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CHARACTERIZATION OF COLD-WORKED TUBING OF TYPES-304H AND -316H STAINLESS STEEL

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U. S. ATOMIC ENERGY COMMISSION
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**CHARACTERIZATION OF COLD-WORKED TUBING OF
TYPES-304H AND -316H STAINLESS STEEL**

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ABSTRACT

Eight lots of cold-worked austenitic stainless steel tubing (5G430G) were characterized. Tubing quality was well within the ordering specification, and hence is considered "nuclear quality" for use in fabrication of fuel pins and tensile test specimens destined for EBR-II reactor experiments.

1. INTRODUCTION

Utilization of austenitic stainless steel tubing in the cold-worked condition has been recommended since the early 1960's as an attractive cladding material for fast reactor fuels. Proponents of the use of such material argued that the higher strength inherent in austenitic structures containing residual cold work would provide a worthwhile supplement to the strengthening produced by irradiation—strengthening which is required to restrict fuel growth during service.

As late as 1967, however, a fundamental problem more ominous than that posed by fuel swelling was injected into the fast reactor development programs here and abroad with the now-classical revelation by Cawthorne and Fulton* that not only the fuel but all core components are subject to swelling. The realization that the material selected and designed to confine the fuel is itself susceptible to nonthermal expansion prompted a vast experimental program to study the nature of swelling. Experimenters discovered early in the study of swelling that the phenomenon was associated in some way with the helium-producing $n-\alpha$ transmutation, the cross section for which is appreciable for virtually all elemental components of austenitic stainless steel irradiated in a fast neutron flux. However, it was soon realized that this cross section for certain impurity elements was huge in comparison with those of the principal alloying constituents. This resulted in the tightening up of standard specifications and eventually the introduction of specifications for "nuclear grade" materials.

Controlling the source of helium, however, offered only a partial solution. Realizing that helium is an omnipresent consequence of fast neutron bombardment, and finding that the "helium bubbles" formed throughout the structures were in fact empty, experimenters turned their attention toward structures capable of accommodating the large number of voids that were being produced. One structure that provided such sinks was a structure containing a high dislocation density, i.e., a cold-worked structure. A need was thus created for cold-worked tubing of austenitic stainless steel—high-quality and well-characterized cold-worked tubing for experimental testing. The 5G430G tubing was procured to fill that need.

Presented in this report are the results of a detailed characterization of the 5G430G material—work that is essential to the eventual assessment of the response of the tubing to fast neutron irradiation.

2. DESCRIPTION OF MATERIALS

The 5G430G tubing consisted of equal quantities of Types-304H and -316H stainless steel, each produced in four lots. 300 feet each of 10, 20, and 30% cold-worked tubing, and 600 feet of 50% cold-worked tubing. The tubing was procured to provide test material for fuels and materials irradiation experiments and out-of-pile cladding development studies. It was ordered to a specification† (22A1779, Rev. 0) which included control of production parameters such as tube hollow manufacture, tube fabrication history, and detailed mechanical properties testing. The designation given this tubing was 5G430G, which represents the purchase order to which the material was procured. General information regarding the various tubing lots received is listed in Table 1.

All tubing was produced by the seamless process and has the nominal dimensions of 0.250-inch outer diameter and 0.015-inch wall. The degrees of cold working were established in the final drawing and represent the percent reduction in cross-sectional area. A flow sheet showing the sequence of operations followed in the final production process is shown in Figure 1. In all cases, starting material (Step 1) was in the "full-hard" condition (>50% cold work).

Additional heat treatments were performed on material from the 50% cold-worked lots to produce annealed and thermo-mechanically treated tubing. These heat treatments (Step 5) are shown in Figure 2. The specific aim of these

* Cawthorne, C., and Fulton, E. J., "Voids in Irradiated Stainless Steel," *Nature*, 216 (1967), 515.

† Lauritzen, T., Albanese, J. J., Berg, G. C., and Gaul, G. G., *An Evaluation of the Quality of Seamless Austenitic Stainless Steel Tubing*, December 1969, (GEAP-13553).

heat treatments was to provide a variety of microstructures for testing as fuel element cladding in EBR-II to determine whether these heat treatments would enhance creep resistance and the resistance of the cladding to irradiation-induced swelling (see Appendix B).

The final quantity of tubing available from this order is shown in Table 2.

Table 1
ORDERING DATA ON 5G430G TUBING

	304H	316H
Basic Specification	A213-65	A213-65
Supplementary Specification	22A1779, Rev. 0	22A1779, Rev. 0
Purchase Order Number	205-5G430G	205-5G430G
Lot Quantity (Ordered)	304H	316H
(Feet)	<u>Ordered/Received</u>	<u>Ordered/Received</u>
10% CW	300/330	300/330
20% CW	300/330	300/380
30% CW	300/330	300/330
50% CW	600/640	600/640

Table 2
**MICROSTRUCTURES AVAILABLE
FROM THE 5G430G TUBING**

Alloy	Microstructure	Quantity	
304H	Solution treated	25 five-foot lengths	Heat No. 04200
304H	Fine grain size	25 five-foot lengths	
304H	Carbide agglomerated	25 five-foot lengths	
304H	10% cold worked	66 five-foot lengths	
304H	20% cold worked	66 five-foot lengths	
304H	30% cold worked	66 five-foot lengths	
304H	50% cold worked	53 five-foot lengths	
316H	Solution treated	25 five-foot lengths	Heat No. M2783
316H	Fine grain size	25 five-foot lengths	
316H	Carbide agglomerated	25 five-foot lengths	
316H	10% cold worked	66 five-foot lengths	
316H	20% cold worked	76 five-foot lengths	
316H	30% cold worked	66 five-foot lengths	
316H	50% cold worked	53 five-foot lengths

1- NUMBERS REFER TO VENDOR'S LOT OR ORDER NUMBER

2- ALL TUBING IN STEP 1 WAS 50% COLD WORKED

3- DIMENSIONS ARE OUTER DIAMETER AND WALL RESPECTIVELY

Figure 1. Final Production Steps in the Manufacture of the 5G430G Tubing

Figure 2. Additional Heat Treatment Given 5G430G Tubing

3. CHEMICAL COMPOSITION

The order for the 5G430G tubing specified that the delivered tubing must conform in chemical composition to that given in the standard specification ASTM A213-65, with the following additional requirements:

Element	Quantity (wt %)
Copper	0.50 (Maximum)
Cobalt	0.10 (Maximum)
Boron	0.003 (Maximum)
Nitrogen	0.10 (Maximum)

The allowable concentration of these impurity elements is not explicitly covered in the ASTM specification. The level of such impurities is controlled, in large measure, by the composition of the raw materials and the steel-making process. For normal industrial applications, the steel-making companies impose unofficial restrictions on the levels of such impurities in their products. However, recent advances in the study of materials behavior during fast neutron irradiation have indicated that these impurities, if present even in seemingly innocuous quantities, can adversely affect the physical and mechanical properties of such material used as fuel cladding. Their level must therefore be not only known, but closely controlled.

For evaluation of chemical composition, 18 elements were selected for analysis. These included all elements that establish the identity of an alloy type (ASTM A213-65) and the following impurities: Ti, Nb, Al, Ta, Pb, Cu, Co, B, and N. Thus, in addition to the general information regarding conformance to specification that chemical analysis provides, the analyses performed in this characterization study also provide a means whereby the overall quality of the material can be gaged.

The tubing vendor provided the ladle and check analyses for both heats of steel. One additional check analysis was performed on samples from each tube hollow and from each lot of tubing by Anamet Laboratories, Inc. A single analysis for boron was performed on both tube hollow materials by Biodynamics Research Corporation. The Anamet results are shown in Table 3, along with certified vendor heat and product analyses and the allowable ASTM-specified compositional ranges. Of these numerous checks and rechecks, the only discrepancy with regard to conformance to

specification was the cobalt content in the Type 304H. This discrepancy was duly noted by the vendor prior to tube fabrication—the ladle analysis yielded a cobalt content of 0.14% (versus an allowable maximum of 0.10%)—but was roundly refuted by the five check analyses which yielded 0.05% in unison. The independent Anamet results on the cobalt content, however, clearly confirm the ladle analysis and cast some doubt on the vendor checks. In fact, the Anamet results on Type 304H consistently support the ladle analysis rather than the checks. In the case of the results on the seven ASTM-specified elements of Type 304H, for example, an average discrepancy of 18% exists between the ladle and check analyses, while the variation between ladle and Anamet averages 5%.

Information that both the check analyses and Anamet analyses provide regarding compositional variation within a heat or between lots is, for the most part, complementary. The check analyses on the ASTM-specified elements show maximum variations of 7 and 9%, and the Anamet results show variations of 6 and 7% for Types 304H and 316H, respectively.

4. ALLOY METALLOGRAPHY

The establishment of alloy microstructure by light optical metallography is perhaps the most important single examination in the characterization of materials destined for subsequent high-temperature service. Not only does this examination allow conformity to specification to be evaluated but also, more significantly, it provides the only direct graphic display of the overall quality of a given alloy heat. Information regarding temper, grain size, surface condition, and inclusion content of an alloy in the as-received condition thus established provides an essential base from which the magnitude of subsequent service-imposed modifications can be assessed.

The metallographic examinations currently specified for cladding tube characterization call for the following photomicrographs to be prepared on one tube sample per lot:

- Transverse and longitudinal cross section (etched) at a magnification of 100X for grain size determination
- Transverse and longitudinal cross section (etched) at a magnification of 250X for general structure
- Longitudinal cross section (unetched) at a magnification of 100X for determination of the size, type, and distribution of inclusions.

Such metallography, performed on the eight lots of the as-received tubing, is summarized in Figure 3, and presented in detail in the Metallographic Characterization sheets of Appendix A. Also included in the latter display is a 500X photomicrograph of the inner surface of each tube section, illustrating the degree of intergranular attack present in this as-received material.

