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REPORT TITLE DETERMINATION OF UNIAXIAL MECHANICAL PROPERTIES OF UNIRRADIATED & IRRADIATED HASTELLOY-N BAR AND BIAXIAL STRESS-RUPTURE PROPERTIES OF CHROMIZED AND COATED UNIRRADIATED HASTELLOY-N

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NAA-SR-MEMO 12556

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	GO NO 7695	
TITLE Determination of Uniaxial Mechanical Properties of Unirradiated and Irradiated Hastelloy-N Bar and Biaxial Stress-Rupture Properties of Chromized and Coated Unirradiated Hastelloy-N	S/A NO 35340	TWR

PROGRAM	SUBACCOUNT TITLE
SNAP-8	ORNL Testing

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STATEMENT OF PROBLEM

To determine the uniaxial mechanical properties of unirradiated and irradiated Hastelloy-N and the unirradiated biaxial stress-rupture properties of SNAP-8 fuel cladding.

ABSTRACT

Short-time tensile tests were conducted on irradiated (2 x 10^{20} nvt) and unirradiated Hastelloy-N bar from heats 5911 and 6252. No significant difference in mechanical properties was noted between the two heats The 1200°F ultimate tensile strength was decreased by irradiation from 65 - 80 ksi and 48 - 52 ksi. The 1400°F ultimate tensile strength was decreased from 45 - 51 ksi to 32 - 34 ksi. The yield strength was not greatly affected by irradiation at either 1200 or 1400°F. The 1200°F elongation at fracture was decreased from 15 - 45% to 5 - 11%. The 1400°F ductility was decreased from 8 - 26% to 1 - 1½%.

Unirradiated uniaxial stress-rupture tests were conducted at both AI and ORNL. No definite difference in stress-rupture properties between heats was noted at either 1200 or 1400°F in ORNL tests, although some of the 1400°F stress-rupture tests indicated that heat 6252 exhibited greater ductility. The AI verification tests showed a definite ductility difference, with heat 6252 exhibiting greater ductility. This phenomenon was attributed to an inhibition in crack propagation due to microsegregation.

Irradiation (2 x 10^{20} nvt) reduced the 1200°F uniaxial rupture life by about a decade; irradiation reduced the 1400°F rupture life by from 1 to 2 decades, depending on the strain rate. Apparently the ductility is dependent upon the strain rate (high strain rate - lower ductility,

low strain rate - higher ductility).

No difference could be distinguished between heats 5911 and 0143 in the ORR S-2 biaxial stress-rupture control tests.

INTRODUCTION:

In order to define the mechanical properties of irradiated SNAP-8 fuel cladding, a comprehensive mechanical test program was conducted. The mechanical behavior of the cladding is under study to provide design information, alloy heat selection, and aid in the selection of optimum process conditions. The test series included:

1) Out-of-pile tests on irradiated material (irradiated at ORNL).

2) Biaxial stress-rupture tests conducted in the Oak Ridge Research Reactor.

3) Control tests on unirradiated material (conducted at ORNL and AI).

This program was divided into two distinct experiments, ORR S-1 and ORR S-2. The ORR S-1 experiment consisted of uniaxial tests only; the ORR S-2 experiment consisted of biaxial stress-rupture tests. This report incorporated the results of the ORR S-1 unirradiated and irradiated tests and the ORR S-2 unirradiated control tests. The ORR S-2 irradiated material tests have been reported elsewhere.(1) In addition to the ORR S-1 test results reported herein, a series of fatigue tests were conducted on irradiated and unirradiated material. These results are also reported elsewhere.(2,3)

FUEL CLADDING DESCRIPTION:

The SNAP-8 reactor core consists of ZrH_x-U alloy fuel elements clad with nominal 10-mil thick Hastelloy-N tubing coated internally with a glass hydrogen permeation barrier. In order for the glass barrier to adhere to the cladding, it was found necessary to chromize the Hastelloy-N. The chromizing treatment imparts a chromium-rich layer to both the ID and OD of the cladding. A post-chromizing diffusion treatment has been added to the cladding processing sequence to improve adherence.

It has been established that hydrogen gas is released from the fuel during reactor operation. Since the glass barrier prevents hydrogen permeation, an internal pressure buildup occurs inside the element. For this reason, biaxial stress-rupture properties of the cladding were considered to be of prime importance.

