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PROPERTIES OF URANIUM DIOXIDE-STAINLESS STEEL DISPERSION FUEL PLATES

by

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The physical and mechanical properties of GCRE-type fuel elements were determined from room temperature to 1650 F. The fuel elements were prepared by cladding Type 318 stainless steel sheet to a core containing 15 to 35 w/o UO_2 in either prealloyed Type 318 stainless steel or elemental iron-18 w/o chromium-14 w/o nickel-2.5 w/o molybdenum.

The tensile strength in the direction perpendicular to the rolling plane decreased from 24,600 psi at room temperature to 9,200 psi at 1650 F for the reference fuel plate, whose core contained 25 w/o UO_2 in the elemental alloy. The tensile strength in the longitudinal direction for this fuel element ranged from 54,800 psi at room temperature to 14,200 psi at 1650 F, with elongation in 2 in. ranging from 8 to 13 per cent. The extrapolated stress for 1000-hr rupture life at 1650 F was 1800 psi, and a 1.4T bend was withstood without cracking. The mean linear thermal coefficient of expansion was 11.0×10^{-6} per F for the range 68 to 1700 F.

INTRODUCTION

As part of the Army Gas Cooled Reactor Experiment (GCRE) program, Battelle, in cooperation with Aerojet-General Corporation (AGC), undertook development of an optimum dispersion fuel element. This development consisted of a complete study of fabrication sequences and materials, destructive and nondestructive property determinations, corrosion and stress-corrosion tests, and in-pile loop studies. Early in the program a Type 318 stainless steel-UO_2 dispersion element was selected as the reference fuel element. Consequently, most of the development centered around a fuel plate clad with Type 318 stainless steel and containing high-fired UO_2 as the fuel dispersed in a matrix of elemental iron-18 w/o chromium-14 w/o nickel-2.5 w/o molybdenum. A topical report presenting a detailed discussion of the fabrication phase of the development program has been issued.(1) The present report summarizes the results of physical- and mechanical-property determinations on these fuel elements and variations thereof. Near the termination of the program, fuel plates loaded with spherical UO_2 and with UN became available, and these were also tested. The properties that were determined were tensile, creep-rupture, bend, and thermal expansion.

Wherever data are presented for UO_2-bearing fuel plates without specifying fabrication procedure, or where "optimum" fabrication procedure is specified, it may be assumed that the following conditions were used:

Particle size

UO_2	Minus 100 to plus 200 mesh
Core matrix	Minus 325 mesh

(1) References at end.

Sintering temperature	
Elemental cores	2300 F
Prealloyed cores	2200 F
Rolling temperature	2200 F
Reduction in first pass	30-40 per cent
Annealing temperature after hot rolling	
Elemental-core specimens	2300 F
Prealloyed-core specimens	2000 F
Cold reduction	15-20 per cent
Annealing temperature after cold rolling	
Elemental-core specimens	2050 F
Prealloyed-core specimens	2150 F
Core description	
Composition	
Fuel	UO_2
Matrix	Elemental 18-14-2.5 alloy or prealloyed Type 318 stainless containing 2.5 w/o silicon
Thickness	31 mils
Cladding description	
Composition	Type 318 stainless
Thickness	7 mils

The same assumptions may be made for UN-bearing fuel plates except that the sintering treatment was omitted.

The commercial Type 318 stainless steel sheet tested was hot rolled at 2200 F with a 30 per cent initial reduction, annealed at 2000 F after hot rolling, cold rolled 15 per cent to a 45-mil thickness, and solution annealed at 2150 F.

Although the mechanical-property data reported herein were obtained primarily from Type 318 stainless steel-UO_2 dispersion elements, the general trends in property changes caused by such variables as fuel particle size, fuel loading, etc., are applicable to other dispersion fuel materials. Of particular importance, and of equal application to other materials, is the effect which fabrication variables have on both the structural appearance and the mechanical properties of otherwise identical elements.

TRANSVERSE TENSILE STRENGTH OF FUEL PLATES

UO_2-Stainless Steel

The effects of core composition and fabrication variables on the transverse tensile strength of GCRE-type fuel plates were investigated. Transverse tensile strength, as used here, refers to tensile strength of a plate specimen perpendicular to the rolling plane. Specimens were prepared by stamping out 5/8-in.-diameter disks from finished fuel plates and copper brazing both faces to 3/4-in.-diameter stainless steel pins in a hydrogen atmosphere at 2050 F. The composite specimen was then turned down to 3/8 in. in diameter to eliminate any possible edge effects, and threads were machined on each end to obtain a 2-in.-long tensile specimen. This specimen was then subjected to a normal tensile test with the stress being applied perpendicular to the rolling plane, and fracture occurring parallel to the rolling plane. This stress-and-fracture situation is believed to correspond to that which normally occurs in stainless steel-UO_2 fuel plates that blister in service, and, consequently, represents a closer correlation between mechanical-property tests and service conditions than is provided by conventional test methods.

Testing was done in air and the time at testing temperature was approximately 30 min. A thin coating of heat-resistant aluminum paint was applied to the specimen to reduce oxidation effects. Metallographic examination of the exposed core edges revealed a minimum oxidation, and no evidence of the presence of U_3O_8 was found.

In studying any one particular fabrication variable, as many others as possible were held constant; however, in these data there is often more than one variable to consider. Usually, tests of different plates made by the same fabrication procedures resulted in similar strengths. Differences were due to slight, uncontrollable variations in fabrication procedure. Each result given in Table 1 represents an average of two to six test determinations. The variation in any one such series was usually from ±2 to 4 per cent, although a few variations as large as ±12 per cent were noted. The large variations were probably due to segregation of UO_2 in the plate involved. Such differences were particularly evident when smaller test specimens were used.

Varying the UO_2 content from 15 to 35 w/o resulted in a fairly linear inverse proportionality with transverse tensile strength. No sharp dropoffs in strength were observed with increases in loading.

Two types of core matrices were tested, prealloyed Type 318 stainless steel with 2.3 w/o silicon and the elemental 18-14-2.5 alloy. Trace quantities of Cr_2O_3 impurity were usually present in the elemental matrices; however, in spite of this, strength properties were usually superior to those of cores having the prealloyed matrices. Metallographic examination shows that stringering is less pronounced and over-all dispersion quality superior for the elemental matrices, showing the close correlation between this strength property and the microscopic appearance of the UO_2 dispersion. A typical comparison of room-temperature transverse tensile strength shows a value of 17,900 psi with a 25 w/o UO_2-prealloyed matrix core versus 24,800 psi with a 25 w/o UO_2-elemental core. One exception to this rule, as seen in Table 1, was a prealloyed matrix plate with a transverse tensile strength of 25,800 psi at room temperature. This plate differed from other plates with prealloyed core matrices in that it was