The results of the metallographic characterization are summarized in Table 4. Hardness values determined from microhardness indentations performed on transverse cross sections are also included. Except for the grain size of the material in the annealed condition, none of the parameters listed in Table 4 was specified on this tubing order. The grain sizes of the annealed material are those provided by the vendor. All are within the allowable range of ASTM 5 to 8. These values are compared with the grain size of the finished tubing as determined from a transverse cross section. The latter determinations are shown here merely to illustrate the modifications in structure that occur with cold drawing. They should be considered only qualitative as should any grain size determination on heavily cold-worked material.

The values for inclusion content, determined from longitudinal cross sections, represent the general type, size, and distribution of inclusions as established by comparing the unknown with a known standard established by ASTM. "C" refers to an inclusion of the silicate type; the numeral indicates the inclusion length or the length of a closely-spaced string of inclusions. For an inclusion of the silicate type, Plate I of ASTM E45 shows that the numerical designation "2" represents a stringer with a maximum length of 0.005 inch. "Thin" denotes a thickness range for the particular type of inclusion. In the case of this work, a "thin" inclusion of the silicate type is no thicker than 0.0002 inch.

The hardness numbers shown in Table 4 are Rockwell-C values, established by conversion of microhardness data. Indentations were made on transverse cross sections with a Knoop indenter and a 500-gram load. The correlation between hardness and degree of cold work is readily apparent.

One of the main disadvantages of the metallographic and, in fact, any sampling technique is the uncertainty in determining the continuity of a given state or condition. This handicap has been shown to be minor when dealing with chemical composition and grain structure, both of which are generally fairly homogeneous, but presents a significant problem when metallography is used to evaluate surface condition. Establishing the degree of intergranular attack is a point in evidence. In the routine examination of the specimens during metallographic preparation, a uniform grain boundary attack was detected on the inner surface of the 30% cold-worked Type-304H tubing. Although the attack

Table 3
CHEMICAL ANALYSES ON THE 5G430G TUBING

Chemical Composition, Percent by Weight

Alloy	Temper	Analysis	C	Mn	P	S	Si	Ni	Cr
304H (04200)		Specification	0.04- 0.10	2.00 max	0.040 max	0.030 max	0.75 max	8.00- 11.00	18.0- 20.00
		Ladle	0.05	1.70	0.024	0.026	0.39	9.61	18.47
		Check 1	0.06	1.42	0.014	0.020	0.46	9.93	18.90
		Check 2	0.06	1.39	0.013	0.018	0.44	10.11	18.96
		Check 3	0.06	1.44	0.013	0.018	0.48	9.96	18.87
		Check 4	0.06	1.45	0.012	0.019	0.43	10.02	18.93
		Check 5	0.06	1.41	0.013	0.021	0.41	9.90	18.96
	Hollow	Anamet	0.06	1.66	0.022	0.022	0.54	9.57	18.43
	10% CW	Anamet	0.052	1.68	0.026	0.021	0.36	9.79	18.39
	20% CW	Anamet	0.050	1.67	0.027	0.024	0.37	9.84	18.40
	30% CW	Anamet	0.055	1.67	0.027	0.023	0.38	9.55	18.47
	50% CW	Anamet	0.052	1.65	0.027	0.025	0.35	9.68	18.50
316H (M2783)		Specification	0.04- 0.10	2.00 max	0.030 max	0.030 max	0.75 max	11.0- 14.00	16.0- 18.00
		Ladle	0.05	1.73	0.018	0.017	0.51	13.28	16.75
		Check 1	0.06	1.76	0.012	0.014	0.43	13.22	17.51
		Check 2	0.06	1.79	0.012	0.015	0.46	13.16	17.56
		Check 3	0.06	1.80	0.010	0.012	0.44	13.10	17.49
		Check 4	0.05	1.75	0.011	0.012	0.44	13.21	17.58
		Check 5	0.06	1.77	0.011	0.013	0.41	13.10	17.56
	Hollow	Anamet	0.06	1.77	0.022	0.015	0.51	13.28	16.43
	10% CW	Anamet	0.054	1.79	0.028	0.015	0.50	13.23	16.48
	20% CW	Anamet	0.058	1.79	0.029	0.017	0.47	12.98	16.81
	30% CW	Anamet	0.061	1.78	0.029	0.013	0.47	12.83	16.79
	50% CW	Anamet	0.054	1.81	0.028	0.016	0.53	13.13	16.58

Table 3 (Continued)

Mo	Nb	Ta	Cu	Co	B	N	Al	Ti	Pb	Fe
—	—	—	0.50 max	0.10 max	0.003 max	0.10 max	—	—	—	Balance
—	—	—	0.20	0.14	<0.001	—	—	—	—	—
—	—	—	0.14	0.05	<0.0005	0.049	—	—	—	—
—	—	—	0.13	0.05	<0.0005	0.049	—	—	—	—
—	—	—	0.14	0.05	<0.0005	0.048	—	—	—	—
—	—	—	0.14	0.05	<0.0005	0.046	—	—	—	—
—	—	—	0.13	0.05	<0.0005	0.046	—	—	—	—
0.24	<0.01	<0.02	0.06	0.14	0.00035 ^(a)	0.030	<0.02	<0.01	<0.02	69.8
0.23	<0.01	<0.02	0.15	0.13	—	0.041	<0.01	<0.02	<0.02	68.7
0.24	<0.01	<0.02	0.14	0.15	—	0.042	<0.01	<0.02	<0.02	69.4
0.25	<0.01	<0.02	0.14	0.14	—	0.038	<0.01	<0.02	<0.02	69.2
0.25	<0.01	<0.02	0.15	0.15	—	0.044	<0.01	<0.02	<0.02	69.1
2.00- 3.00	—	—	0.50 max	0.10 max	0.003 max	0.10 max	—	—	—	Balance
2.50	—	—	0.09	0.073	0.0005	0.043	—	—	—	—
2.52	—	—	<0.10	<0.05	0.0011	0.049	—	—	—	—
2.54	—	—	<0.10	<0.05	0.0012	0.045	—	—	—	—
2.51	—	—	<0.10	<0.05	0.0012	0.049	—	—	—	—
2.50	—	—	<0.10	<0.05	0.0011	0.048	—	—	—	—
2.51	—	—	<0.10	<0.05	0.0011	0.047	—	—	—	—
2.29	<0.01	<0.02	0.02	0.06	0.00015 ^(a)	0.026	<0.02	0.02	<0.02	65.3
2.41	<0.01	<0.02	0.08	0.06	—	0.018	<0.01	<0.02	<0.02	65.4
2.46	0.01	<0.02	0.08	0.07	—	0.030	<0.01	<0.02	<0.02	65.8
2.40	0.01	<0.02	0.09	0.06	—	0.027	<0.01	<0.02	<0.02	65.4
2.49	<0.01	<0.02	0.10	0.06	—	0.014	<0.01	<0.02	<0.02	64.8

(a) Boron analysis was performed by Biodynamics Research Corp using spark source mass spectrometer.

Figure 3. Comparative Micrography of 5G430G Tubing.
Photos are longitudinal sections at X250, etched with $HCl-H_2O_2$.

Table 4
METALLOGRAPHIC AND HARDNESS DATA ON THE 5G430G TUBING

Alloy	Temper	Transverse Grain Size (ASTM)		Inclusion Content	Hardness (Rc)
		Annealed	Cold Worked		
304H	10% CW	7-1/2 to 8	8	C1 Thin ^(a)	23
304H	20% CW	7-1/2 to 8	8-1/2	C2 Thin	31
304H	30% CW	6 to 8	9	C2 Thin	35
304H	50% CW	7-1/2	10	C1 Thin	39
316H	10% CW	7 to 8	7	C2 Thin	18
316H	20% CW	7-1/2 to 8	7-1/2	C1 Thin	31
316H	30% CW	7-1/2	8-1/2	C1 Thin	35
316H	50% CW	7	9	C2 Thin	36

(a) "Thin," in the case of a C-type (silicate) inclusion, denotes an inclusion no thicker than 0.0002 inch.

depth was less than that allowed in the specification, the nature of the attack gives cause for concern. As Figure 4 shows, this attack is not restricted simply to the local fissuring of surface grain boundaries, but propagates to a depth of several grains and results in surface grain fallout. A surface such as this would be extremely difficult to clean; the pockets formed by removed grains could serve as extremely effective traps for noxious materials. The problem becomes even more acute, considering the fact that while this effect is uniform in a given cross section, it is not uniform in the axial direction. Cross sections prepared from the same tube and another randomly picked tube failed to reveal more than a trace of surface attack; hence, the condition could easily escape detection. In view of this observation, it is likely that many of the local surface "reactions" noted on irradiated cladding could conceivably have initiated at such an "as-received" defect.

5. DIMENSIONAL EVALUATION

One of the principal requirements in the application of thin-wall tubing as cladding material for nuclear fuels is specific knowledge of tubing dimensions and the variations of a given dimension within a given length of tubing. Precise information regarding tubular dimensions is particularly important in experimental studies of the behavior of fuels under irradiation and is essential in the precise evaluation of irradiation-induced swelling of the cladding. Because of these needs, purchasing specifications for "nuclear grade" tubing included dimensional requirements supported by test results of measurements performed on each lot. Dimensions specified included: outside and inside diameters (0.250 ± 0.001 inch and 0.220 ± 0.001 inch, respectively), bow (not to exceed 0.010 inch per lineal foot), ovality (not to exceed 0.002 inch), and eccentricity (not to exceed 0.0015 inch).

A bar graph representation of outside diameter and inside diameter measurements provided by the vendor is shown in Figures 5 and 6 for Types 304H and 316H lots, respectively. Also included are additional measurements performed by GE on tube sections selected at random from the lots. The vendor results represent random readings taken on 25 tube sections; the GE measurements represent a weighted average of a continuous dimensional scan along the tube length. The two groups of data are shown to be generally complementary. One exception, however, is illustrated in the outside diameter data on the Type 316H. The GE data on the 10, 20, and 30% cold-worked lots are consistently higher. In fact, in the three cases cited, the GE results revealed out-of-specification dimensions, while the vendor data lay, without exception, within the allowable tolerance range. This is, of course, understandable in view of the clear basis for rejection that an out-of-size tube section presents.

General trends shown by both groups of data indicate that all dimensions lie on the high side of nominal. Dimensional variations in inside diameter are consistently better than those measured on the outside diameter.