TEST DESCRIPTION:

ORR S-1

The ORR S-1 test matrix and specimen design for the irradiated tests are presented in Table I and Figure 1, respectively. The material treatments presented in Table I were selected to closely simulate the cladding fabrication process. Process 3A is an exception, and was included to produce a large grain size in the cladding. The first heat, 5911, is the SNAP 15-mil tubing heat. The second heat, 6252, was a backup heat, and was not committed to tubing fabrication. The reference SNAP-8 10-mil heat, 281-4-0143, did not have bar stock available; it was not included in the ORR S-1 experiment. ORR S-1 tests were conducted with heat treated bar stock, with no chromizing or coating treatment.

Most of the ORR S-1 control tests were conducted at ORNL; a limited number of verification tests were conducted at AI. The control specimens were subjected to thermal treatments to simulate the thermal treatment received by irradiated specimens. The aging treatments allowed differentiation between thermal effects and aging effects.

The irradiated specimens were irradiated to a dose of $\sim 2 \times 10^{20}$ nvt thermal in the Oak Ridge Research Reactor and then tested at AI.

ORR S-2

A schematic sketch of an ORR S-2 test specimen is presented in Figure 2. For these biaxial stress-rupture tests, the specimens were chromized and coated with the glass hydrogen permeation barrier. However, none of these specimens were subjected to the chromium diffusion treatment. Most of the ORR S-2 control tests were conducted at ORNL, although some post-test analyses were performed on these specimens at AI. Since stress-rupture tests may be sensitive to test conditions and eouipment systems, and tests of irradiated specimens were conducted at AI, a limited number of verification tests on unirradiated material were conducted at AI.

Although the biaxial stress-rupture specimens were identical for both the AI and ORNL tests, the test conditions differed somewhat. A potentially significant variation between the AI tests and ORNL tests was the thermal gradient (ends

TABLE I

ORR S-1 HASTELLOY-N TENSILE SPECIMEN IRRADIATION TEST

UNIAXIAL CREEP DUCTILITY

*ALL TENSILE TESTS AT 0.002 in./in. min^{-1}

5911 AW IS 15-mil HEAT AS-WORKED
5911 AT IS 15-mil TUBE HOLLOW
6252 AC IS NEW ALLVAC HEAT AS CAST

PROCESS 1 ANNEAL AT 2150°F FOR 61 min

PROCESS 2 HOT ROLL (AT ORNL) PROVIDING 50% REDUCTION AT 2100°F. ANNEAL 60 min AT 2150°F

PROCESS 3A FOLLOWING 25% COLD REDUCTION AND 1950°F ANNEAL FOR 90 min, THE SPECIMENS WILL BE ANNEALED AT ~2300°F TO REPRODUCE S8DS GRAIN SIZE

PROCESS 3B FOLLOWING 25% COLD REDUCTION AND 1950°F ANNEAL FOR 90 min, THE SPECIMENS WILL BE ANNEALED 2 hr AT 2000°F AND 10 min AT 2100°F

HEAT NO	SPECIMEN QUANTITY	TEMP (°F)	PROCESS	TEST TYPE
5911 AW	2	1400	1	TENSILE*
5911 AW	1	1400	1 + 3A	CREEP
5911 AW	3	1400	1 + 3B	CREEP
5911 AW	3	1400	1	CREEP
5911 TH	3	1400	1	CREEP
5911 AW	3	1200	1	CREEP
5911 AW	2	1200	1	TENSILE
5911 AW	1	1400	1 + 3A	CREEP
6252 AC	3	1400	2 + 3B	CREEP
6252 AC	2	1400	2	TENSILE
6252 AC	1	1400	2 + 3A	CREEP
6252 AC	3	1400	2	CREEP
6252 AC	3	1200	2	CREEP
6252 AC	2	1400	2	TENSILE
6252 AC	1	1400	2 + 3A	CREEP
5911 TH	1	1400	1	TENSILE

