches a greater magnitude. This is a direct consequence of the larger surface area of the smaller particles. Gas evolution depends some on the method of manufacture, probably because of a difference in surface areas. Gas continues to be evolved even after prolonged degassing.

Figure 7 shows the change in electrical resistance during degassing at 600°C for 40 wt % dispersions of the various particle sizes of UAl_3.

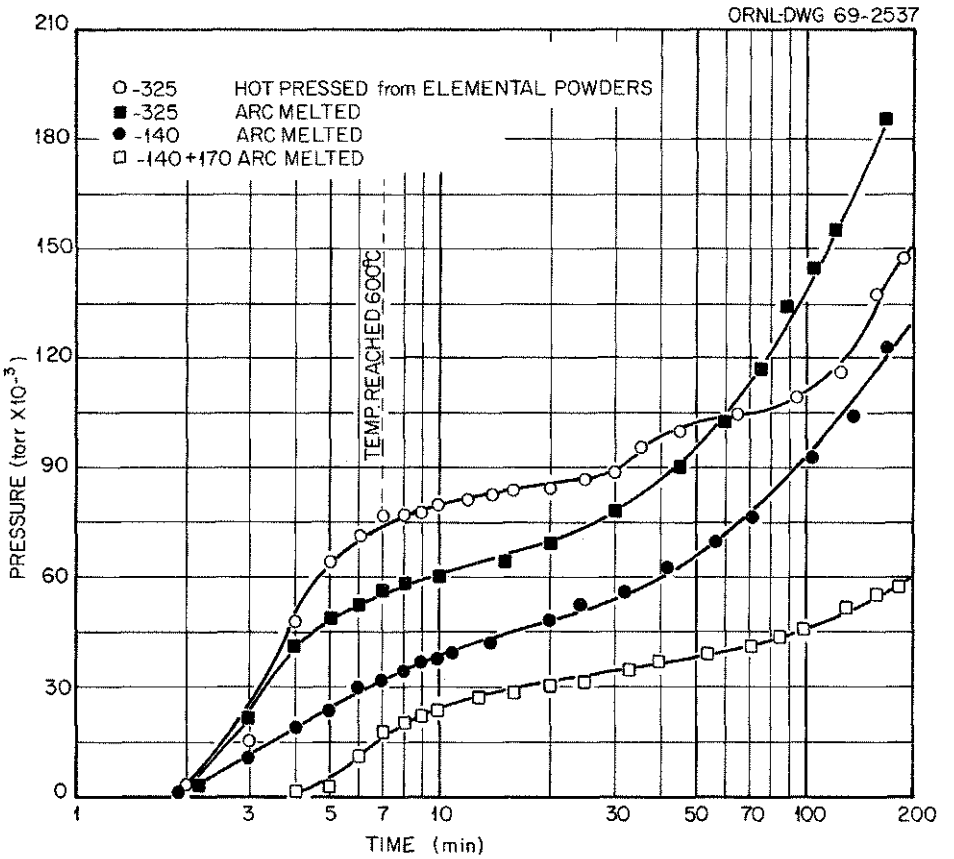

Fig. 6. Effect of Particle Size on Gas Evolution from Compacts Heated at 600°C.

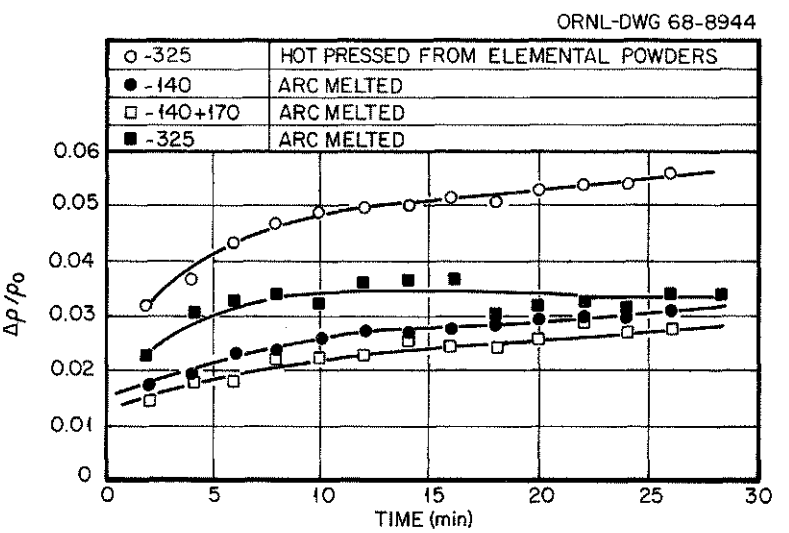

Fig. 7. Variation of Electrical Resistivity During Degassing at 600°C of Pellets Containing 40 wt % UAl_3 of Various Particle Sizes.