LONGITUDINAL SECTION NO. 69 APO 0553

TRANSVERSE SECTION NO. 69 APO 0552

Figure 4. Surface Attack on 30% Cold-Worked Tubing of Type 304H. X500, unetched.

NOTE: THE SHADED REGIONS ON THE BARGRAPH REPRESENT GE DATA ON RANDOMLY SELECTED TUBE SECTIONS. THE REMAINDER ARE VENDOR-SUPPLIED DATA.

Figure 5. Diametral Variations in Cold-Worked Tubing of Type 304H

NOTE: THE SHADED REGIONS ON THE BARGRAPHS REPRESENT GE DATA ON RANDOMLY-SELECTED TUBE SECTIONS. THE REMAINDER ARE VENDOR-SUPPLIED DATA.

Figure 6. Diametral Variations in Cold-Worked Tubing of Type 316H

Measurements for straightness were not recorded by the vendor, nor were they made by GE on incoming inspection. (This measurement is normally performed as one of the initial steps in the selection of tubing for a particular experimental program.) Vendor certifications did, however, indicate that all tubes tested for straightness registered a bow not exceeding 0.040 inch per 5-foot length. This is within the allowable range.

Ovality, as defined in the ordering specification, refers to the difference between maximum and minimum outer diameter dimension in any one tube length. The vendor included on his option not only this parameter but inside diameter ovality as well. A maximum ovality of 0.0005 was reported. This is a factor of four better than the maximum specified. Ovality measurements performed by GE, although showing somewhat higher values, were all within the range permitted.

Eccentricity measurements performed by the vendor on 25 pieces from each lot showed that all tubes fell within the 0.0015-inch maximum. GE measurements on a somewhat smaller sampling—10 tubes per lot—revealed three tubes with greater-than-allowable eccentricities. All three were from the 30 and 50% cold-worked material of Type 304H.

6. MECHANICAL PROPERTIES

6.1 TENSILE AND BURST TESTS

Both tensile and burst properties were measured at room temperature and at 1000°F. Ten tests were performed on each lot of tubing at each temperature. This provided enough data points to do a reasonable statistical analysis. The results are shown in Table 5 as mean values and a 1σ standard deviation for each lot of tubing.

6.2 STRESS-RUPTURE TESTS

A comprehensive experimental and analytical program was undertaken to establish the stress-rupture behavior of austenitic stainless steel as a function of the degree of initial cold work. The 5G430G tubing, with its four degrees of cold work in two alloy grades, was ideally suited for this evaluation. The test program also utilized comparable quantities of annealed tubing, produced by heat treatment of a portion of the as-received 50% cold-worked stock from each grade. Test parameters included a series of hoop stresses, selected to produce failure in times on the order of 400, 1000, and 4000 hours at a test temperature of 1300°F. All tubular test sections contained welded closures; the tubes were internally pressurized with argon, producing an essentially constant stress on the tube wall. Each test section was encased in a monitored low-pressure tube; failure of the section was inferred by an alarm signalling a pressure rise of 20 psi in the outer tube. Examination of each failed tube included: (1) establishment of point of failure (in some cases, this required pressurizing after failure to as much as 1000 psi before a leak was detectable), (2) diametral measurements for the assessment of failure strain, and (3) metallographic sectioning (in selected cases) to evaluate the mode of failure. Test and analytical results are presented and discussed in the following paragraphs.

Test parameters used on all specimens in the current program and experimental results are listed in Tables 6 and 7 for Types 304H and 316H, respectively. The relationship of initial hoop stress to stress-rupture life is illustrated in Figures 7 and 8 for the four cold-worked lots and one annealed lot of each grade tested. Although the current test program was restricted to a time range not exceeding two orders of magnitude, the data are sufficiently consistent to permit extrapolation to periods of time approaching those anticipated in service. The trends thus developed in the behavior of the tubing to stress-rupture conditions—trends which are qualitatively comparable for both grades—may be summarized as follows:

- a. Although moderate cold-working enhances short-term stress-rupture strength, its influence on long-term strength is no better and generally poorer than annealed material.
- b. Heavily cold-worked material—in this instance, greater than 50%—is at all times inferior to annealed material (and lesser cold-worked material) in stress-rupture strength.

One of the most interesting correlations to emerge from these tests, however, is that of diametral strain at failure versus degree of cold work. The correlation is illustrated in Figure 9 for both grades tested. Analytical data were provided by micrometer measurements of maximum diametral expansion of each test section. (It should be noted here that virtually all specimens failed with an extremely small perforation and little local deformation beyond that of uniform diametral strain. In only one case did failure occur by explosive rupture and attendant axial splitting of the tube. Such a catastrophic failure is typical of a short-term burst test and, significantly, the failure so observed occurred in less than 100 hours. Since the behavior of this specimen was judged to be atypical in regard to stress-rupture failure, the diametral expansion data were eliminated from the correlation.)

Table 5
TENSILE AND BURST PROPERTIES OF 5G430G TUBING

Alloy	Percent Coldwork	0.2% Yield Stress (ksi)	Ultimate Stress (ksi)	Elongation in 2 Inches (%)	Burst Pressure (psi)	Hoop Stress ^(a) (ksi)
Room Temperature						
304H	10	84.6 (1.3) ^(b)	113.2 (0.8)	38.6 (1.9)	15,090 (380)	125.7 (3.2)
304H	20	100.2 (2.0)	122.9 (2.5)	28.0 (3.9)	17,570 (700)	146.4 (5.8)
304H	30	111.1 (6.3)	140.4 (1.9)	17.3 (1.6)	18,770 (800)	156.4 (6.7)
304H	50	136.8 (4.9)	162.1 (2.9)	10.1 (1.1)	20,030 (340)	166.9 (2.8)
316H	10	90.9 (1.6)	110.7 (1.0)	34.8 (2.4)	14,970 (220)	124.7 (1.8)
316H	20	104.1 (1.7)	121.2 (1.6)	20.4 (2.5)	18,200 (470)	156.7 (3.9)
316H	30	122.2 (3.7)	141.5 (5.8)	12.3 (1.9)	19,950 (100)	166.2 (0.8)
316H	50	134.0 (2.3)	156.3 (2.6)	10.6 (1.0)	20,070 (190)	167.2 (1.6)
1000°F						
304H	10	59.4 (0.8)	76.2 (0.8)	17.8 (1.2)	8,290 (290)	69.1 (2.4)
304H	20	74.1 (2.2)	85.8 (0.6)	9.6 (0.5)	11,350 (530)	94.6 (4.4)
304H	30	89.3 (3.1)	100.6 (2.0)	5.8 (1.5)	13,500 (410)	112.5 (3.4)
304H	50	105.4 (2.4)	116.6 (1.4)	4.3 (0.8)	16,200 (420)	135.0 (3.5)
316H	10	65.5 (1.3)	86.9 (0.9)	18.6 (2.6)	8,670 (190)	72.2 (1.6)
316H	20	77.0 (1.5)	94.8 (2.4)	10.2 (1.9)	13,710 (290)	114.2 (2.4)
316H	30	99.4 (2.1)	111.6 (2.0)	6.6 (1.2)	13,750 (1090)	114.6 (9.1)
316H	50	110.2 (1.8)	124.5 (1.3)	4.9 (1.5)	17,600 (620)	146.7 (5.2)

(a) Hoop Burst Stress = $\frac{PD}{2t} = \frac{P 1/4}{2 (0.015)} = 8.333P$,

where P = burst pressure and D = tube outer diameter.

(b) Values given are mean of ten tests. Values in parentheses are standard deviation from given mean values.

The precipitous reduction in diametral ductility that a small degree of cold work impresses on austenitic stainless steel is clearly illustrated in the curves of Figure 9. The minimum values of strain for 10 and 20% cold-worked tubing—approximately 3 and 6% for Types 316H and 304H, respectively—contrast sharply with those of the 30 and 50% cold-worked material. This suggested initially that the more severely cold-worked structures are highly unstable at this temperature—a condition that might enhance the onset of recovery and grain refinement mechanisms. Subsequent structural examination of representative test sections confirmed that recrystallization had in fact occurred in the 50% cold-worked material. This modification is shown in the photomicrographs of Figure 10. Similar restructuring of the 30% cold-worked material is suggested by the tendency toward higher ductility with increasing test times in these specimens. A factor of two increase in diametral ductility was measured over the time periods tested. No such relaxation was evident in either of the two lesser cold-worked materials, the ductilities of which remained essentially constant.

In all cases, failure of the tubes occurred by intergranular fracture, precipitated by the propagation and eventual interconnection of grain boundary cracks. Grain boundary cavitation was widespread in all material types and grades tested. Cavitation was most predominant, however, in the lesser cold-worked materials. The cross section through a tube of 20% cold-worked Type 304H (Figure 11) is fairly typical of the type of failure occurring under the conditions of this test. In viewing these photographs, one should be cautioned not to presume that all the cavities are the result of grain boundary separation occurring as a result of the strain imposed during the test. The sigma phase was observed to have formed in the lesser cold-worked materials; a portion of the voidage may be the site of an island of sigma, a highly reactive phase to the reagents commonly used for grain delineation.