TABLE 1. EFFECT OF MATERIALS AND FABRICATION PROCEDURE ON TRANSVERSE TENSILE STRENGTH OF UO_2-BEARING FUEL PLATES

Cladding: 7 mils, Type 318 stainless steel
Core Thickness: 31 mils

Test Temperature, F	Ultimate Tensile Strength, psi	UO_2 Mesh Size	Core-Matrix Mesh Size	Sintering Temperature, F	Rolling Temperature, F	Reduction in First Pass, per cent	Annealing Temperature, F	Cold Work, per cent
			15 w/o UO_2-Elemental 18-14-2.5 Alloy Core					
Room	36, 800	-100 +200	-325	2300	2200	40	2300	14
Room	>44, 800[(a)]	-325	-325	2300	2200	40	2300	14
1000	>22, 600[(a)]	-325	-325	2300	2200	40	2300	14
			20 w/o UO_2-Elemental 18-14-2.5 Alloy Core					
Room	32, 500	-100 +200	-325	2300	2200	40	2300	14
			25 w/o UO_2-Elemental 18-14-2.5 Alloy Core					
Room	24, 800	-100 +200	-325	2300	2200	40	2300	14
Room	26, 000	-100 +140	-400	2300	2200	40	2300	21
1000	17, 800	-100 +140	-400	2300	2200	40	2300	21
1100	16, 000	-100 +140	-400	2300	2200	40	2300	21
Room	23, 100	-140 +200	-325	2300	2200	40	2300	18
1000	16, 400	-140 +200	-325	2300	2200	40	2300	18
1300	14, 000	-140 +200	-325	2300	2200	40	2300	18
1500	12, 500	-140 +200	-325	2300	2200	40	2300	18
1650	9, 200	-140 +200	-325	2300	2200	40	2300	18
Room	30, 500	-325	-325	2300	2200	40	2300	14
1000	20, 000	-325	-325	2300	2200	40	2300	14
1300	13, 800	-325	-325	2300	2200	40	2300	14
Room	8, 600	-270 +325	-325	2200	2200	30	2000	71
1300	5, 500	-270 +325	-325	2200	2200	30	2000	71
Room	13, 800	-270 +325	-325	2200	2200	30	2000	17
Room	19, 400[(b)]	-100 +200	-325	2300	2200	30	2300	16

TABLE 1. (Continued)

Test Temperature, F	Ultimate Tensile Strength, psi	UO_2 Mesh Size	Core-Matrix Mesh Size	Sintering Temperature, F	Rolling Temperature, F	Reduction in First Pass, per cent	Annealing Temperature, F	Cold Work, per cent
				30 w/o UO_2-Elemental 18-14-2.5 Alloy Core				
Room	31,300[c]	-100 +200	-325	2300	2200	40	2300	21
1300	>16,100[a, c]	-100 +200	-325	2300	2200	40	2300	21
Room	21,800	-100 +200	-325	2300	2200	40	2300	14
1000	13,700	-100 +200	-325	2300	2200	40	2300	14
1300	12,300	-100 +200	-325	2300	2200	40	2300	14
Room	16,600[b]	-100 +200	-325	2300	2200	40	2300	16
				35 w/o UO_2-Elemental 18-14-2.5 Alloy Core				
Room	16,600	-100 +200	-325	2300	2200	40	2300	14
1000	12,300	-100 +200	-325	2300	2200	40	2300	14
1300	9,900	-100 +200	-325	2300	2200	40	2300	14
Room	22,400	-325	-325	2300	2200	40	2300	14
1000	16,300	-325	-325	2300	2200	40	2300	14
1300	13,200	-325	-325	2300	2200	40	2300	14
Room	12,100[b]	-100 +200	-325	2300	2200	40	2300	14
				15 w/o UO_2-Prealloyed Type 318 Stainless Core				
Room	28,800	-100 +200	-200 +270	2200	2200	40	2150	14
1000	18,000	-100 +200	-200 +270	2200	2200	40	2150	14
Room	36,400	-325	-200 +270	2200	2200	40	2150	14
1000	>21,800	-325	-200 +270	2200	2200	40	2150	14
Room	1,200[d]	-100 +200	-200 +270	2200	1900	10	2150	20
				20 w/o UO_2-Prealloyed Type 318 Stainless Core				
1000	17,600	-100 +200	-200 +270	2200	2200	40	2150	14

TABLE 1. (Continued)

Test Temperature, F	Ultimate Tensile Strength, psi	UO_2 Mesh Size	Core-Matrix Mesh Size	Sintering Temperature, F	Rolling Temperature, F	Reduction in First Pass, per cent	Annealing Temperature, F	Cold Work, per cent
			25 w/o UO_2-Prealloyed Type 318 Stainless Core					
Room	15,400	-140 +200	-325	2200	2200	40	2150	14
1000	11,900	-140 +200	-325	2200	2200	40	2150	14
1300	10,200	-140 +200	-325	2200	2200	40	2150	14
Room	25,800	-100 +140	-400	2300	2200	40	2150	21
1000	15,800	-100 +140	-400	2300	2200	40	2150	21
1300	13,400	-100 +140	-400	2300	2200	40	2150	21
Room	17,900	-100 +140	-325	2200	2200	40	2150	18
1000	13,700	-100 +140	-325	2200	2200	40	2150	18
1300	11,600	-100 +140	-325	2200	2200	40	2150	18
Room	14,300	-100 +140	-100 +140	2100	2200	30	2150	24
Room	17,200	-325	-200 +270	2200	2200	40	2150	14
1000	12,400	-325	-200 +270	2200	2200	40	2150	14
Room	16,100	-200 +270	-100	2200	2200	40	2050	18
			30 w/o UO_2-Prealloyed Type 318 Stainless Core					
Room	16,200	-100 +200	-200 +270	2200	2200	40	2150	14
1000	12,200	-100 +200	-200 +270	2200	2200	40	2150	14
1300	10,800	-100 +200	-200 +270	2200	2200	40	2150	14
Room	30,100(c)	-100 +200	-325	2300	2200	40	2300	21
			35 w/o UO_2-Prealloyed Type-318 Stainless Core					
Room	11,300	-100 +200	-200 +270	2200	2200	40	2150	14
1000	9,900	-100 +200	-200 +270	2200	2200	40	2150	14
1300	7,800	-100 +200	-200 +270	2200	2200	40	2150	14

(a) Exceeded strength of braze, fracture partly through braze and partly through core.
(b) Core thickness 67 mils.
(c) Spherical UO_2.
(d) Intentionally poor fabrication procedure caused blistering, coining omitted.

sintered at 2300 F rather than 2200 F and the core-matrix powder size was minus 400 mesh. This plate contained approximately 15 per cent sigma phase that transformed during cooling from ferrite which formed during the high-temperature sinter.

The UO_2 mesh sizes resulting in the best strength were minus 325 mesh and minus 100 plus 140 mesh, in that order, for plates having elemental core matrices, and minus 100 plus 140 mesh for plates with prealloyed core matrices. This effect of mesh size is shown graphically in Figure 1.

Varying amount of cold work between 14 and 24 per cent had no appreciable effect on strength; however, with greater cold reductions strength was drastically reduced. For example, the strength of a plate which was cold reduced 71 per cent was 8,600 psi at room temperature compared with 13,800 psi for a specimen of the same composition and fabricated under identical conditions except that it was given a 17 per cent reduction.