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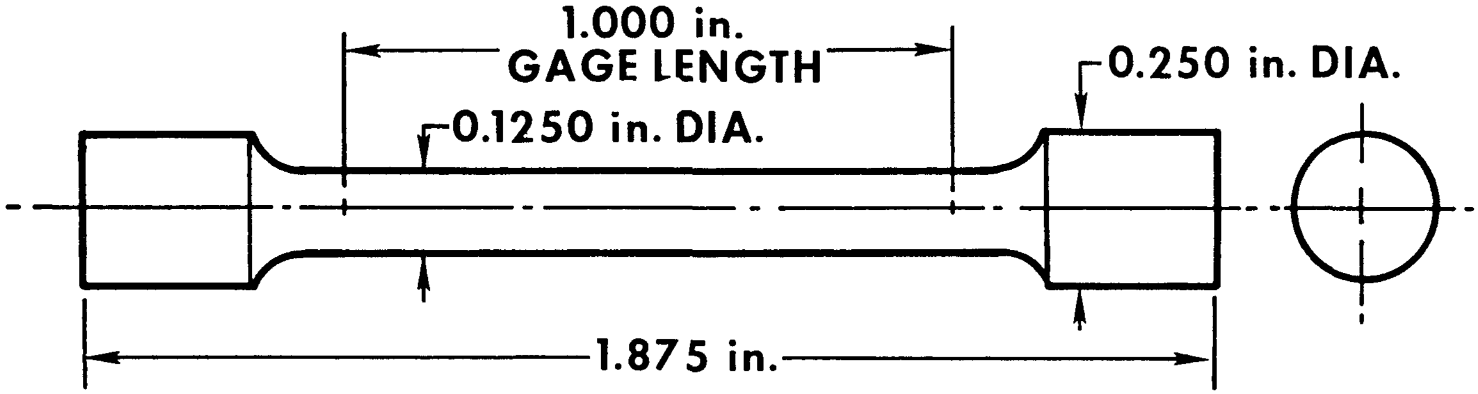
Figure 1

ORR S-1 TEST MATRIX AND SPECIMEN DESIGN



HEAT NUMBER	IRRAD. & TEST TEMP (°F)	NUMBER SAMPLES FOR STRESS RUPTURE	NUMBER OF STRESS LEVELS	RANGE OF STRESS LEVELS (ksi)
5911AW	1200 1400	3 8	3 4	32-47 8-20
5911TH	1400	3	3	8-20
6252AC	1200 1400	3 8	3 3	32-47 10-15

ALL SAMPLES IRRADIATED FOR 1 FULL REACTOR CYCLE AT ORNL PRIOR TO TEST (approx. 1000 hr)
DOSE WAS APPROXIMATELY 2×10^{20} nvt THERMAL

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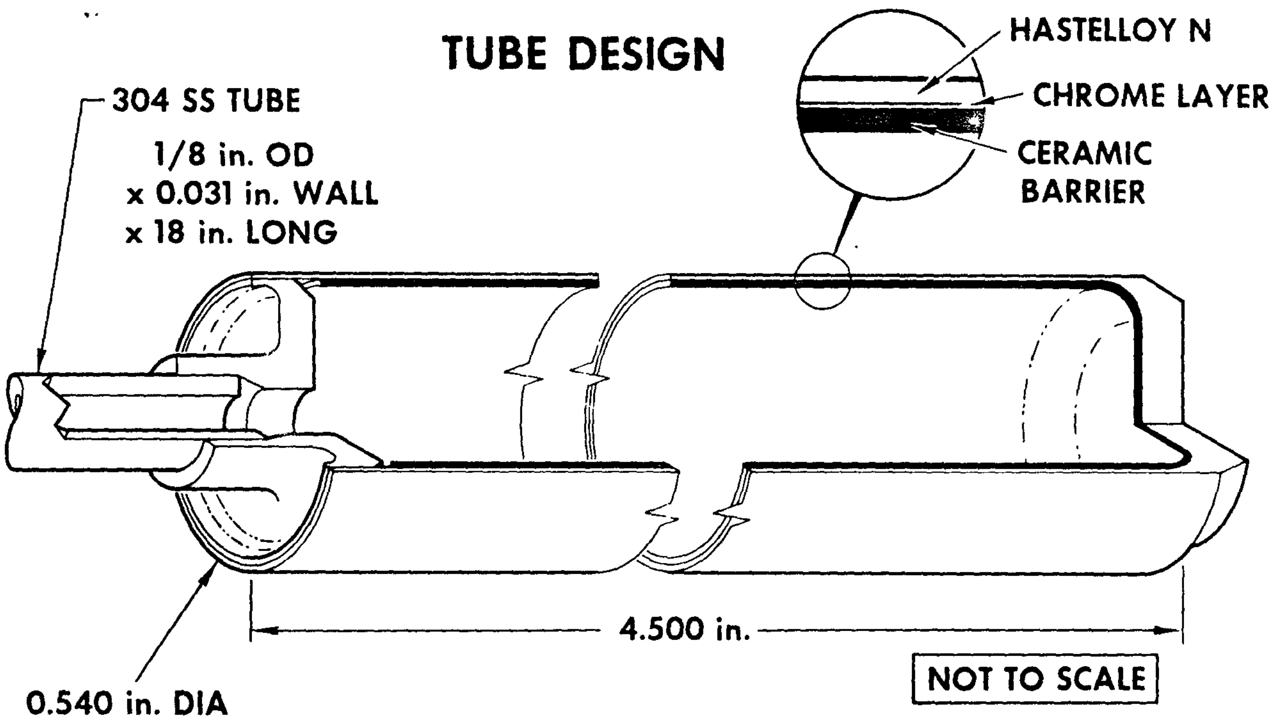