Table 6
1300°F STRESS-RUPTURE TEST RESULTS—TYPE-304H TUBING

Temper	Initial Hoop Stress (psi)	Time to Failure (hours)	ΔD/D Maximum (%)
Annealed	7000	4700	16
Annealed	9000	2537	16
Annealed	11000	645	29
Annealed	13000	168	24
Annealed	15000	77	43
Annealed	15000	41	20
10% CW	8000	4290	7
10% CW	8000	3367	6
10% CW	9000	2359	6
10% CW	9000	2190	6
10% CW	11000	1477	8
10% CW	11000	1213	6
20% CW	7000	2342	6
20% CW	7000	2527	7-1/2
20% CW	8000	2503	5
20% CW	8000	2078	5
20% CW	9000	1663	6
20% CW	9000	1342	5
20% CW	11000	760	4-1/2
20% CW	11000	496	4-1/2
30% CW	5000	2527	15-1/2
30% CW	5000	2733	17
30% CW	7000	1100	16
30% CW	7000	1231	16
30% CW	9000	587	15
30% CW	9000	5252	23
30% CW	11000	352	8
30% CW	13000	271	7-1/2
50% CW	5000	557	27-1/2
50% CW	5000	1006	22
50% CW	7000	391	23
50% CW	7000	450	22
50% CW	8000	153	20
50% CW	9000	153	24

Table 7
1300°F STRESS-RUPTURE TEST RESULTS—TYPE-316H TUBING

Temper	Initial Hoop Stress (psi)	Time to Failure (hours)	ΔD/D Maximum (%)
Annealed	9000	9625	10
Annealed	11000	3781	19
Annealed	13000	805	18
Annealed	13000	1182	15
Annealed	15000	377	18
Annealed	15000	489	20
Annealed	17000	147	30
Annealed	17000	157	24
10% CW	9000	8960	5
10% CW	9000	6720	3
10% CW	11000	4491	3-1/2
10% CW	11000	5244	3
10% CW	13000	2940	3
10% CW	15000	3051	3-1/2
10% CW	15000	2893	3
10% CW	17000	1111	5
20% CW	8000	14500	7-1/2
20% CW	8000	11328	3
20% CW	9000	7951	4
20% CW	9000	5784	4
20% CW	11000	2935	4
20% CW	11000	2506	3
20% CW	13000	1117	4
20% CW	15000	1290	4-1/2
20% CW	17000	754	5-1/2
30% CW	8000	5433	10
30% CW	8000	4591	10
30% CW	9000	2863	6
30% CW	9000	2060	6
30% CW	11000	2221	5
30% CW	13000	1521	4-1/2
30% CW	15000	477	4-1/2
30% CW	17000	408	4
50% CW	5000	8029	13
50% CW	7000	3415	18
50% CW	7000	2911	26
50% CW	8000	1650	15
50% CW	9000	1045	22
50% CW	11000	541	18
50% CW	15000	181	22

Figure 7. 1300°F Stress Rupture Properties of Type-304H Tubing

Figure 8. 1300°F Stress Rupture Properties of Type-316H Tubing

Figure 9. Diametral Ductility of Cold-Worked Tubing Tested in Stress-Rupture at 1300°F

(a) AS-RECEIVED 50% COLD WORKED TUBING

(b) 50% COLD WORKED TUBING, PRESSURIZED TO FAILURE AT 1300°F.
INITIAL HOOP STRESS: 9000 psi.

Figure 10. Microstructural Comparison of Type-304H Tubing As-Received and After Stress-Rupture Testing

(a) THROUGH FAILURE

(b) 180° FROM FAILURE

Figure 11. Stress-Rupture Failure in 20% Cold-Worked Tubing of Type-304 Stainless Steel.
70APO0127, Glyceregia Etch, X250

7. CONCLUSIONS

- a. The 5G430G material successfully met the specification, with the exception that some tubing exceeded the maximum allowable outside diameter (0.2510 inch).
- b. At contemplated LMFBR temperatures, cold-worked tubing does not appear superior to annealed material for long-term applications in an out-of-reactor environment. (The tests reported here did not include in-pile exposure.)

Discussion

The tests and examinations performed on the 5G430G tubing were planned and executed to establish the as-received quality of this order of nuclear-grade tubing of cold-worked austenitic stainless steel. The results and analyses presented here attest to the high-quality material that this order was intended to provide. The only significant departure from the requirements stated in the ordering documents is that of a somewhat oversize outside diameter. It should be noted, however, that the majority of the tubing examined lay well within the specified dimension.

One of the essential functions of this characterization study was the evaluation of the influence of cold work on the stress-rupture behavior of the two austenitic grades. The results presented here indicate that, at temperatures comparable to those anticipated in service, little benefit would be realized by utilizing cold-worked tubing rather than annealed material for long-term applications. The utilization of heavily cold-worked tubing, in fact, would compromise and significantly reduce stress-rupture life. These results should not be interpreted as a recommendation that cold-worked materials not be considered as potential fuel cladding, but only to emphasize their behavior in non-nuclear environments. It is quite possible, for example, that the advantage gained in reducing the magnitude of swelling by utilizing tubing with cold-worked structures far outweighs the penalty imposed by a reduction in stress-rupture life. These factors can be conclusively evaluated only by testing in the environment for which the material was intended.

8. RECOMMENDATIONS

- a. The number of chemical analyses required to be performed by the manufacturer should be limited to a standard ladle analysis and a single-check analysis.
- b. Independent analyses should continue to be performed by the purchaser.
- c. Inspection procedure, including NDT methods, should be expanded toward the detection and elimination of tubing showing intergranular attack.
- d. Precise and explicit designation for the extent of cold work should be developed and used.

Discussion

A principal objective of the program under which this tubing evaluation was made is the development of a commercially sound, economically viable tubing specification. To conform to these general requirements, a specification should limit its provisions to those necessary to ensure proper quality in the product. In view of the analytical results discussed in Section 3, it is difficult, for example, to justify the requirement of a fivefold increase in the quantity of check analyses over that specified by ASTM. The chemical analysis results provided by the vendor show quite clearly that the materials are homogeneous. Moreover, an independent analysis will invariably be performed by the purchaser, not only as a confirmatory check but also to provide compositional data on residual elements not included in the ordering specifications. A single check analysis, along with the standard ladle analysis, is therefore recommended to be a fully sufficient vendor requirement for establishing alloy chemistry and confirming alloy grade.

The observation of intergranular attack of the type shown on the 304H 30% cold-worked tubing suggests that a more vigorous attempt should be made during tube inspection to eliminate tube sections containing such areas. The inspection procedure for tubing should contain a provision that a small sample be cut from the end of each tube section (it need be no longer than 1/4 inch) and metallographically prepared in transverse cross section for surface examination. By judicious selection of a sample identification scheme, as many as seven sections can be prepared in the same metallographic mount. However, since a sampling of this type cannot guarantee the selection of tubing containing no intergranular attack, a concurrent effort should be undertaken to devise NDT methods that could detect such defects and permit 100% inspection.

The continuing uncertainty regarding temper designation requires clarification. It is quite difficult, for example, to attempt correlations between experimental results in which the levels of cold working are expressed in terms of some ill-defined reduction in tubular dimension occurring during the final cold draw. The confusion that could arise may be aptly illustrated in comparing the current order with previous orders for cold-worked tubing. In the latter, the material was prescribed to be cold worked to some percentage reduction in wall. The current order, of course, specified the working to be expressed as reduction in area. Failure to clarify the method used to describe the extent of cold work could result in rather inaccurate correlations. Confusion regarding the designation of cold working might be removed by adopting a standard measure based on x-ray diffraction techniques. The 5G430G tubing, with its several degrees of cold working, is well suited for use in developing such a system.

9. IN-REACTOR EXPERIMENTS

Portions of the 5G430G tubing have been used in various EBR-II experiments being performed on the P.A. 10 program. These experiments (Table 8) will evaluate the in-pile behavior of these materials under a variety of conditions, including actual fuel cladding condition. Details of the experiments are included in Appendix B.

Table 8
EBR-II EXPERIMENTS UNDER THE
PA-10 PROGRAM, UTILIZING THE 5G430G TUBING

Experiment	Number of Pins or Specimens	Test Objectives
Task F ^(a)		
F10A	10	Determine fuel-cladding interactions at elevated cladding temperatures (1250°F maximum at o.d.) to 100,000 MWd/Te.
F10B	6	Same as F10A
F11A	25	Determine performance of FCR fuel pins in flowing sodium at peak cladding temperatures of 1250°F
Task L		
L16B	76	Determine magnitude of alloy swelling for different microstructure of Type 304H and Type 316H in temperature range of 800°F to 1250°F.

^(a) Details of the Task F experiments are listed in Appendix B.

APPENDIX A. METALLOGRAPHY OF THE 5G430G TUBING

TYPE 304H

TEMPER 10% CW (RIA)

HEAT NO. 04200

PO NC 5G430G

MFG PROCESS SEAMLESS

OD (in.) 0.250

ID (in.) 0.220

X250

X100

SPECIMEN NO. 69 APO 0548

SECTION TRANSVERSE

ETCHANT HCl+H₂O₂

X250

SPECIMEN NO. 69 APO 0549

SECTION LONGITUDINAL

ETCHANT HCl+H₂O₂

X100

Figure A-1

TYPE 304H
 TEMPER 10% CW (RIA)
 HEAT NO. 04200
 PO NO. 5G430G

MFG PROCESS SEAMLESS
 OD (in.) 0.250
 ID (in.) 0.220

X100

SPECIMEN NO. 69 APO 0549
 SECTION LONGITUDINAL
 ETCHANT (NONE)
 INCLUSIONS C1 THIN

X500

SPECIMEN NO. 69 APO 0548
 SECTION TRANSVERSE
 ETCHANT (NONE)

Figure A-2

TYPE 304H
 TEMPER 20% CW (RIA)
 HEAT NO. 04200
 PO NO. 5G430G

MFG PROCESS SEAMLESS
 OD (in.) 0.250
 ID (in.) 0.220

X250

X100

SPECIMEN NO. 69 APO 0550
 SECTION TRANSVERSE
 ETCHANT HCl + H₂O₂

SPECIMEN NO. 69 APO 0551
 SECTION LONGITUDINAL
 ETCHANT HCl + H₂O₂

X250

X100

Figure A-3

TYPE 304H
 TEMPER 20% CW (RIA)
 HEAT NO. 04200
 PO NO. 5G430G

MFG PROCESS SEAMLESS
 OD (in.) 0.250
 ID (in.) 0.220

X100

SPECIMEN NO. 69 APO 0551
 SECTION LONGITUDINAL
 ETCHANT (NONE)
 INCLUSIONS C2 THIN

X500

SPECIMEN NO. 69 APO 0550
 SECTION TRANSVERSE
 ETCHANT (NONE)