Relatively speaking, plates with superior room-temperature strengths were usually superior at high temperatures. The effect of testing temperatures from room to 1650 F is shown in Figure 1. An approximately straight-line proportionality between strength and temperature was found to exist above 1000 F.

Near the end of this program, plates containing spherical UO_2 became available. These latter plates were considerably stronger than any other plate tested. Room-temperature transverse tensile strengths of plates containing 30 w/o spherical UO_2, averaged about 31,000 psi with both prealloyed Type 318 stainless steel and elemental 18-14-2.5 alloy core matrices. At 1300 F, with an elemental 18-14-2.5 alloy matrix, the tensile strength exceeded the strength of the copper braze, 16,100 psi, as part of the fractures occurred in the core and part in the braze. Microscopic examination of these cores showed a minimum of stringering, breakup, and deformation of the UO_2 particles. By comparison the best strength (extrapolated or actual) for a plate made with 30 w/o Hi-Fired UO_2 was 26,400 psi and 13,500 psi at room temperature and 1300 F, respectively, and this best strength occurred with a minus 325-mesh UO_2, which is too fine to be useful in reactor applications. Transverse tensile strength for dispersions containing spherical UO_2 are given in Table 1.

UN-Stainless Steel

The effect of fabrication variables on the transverse tensile strength of fuel plates loaded with UN is shown in Table 2. Data reported are an average of two or more tests. No direct comparison of the relative merits of a prealloyed versus an elemental core matrix can be made due to the different loadings used, 30 w/o in the former, and 28 w/o in the latter. However, by extrapolation, the optimum plates containing the elemental core matrices appear stronger than their counterparts in plates containing prealloyed core matrices. This is exemplified by the plate whose transverse tensile strength of 33,600 psi at room temperature was superior to the best 25 or 30 w/o UO_2 plate tested (see Table 1). The best strength from a plate with a prealloyed core was 27,200 psi. The UN particle size in the best plate with the elemental matrix was minus 200 plus 270 mesh, unlike its optimum UO_2 counterpart. Metallographic examination showed the dispersion quality of this plate to be excellent, once again confirming the relationship between distortion and breakup of fuel in fabrication and transverse tensile strength.

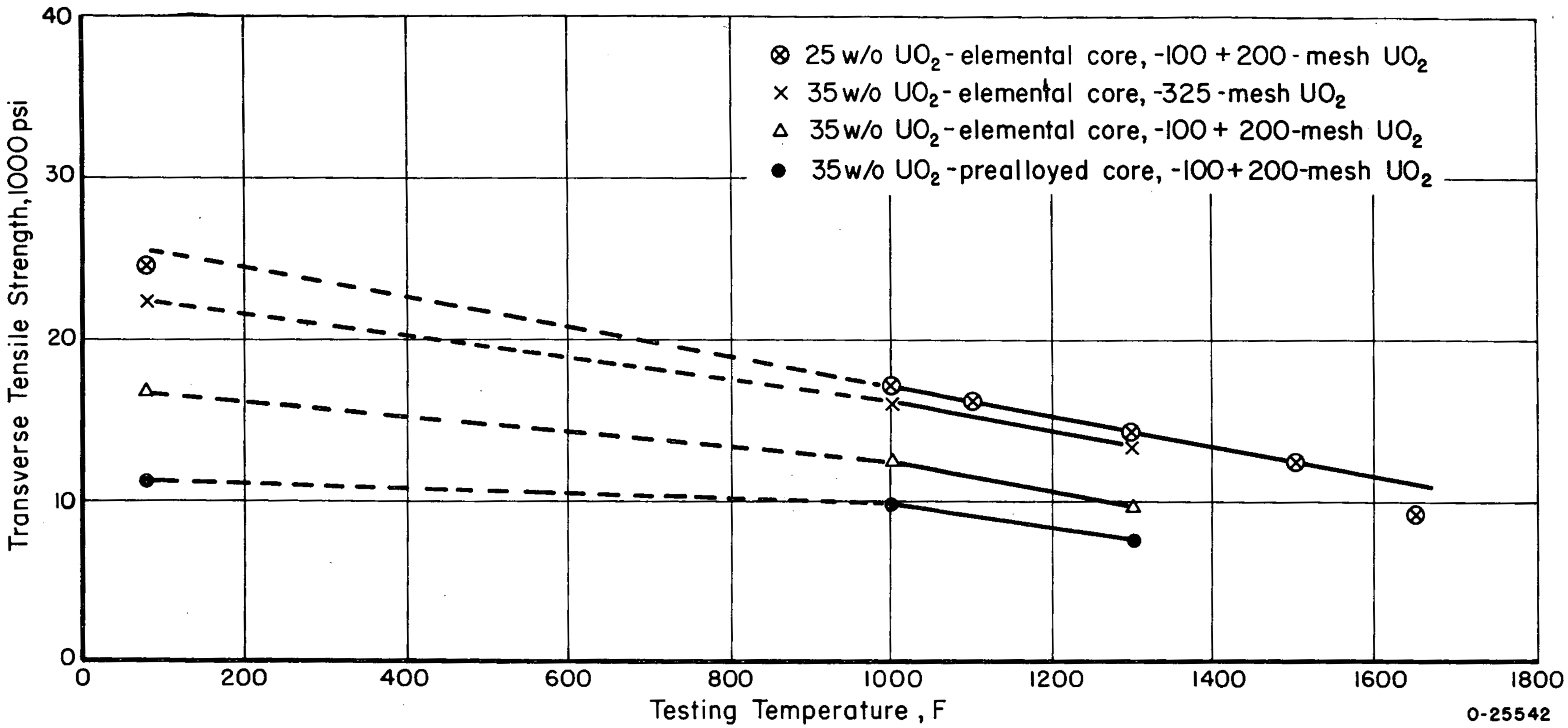

FIGURE 1. THE EFFECT OF TEMPERATURE ON THE TRANSVERSE TENSILE STRENGTH OF VARIOUS FUEL PLATES

TABLE 2. EFFECT OF COMPOSITION AND FABRICATION PROCEDURE ON TRANSVERSE TENSILE STRENGTH OF UN-BEARING FUEL PLATES

Cladding Thickness: 6 mils, Type 318 stainless steel
Core Thickness: 33 mils

Test Temperature, F	Ultimate Tensile Strength, psi	UN Mesh Size	Core-Matrix Mesh Size	Rolling Temperature, F	Reduction in First Pass, per cent	Annealing Temperature, F	Cold Work, per cent
			28 w/o UN-Elemental 18-14-2.5 Alloy Core				
Room	33,600	-200 +270	-325	2100	30	2300	18
	23,700	-200 +270	-325	2000	30	2300	18
	24,100	-100 +200	-325	2100	30	2300	18
	29,200	-200 +325	-325	2100	30	2300	18
1300	>15,100[a]	-200 +325	-325	2100	30	2300	18
			30 w/o UN-Prealloyed Type-318 Stainless Steel Core				
Room	22,600	-200 +270	-325	2000	20	2050	18
	22,900	-200 +270	-325	2000	30	2050	18
	25,200	-200 +270	-325	2000	40	2050	18
	22,400	-200 +270	-325	2000	50	2050	18
	22,000	-200 +270	-325	1900	30	2050	18
	27,200	-200 +270	-325	2100	30	2050	18
	22,200	-200 +270	-325	2200	30	2050	18
	16,800	-100 +140	-325	2000	30	2050	18
	17,500	-140 +200	-325	2000	30	2050	18
	17,300	-270 +325	-325	2000	30	2050	18
	21,400	-325	-325	2000	30	2050	18

(a) Exceeded strength of braze, fracture partly through braze and partly through core.

