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Category: UC-25

AEC RESEARCH AND DEVELOPMENT REPORT

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EFFECT OF SMALL ADDITIONS OF IRON, SILICON,
AND ALUMINUM ON THE HARDNESS AND DEFORMATION
OF CAST URANIUM AT ELEVATED TEMPERATURES:
STATISTICAL EVALUATION

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Date Published: March, 1970

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EFFECT OF SMALL ADDITIONS OF IRON, SILICON, AND ALUMINUM
ON THE HARDNESS AND DEFORMATION OF CAST URANIUM
AT ELEVATED TEMPERATURES: STATISTICAL EVALUATION

Topical Report

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Prepared for the U. S. Atomic Energy
Commission under Contract No. AT(30-1)-1156

Date Published: March, 1970

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ABSTRACT

Mechanical property data from 27 cast alloys of the U-Fe-Si-Al system were statistically evaluated. The alloy levels were 300 and 1000 ppm. Hardness and drop hammer values were obtained at temperatures ranging from 885 to 1200°F. Both resistance to deformation and hardness values decreased as temperatures increased and increased as the silicon level increased.

INTRODUCTION

Small additions of iron and silicon to uranium are known to refine the grains,^{1,2} and a finer grain size in uranium, as in most metals, increases the mechanical strength. Higher mechanical strength is being sought because this property in a uranium fuel core apparently restrains swelling during irradiation in the reactor.

In a major investigation of uranium-base dilute alloys, hardness, drop hammer, and tensile tests have been performed on binary, ternary, quaternary, and quinary combinations of uranium with carbon, iron, silicon, and aluminum.³⁻¹¹ To compare the data gathered from the mechanical tests of the various alloy combinations, a statistical analysis of variance was run on the hardness and drop hammer data.

SUMMARY OF RESULTS

Temperature. The resistance to deformation (inverse of the measured reduction of height) and the hardness of the dilute alloys decreased with increasing test temperature.

Alloying Elements. Silicon was the most influential of the alloying elements in increasing hardness and resistance to deformation. Aluminum also increased hardness and resistance to deformation. Iron had the least effect on the mechanical properties of uranium.

ALLOY PREPARATION

Specimens for the mechanical property tests were prepared from alloys having a total impurity level of less than 150 ppm, except for carbon. Carbon was present in amounts varying from 100 to 900 ppm, but based on the results of previous work, carbon is considered to have had little effect on the results. The maximum limit for silicon in alloys without silicon additions was <30 ppm, for aluminum in alloys without aluminum additions was <15 ppm, and for iron in alloys without iron additions was <50 ppm.

The 27 alloys were cast under controlled conditions in a laboratory vacuum induction furnace.¹¹ Each casting consisted of a cylinder 12 inches long and 3 inches in diameter below which were four integrally cast test bars 7 inches long and $\frac{15}{16}$ inch in diameter. These bars were cut from

the casting body and were radiographed to determine internal soundness. Test specimens were machined from sound portions of the test bars.

Additions of 300 ± 100 ppm and 1000 ± 100 ppm were made to produce the required alloys. The average levels of the alloying elements actually found in the various alloys are given in Table I; however, for simplicity, references to these alloys will be by the above nominal composition.

EQUIPMENT

Drop hammer tests were performed on a machine designed and constructed at this site. Hardness was measured by a standard Rockwell hardness tester modified for elevated temperature testing. Details of the equipment and procedures were reported previously.^{3,4}

DESIGN OF THE EXPERIMENT

All specimens were tested in duplicate at temperatures of 885, 955, 1025, 1095, 1150, and 1200°F. The factorial block design of the 27 alloys tested is shown in Table I.

The data (Tables II and III) were subjected to statistical analyses of variance and plotted (Figures 1 and 2) to assist in the interpretation of the results and to ascertain the significance of the independent variables (Fe, Si, Al, temperature) and their interactions. Duplicate analyses were used to estimate error.

RESULTS

Drop Hammer Tests

Specimen deformation was measured by the percent reduction of height. The term "resistance to deformation" (inverse of the measured reduction of height) will be used to describe the drop hammer properties.

Data taken at 1200°F were deleted from the statistical analyses because some were anomalous. The anomalies were believed to be caused by the occurrence of a partial alpha-to-beta transformation in these samples during testing. This transformation is possible as tests have demonstrated that the temperature of the specimen increases approximately 50°F on impact.

The four-factor analysis of variance showed that all the independent variables and their interactions were significant at the 99% confidence level (see Table IV). The results of the three-factor analysis of variance are listed in Table V. Major findings are summarized below:

Effect of Temperature Temperature had a significant effect on resistance to deformation for all alloy combinations (99% confidence level). Resistance to deformation decreased as temperature

increased (see Table VI). The alloys containing 1000 ppm Si, Al, or Fe were the least affected by temperature changes.