Relative values are plotted because of the uncertainties and inaccuracies in the geometry of the pellets. The rapid increase of resistance during the onset of transformation is in accordance with the other measurements. The finer particles react more rapidly and give a greater total change.

Influence of Steam on the Swelling Behavior

We investigated the swelling of UAl_3-Al compacts by adding steam during degassing. In one case 0.175 torr of steam was added initially, and in the second case steam was added after 300 min (i.e., when no further change in length was observed) to see whether steam has any influence on further swelling. The results are shown in Fig. 8.

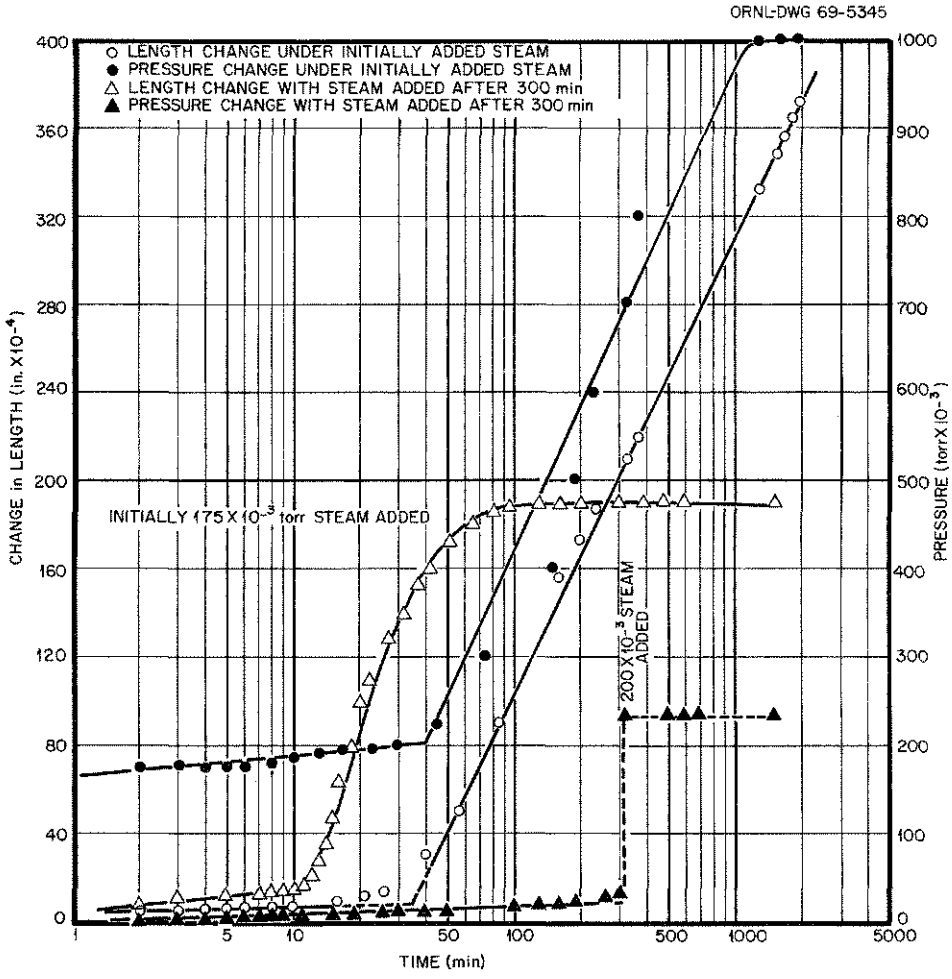

Fig. 8. Swelling and Outgassing of Compacts Degassed in the Presence of Steam.

Increasing the pressure by adding 0.20 torr of steam after swelling had stopped had no influence on the swelling. An identical compact gave a different result if measured under 0.175 torr initially added steam. The length increased up to 0.030 in. after 2000 min and reached no constant value, whereas the total pressure increased up to 1 torr and became parallel with the time axis. Evidently water vapor changed the swelling kinetics considerably.

The oxide forming on aluminum surfaces below 450 to 500°C is known to be amorphous. Oxide that forms in the presence of moisture contains some hydroxyl ions and can be represented as $Al_xO_y(OH)_z$. This oxide decomposes at elevated temperatures, forming either a more stable hydrate or Al_2O_3. The decomposition reaction is governed by the partial pressures of $H_2O + H_2$. When water vapor is introduced the decomposition is shifted toward a slower process. The retardation may account for the delay of second-stage swelling by the additional hydrate or oxide presenting a barrier to the diffusion of aluminum into the fuel. Also, once second-stage swelling does proceed, the presence of water vapor enhances the magnitude of swelling. The greater swelling could be caused by an interaction of the hydrogen from the steam with the porous structure produced during the transformation.