Different test specimens from the same plate containing an elemental core matrix were found to be more prone to transverse-strength variations than were plates loaded with UO_2. Microscopic examination of these plates showed wide areas of inhomogeneities in the core matrices. These inhomogeneities were manifested by hard and soft regions due to incomplete solution of the elemental-matrix components. Hardness varied from 140 to 400 VHN, whereas 160 VHN is considered normal. The elimination of the sintering procedure was probably responsible for this incomplete solution.

As mentioned above, higher strengths were obtained from the plates with the elemental matrices. In spite of this, it seems noteworthy that, with the right combination of fabricating conditions, the plates with the prealloyed matrices were slightly stronger than were the reference 25 w/o UO_2 fuel plates, even though they were loaded with 30 w/o UN. Test results are shown in Table 2. The microstructures of these prealloyed matrices showed no evidence of inhomogeneities, but, rather, were clean and sound. However, fuel breakup and stringering were moderately severe.

LONGITUDINAL TENSILE PROPERTIES OF FUEL PLATES

UO_2-Stainless Steel

Conventional sheet tensile specimens that were 1/2 in. wide in the gage section by 9 in. long were used in obtaining tensile data. Unless otherwise noted, cores were exposed to the air atmosphere on both edges of these specimens. The materials tested were 45-mil fuel plates containing UN or Hi-Fired UO_2, powder-metallurgy plates unfueled but otherwise similar to the fuel plates, and commercial Type 318 stainless steel sheet. Optimum fabrication conditions were used in preparing the UO_2-bearing plates; however, these conditions were varied in UN-containing plates because optimum conditions had not yet been determined when the program ended.

Longitudinal versus transverse tensile strength for similar fuel plates with 25 w/o UO_2-elemental 18-14-2.5 alloy cores is compared in Figure 2 from room temperature to 1650 F. The slope of the curve for the longitudinal tests was much steeper than for the transverse tests; in fact, strengths become equal at approximately 1800 F, if the data in Figure 2 are extrapolated. Considering the fact that about 30 per cent of the cross section of the longitudinal test specimens was cladding material, the effect becomes all the more important. It would seem that at some temperature lower than 1650 F a transition occurs whereby at lower temperatures strength is greater in the longitudinal direction, and at higher temperatures strength is greater in the transverse direction. The reason for this transition is not known, but is probably related to the relative loss in strength with temperature of UO_2 and stainless steel.

No significant variation in ductility of UO_2-bearing plates, as measured by per cent elongation in 2 in. was observed. Elongations ranged from 8 to 13 per cent, except in the plates with low-silicon prealloyed-powder core matrices, where elongation averaged 4 per cent. The reason for the low elongation of these plates was the high oxide-impurity content characteristic of this low-silicon powder. About 5 to 10 w/o chromite was microscopically observed in these plates. The gap between strength of loaded and unloaded elemental-matrix plates decreased with an increase in testing temperature, as shown in Table 3. In fact, at 1650 F elemental-matrix plates containing