Figure A-4

TYPE 304H
 TEMPER 30% CW (RIA)
 HEAT NO. 04200
 PO NO. 5G430G

MFG PROCESS SEAMLESS
 OD (in.) 0.250
 ID (in.) 0.220

X100

SPECIMEN NO. 69 APO 0552
 SECTION TRANSVERSE
 ETCHANT HCl+H₂O₂

X250

SPECIMEN NO. 69 APO 0553
 SECTION LONGITUDINAL
 ETCHANT HCl+H₂O₂

X100

Figure A-5

TYPE 304H
 TEMPER 30% CW (RIA)
 HEAT NO. 04200
 PO NO. 5G430G

MFG PROCESS SEAMLESS
 OD(in.) 0.250
 ID (in.) 0.220

X100

SPECIMEN NO. 69 APO 0553
 SECTION LONGITUDINAL
 ETCHANT (NONE)
 INCLUSIONS C2 THIN

X500

SPECIMEN NO. 69 APO 0552
 SECTION TRANSVERSE
 ETCHANT (NONE)

Figure A-6

TYPE 304H
 TEMPER 50% CW (RIA)
 HEAT NO. 04200
 PO NO. 5G430G

MFG PROCESS SEAMLESS
 OD (in.) 0.250
 ID (in.) 0.220

X250

X100

SPECIMEN NO. 69 APO 0554
 SECTION TRANSVERSE
 ETCHANT HCl+H₂O₂

X250

SPECIMEN NO. 69 APO 0555
 SECTION LONGITUDINAL
 ETCHANT HCl+H₂O₂

X100

Figure A-7

TYPE 304H
 TEMPER 50% CW (RIA)
 HEAT NO. 04200
 PO NO. 5G430G

MFG PROCESS SEAMLESS
 OD (in.) 0.250
 ID (in.) 0.220

X100

SPECIMEN NO. 69 APO 0555
 SECTION LONGITUDINAL
 ETCHANT (NONE)
 INCLUSIONS C1 THIN

X500

SPECIMEN NO. 69 APO 0554
 SECTION TRANSVERSE
 ETCHANT (NONE)

Figure A-8

TYPE 316H
 TEMPER 10% CW (RIA)
 HEAT NO. M2783
 PO NO. 5G430G

MFG PROCESS SEAMLESS
 OD (in.) 0.250
 ID (in.) 0.220

X250

X100

SPECIMEN NO. 69 APO 0556
 SECTION TRANSVERSE
 ETCHANT HCl + H₂O₂

X250

SPECIMEN NO. 69 APO 0557
 SECTION LONGITUDINAL
 ETCHANT HCl + H₂O₂

X100

Figure A-9

TYPE 316H
 TEMPER 10% CW (RIA)
 HEAT NO. M2783
 PO NO. 5G430G

MFG PROCESS SEAMLESS
 OD(in.) 0.250
 ID (in.) 0.220

SPECIMEN NO. 69 APO 0557
 SECTION LONGITUDINAL
 ETCHANT (NONE)
 INCLUSIONS C2 THIN

X100

SPECIMEN NO. 69 APO 0556
 SECTION TRANSVERSE
 ETCHANT (NONE)

X500

Figure A-10

TYPE 316H
 TEMPER 20% CW (RIA)
 HEAT NO. M2783
 PO NO. 5G430G

MFG PROCESS SEAMLESS
 OD (in.) 0.250
 ID (in.) 0.220

X250

X100

SPECIMEN NO. 69 APO 0558
 SECTION TRANSVERSE
 ETCHANT HCl + H₂O₂

X250

SPECIMEN NO. 69 APO 0559
 SECTION LONGITUDINAL
 ETCHANT HCl + H₂O₂

X100

Figure A-11

TYPE 316H
 TEMPER 20% CW(RIA)
 HEAT NO. M2783
 PO NO. 5G430G

MFG PROCESS SEAMLESS
 OD (in.) 0.250
 ID (in.) 0.220

X100

SPECIMEN NO. 69 APO 0559
 SECTION LONGITUDINAL
 ETCHANT (NONE)
 INCLUSIONS C1 THIN

X500

SPECIMEN NO. 69 APO 0558
 SECTION TRANSVERSE
 ETCHANT (NONE)

Figure A-12

TYPE 316H
 TEMPER 30% CW (RIA)
 HEAT NO. M2783
 PO NO. 5G430G

MFG PROCESS SEAMLESS
 OD (in.) 0.250
 ID (in.) 0.220

X250

X100

SPECIMEN NO. 69 APO 0560
 SECTION TRANSVERSE
 ETCHANT HCl+H₂O₂

X250

SPECIMEN NO. 69 APO 0561
 SECTION LONGITUDINAL
 ETCHANT HCl+H₂O₂

X100

Figure A-13

TYPE 316H
 TEMPER 30% CW (RIA)
 HEAT NO. M2783
 PO NO. 5G430G

MFG PROCESS SEAMLESS
 OD (in.) 0.250
 ID (in.) 0.220

X100

SPECIMEN NO. 69 APO 0561
 SECTION LONGITUDINAL
 ETCHANT (NONE)
 INCLUSIONS CI THIN

X500

SPECIMEN NO. 69 APO 0560
 SECTION TRANSVERSE
 ETCHANT (NONE)

Figure A-14

TYPE 316H
 TEMPER 50% CW (RIA)
 HEAT NO. M2783
 PO NO. 5G430G

MFG PROCESS SEAMLESS
 OD (in.) 0.250
 ID (in.) 0.220

X250

X100

SPECIMEN NO. 69 APO 0562
 SECTION TRANSVERSE
 ETCHANT HCl + H₂O₂

X250

SPECIMEN NO. 69 APO 0563
 SECTION LONGITUDINAL
 ETCHANT HCl + H₂O₂

X100

Figure A-15

TYPE 316H

TEMPER 50% CW (RIA)

HEAT NO. M2783

PO NO. 5G430G

MFG PROCESS SEAMLESS

OD (in.) 0.250

ID (in.) 0.220

X100

SPECIMEN NO. 69 APO 0563

SECTION LONGITUDINAL

ETCHANT (NONE)

INCLUSIONS C2 THIN

X500

SPECIMEN NO. 69 APO 0562

SECTION TRANSVERSE

ETCHANT (NONE)

Figure A-16

**APPENDIX B. TASK F DATA RETRIEVAL SYSTEM (BROADLOG) PRINTOUT
FOR FUEL ROD CLADDING AND FUEL PARAMETERS FOR
F10A, F10B, AND F11A EXPERIMENTS**

GROUP F10A

TEST DESCRIPTION

THE PURPOSE OF THE GROUP F10A EXPERIMENT IS TO IRRADIATE A SUBASSEMBLY OF 19 ENCAPSULATED FUEL PINS UNDER TYPICAL FAST REACTOR CONDITIONS IN THE EBR-II TO DETERMINE FUEL-CLAD INTERACTION AT ELEVATED CLADDING TEMPERATURES (1250 DEGREES F MAXIMUM AT O.D.). THE 19 PINS WILL BE CONTAINED IN AN EBR-II MARK J-19 SUBASSEMBLY. THE FUEL PINS ARE 0.250 INCHES IN OUTSIDE DIAMETER AND ARE DESIGNED TO OPERATE AT AN AVERAGE LINEAR POWER OF 16.0 KW/FT TO A BURNUP OF 100,000 MWD/TE. FUEL PINS F10A1 THRU 19 USED FUEL PIN DRAWING NO. 115D7822 AND CAPSULE DRAWING NO. 115D7821.

GROUP F10A
CLADDING
PRE-IRRADIATION INFORMATION

P I N	TYPE	ID INCHES	WALL THICKNESS INCHES	OD INCHES	CLAD COND.	TUBE NUMBER	P.O. NUMBER	HEAT NUMBER	CERT. NUMBER	FAB. TECH	ASTM GRAIN SIZE	O/A PIN LENGTH INCHES
F10A014A	304	.2200-.2202 .2201	.0148-.0150 .0150	.2498-.2499 .2498	ANN	4A3	K2177G	20184		SMLESS	6	36.7450
F10A024A	304	.2201-.2202 .2201	.0146-.0148 .0150	.2493-.2496 .2495	ANN	4A1	K2177G	20184		SMLESS	6	36.7400
F10A034C	304	.2201-.2202 .2201	.0149-.0152 .0150	.2500-.2504 .2502	CA	4CA8	5G430G	04200		SMLESS		36.7500
F10A044C	304	.2200-.2201 .2201	.0149-.0152 .0150	.2499-.2504 .2501	CA	4CA6	5G430G	04200		SMLESS		36.7590
F10A054C	304	.2202-.2203 .2202	.0150-.0151 .0150	.2503-.2504 .2503	20% CW	42CW29	5G430G	04200		SMLESS		36.7350
F10A064H	304	.2201-.2202 .2202	.0149-.0153 .0150	.2500-.2506 .2505	20% CW	42CW2	5G430G	04200		SMLESS		36.7460
F10A074H	304	.2203-.2204 .2203	.0149-.0151 .0150	.2501-.2505 .2503	30% CW	43CW12	5G430G	04200		SMLESS		36.7440
F10A084H	304	.2202-.2203 .2202	.0150-.0152 .0150	.2502-.2505 .2504	30% CW	43CW3	5G430G	04200		SMLESS		36.7490
F10A096A	316	.2197-.2198 .2197	.0151-.0152 .0150	.2499-.2501 .2500	ANN	6A34	K2177G	20303		SMLESS	6	36.7380
F10A106A	316	.2199-.2200 .2199	.0151-.0153 .0150	.2501-.2504 .2503	ANN	6A7	K2177G	20303		SMLESS	6	36.7490
F10A116H	316	.2201-.2202 .2202	.0152-.0156 .0150	.2506-.2512 .2511	20% CW	62CW13	5G430G	M2783		SMLESS		36.7450
F10A126H	316	.2200-.2201 .2201	.0150-.0154 .0150	.2500-.2507 .2505	20% CW	62CW34	5G430G	M2783		SMLESS		36.7470
F10A136H	316	.2202-.2202 .2202	.0151-.0152 .0150	.2503-.2506 .2504	20% CW	62CW6	5G430G	M2783		SMLESS		36.7570
F10A146A	316	.2296-.2298 .2297	.0097-.0106 .0100	.2492-.2508 .2506	ANN	6AT5	K0666G	20303		SMLESS	7	36.7400
F10A156A	316	.2293-.2298 .2296	.0098-.0105 .0100	.2493-.2502 .2507	ANN	6AT11	K0666G	20303		SMLESS	7	36.7370
F10A166A	316	.2300-.2303 .2301	.0098-.0109 .0100	.2498-.2517 .2510	ANN	6AT1	K0666G	20303		SMLESS	7	36.7460
F10A176A	316	.2296-.2298 .2297	.0100-.0104 .0100	.2498-.2503 .2499	ANN	6AT20	K0666G	20303		SMLESS	7	36.7380
F10A186H	316	.2201-.2202 .2201	.0155-.0156 .0150	.2510-.2512 .2511	30% CW	63CW15	5G430G	M2783		SMLESS		36.7460
F10A196H	316	.2201-.2202 .2201	.0153-.0154 .0150	.2507-.2509 .2508	30% CW	63CW4	5G430G	M2783		SMLESS		36.7540