The swelling of the aluminum-dispersed UAl_3 compacts depends not only on the diffusion-controlled reaction between UAl_3 + Al but also on the presence of gases during the transformation.

Effect of Ternary Alloy Additions

Table 1 lists the alloys prepared, their compositions and preparation methods, and some results to be described later.

Zr-U-Al Alloys

Figure 9 shows the change in length at 600°C of the pellets containing different concentations of zirconium. The change in length can essentially be resolved into two steps, except for the pellet containing 14 wt % Zr. The first stage is believed to be due to the evolution of adsorbed gases, as was observed for the binary UAl_3-Al alloys. The second

Table 1. Intermetallic Alloys Investigated and Summary of Results

Alloy	Fuel Particle Concentration[a] (wt %)	Materials Sintered	Major Phases[b]	Reaction[c] in 1 hr	Length Change[d] (%)	Stabilized
A-1a	3.77 Zr	Hydrided powders	UAl_3 + UAl_2	Slight	< 1	No
A-3	31.10 Al, 14.02 Zr	Metal powders	UAl_3	No	< 1	Yes
A-5	1.48 Zr	Hydrided powders	UAl_3 + UAl_2	Yes	2	No
A-6	4.44 Zr	Hydrided powders	UAl_3 + UAl_2	Yes	3	Yes
A-7	5.91 Zr	Hydrided powders	UAl_3 + UAl_2	Slight	< 1	Yes
B-1	3.77 Si	Hydrided powders	UAl_3 + UAl_2	Slight	< 1	Yes
B-4	1.48 Si	Hydrided powders	UAl_3	Yes	< 1	No
B-5	4.44 Si	Hydrided powders	UAl_3	No	< 1	Yes
B-6	5.91 Si	Hydrided powders	UAl_3	No	< 1	Yes
C-1	3.77 Ge	Hydrided powders	UAl_3 + UAl_2	Yes	< 1	No
C-2	1.48 Ge	Hydrided powders	UAl_3 + UAl_2	Yes	< 1	No
C-3	4.44 Ge	Hydrided powders	UAl_3	No	< 1	Yes
C-4	5.91 Ge	Hydrided powders	UAl_3	No	< 1	Yes
D-1	3.77 Sn	Hydrided powders	UAl_3 + UAl_2	Yes	< 1	No
D-2	1.48 Sn	Hydrided powders	UAl_3 + UAl_2	Slight	< 1	Yes
D-3	6 Sn	Metal powders	UAl_3 + UAl_2	Yes	2	No
D-4	8 Sn	Metal powders	UAl_3 + UAl_2	Yes	1	No

[a]26% Al unless otherwise noted. Balance uranium.

[b]Determined by x-ray diffraction.

[c]By hot-stage metallography at 600°C.

[d]In 100 min at 600°C.