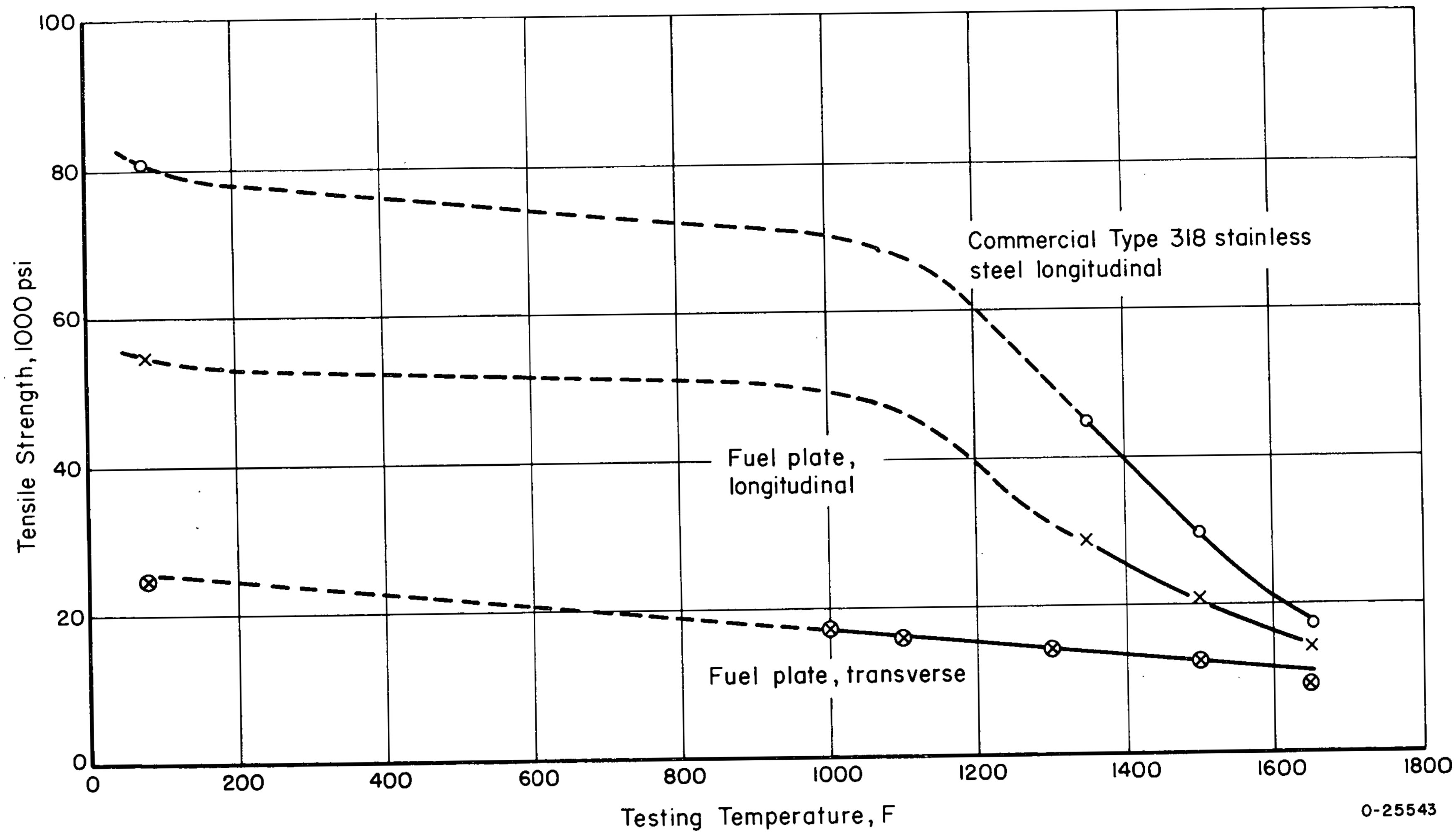

FIGURE 2. COMPARISON OF LONGITUDINAL WITH TRANSVERSE TENSILE STRENGTH OF FUEL PLATES

TABLE 3. EFFECT OF MATRIX AND UO_2 LOADING ON THE HIGH-TEMPERATURE TENSILE PROPERTIES OF FUEL PLATES

Cladding Thickness: 7 mils, Type 318 stainless steel
Core Thickness: 31 mils

Core	Test Temperature, F	Ultimate Tensile Strength[a], psi	Elongation in 2 In.[a], per cent
Commercial Type 318 stainless sheet	Room	81,000	61
	1350	45,000	37
	1500	29,000	27
	1650	17,500	35
No UO_2, prealloyed Type 318 stainless	Room	95,800	53
	1350	41,000	45
	1500	28,200	30
	1650	15,000	42
25 w/o UO_2-prealloyed Type 318 stainless	Room	62,300	10
	1350	33,500	9
	1500	22,900	13
	1650	14,500	9
25 w/o UO_2-prealloyed Type 318 stainless[b]	Room	44,800	4
	1350	30,000	3
	1500	23,100	4
	1650	14,500	6
No UO_2, elemental 18-14-2.5 alloy	Room	79,100	40
	1350	35,200	28
	1500	21,800	20
	1650	13,000	13
25 w/o UO_2-elemental 18-14-2.5 alloy	Room	54,800	13
	1350	28,200	12
	1500	20,200	10
	1650	14,200	8
30 w/o UO_2-elemental 18-14-2.5 alloy[c]	Room	47,000	12
	1350	25,800	9
	1500	17,800	9
	1650	11,700	12
30 w/o spherical UO_2-elemental 18-14-2.5 alloy[c]	Room	52,600[d]	16.4[d]

(a) Average of three or more tests.
(b) Containing 1 w/o silicon compared with usual 2.3 w/o.
(c) Cladding thickness, 6 mils; core thickness, 33 mils.
(d) One test.

25 w/o UO_2 were stronger than similar plates which did not contain any UO_2, and about 80 per cent as strong as commercial Type 318 stainless steel. The 30 w/o UO_2 plates in Table 3 were 90 per cent as strong as the unfueled elemental plates and 67 per cent as strong as the commercial sheet at 1650 F. The Cr_2O_3 content in elemental matrices was discussed in the section on transverse tensile strength. Variations in results for these plates, and weakness and low ductility in the unloaded plates, were probably partly due to uncontrollable variations in the quantity of Cr_2O_3 present.

In comparing the effect of prealloyed versus elemental matrices on tensile strength, it may be seen from Table 3 that plates having prealloyed matrices were stronger than plates with elemental matrices; however, the margin of difference decreased with temperature.

Increasing the UO_2 content from 25 to 30 w/o decreased strength 10 to 20 per cent at all temperatures. Figure 3 shows this effect graphically. However, as mentioned above, ductility was essentially unchanged. As indicated in Table 3, these plates contained 33-mil cores rather than the 31-mil-thick cores the 25 w/o UO_2 plates contained.

The one test performed on a plate containing 30 w/o spherical UO_2 resulted in a room-temperature tensile strength of 52,600 psi and a 16.4 per cent elongation, as indicated in Table 3. These values are 12 and 37 per cent greater, respectively, than for similar plates containing Hi-Fired UO_2, and continue the trend observed in other property tests.

UN-Stainless Steel

Tensile data for fuel plates loaded with UN are presented in Table 4. Since an optimum fabrication procedure had not yet been established at the termination of the program, results are reported as individual tests for varying UN particle sizes. The spread in results was no greater than what would be expected for a large number of tests of the same material, so it was concluded that tensile properties of these plates were relatively insensitive to the fabrication variable considered. Several specimens were machined so as to leave cladding material on the edges. As shown in Table 4, the 20 mils of cladding had no appreciable effect on results. The average tensile strength of these plates at test temperatures is compared with the tensile strengths of UO_2-bearing fuel plates and the cladding material in Figure 3. As may be seen from this plot, the UN-bearing plates surpassed both 25 and 30 w/o UO_2-bearing plates at all temperatures up to 1650 F, where the strength essentially equalled that of the 25 w/o UO_2 plates.

CREEP-RUPTURE PROPERTIES OF FUEL PLATES

Creep-rupture tests were performed at 1500 and 1650 F on the following materials: fuel plates with 25 w/o UO_2 in both elemental and prealloyed matrices, fuel plates with 28 w/o UN in elemental matrices, nonfueled powder-metallurgy plates with elemental and prealloyed cores, and commercial Type 318 stainless steel sheet. All plates were fabricated by the optimum fabrication technique, and solution annealed prior to testing.