Figure 2 ORR S-2 Test Specimen

200 to 300°F cooler) imposed on the specimens in the ORNL tests to avoid end closure rupture. The AI tests were conducted isothermally at 1400°F since the results were to be used for the NaK environmental test program. The ORNL tests were conducted at both 1200 and 1400°F but the verification tests at AI were performed only at 1400°F.

Another variation between the AI tests and ORNL tests was the test environment for the control specimens. The AI tests were conducted with helium internal and external, whereas, the ORNL specimens were pressurized with argon; air was the external environment. The control specimens for the ORR S-2 experiment were also subjected to thermal treatments to simulate the thermal aging received by irradiated specimens.

Dimensional measurements on the ORR S-2 specimens were performed at Oak Ridge by dial micrometer. Subsequent to these measurements, the specimens were shipped to AI for Supermicrometer and profilometer measurements. The stress-rupture ductilities were then recalculated using the PROFESSOR and MENTOR computer codes. No difference in ductility could be distinguished between the two methods of measurement.

RESULTS:

Several processing variables were introduced into the program, many of which were necessitated by material availability. Few tests were conducted with the same processing, test temperature, and stress level. Therefore, a rigorous comparison becomes quite difficult if processing variables are considered. The results did not indicate a definite dependence on processing variables. Is such a dependence does exist, it is of small magnitude and is masked by the scatter of the data. Therefore, for purposes of this report, processing variables will be neglected.

<u>ORR S-1 Short-Time Tensile Test Results</u>

Table II (the ORNL test results) indicates that the short-time unirradiated tensile properties of heats 5911 and 6252 are not different within the scatter band of the data. The ultimate tensile strength for heat 5911 ranged from 71 to 78 ksi at 1200°F and 46 to 51 ksi at 1400°F. Ultimate tensile strength values for heat 6252 ranged from 67 to 74 ksi at 1200°F and 45 to 47 ksi at 1400°F. Heat 5911 material exhibited greater ductility at 1400°F, but there is considerable scatter in the results. There appears to be a significant decrease in ductility at 1400°F for both heats when compared with 1200°F and lower temperature test results. Processing variables apparently did not affect the results.

TABLE II

OPNL Test Matrix: ORR S-1 Controls
Tensile Tests (0.002 in./in./min.)

Heat Number	Specimen Number	Heat Treat Process	Pre-* Test Aging	Test Temp. (°F)	Ultimate Strength (psi)	Yield Strength (psi)	Uniform Elong. (%)	Total Elong. (%)	Reduction in Area (%)
5911AW	3113	1	B	1020	87,800	32,600	57.1	58.2	43.6
	3117	1	A	1020	96,500	31,400	61.7	64.8	47.5
	3114	1	B	1110	65,200	35,400	22.5	23.5	23.2
	3119	1	A	1110					
	3108	1	A	1200	77,700	29,700	39.8	40.8	35.3
	3106	3A	A	1200	70,800	26,400	43.2	43.4	36.6
	2959	3	A	1200	76,600	34,300	29.6	30.3	25.7
5911TH	3103	1	A	1200	74,300	29,200	21.1	42.7	33.5
5911AW	3121	1	A	1400	50,900	28,900	12.5	25.9	27.3
	3109	1	B	1400	47,700	32,200	8.0	13.4	14.4
	3115	1	B	1400	51,100	31,700	12.8	16.6	13.1
	2854	3A	B	1400	46,700	31,700	8.0	13.6	12.5
	2953	3	B	1400	45,800	32,200	8.2	22.9	22.1
5911TH	3091	1	B	1400	47,800	32,400	7.7	16.2	13.9
6252AC	2919	2	A	1200	66,600	34,000	15.1	15.4	17.4
	2948	2+3	A	1200	73,500	37,500	21.6	21.9	19.1
	2921	2	B	1400	45,000	32,000	6.1	8.6	7.3
	3130	2A	B	1400	46,800	25,700	7.7	10.6	10.1
	2944	2+3	B	1400	44,900	37,500	8.7	20.2	17.6