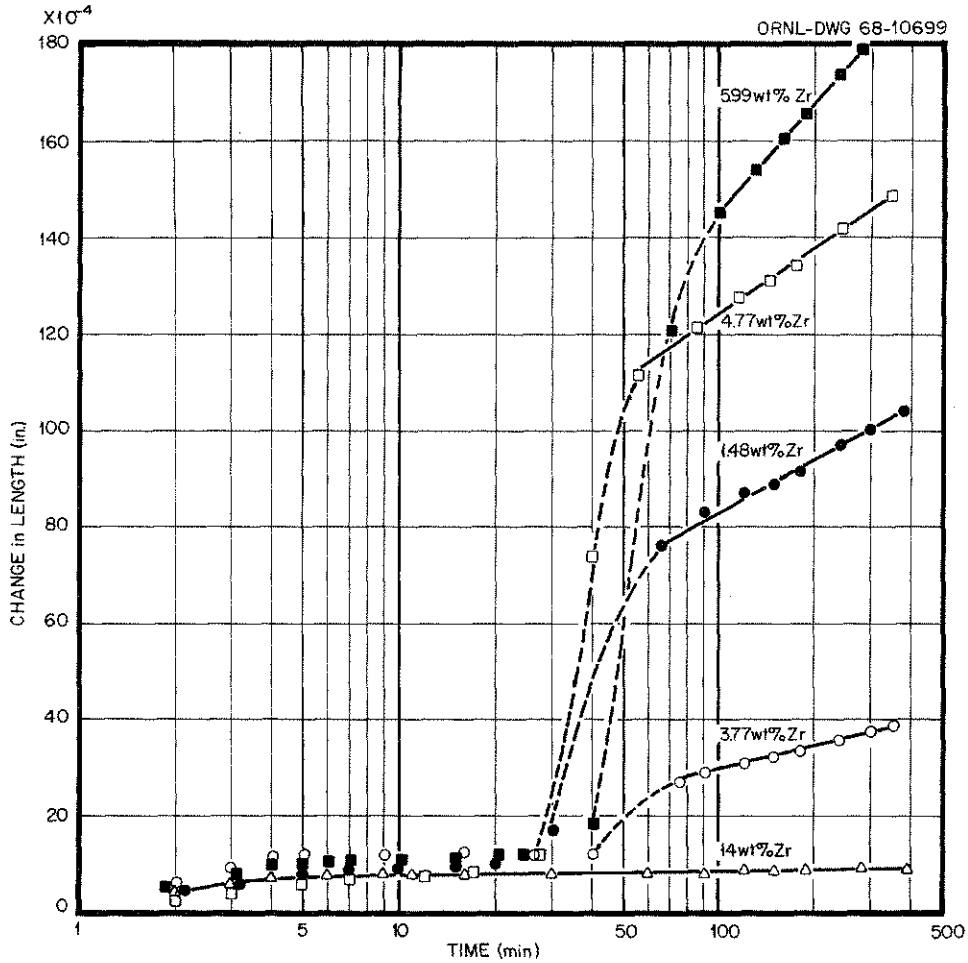

Fig. 9. Swelling of 0.5-in. Pellets Containing 40% U-Al Intermetallic Made with Various Zirconium Contents, Expressed as a Function of Annealing Time at 600°C.

stage of swelling is connected with the transformation of UAl_3 to UAl_4. In the case of 14 wt % Zr no transformation can be seen at the heating-stage microscope even after 6 hr annealing at 600°C. The slope of the swelling curves during the second stage varies for different concentrations in the range 1.48 to 5.99 wt % Zr.

With 14 wt % Zr a stable two-phase region containing UAl_3 and aluminum exists in equilibrium and extends down to room temperature. Figure 10 shows an optical micrograph and cathode ray tube x-ray displays with $K\alpha$ for aluminum and $L\alpha$ for zirconium for the same area. The optical image here is reversed with respect to the x-ray scanning images. Here the pellet was heat treated for 2 hr at 625°C. The aluminum and

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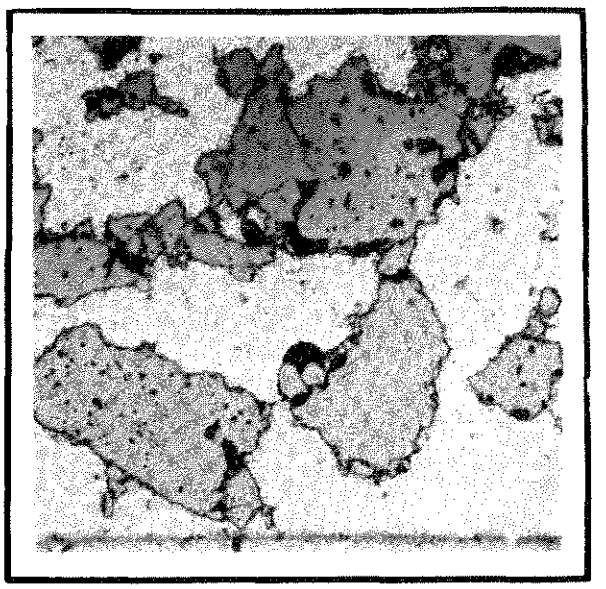
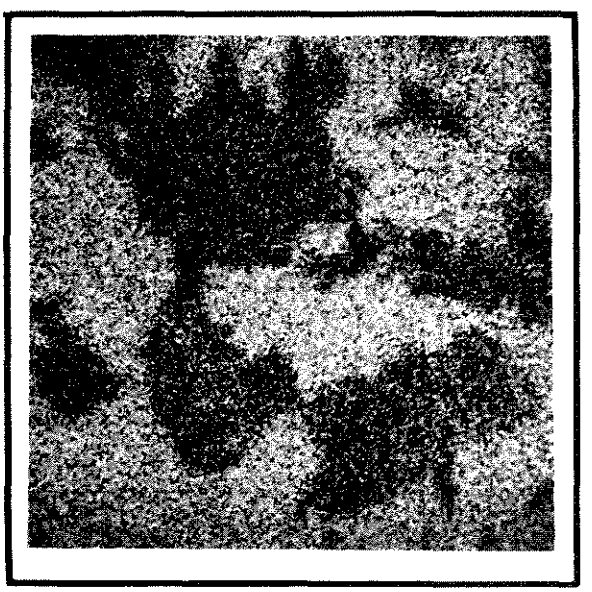