GROUP F10A
MIXED OXIDE FUEL
PRE-IRRADIATION INFORMATION

P I N	TYPE	FORM	FUEL WEIGHT GRAMS	FUEL LENGTH INCHES	COMPOSITION xPu-O2	ENRICHMENT %U235	*** D E N S I T Y **		O/M	DIAMETER (PELLET) INCHES	CENTER HOLE INCHES	DIAMETRAL GAP MILS
*****	****	****	*****	*****	*****	*****	*****	*****	*****	*****	*****	*****
F10A014A	SP	CPT	80.93	13.482	24.24-24.24	90.32-90.32	90.65-92.33	87.24	1.968-1.969	.2148-.2150	-	5.0-5.3
F10A024A	SP	CPT	80.96	13.540	24.24-24.24	90.32-90.32	90.51-92.19	87.01	1.966-1.968	.2147-.2150	-	5.1-5.5
F10A034C	SP	CPT	80.61	13.532	24.24-24.24	90.32-90.32	90.43-92.06	86.73	1.966-1.970	.2147-.2151	-	5.0-5.5
F10A044C	SP	CPT	80.50	13.464	24.24-24.24	90.32-90.32	90.53-91.96	87.09	1.966-1.970	.2147-.2151	-	4.9-5.4
F10A054C	SP	CPT	80.53	13.455	24.24-24.24	90.32-90.32	90.54-92.29	87.15	1.966-1.966	.2147-.2150	-	5.2-5.5
F10A064H	SP	CPT	80.78	13.515	24.24-24.24	90.32-90.32	90.75-92.45	87.08	1.966-1.970	.2144-.2149	-	5.3-5.8
F10A074H	SP	CPT	80.76	13.544	24.24-24.24	90.32-90.32	90.47-92.33	86.68	1.970-1.970	.2145-.2149	-	5.4-5.9
F10A084H	SP	CPT	81.04	13.526	24.24-24.24	90.32-90.32	90.56-93.15	87.16	1.966-1.970	.2147-.2153	-	4.9-5.6
F10A096A	SP	CPT	83.17	13.541	24.24-24.24	90.32-90.32	90.46-92.07	89.69	1.968-1.968	.2175-.2180	-	1.7-2.2
F10A106A	SP	CPT	83.63	13.522	24.24-24.24	90.32-90.32	90.75-92.92	90.10	1.968-1.969	.2178-.2181	-	1.8-2.2
F10A116H	SP	CPT	81.08	13.536	24.24-24.24	90.32-90.32	90.48-92.40	87.32	1.966-1.968	.2149-.2152	-	4.9-5.3
F10A126H	SP	CPT	80.13	13.470	24.24-24.24	90.32-90.32	90.45-91.38	86.64	1.968-1.968	.2149-.2151	-	4.9-5.2
F10A136H	SP	CPT	73.84	12.291	24.24-24.24	90.32-90.32	90.74-92.33	87.31	1.969-1.969	.2149-.2149	-	5.2-5.3
F10A146A	SP	CPT	88.77	13.504	24.24-24.71	90.32-91.39	90.41-93.18	88.01	1.959-1.961	.2245-.2277	-	1.8-5.3
F10A156A	SP	CPT	88.97	13.482	24.24-24.71	90.32-91.39	90.48-93.25	88.10	1.960-1.961	.2246-.2277	-	1.6-5.2
F10A166A	SP	CPT	88.91	13.490	24.24-24.71	90.32-91.39	90.45-92.98	87.63	1.959-1.961	.2245-.2277	-	2.2-5.9
F10A176A	SP	CPT	88.85	13.491	24.24-24.71	90.32-91.39	90.47-92.56	87.87	1.960-1.961	.2246-.2282	-	1.4-5.2
F10A186H	SP	CPT	81.43	13.506	24.24-24.71	90.32-91.39	90.54-93.03	87.58	1.960-1.968	.2145-.2151	-	5.0-5.7
F10A196H	SP	CPT	81.52	13.506	24.71-24.71	91.39-91.39	91.17-92.96	87.76	1.960-1.960	.2146-.2148	-	5.3-5.6
							92.25		1.960	.2147		

GEAP-13736

GROUP F10B

TEST DESCRIPTION

THE PURPOSE OF THE GROUP F10B EXPERIMENT IS TO IRRADIATE A SUBASSEMBLY OF NINETEEN ENCAPSULATED FUEL PINS IN THE EBR-II TO DETERMINE THE EFFECT OF CLAD TEMPERATURE (1250 DEGRESS F CLADDING ID) ON FUEL-CLAD INTERACTION, THIS GROUP IS DESIGNED TO OPERATE AT A PEAK LINEAR POWER OF 16.0 KW/FT WITH A TARGET BURNUP OF 100,000 MWD/TE;

NOTE:

FUEL PIN F10B176A WAS MISTAKENLY MARKED ON THE "FUEL PIN END PLUG" AS F10B176H.

ANNEALED CLADDING WAS USED FOR F10B144C, CLADDING FOR THIS PIN WAS TO BE CARBIDE AGGLOMERATED,

FUEL PINS F10B1 THRU 4, 9 THRU17 , AND 20 THRU 25 USED FUEL PIN DRAWING NO. 115D7716 AND CAPSULE DRAWING NO. 115D7717.

GROUP F108
CLADDING
PRE-IRRADIATION INFORMATION

P I N	TYPE	ID INCHES	WALL THICKNESS INCHES	OD INCHES	CLAD COND.	TUBE NUMBER	P.O. NUMBER	HEAT NUMBER	CERT. NUMBER	FAB. TECH	ASTM GRAIN SIZE	O/A PIN LENGTH INCHES
*****	****	*****	*****	*****	*****	*****	*****	*****	*****	*****	*****	*****
F10B016A	316H	.2195-.2204	.0150-.1570	.2503-.2508	ANN	16587	K2374	03078	15742	SMLESS		36.7450
		.2199	.0150	.2507								
F10B026A	316H	.2194-.2204	.0150-.1580	.2504-.2509	ANN	16585	K2374	03078	15742	SMLESS		36.7670
		.2199	.0150	.2507								
F10B036C	316H	.2196-.2199	.0149-.1540	.2497-.2503	C.A.	16554	K2177	20303	185502	SMLESS		36.7630
		.2197	.0150	.2500								
F10B046C	316H	.2195-.2201	.0150-.1550	.2500-.2505	C.A.	16548	K2177	20303	185502	SMLESS		36.7460
		.2198	.0150	.2503								
F10B097A	347	.2198-.2201	.0150-.1550	.2500-.2508	ANN	47036	K0666G	24772X	158394	SMLESS	10	36.7470
		.2200	.0150	.2507								
F10B107A	347H	.2198-.2205	.0149-.1550	.2503-.2507	ANN	47041	K0666G	24772X	158394	SMLESS		36.7460
		.2199	.0150	.2506								
F10B111A	321	.2199-.2204	.0147-.1510	.2498-.2501	ANN	21123	K0666G	28967	158419	SMLESS	8	36.7510
		.2202	.0150	.2500								
F10B121A	321	.2198-.2205	.0147-.1540	.2499-.2505	ANN	21124	K0666G	28967	158419	SMLESS	8	36.7470
		.2203	.0150	.2500								
F10B134A	304	.2197-.2204	.0146-.1530	.2496-.2503	ANN	04343	K2177	20184	185512	SMLESS	6	36.7480
		.2202	.0150	.2510								
F10B144C	304	.2197-.2203	.0147-.1580	.2497-.2513	ANN	04346	K2177	20184	185512	SMLESS	6	36.7480
		.2201	.0150	.2499								
F10B150A	1800	.2198-.2202	.0147-.1520	.2495-.2502	ANN	80106	K0666G	HH2051A	160341	SMLESS	8	36.7500
		.2200	.0150	.2480								
F10B160A	1800	.2196-.2202	.0148-.1540	.2498-.2503	ANN	80110	K0666G	HH2051A	160341	SMLESS	8	36.7500
		.2198	.0150	.2502								
F10B176A	316H	.2196-.2200	.0150-.1570	.2499-.2509	ANN	16557	K2177	20303	185502	SMLESS		36.7480
		.2198	.0150	.2503								
F10B206H	316	.2202-.2204	.0153-.1550	.2509-.2511	20% CW	62CW45	5G430G	M2783		SMLESS		36.7320
		.2203	.0150	.2510								
F10B216H	316	.2201-.2202	.0153-.1550	.2507-.2511	20% CW	62CW50	5G430G	M2783		SMLESS		36.7450
		.2201	.0150	.2509								
F10B226H	316	.2201-.2203	.0148-.1570	.2498-.2515	20% CW	62CW57	5G430G	M2783		SMLESS		36.7350
		.2202	.0150	.2505								
F10B236H	316	.2201-.2202	.0151-.1530	.2503-.2506	20% CW	62CW59	5G430G	M2783		SMLESS		36.7510
		.2201	.0150	.2505								
F10B246H	316	.2200-.2202	.0153-.1550	.2507-.2510	20% CW	62CW52	5G430G	M2783		SMLESS		36.7420
		.2201	.0150	.2508								
F10B256H	316	.2201-.2202	.0153-.1550	.2507-.2511	20% CW	62CW54	5G430G	M2783		SMLESS		36.7520
		.2201	.0150	.2508								