Effect of Iron Level The effect of iron as an additive was significant across all levels of silicon, at the 300 ppm Al level, and at all temperatures studied (99% confidence level). The effect of iron in combination with 1000 ppm Al was not significant (i.e., increasing iron from 50 to 1000 ppm contributed very little to the resistance to deformation when the alloy contained 1000 ppm Al).

Effect of Silicon Level As with temperature, silicon appeared to be most influential on resistance to deformation. The effect of silicon was significant (99% confidence level) at all temperatures tested and at all iron and aluminum levels. Resistance to deformation increased as the silicon level increased (see Table VI).

Effect of Aluminum Level The effect of aluminum as an additive was significant across all levels of silicon, iron, and temperature (99%) except when iron was at the 1000 ppm level. In this instance, the aluminum level was significant only at 95%. This is to say, the resistance to deformation was affected less by aluminum additions from 15 to 1000 ppm when iron was held at the 1000 ppm level than when iron was held to less than 1000 ppm.

The 1000 ppm Si, 1000 ppm Al alloys had the greatest resistance to deformation of the alloys tested.

Hardness Tests

The data used in the statistical analysis consisted of the actual experimental data adjusted when replications varied by eight or more Rockwell H units. Adjustments were needed on only five of the 324 data points and were made using missing value formulas and graphic techniques.

The four-factor analysis of variance showed that each of the independent variables and their interactions was significant (i.e., had a significant effect on the dependent variable, hardness) at the 99% confidence level with the exception of the two following interactions for which no significant difference was detected:

- a. Fe $\times$ temperature.
- b. Fe $\times$ Al $\times$ temperature.

The major results are summarized below:

Effect of Temperature Temperature had a significant effect on hardness (99% confidence level) for all alloy combinations. All alloys became softer as temperatures increased (see Table VI). The 1000 ppm Si, 1000 ppm Al alloy (No. 25) was the hardest and appeared to be the least affected by temperature of the 27 alloys.

Effect of Iron Level Iron had a significant effect on hardness (99% confidence level) at all levels of aluminum. However, the iron level had no significant effect with silicon at the 1000 ppm

level. Iron had a significant effect on hardness (99%) at all temperature levels except 1095 and 1200°F. Additions of iron from 50 to 300 ppm sometimes caused a softening of the alloy (see Table VI).

Effect of Silicon Level Along with temperature, silicon appeared to be most influential on hardness. The effect of silicon was significant (99% confidence level) at all temperatures tested and at all iron and aluminum levels. Hardness increased as the silicon level increased (see Table VI).

Effect of Aluminum Level The aluminum level was significant (99% confidence level) at all levels of iron and silicon and at all temperatures tested. Increasing the level of aluminum resulted in increased hardness (see Table VI). However, the F ratios seem to indicate that aluminum had a greater effect on hardness when silicon was not present as an additive element.

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TABLE I Factorial Block Design - 27 Alloys of the U-Fe-Si-Al System*

	< 30 ppm Si			300 ppm Si			1000 ppm Si		
	< 15 ppm Al	300 ppm Al	1000 ppm Al	< 15 ppm Al	300 ppm Al	1000 ppm Al	< 15 ppm Al	300 ppm Al	1000 ppm Al
< 50 ppm Fe	1	4	7	10	13	16	19	22	25
300 ppm Fe	2	5	8	11	14	17	20	23	26
1000 ppm Fe	3	6	9	12	15	18	21	24	27

* Numbers in blocks are alloy designations.