Optical



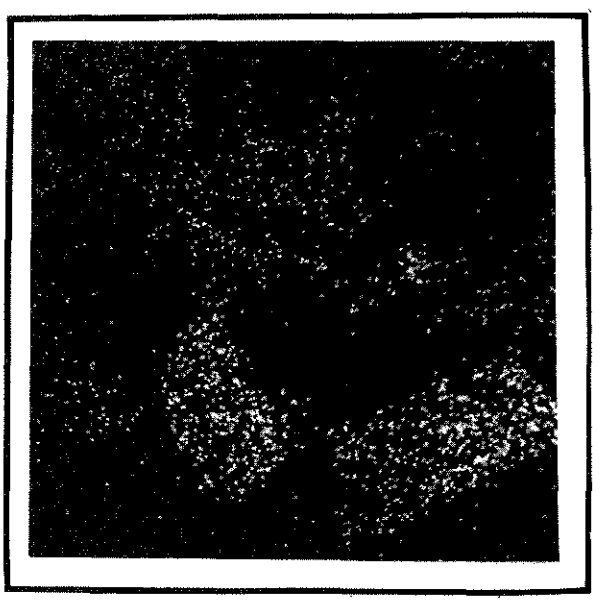


Fig. 10. Optical and Cathode Ray Tube Displays of Compacts of UAl_3 Doped with 14 wt % Zr.

zirconium distributions in the UAl_3 particles are practically uniform, and no diffusion or transformation has taken place with depletion or increase of either element.

Si-U-Al Alloys

Figure 11 shows the change in length at 600°C of the pellets containing silicon in UAl_3. Alloys containing 3.77, 4.44, and 5.91 wt % Si show only the first stage of increase, even after 400 min annealing at 600°C. Only the alloy with 1.48 wt % Si shows the second stage of increase and a corresponding transformation under the heating-stage microscope. This figure reveals that higher percentages of silicon stabilize UAl_3 and thus confirms the experimental results of Thurber and Beaver.[17] Figure 12 shows x-ray scanning of compacts containing UAl_3 doped with 1.48 wt % Si after 2 hr of annealing at 625°C. On the left the lightest portion is aluminum, the darkest is untransformed UAl_3, and the gray is completely transformed UAl_4. The Kα distribution for

[17]W. C. Thurber and R. J. Beaver, Development of Silicon Modified 48 wt % U-Al Alloys for Aluminum Plate-Type Fuel Elements, ORNL-2602 (Mar. 9, 1959).

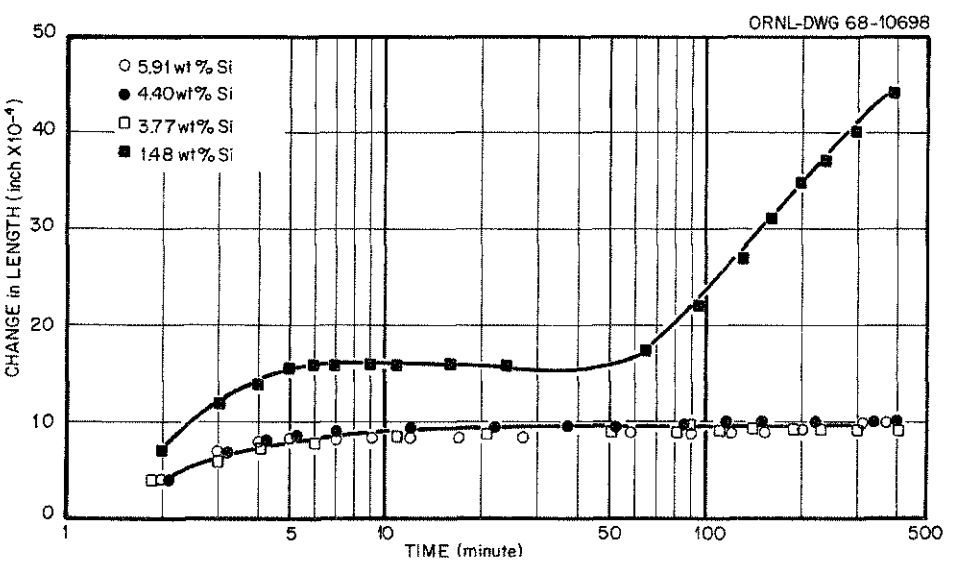


Fig. 11. Change in Length of 0.5-in. Pellets with 40 wt % U-Al Intermetallics Having Different Silicon Contents as a Function of Annealing Time at 600°C.