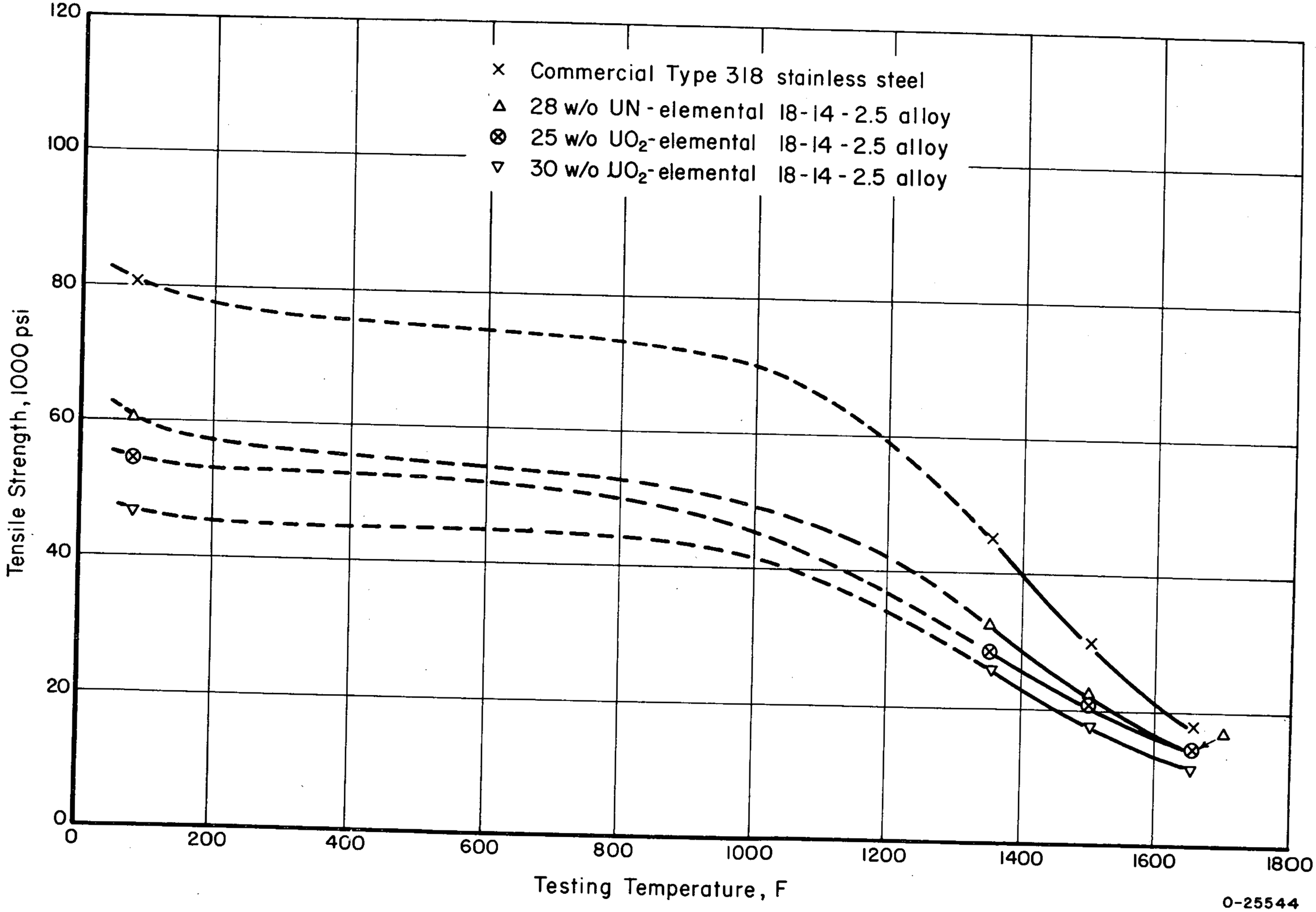

FIGURE 3. EFFECT OF TEMPERATURE ON TENSILE STRENGTH OF FUEL PLATES AND CLADDING MATERIAL

TABLE 4. EFFECT OF UN PARTICLE SIZE ON TENSILE PROPERTIES OF FUEL PLATES

Cladding Thickness: 6 mils, Type 318 stainless steel
Core Thickness: 33 mils, 28 w/o UN-elemental 18-14-2.5 alloy

Test Temperature, F	Ultimate Tensile Strength, psi	Elongation in 2 In., per cent	UN Mesh Size	Rolling Temperature, F	Reduction in First Pass, per cent	Comments
Room	59,700	14	-100+200	2100	30	--
	59,800	16	-100+200	2100	30	20-mil cladding on core edges
	62,200	14	-200+325	2100	30	Blistered during fabrication
	59,000	13	-200+270	2000	30	--
	61,000	15	-200+270	2100	30	--
	60,200	16	-200+325	2200	30	--
	Avg 60,300	Avg 15				
1350	31,500	13	-100+200	2100	30	--
	32,500	6	-100+200	2100	30	--
	32,600	9	-100+325	2100	30	--
	Avg 32,200	Avg 9				
1500	20,900	13	-100+200	2100	30	--
	22,700	11	-100+200	2100	30	20-mil cladding on core edges
	22,500	13	-200+325	2100	30	--
	Avg 22,000	Avg 12				
1650	15,100	8	-100+200	2100	30	--
	14,800	11	-200+325	2100	30	20-mil cladding on core edges
	14,100	14	-200+325	2100	30	--
	Avg 14,700	Avg 11				

Creep-rupture test specimens were similar to tensile specimens. The core edges were exposed to the helium test atmosphere.

The stress-rupture and minimum-creep-rate data show that best creep-rupture properties for UO_2-containing fuel plates were obtained with a prealloyed Type 318 stainless steel core matrix. Data are presented in Figure 4 and Table 5. The difference in rupture and creep strength between these best fuel plates and commercial Type 318 stainless steel was negligible. The fuel plates having elemental 18-14-2.5 alloy-25 w/o UO_2 cores had an extrapolated rupture life of 10,000 hr with a 1100-psi stress, and stress for rupture in 1000 hr was 60 per cent of stress for 1000-hr rupture in the commercial Type 318 stainless steel compared with 95 per cent for the plates with prealloyed core matrices. It was surprising to obtain inferior properties in these plates with elemental cores, since stringering and fracturing of the UO_2 was much less pronounced than in the plates having prealloyed core matrices. The behavior is at least partly explained by the presence of Cr_2O_3 in the elemental matrices. Another significant difference was sigma-phase formation. The prealloyed matrices usually contained about 10 per cent ferrite which transformed to sigma plus austenite less than 2 hr after the tests began, whereas several hundred hours was required before sigma began forming from the austenitic elemental matrices.

Two tests of fuel plates containing cores of 28 w/o UN in elemental 18-14-2.5 alloy were performed. Extrapolating these results, shown in Table 5, shows that rupture strength is greater and minimum creep rate lower than for similar fuel plates containing 25 w/o UO_2 at 1650 F.

BEND DUCTILITY OF FUEL PLATES

UO_2-Stainless Steel

Bend tests were performed by means of a V-die and mating punches, the point of the V on the punches having been machined to various radii ranging from zero to 3/8 in. The included angle on the V was 90 deg. Bend tests were performed by pressing the test specimen between the V-die and punches of decreasing tip diameter until fracture occurred in the cladding as determined visually. Thus, the test consisted, in effect, of bending the test specimen 90 deg around varying radii until fracture occurred. The test specimen was bent so that stresses were applied perpendicular to the rolling direction and fracture occurred parallel with the rolling direction. The ratio of the minimum radius where no cracks were observed in the cladding to plate thickness is referred to here as T-bend, and all bend data are reported in terms of T-bend figures. Spot metallographic checks indicated that subsurface cracks occurred in the core of loaded test specimens before they were manifested by surface cracking. In general, adding 2.8 to reported T-bend figures was found to give a T-bend value that corresponded to a completely crack-free specimen as determined microscopically. This corresponds to a 1/8-in. punch-radius difference on a 45-mil plate. All annealing treatments for bend specimens were performed in hydrogen, since heavy scaling was found to occur in air under certain conditions of time and temperature which adversely affected test results.