GEAP-13736

GROUP F10B
MIXED OXIDE FUEL
PRE-IRRADIATION INFORMATION

P I N	TYPE	FORM	FUEL WEIGHT GRAMS	FUEL LENGTH INCHES	COMPOSITION XPU-02	ENRICHMENT %U235	*** D E N S I T Y ** THEORETICAL X	SMEARED X	O/M	DIAMETER (PELLET) INCHES	CENTER HOLE INCHES	DIAMETRAL GAP MILS
*****	****	****	*****	*****	*****	*****	*****	*****	*****	*****	*****	*****
F10B016A	SP	CPT	84.13	13.461	24.90-25.00	92.44-92.44	94.56-95.52	90.94	1.964-1.969	.2145-.2156	-	3.9-5.9
F10B026A	SP	CPT	84.17	13.488	25.00-25.00	92.44-92.44	94.10-95.67	90.94	1.966 1.000-2.001	.2151 .2148-.2160	-	3.4-5.6
F10B036C	SP	CPT	84.87	13.472	25.00-25.00	92.44-92.44	94.69-96.02	91.92	1.986 1.963-1.963	.2152 .2149-.2165	-	3.1-5.0
F10B046C	SP	CPT	84.08	13.467	25.00-25.00	92.44-92.44	94.41-95.99	91.08	1.963 1.968-2.001	.2159 .2148-.2156	-	3.9-5.3
F10B097A	SP	CPT	84.13	13.442	25.00-25.00	92.44-92.44	94.44-96.44	91.09	2.000 1.963-1.969	.2151 .2143-.2162	-	3.6-5.8
F10E107A	SP	CPT	84.46	13.530	25.00-25.00	92.44-92.44	94.57-95.89	91.01	1.967 1.968-2.001	.2151 .2147-.2160	-	3.8-5.8
F10E111A	SP	CPT	84.67	13.530	25.00-25.00	92.44-92.44	94.43-95.81	90.96	2.000 1.965-1.965	.2152 .2149-.2162	-	3.7-5.5
F10E121A	SP	CPT	84.11	13.483	25.00-25.00	92.44-92.44	94.48-95.94	90.62	1.965 1.968-2.001	.2155 .2147-.2158	-	4.0-5.8
F10E134A	SP	CPT	84.78	13.511	25.00-25.00	92.44-92.44	94.44-96.29	90.91	2.000 1.963-1.965	.2150 .2148-.2164	-	3.3-5.5
F10E144C	SP	CPT	84.44	13.516	25.00-25.00	92.44-92.44	94.61-95.78	90.90	1.965 1.968-2.001	.2153 .2147-.2160	-	3.7-5.6
47- F10E150A	SP	CPT	84.59	13.531	25.00-25.00	92.44-92.44	94.38-96.30	91.10	2.000 1.965-1.965	.2152 .2148-.2162	-	3.6-5.4
F10E160A	SP	CPT	84.10	13.476	25.00-25.00	92.44-92.44	94.39-95.65	91.05	1.965 1.968-2.001	.2155 .2147-.2162	-	3.4-5.5
F10E176A	VC	CPT	76.00	13.541	24.72-24.94	92.51-93.18	82.14-82.14	82.14	2.000 1.972-1.973	.2152 -	-	-
F10E206H	SP	CPT	84.94	13.492	25.03-25.03	92.36-92.36	94.42-96.42	91.33	1.972 1.966-1.971	.2152 .2151-.2156	-	4.6-5.3
F10E216H	SP	CPT	84.44	13.477	25.03-25.03	92.36-92.36	94.44-96.07	91.04	1.970 1.966-1.971	.2152 .2151-.2154	-	4.7-5.1
F10E226H	SP	CPT	84.52	13.483	25.03-25.03	92.36-92.36	94.46-96.04	91.01	1.967 1.966-1.972	.2153 .2151-.2155	-	4.6-5.2
F10B236H	SP	CPT	84.85	13.526	25.03-25.03	92.36-92.36	94.45-96.21	91.04	1.972 1.968-1.972	.2152 .2151-.2155	-	4.6-5.1
F10B246H	SP	CPT	85.22	13.485	25.03-25.03	92.36-92.36	94.48-96.45	91.59	1.969 2.000-2.000	.2153 .2151-.2159	-	4.1-5.1
F10B256H	SP	CPT	85.70	13.540	25.03-25.03	92.36-92.36	94.48-96.48	91.86	2.000 2.000-2.000	.2155 .2152-.2166	-	4.1-5.0
							95.71		2.000	.2156		

GROUP F11A

TEST DESCRIPTION

THE PURPOSE OF THE GROUP F11A EXPERIMENT IS TO IRRADIATE A COMPLETE SUBASSEMBLY OF FUEL PINS IN A FLOWING SODIUM ENVIRONMENT, AT PEAK CLAD I.D. TEMPERATURES OF APPROXIMATELY 1250 DEGREES F. THIS IS THE TEMPERATURE MOST LIKELY TO PREVAIL IN THE ADVANCED LMFBRs. SINCE THE FUEL PINS WILL BE IN DIRECT CONTACT WITH FLOWING SODIUM AND CONTAINED IN A HEXAGONAL ARRANGEMENT, CONDITIONS WILL BE OBTAINED WHICH ARE REALISTIC AND TYPICAL OF A LARGE FAST REACTOR. FUEL PINS F11A1 THRU 37 USED FUEL PIN DRAWING NO. 115D7865.

GROUP F11A
CLADDING
PRE-IRRADIATION INFORMATION

P I N	TYPE	ID INCHES	WALL THICKNESS INCHES	OD INCHES	CLAD COND.	TUBE NUMBER	P.O. NUMBER	HEAT NUMBER	CERT. NUMBER	FAB. TECH	ASTM GRAIN SIZE	O/A PIN LENGTH INCHES
*****	****	*****	*****	*****	*****	*****	*****	*****	*****	*****	*****	*****
F11A014H	304	.2194-.2201	.0143-.0153	.2494-.2498	ANN	4A12	K2177G	20184	185512	SMLESS	6	39.6510
F11A024H	304	.2190-.2202	.0145-.0155	.2497-.2500	ANN	4A10	K2177G	20184	185512	SMLESS	6	39.6530
F11A034H	304	.2201-.2203	.0150-.0150	.2505-.2509	20X CW	42CW5	5G430G	04200	204584	SMLESS		39.6530
F11A044H	304	.2201-.2202	.0150-.0150	.2502-.2510	20X CW	42CW6	5G430G	04200	204584	SMLESS		39.6510
F11A054H	304	.2201-.2203	.0150-.0150	.2506-.2510	20X CW	42CW7	5G430G	04200	204584	SMLESS		39.6520
F11A064H	304	.2202-.2203	.0150-.0150	.2503-.2508	20X CW	42CW8	5G430G	04200	204584	SMLESS		39.6530
F11A074H	304	.2199-.2202	.0148-.0158	.2500-.2508	CA	4CA1	5G430G	04200	204584	SMLESS		39.6550
F11A084H	304	.2195-.2201	.0145-.0158	.2502-.2509	CA	4CA2	5G430G	04200	204584	SMLESS		39.6550
F11A094H	316	.2192-.2197	.0150-.0160	.2502-.2509	ANN	6A6	K2177G	20303	185502	SMLESS	6	39.6560
F11A104H	316	.2192-.2198	.0151-.0160	.2499-.2505	ANN	6A12	K2177G	20303	185502	SMLESS	6	39.6540
F11A114H	316	.2192-.2198	.0152-.0158	.2497-.2501	ANN	6A13	K2177G	20303	185502	SMLESS	6	39.6470
F11A124H	316	.2191-.2198	.0149-.0160	.2498-.2502	ANN	6A15	K2177G	20303	185502	SMLESS	6	39.6530
F11A134H	316	.2201-.2201	.0150-.0150	.2504-.2509	20X CW	62CW2	5G430G	M2783	203643	SMLESS	8	39.6530
F11A144H	316	.2201-.2203	.0150-.0150	.2504-.2508	20X CW	62CW4	5G430G	M2783	203643	SMLESS	8	39.6550
F11A154H	316	.2201-.2202	.0150-.0150	.2504-.2507	20X CW	62CW5	5G430G	M2783	203643	SMLESS	8	39.6510
F11A164H	316	.2201-.2201	.0150-.0150	.2506-.2510	20X CW	62CW7	5G430G	M2783	203643	SMLESS	8	39.6570
F11A174H	316	.2199-.2202	.0150-.0150	.2498-.2502	20X CW	62CW8	5G430G	M2783	203643	SMLESS	8	39.6560
F11A184H	316	.2201-.2202	.0150-.0150	.2499-.2506	20X CW	62CW9	5G430G	M2783	203643	SMLESS	8	39.6510
F11A194H	316	.2201-.2202	.0150-.0150	.2505-.2511	20X CW	62CW9	5G430G	M2783	203643	SMLESS	8	39.6540
F11A204H	316	.2201-.2202	.0150-.0150	.2508-.2511	20X CW	62CW11	5G430G	M2783	203643	SMLESS	8	39.6590
F11A214H	316	.2201-.2201	.0150-.0150	.2500-.2508	20X CW	62CW12	5G430G	M2783	203643	SMLESS	8	39.6540
F11A224H	316	.2201-.2202	.0150-.0150	.2505-.2511	20X CW	62CW14	5G430G	M2783	203643	SMLESS	8	39.6620
F11A234H	316	.2201-.2202	.0150-.0150	.2507-.2511	20X CW	62CW16	5G430G	M2783	203643	SMLESS	8	39.6550
F11A244H	316	.2198-.2202	.0150-.0150	.2501-.2505	20X CW	62CW17	5G430G	M2783	203643	SMLESS	8	39.6540
F11A254H	316	.2196-.2201	.0149-.0158	.2500-.2503	CA	6CA16	5G430G	M2783	203643	SMLESS		39.6510
		.2201	.0153	.2502								