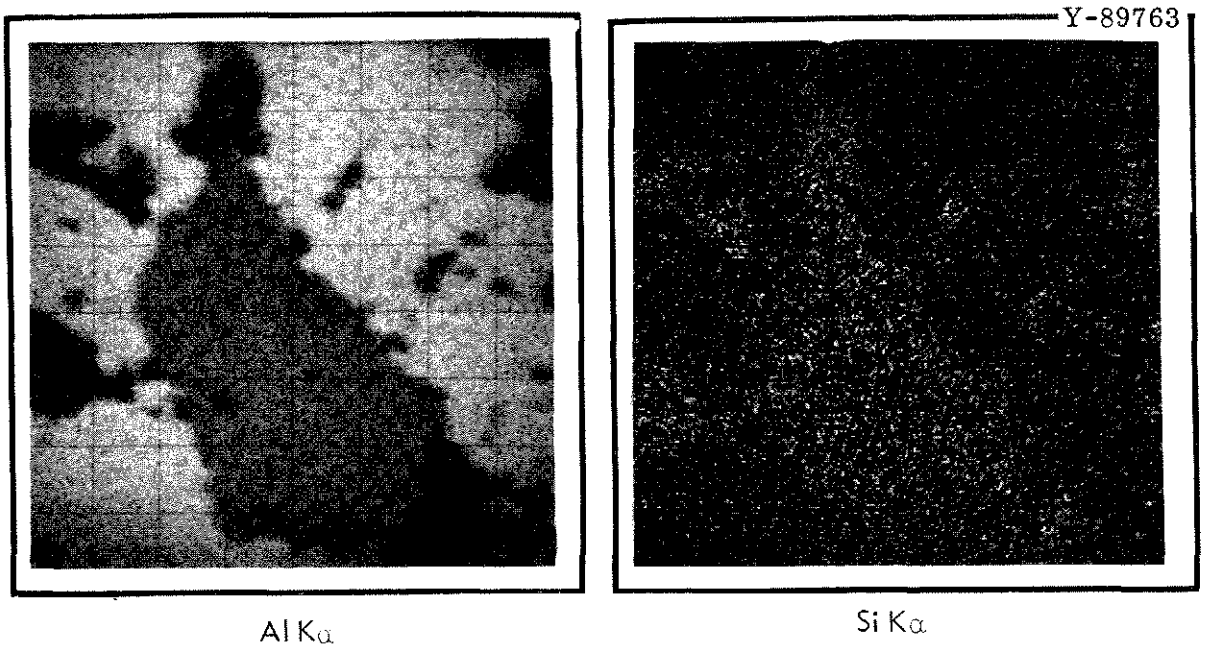


Fig. 12. Cathode Ray Tube Displays of Silicon-Doped UAl_3.

silicon in the corresponding portions of UAl_3 appears somewhat brighter than in UAl_4. However, the difference is small, showing that silicon can migrate from UAl_3 to UAl_4 without being rejected in UAl_4. The slight difference of the atomic diameters of aluminum and silicon makes it possible for the mutual exchange of the lattice places.

Ge-U-Al Alloys

Figure 13 represents the change in length at 600°C of 0.5-in. pellets with different concentrations of germanium. In intermetallics containing 1.48 and 3.77 wt % Ge a change is marked, as indicated by the second stage of length change. Higher concentrations of germanium are stable. Heating-stage microscopy with 3.77 wt % Ge revealed slow reaction. X-ray scanning with germanium Kα rays show a slightly uneven distribution within different intermetallic particles. This result can probably be related to uneven concentration distributions during reaction sintering. Otherwise the difference of the atomic diameters of germanium and aluminum (2.8%) is too small to explain the rejection of germanium by UAl_4.