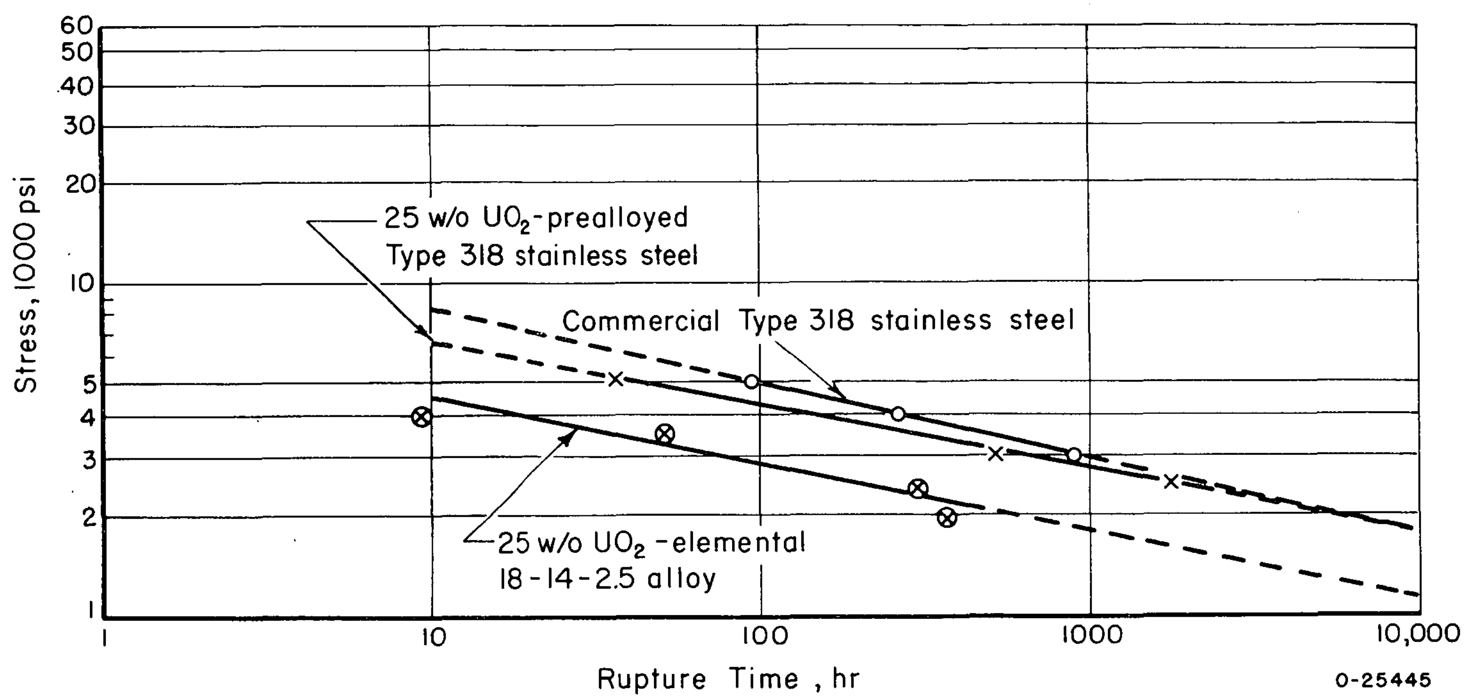

FIGURE 4. COMPARISON OF STRESS-RUPTURE CURVES OF UO_2-STAINLESS STEEL FUEL PLATES WITH COMMERCIAL SHEET AT 1650 F

TABLE 5. THE EFFECT OF COMPOSITION ON CREEP-RUPTURE PROPERTIES OF ANNEALED FUEL PLATES

See "Introduction" for Fabrication History

Core	Test Temperature, F	Stress, psi	Rupture, Time, hr	Minimum Creep Rate, per cent per hr	Final Elongation, per cent
Commercial Type 318 stainless steel	1650	5000	95.6	0.054	11.3
	1650	4000	266.4	0.017	8.5
	1650	3000	927.2	0.0035	7.1
No UO_2, prealloyed Type 318 stainless steel	1650	5000	71.5	0.130	23.9
	1650	3500	255.4	0.040	29.4
	1650	3000	1368.1[(a)]	0.0035	8.4
25 w/o UO_2, prealloyed Type 318 stainless steel	1650	5000	36.3	0.114	6.3
	1650	3000	516.8	0.0032	5.1
	1650	2500	1798.0	0.00094	4.7
	1500	8000	68.4	0.049	8.0
	1500	6000	282.7	0.0069	5.1
	1500	5200	762.0	0.0025	4.3
No UO_2, elemental 18-14-2.5 alloy	1650	4000	47.4	0.056	3.8
	1650	2500	351.4	0.0129	6.1
25 w/o UO_2, elemental 18-14-2.5 alloy	1650	4000	9.4	--	4.0
	1650	3500	52.7	0.075	8.5
	1650	2400	302.9	--	12.3
	1650	1900	361.8	--	4.7
	1500	5000	34.3	0.094	5.0
	1500	3000	2117.0[(a)]	0.00023	8.1
28 w/o UN, elemental 18-14-2.6 alloy[(b)]	1650	4000	120.9	0.043	11.5
	1650	3000	172.1	0.037	15.0

(a) Test discontinued, no rupture.
(b) Cladding-core-cladding thicknesses, 6-33-6 mils.

The effect of variables on bend ductility of fuel plates is shown in Table 6. As may be seen, annealing after cold rolling was important, since no ductility was present after the normal 15 to 20 per cent cold reduction, and complete recrystallization was required to restore optimum ductility. For a 45-min holding time, annealing temperatures of 1900 F and higher were required for complete recrystallization and optimum ductility. Transforming ferrite in prealloyed matrices to sigma phase by annealing at 1550 F subsequent to complete recrystallization had no effect on bend ductility, cooling rate was inconsequential, and UO_2 mesh size had little influence in plates having elemental, or prealloyed matrices.

The above discussion refers to tests on plates having a cladding thickness of 7 mils and core thickness of 31 mils (7-31-7) with a 25 w/o UO_2 loading. Plates having 30 w/o UO_2 dispersed in elemental 18-14-2.5 alloy had 6-33-6 cladding-core-cladding thicknesses, and were not quite as ductile as the above plates, usually withstanding only a bend of 2.8T, as shown in Table 6. Although the UO_2 increase was probably primarily responsible for the ductility decrease, it should be remembered that, although the effective plate thickness was increased, the thickness used in calculating T-bends was not.

Most significant of the bend data obtained were those for plates containing 30 w/o spherical UO_2. Although cladding-core-cladding thicknesses were 6-33-6 mils, bends of 0.4 to 0.7T were obtained with both elemental 18-14-2.5 alloy and prealloyed Type 318 stainless steel core matrices, as shown in Table 6. This ductility was superior to anything of comparable loading tested.

UN-Stainless Steel

The bend ductility of fuel plates loaded with 30 w/o UN in prealloyed Type 318 stainless steel was superior to that of plates loaded with 25 w/o UO_2. As shown in Table 7 the former plates withstood a bend of 1.4T for a wide range of fabrication procedures, including the varying of UN particle size from minus 100 to plus 325 mesh.

Although over-all dispersion quality in plates containing elemental 18-14-2.5 alloy core matrices was far superior to the plates with prealloyed matrices, bend ductility was consistently lower, a bend of 2.8T being normal. Less UN was also present in these plates, 28 w/o compared with 30 w/o in the plates with prealloyed matrices. Here, too, fabrication variables had only a slight effect on ductility. The reason for poorer ductility in these plates is to be found in their microstructure, as discussed in the section on transverse tensile tests. The hard and soft phases observed in the elemental matrix were not present in the prealloyed matrices; in fact the latter were similar to the best sintered prealloyed matrices.