GROUP F11A
CLADDING
PRE-IRRADIATION INFORMATION

P I N	TYPE	ID INCHES	WALL THICKNESS INCHES	OD INCHES	CLAD COND.	TUBE NUMBER	P.O. NUMBER	HEAT NUMBER	CERT. NUMBER	FAB. TECH	ASTM GRAIN SIZE	O/A PIN LENGTH INCHES
F11A264H	316	.2192-.2201	.0150-.0156	.2502-.2505	CA	6CA19	5G430G	M2783	203643	SMLESS		39.6550
F11A274H	316	.2194-.2201	.0148-.0159	.2496-.2508	CA	6CA20	5G430G	M2783	203643	SMLESS		39.6510
F11A284H	316	.2200-.2201	.0150-.0156	.2501-.2504	CA	6CA1	5G430G	M2783	203643	SMLESS		39.6540
F11A294H	316	.2200-.2201	.0150-.0155	.2499-.2507	CA	6CA3	5G430G	M2783	203643	SMLESS		39.6510
F11A304H	316	.2199-.2201	.0145-.0156	.2499-.2502	CA	6CA10	5G430G	M2783	203643	SMLESS		39.6500
F11A314H	321	.2200-.2202	.0147-.0152	.2497-.2501	ANN	1A5	K0666G	28967	158419	SMLESS	8	39.6670
F11A324H	321	.2205-.2206	.0144-.0154	.2496-.2502	ANN	1A6	K0666G	28967	158419	SMLESS	8	39.6550
F11A334H	321	.2204-.2207	.0146-.0155	.2497-.2540	ANN	1A8	K0666G	28967	158419	SMLESS	8	39.6470
F11A344H	347	.2206-.2200	.0150-.0155	.2495-.2507	ANN	7A2	K0666G	24772X	158394	SMLESS	10	39.6750
F11A354H	347	.2199-.2200	.0152-.0155	.2498-.2502	ANN	7A3	K0666G	24772X	158394	SMLESS	10	39.6480
F11A364H	316	.2192-.2199	.0151-.0160	.2495-.2506	ANN	6A18	K2177G	20303	185502	SMLESS	6	39.6590
F11A374H	316	.2201-.2200	.0150-.0150	.2505-.2510	20% CW	62CW21	5G430G	M2783	203643	SMLESS	8	39.6540

GEAP-13736

GROUP F11A
MIXED OXIDE FUEL
PRE-IRRADIATION INFORMATION

P I N	TYPE	FORM	FUEL WEIGHT GRAMS	FUEL LENGTH INCHES	COMPOSITION X _{PU} -02	ENRICHMENT X _{U235}	*** D E N S I T Y ** THEORETICAL %	SMEARED %	O/M	DIAMETER (PELLET) INCHES	CENTER HOLE INCHES	DIAMETRAL GAP MILS
*****	****	*****	*****	*****	*****	*****	*****	*****	*****	*****	*****	*****
F11A014H	SP	CPT	81.64	13.497	24.43-24.71	91.01-91.42	91.90-93.13	88.00	1.961-1.961	.2145-.2148	-	4.6-5.6
F11A024H	SP	CPT	81.51	13.473	24.43-24.71	91.01-91.42	91.90-93.31	87.97	1.961-1.961	.2145-.2148	-	4.2-5.7
F11A034H	SP	CPT	81.71	13.504	24.43-24.71	91.01-91.42	91.90-93.28	87.86	1.960-1.961	.2145-.2148	-	5.3-5.8
F11A044H	SP	CPT	82.08	13.529	24.43-24.71	91.01-91.42	91.31-93.37	88.34	1.964-1.964	.2149-.2154	-	4.7-5.3
F11A054H	SP	CPT	81.80	13.484	24.41-25.16	92.47-92.76	91.73-92.49	87.78	1.968-1.968	.2148-.2151	-	5.0-5.5
F11A064H	SP	CPT	80.90	13.528	24.41-25.16	92.47-92.76	90.53-92.19	87.39	1.966-1.968	.2149-.2152	-	5.0-5.4
F11A074H	SP	CPT	82.20	13.526	24.41-25.16	92.47-92.76	91.27-93.02	88.46	1.960-1.964	.2147-.2158	-	4.1-5.5
F11A084H	SP	CPT	82.15	13.528	24.43-24.71	91.01-91.42	91.36-93.36	88.39	1.960-1.964	.2147-.2154	-	4.1-5.4
F11A094H	SP	CPT	81.92	13.492	24.43-24.71	91.01-91.42	92.11-93.05	88.72	1.965-1.965	.2150-.2157	-	3.5-4.7
F11A104H	SP	CPT	82.30	13.525	24.43-24.71	91.01-91.42	92.06-93.06	88.69	1.964-1.965	.2148-.2158	-	3.4-5.0
F11A114H	SP	CPT	82.10	13.485	24.41-25.16	92.47-92.76	91.12-92.25	87.94	1.966-1.968	.2149-.2151	-	4.1-4.9
F11A124H	SP	CPT	82.00	13.480	24.41-25.16	92.47-92.76	91.27-92.13	88.02	1.966-1.968	.2149-.2158	-	3.3-4.9
F11A134H	SP	CPT	81.66	13.499	24.43-24.71	91.01-91.42	92.04-93.19	88.02	1.961-1.965	.2145-.2154	-	4.7-5.6
F11A144H	SP	CPT	81.95	13.520	24.43-24.71	91.01-91.42	92.06-93.04	88.34	1.961-1.965	.2146-.2154	-	4.6-5.7
F11A154H	SP	CPT	81.90	13.482	24.41-25.16	92.47-92.76	91.38-92.27	87.69	1.968-1.968	.2148-.2151	-	5.0-5.4
F11A164H	SP	CPT	82.00	13.505	24.41-25.16	92.47-92.76	91.37-92.59	87.95	1.968-1.968	.2147-.2150	-	5.1-5.4
F11A174H	SP	CPT	82.10	13.518	24.41-25.16	92.47-92.76	90.83-92.19	87.46	1.966-1.968	.2148-.2151	-	4.8-5.4
F11A184H	SP	CPT	82.00	13.472	24.41-25.16	92.47-92.76	91.86-92.68	88.03	1.966-1.968	.2149-.2153	-	4.8-5.2
F11A194H	SP	CPT	81.65	13.475	24.41-25.16	92.47-92.76	92.04-93.13	88.31	1.967-1.967	.2149-.2152	-	4.9-5.3
F11A204H	SP	CPT	82.00	13.506	24.41-25.16	92.47-92.76	91.85-92.67	88.17	1.966-1.968	.2149-.2153	-	4.7-5.2
F11A214H	SP	CPT	82.00	13.507	24.41-25.16	92.47-92.76	91.74-92.80	88.31	1.967-1.968	.2151-.2153	-	4.8-5.1
F11A224H	SP	CPT	82.00	13.509	24.41-25.16	92.47-92.76	91.78-93.05	88.16	1.967-1.968	.2150-.2153	-	4.8-5.2
F11A234H	SP	CPT	81.80	13.486	24.41-25.16	92.47-92.76	91.55-92.72	88.05	1.967-1.968	.2150-.2153	-	4.8-5.2
F11A244H	SP	CPT	81.80	13.472	24.41-25.16	92.47-92.76	91.63-92.70	87.85	1.967-1.969	.2149-.2153	-	4.5-5.3
F11A254H	SP	CPT	81.77	13.514	24.43-24.71	91.01-91.42	90.59-92.72	88.22	1.965-1.965	.2150-.2154	-	4.2-5.1

GROUP F11A
MIXED OXIDE FUEL
PRE-IRRADIATION INFORMATION

P I N	TYPE	FORM	FUEL WEIGHT GRAMS	FUEL LENGTH INCHES	COMPOSITION xP _U -O ₂	ENRICHMENT xU ₂₃₅	*** D E N S I T Y ** THEORETICAL SWEARED		O/M	DIAMETER (PELLET) INCHES	CENTER HOLE INCHES	DIAMETRAL GAP MILS
*****	****	****	*****	*****	*****	*****	*****	*****	*****	*****	*****	*****
F11A264H	SP	CPT	81.96	13.508	24.43-24.71	91.01-91.42	91.93-93.19	88.39	1.961-1.961	.2148-.2154	-	3.8-5.3
F11A274H	SP	CPT	82.00	13.502	24.41-25.16	92.47-92.76	90.30-92.55	87.84	1.961-1.969	.2150-.2153	-	4.1-5.1
F11A284H	SP	CPT	81.90	13.504	24.41-25.16	92.47-92.76	91.17-92.59	87.97	1.967-1.969	.2148-.2153	-	4.7-5.3
F11A294H	SP	CPT	82.00	13.501	24.41-25.16	92.47-92.76	91.41-92.67	87.98	1.967-1.969	.2150-.2152	-	4.8-5.1
F11A304H	SP	CPT	81.54	13.496	24.41-25.16	92.47-92.76	91.37-92.83	87.90	1.966-1.966	.2149-.2152	-	4.7-5.2
F11A314H	SP	CPT	81.99	13.512	24.43-24.71	91.01-91.42	92.01-93.00	88.39	1.961-1.961	.2147-.2155	-	4.5-5.5
F11A324H	SP	CPT	81.85	13.499	24.43-24.71	91.01-91.42	91.95-93.42	87.96	1.961-1.965	.2146-.2154	-	5.1-6.0
F11A334H	SP	CPT	82.20	13.491	24.41-25.16	92.47-92.76	90.83-92.49	87.35	1.966-1.966	.2151-.2153	-	5.1-5.6
F11A344H	SP	CPT	82.03	13.517	24.43-24.71	91.01-91.42	91.85-93.83	88.52	1.960-1.965	.2147-.2155	-	4.5-5.3
F11A354H	SP	CPT	81.51	13.483	24.41-25.16	92.47-92.76	91.52-92.54	88.11	1.966-1.966	.2151-.2153	-	4.6-4.9
F11A364H	VP	CPT	74.82	13.514	24.62-24.62	92.38-92.38	81.24-81.24	81.24	1.974-1.974	-	-	-
F11A374H	VP	CPT	74.88	13.505	24.76-24.76	92.27-92.27	80.95-80.95	80.95	1.973-1.973	-	-	-

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