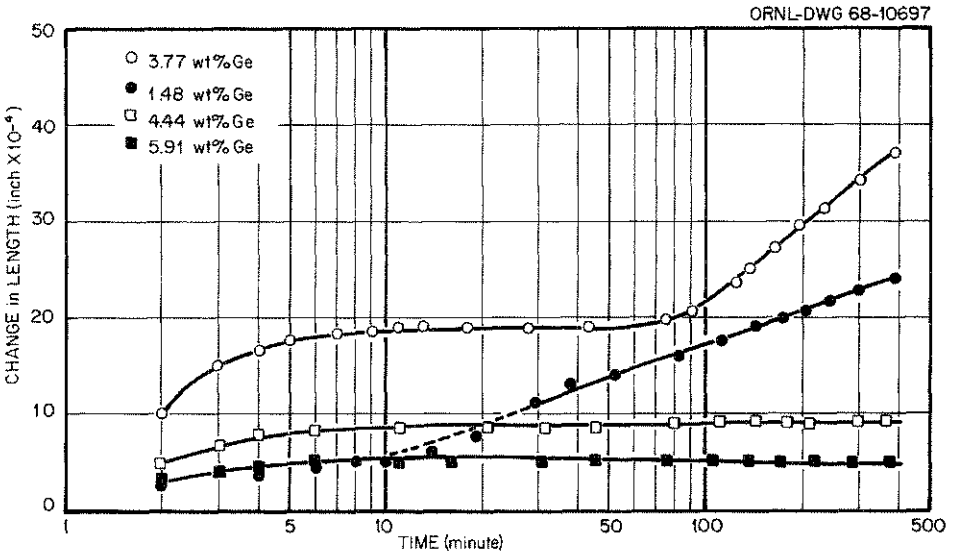


Fig. 13. Change in Length of 0.5-in. Pellets with 40 wt % U-Al Intermetallics with Different Germanium Contents as a Function of Annealing Time at 600°C.

Sn-U-Al Alloys

Figure 14 shows the change in length of pellets containing intermetallics with different concentrations of tin. Here, interpreting the results is made difficult because of the existence of some other phases, particularly with 8 wt % Sn. However, only the intermetallic containing 1.48 wt % Sn showed stabilizing behavior. In this case the second stage in length change did not occur even after annealing for 400 min at 600°C. Figure 15 shows a microprobe analysis of a particle of 6 wt % Sn in UAl_3 partially transformed to UAl_4. Points 5 and 6 show the places where transformation to UAl_4 has taken place.

Comparison of These Alloy Systems

Figure 16 shows the change in length of 0.5-in. compacts containing different concentrations of the doping elements after annealing at 600°C for 100 min. It is evident from this figure that silicon and germanium have the most effective stabilizing capacity. Zirconium shows a drop in increase in length at 3.77 wt % and increases again with higher concentrations. The intermetallic containing 14 wt % of dissolved zirconium is the most stable because of the stable two-phase region of UAl_3 and

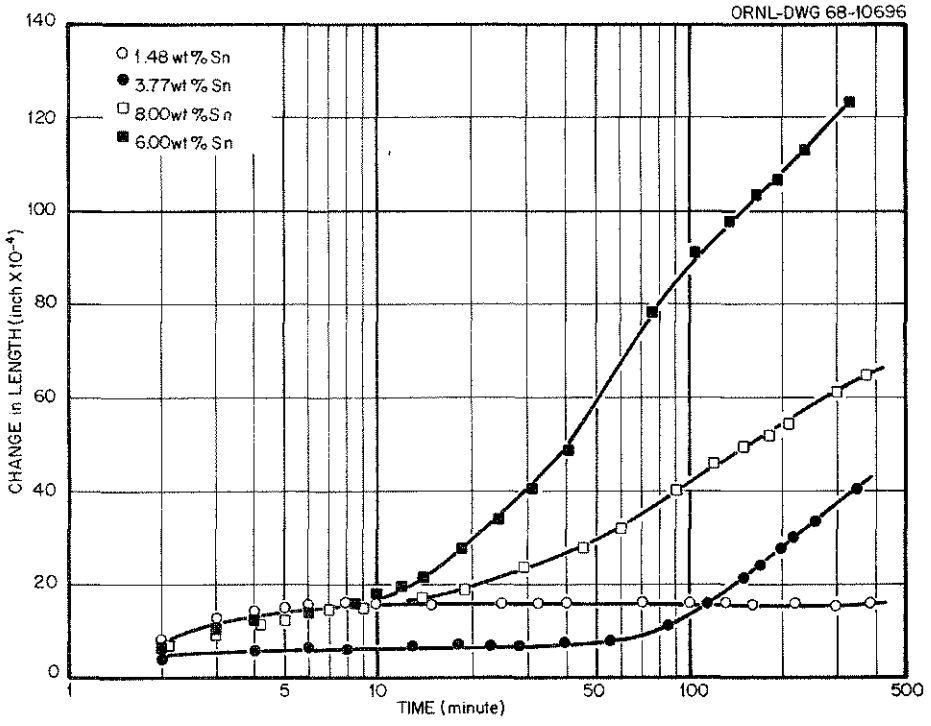


Fig. 14. Change in Length of 0.5-in. Pellets with 40% U-Al Intermetallics with Different Tin Contents as a Function of Annealing Time at 600°C.