THERMAL EXPANSION OF FUEL PLATES

Thermal-expansion characteristics of fuel plates are important from the standpoint of dimensional stability. Data were obtained on longitudinal specimens taken from plates fabricated by optimum procedures, and containing 25 w/o UO_2 in elemental and prealloyed core matrices. Table 8 summarizes these data. No essential difference was

TABLE 6. THE EFFECT OF COMPOSITION AND FABRICATION VARIABLES ON THE BEND DUCTILITY OF UO_2-STAINLESS STEEL FUEL PLATES TRANSVERSE TO THE ROLLING DIRECTION

Cladding Thickness: 7 mils, Type 318 stainless steel
Core Thickness: 31 mils

Core Matrix	UO_2 Mesh Size	UO_2, w/o	Heat Treatment and Comments	T-Bend Rating
		Effect of Annealing Temperature After Cold Rolling		
Prealloyed Type 318 stainless	-200 + 270	25	15 min at 2250 F	4.2
			45 min at 2150 F	4.2
			45 min at 2150 F plus 2 hr at 1550 F	4.2
			45 min at 2025 F	4.2
			45 min at 1900 F	4.2
			45 min at 1800 F	5.6
			45 min at 1700 F	5.6
			2 hr at 1500 F	>8.3
			As cold rolled	>8.3
		Effect of Cooling Rate From Annealing Temperature		
Prealloyed Type 318 stainless	-200 + 270	25	10 min at 2150 F plus slow cool	4.2
			10 min at 2150 F plus fast cool	4.2
Elemental 18-14-2.5 alloy	-140 + 200	25	10 min at 2150 F plus slow cool	1.4
			10 min at 2150 F plus fast cool	1.4
		Effect of UO_2 Particle Size		
Elemental Fe-18 w/o Cr-10 w/o Ni	-270 + 325	25	Solution annealed[a]	0.5
	-200 + 270	25	Solution annealed[a]	1.0
	-140 + 200	25	Solution annealed[a]	1.0
	-100 + 140	25	Solution annealed[a]	1.0, 1.6
		Effect of Higher UO_2 Loading		
Elemental 18-14-2.5 alloy	-100 + 200	30	Solution annealed[b]	2.8
			Solution annealed, spherical UO_2[b]	0.4
Prealloyed Type 318 stainless	-100 + 200	30	Solution annealed, spherical UO_2, sintered at 2300 F[b]	0.7

(a) Cladding-core-cladding thicknesses, 5-40-5 mils.
(b) Cladding-core-cladding thicknesses, 6-33-6 mils.

TABLE 7. THE EFFECT OF COMPOSITION AND FABRICATION VARIABLES ON THE BEND DUCTILITY OF UN-STAINLESS STEEL FUEL PLATES TRANSVERSE TO THE ROLLING DIRECTION

Cladding Thickness: 6 mils, Type 318 stainless steel
Core Thickness: 33 mils

Core Matrix	UN Mesh Size	Rolling Temperature, F	Reduction in First Pass, per cent	T-Bend Rating
		30 w/o UN		
Prealloyed Type 318 stainless	-200+270	2000	20	1.4
	-200+270	2000	30	1.4
	-200+270	2000	40	1.4
	-200+270	2000	50	1.4
	-200+270	1900	30	2.1
	-200+270	2100	30	1.4
	-200+270	2200	30	1.4
	-100+140	2000	30	1.4
	-140+200	2000	30	1.4
	-270+325	2000	30	1.4
	-325	2000	30	4.2
		28 w/o UN		
Elemental 18-14-2.5 alloy	-200+325	2000	30	2.8
	-200+270	2000	30	2.8
	-200+270	2100	30	2.8
	-200+325	2200	30	2.8
	-200+325	2000	30	2.8
	-100+200	2100	40	2.8
	-100+200	2100	35	2.8
	-100+200	2100	45	2.8
	-100+200	2100	30	2.8
	-200+325	2100	30	2.8
	-200+325	2100	30	4.2[a]

(a) Plate blistered during fabrication.

observed and, furthermore, the expansion curve of a comparison specimen, commercial Type 318 stainless steel fabricated in the same manner as the fuel plates, was also substantially identical. This indicates that the claddings were pre-eminent in influencing thermal expansion of the fuel plate, and, furthermore, for most practical purposes, the expansion coefficient of a fuel plate could be considered identical to that of its cladding material.

TABLE 8. COMPARISON OF MEAN LINEAR-THERMAL-EXPANSION COEFFICIENTS OF ANNEALED FUEL PLATES HAVING DIFFERENT CORE COMPOSITIONS (LONGITUDINAL DIRECTION)

Temperature Range, F	Mean Linear-Thermal-Expansion Coefficient, 10^{-6} per F		
	Commercial Type 318 Stainless Steel	Fuel Plate Containing 25 w/o UO_2 in Elemental Matrix	Fuel Plate Containing 25 w/o UO_2 in Prealloyed Matrix
68-200	8.9	8.6	9.0
68-400	9.3	9.1	9.2
68-600	9.5	9.4	9.4
68-800	9.7	9.8	9.6
68-1000	9.9	10.1	9.9
68-1200	10.1	10.4	10.1
68-1400	10.4	10.7	10.4
68-1600	10.6	10.9	10.6
68-1700	10.7	11.0	10.7

CONCLUSIONS

The tensile strength of the reference fuel plate (25 w/o UO_2-elemental 18-14-2.5 alloy core) decreased from 24,600 psi at room temperature to 9,200 psi at 1650 F in the direction perpendicular to the rolling plane. Tensile strength in the longitudinal direction decreased from 54,800 psi at room temperature to 14,200 psi at 1650 F, with elongation in 2 in. ranging from 8 to 13 per cent. This element withstood a 1.4T bend without cracking, and had a 1000-hr rupture life at 1650 F under an extrapolated stress of 1,800 psi. The mean linear-thermal-expansion coefficient was 11.0×10^{-6} per F for the range 68 to 1700 F.

A transition temperature existed in these fuel elements. Above this transition temperature tensile properties perpendicular to the rolling plane were greater than in the longitudinal direction and vice versa.

The creep-rupture properties of this fuel plate were improved by the substitution of prealloyed Type 318 stainless steel for the elemental alloy in the core matrix; however, transverse tensile strength was reduced.

A marked improvement in properties resulted with the use of spherical UO_2 or of UN instead of Hi-Fired UO_2, but not enough tests were made to determine whether the UN was better than spherical UO_2.

REFERENCE

(1) Paprocki, S. J., Keller, D. L., and Cunningham, G. W., "The Effect of Fabrication Variables on the Structure and Properties of UO_2-Stainless Steel Dispersion Fuel Plates", BMI-1322 (February 18, 1959). Confidential.