TABLE II Average Reduction of Height (%) of Uranium-Base Dilute Alloys

Alloy No.	Average Alloy Composition (ppm)			Test Temperature (°F)						Change in Reduction of Height*
	Fe	Si	Al	885	955	1025	1095	1150	1200	
1	—	—	—	29.4	32.5	30.2	35.6	38.6	36.1	9.2
2	340	—	—	26.6	30.4	34.2	37.8	40.0	40.7	13.4
3	970	—	—	27.3	29.2	31.2	29.4	36.0	30.8	8.7
4	—	—	330	27.8	30.5	33.6	35.4	39.4	34.5	11.6
5	230	—	230	27.8	26.8	34.1	37.0	39.4	37.8	11.6
6	1000	—	250	23.6	27.5	30.2	31.1	32.4	35.1	8.8
7	—	—	1040	23.4	26.4	29.8	30.4	36.1	29.1	12.7
8	230	—	980	22.9	24.8	27.5	31.0	32.8	32.8	9.9
9	1000	—	1050	22.6	24.1	28.5	31.6	34.5	34.5	11.9
10	—	340	—	24.6	28.6	32.0	35.4	37.3	32.8	12.7
11	230	240	—	23.4	17.0	30.1	33.8	37.2	36.5	13.8
12	1020	210	—	14.4	22.4	24.4	31.6	35.2	33.2	20.8
13	—	230	230	24.7	27.6	31.4	34.6	34.6	35.2	9.9
14	220	200	240	25.4	29.8	31.5	34.6	39.4	36.1	14.0
15	940	250	260	21.5	24.8	25.8	30.1	33.6	28.8	12.1
16	—	230	1000	21.5	23.8	28.0	28.4	31.0	32.4	9.5
17	250	280	1020	22.0	23.9	26.6	27.4	32.1	32.5	10.1
18	950	190	990	22.4	22.6	27.6	30.2	33.0	34.9	10.6
19	—	990	—	21.7	23.4	25.9	31.0	30.0	28.8	8.3
20	240	940	—	18.6	15.4	23.4	26.5	27.2	29.3	8.6
21	1020	960	—	18.7	22.2	23.0	24.6	29.3	30.3	10.6
22	—	940	220	17.8	20.0	24.4	25.0	27.4	26.3	9.6
23	260	1070	250	18.5	21.8	23.8	25.9	29.9	31.7	11.4
24	960	930	220	17.7	19.8	22.1	24.1	26.4	28.7	8.7
25	—	910	960	18.8	19.0	21.3	23.8	24.8	26.1	6.0
26	240	990	980	18.4	20.8	22.4	24.1	28.6	30.0	10.2
27	1020	930	970	17.2	19.0	21.2	25.1	27.8	29.8	10.6

* Data at 1200°F not included

95% Confidence limits on each mean value listed = ± 0.19

TABLE III Average Hardness (R_H) of
Uranium-Base Dilute Alloys

Alloy No.	Test Temperature ($^{\circ}F$)						Change in Hardness
	885	955	1025	1095	1150	1200	
1	99	99	93	90	79	75	24
2	100	96	88	84	64	60	40
3	103	100	96	90	74	66	37
4	106	105	96	91	84	76	30
5	104	102	97	92	86	81	23
6	109	106	104	96	92	84	25
7	108	106	104	102	94	88	20
8	111	106	106	99	98	96	15
9	110	105	102	95	93	86	24
10	110	106	102	98	90	84	26
11	104	102	98	91	89	82	22
12	109	108	104	100	94	90	19
13	104	104	103	101	96	88	16
14	104	104	99	98	91	86	18
15	110	110	108	103	96	86	24
16	112	110	108	105	99	98	14
17	110	109	106	108	98	92	18
18	110	108	108	104	97	94	16
19	114	112	109	104	100	92	22
20	114	111	111	107	102	97	17
21	114	112	110	104	100	97	17
22	113	112	110	106	104	96	17
23	114	112	110	106	103	96	18
24	114	114	112	107	102	98	16
25	115	113	112	108	106	102	13
26	114	114	112	110	104	100	14
27	114	113	113	107	103	100	14

95% Confidence limits on each mean value listed = ± 0.22 .

TABLE IV Four-Factor Analysis of Variance of
Drop Hammer and Hardness Data

Variables and Interactions	Drop Hammer		Hardness		
	Computed F Ratio	F Level to be Exceeded at 99% Confidence Level	Computed F Ratio	F Level to be Exceeded at Indicated Confidence Level	
				95%	99%
Iron	93.3	4.77	52.0	—	4.74
Silicon	1121.3	4.77	2470.6	—	4.74
Aluminum	150.0	4.77	845.4	—	4.74
Temperature	812.8	3.46	1781.9	—	3.13
Fe × Si	8.2	3.46	19.0	—	3.44
Fe × Si	39.7	3.46	54.2	—	3.44
Fe × Temp	6.2	2.64	1.83*	1.89	2.44
Si × Al	22.4	3.46	167.0	—	3.44
Si × Temp	7.0	2.64	42.0	—	2.44
Al × Temp	3.69	2.64	30.8	—	2.44
Fe × Si × Al	12.6	2.64	21.6	—	2.62
Fe × Si × Temp	3.66	2.14	2.06	—	2.00
Fe × Al × Temp	6.8	2.14	1.30*	1.64	2.00
Si × Al × Temp	6.0	2.14	9.24	—	2.00
Fe × Si × Al × Temp	3.04	1.82	6.64	—	1.72