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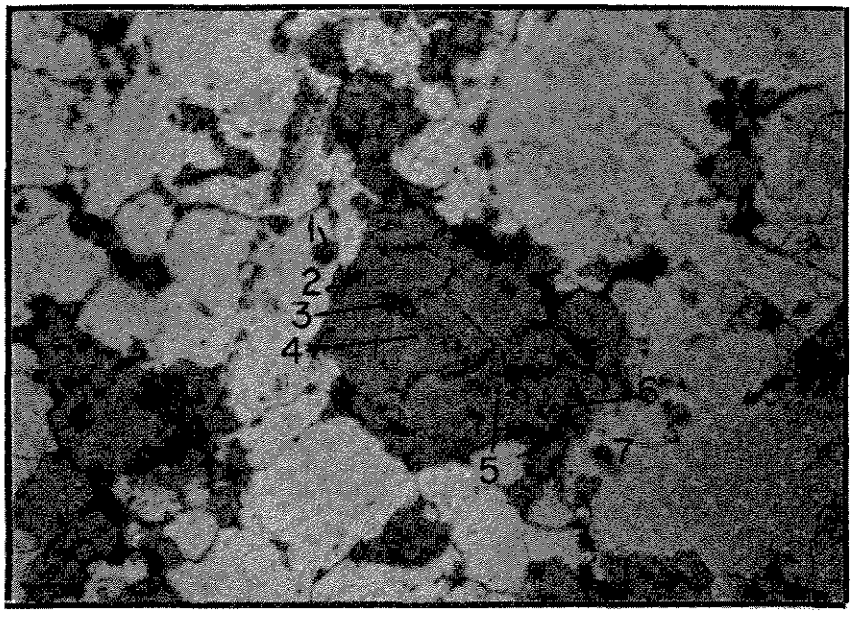

STEP	wt%Sn
1	0
2	6.0
3	6.3
4	6.5
5	1.5
6	1.7
7	0

Fig. 15. Microprobe Step Scan for Tin in UAl_3. 400x.

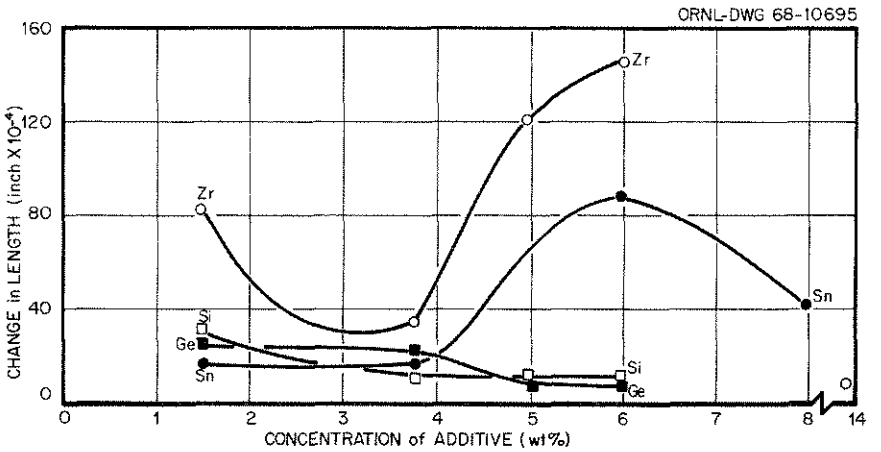

Fig. 16. Effect of Ternary Additive Concentration in UAl_3 on the Swelling of Compacts in 100 min at 600°C.

aluminum. With the increase in tin concentration the stabilizing action of tin diminishes.

CONCLUSIONS

Dispersions of UAl_3 in aluminum swell in two stages on degassing at elevated temperature. In the first stage, which is normally small, powder particles separate most likely because of the pressure of evolved gases. Gas evolution from the compacts has been observed along with swelling during which no transformation was noted. Also the degree of swelling in the first stage has been observed with U_3O_8 dispersions.[18] In the second stage, the reaction of UAl_3 with aluminum to form UAl_4 causes an expansion, which can be affected by degassing conditions and material characteristics. The factors affecting incubation time for the second stage are: (1) decreasing the heat treating temperature of the compact delays the onset of second-stage swelling; (2) increasing the particle size to +170 mesh delays the onset and completion of the second-stage swelling, particularly at 550 and 500°C; (3) water vapor present during first-stage swelling delays the start of second-stage swelling but does increase the magnitude of swelling once the transformation to

[18]M. M. Martin and W. R. Martin, Fuels and Materials Development Program Quart. Progr. Rept. June 30, 1968, ORNL-4330, pp. 316–317.

UAl_4 begins; and (4) ternary additions to UAl_3 delay the start of and decrease the magnitude of second-stage swelling. The phase UAl_3 containing 14 wt % Zr exists in equilibrium with aluminum and can be applied as nuclear fuel. Alloys modified with silicon and germanium can also be effective; these elements replace aluminum in UAl_3. Tin does not seem to be a very suitable addition within the range of compositions investigated; it appears to be less soluble in UAl_4 than in UAl_3.

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