* Not significant

TABLE V Three-Factor Analysis of Variance of Drop Hammer Data, F Ratios

	Elements and Levels									F Level to be Exceeded	
	Aluminum			Silicon			Iron				
	1	2	3	1	2	3	1	2	3	95%	99%
Temperature	193.96	402.07	356.92	227.63	431.89	197.61	238.02	271.42	320.79	2.58	3.77
Iron	50.27	135.20	N.S.	43.53	63.98	6.32				3.19	5.11
Silicon	244.73	786.35	377.79				461.49	363.91	312.03	3.19	5.11
Aluminum				100.62	72.05	20.69	141.10	78.07	4.02*	3.19	5.11
Temp × Fe	8.95	3.66	3.16	4.07	7.88	2.16*				2.15	2.93
Temp × Si	9.07	2.96	2.60*				4.46	2.31*	8.66	2.15	2.93
Temp × Al				N.S.	13.73	N.S.	2.75*	8.79	4.67	2.15	2.93
Fe × Si	12.01	13.25	6.83							2.58	3.77
Fe × Al				11.15	38.50	18.98				2.58	3.77
Si × Al							8.38	24.40	11.99	2.58	3.77
Temp × Fe × Si	3.72	3.44	N.S.							1.88	2.43
Temp × Fe × Al				3.40	7.15	2.87				1.88	2.43
Temp × Si × Al							1.95*	4.35	5.90	1.88	2.43
	Temperature Levels										
	1	2	3	4	5						
Iron	30.63	25.04	22.71	20.16	20.23					3.35	5.49
Silicon	193.49	226.97	199.41	186.68	402.04					3.35	5.49
Aluminum	15.01	27.71	25.72	42.81	57.38					3.35	5.49
Fe × Si	4.90	2.99*	3.58*	4.13	8.63					2.73	4.11
Fe × Al	8.24	23.27	5.17	14.94	17.14					2.73	4.11
Si × Al	16.43	21.69	N.S.	4.22	4.62					2.73	4.11
Fe × Si × Al	6.34	8.41	3.85	N.S.	5.63					2.30	3.26

* Significant at 95% confidence level

N.S. — Not Significant

TABLE VI Average Value of Percent Reduction of Height and Hardness at Each Level of the Independent Variables

Variable (ppm)		Average % Reduction of Height	Average Hardness
Iron		(± 24)*	(± 27)*
	< 50	28.37	100.69
	300	27.84	99.58
	1000	26.15	101.53
Silicon	< 30	30.91	93.93
	300	28.39	100.50
	1000	23.06	107.38
Aluminum	< 15	28.37	96.66
	300	28.23	100.61
	1000	25.76	104.52
Temperature (°F)		(± 31)* *	(± 38)* *
	885	22.19	109.30
	955	24.22	107.40
	1025	27.57	104.31
	1095	30.19	100.11
	1150	33.10	94.00
	1200	—	88.48

* 95% Confidence limits on means listed for Al, Si and Fe

** 95% Confidence limits on means listed for Temperature

TABLE VII Three-Factor Analysis of Variance of Hardness Data, F Ratios

	Elements and Levels											
	Aluminum			Silicon			Iron			F Level to be Exceeded		
	1	2	3	1	2	3	1	2	3	95%	99%	
Temperature	801.38	492.38	526.40	1104.84	364.24	528.63	562.00	700.45	547.94		3.38	
Iron	64.62	61.48	21.99	25.74	46.05	N.S.				3.17	5.02	
Silicon	1618.94	568.19	474.28				748.83	1229.38	628.35		5.02	
Aluminum				1059.38	139.00	58.51	276.56	626.75	131.33		5.02	
Temp × Fe	N.S.	N.S.	2.14*	4.30	N.S.	N.S.				2.00	2.67	
Temp × Si	38.09	10.80	7.65				11.50	20.21	15.22		2.67	
Temp × Al				43.24	5.72	3.98	9.07	19.64	6.81		2.67	
Fe × Si	37.15	10.95	11.38								3.69	
Fe × Al				82.47	14.22	5.71					3.69	
Si × Al							21.75	165.26	42.95		3.69	
Temp×Fe×Si	7.14	2.79	5.87								2.23	
Temp×Fe×Al				11.00	2.46	1.89*				1.76	2.23	
Temp×Si×Al							3.82	14.70	5.49		2.23	
	Temperature Levels											
	1	2	3	4	5	6						
Iron	13.98	13.18	16.56	4.66*	10.50	N.S.					3.35	5.49
Silicon	217.77	379.37	260.26	405.08	691.89	667.65						5.49
Aluminum	55.33	68.53	72.49	145.66	274.84	321.32						5.49
Fe × Si	4.62	4.27	3.13*	7.04	5.64	4.88					2.73	4.11
Fe × Al	5.12	10.54	6.65	14.22	12.46	11.58						4.11
Si × Al	23.02	17.39	13.06	12.22	80.00	59.65						4.11
Fe×Si×Al	3.90	N.S.	3.69	4.96	14.24	22.10					2.30	3.26

* Significant at 95% confidence level

N.S. — Not Significant

FIGURE 1 Drop Hammer Data

FIGURE 2 Hardness Data