*Pretest aging treatments A = 1080 hours at 1200°F
B = 1030 hours at 1400°F

Table III reveals that the short-time tensile properties of heats 5911 and 6252 are also quite similar after 2 x 10^{20} nvt thermal neutron dosage, with the possible exception of the 1200°F ductility. Heat 5911 exhibited 8 to 11% elongation at fracture while heat 6252 exhibited only 5 to 6% elongation at 1200°F. However, since considerable scatter has been observed in the results, it is entirely possible that the apparent difference in ductility could be attributed to normal scatter. Irradiation to a level of 2 x 10^{20} nvt thermal reduced the 1200°F ultimate tensile strength from a range of about 65 to 80 ksi to a range of about 48 to 52 ksi. The 1200°F yield strength may have been slightly decreased from about 36 to 40 ksi to about 30 to 34 ksi. The elongation was decreased from a range of 15 to 45% to 5 to 11%; the reduction in area was decreased from a range of 17 to 37% to about 6 to 15%.

Tables II and III also show the 1400°F ultimate tensile strength to be decreased after irradiation (also 2 x 10^{20} nvt thermal) from a range of 45 to 51 ksi to a range of 32 to 34 ksi. The yield strength appeared to increase slightly from about 26 to 33 ksi to 32 to 34 kwi. The elongation was decreased from a range of 8 to 26% to 1 to 1½%; and the 1400°F reduction in area was decreased from 7 to 28% to 1 to 4%.

ORR S-1 Uniaxial Stress-Rupture Tests

The unirradiated uniaxial stress-rupture tests performed at Oak Ridge (Table IV) indicated that both heats of Hastelloy-N bar exhibited similar stress-rupture properties at 1200 and 1400°F. A possible exception was the 1400°F ductility measurements. Heat 5911 specimens exhibited 18 - 36% elongation at a 20,000 psi stress level while heat 6252 specimens exhibited 36 - 53%. Tests conducted at other stress levels were not definitive. Tests at 1200°F did not indicate a difference in ductility, but the data were limited. The uniaxial stress-rupture tests conducted at AI (Table V) indicated that the 1400°F ductility of heat 6252 was superior to that of heat 5911. Metallography was conducted on several of the samples. It was concluded that microsegregation in heat 6252 contributed to the increase in ductility.(4) The microsegregation apparently inhibited crack propagation. All other properties were apparently quite similar.

TABLE III

ORR S-1 IRRADIATED HASTELLOY-N SHORT TIME TENSILE TESTS

(0.002 in./in. MIN^{-1})

SPECIMEN NO.	HEAT NO.	IRRAD AND TEST TEMP (°C)	HEAT TREATMENT	YIELD STRESS	ULTIMATE STRESS (psi)	TOTAL ELONGATION (%)	REDUCTION IN AREA (%)
2837	5911	760	1	32,566	32,651	1.00	3.55
2839	5911	760	1	33,674	33,674	1.40	1.90
2846	5911	650	1	38,174	50,609	8.1	11.2
2847	5911	650	1	36,378	52,547	11.2	14.5
2917	6252	760	2	32,174	32,174	1.5	0.8
2918	6252	760	2	31,830	31,830	1.5	–
2926	6252	650	2	39,049	48,477	4.8	5.7
2921	6252	650	2	40,236	48,907	5.6	8.0

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TABLE IV

UNIAXIAL STRESS RUPTURE ORR S-1 CONTROLS

HEAT NO.	SPECIMEN NO.	HEAT TREAT PROCESS	PRE-TEST AGING*	TEST TEMP (°F)	STRESS (psi)	RUPTURE LIFE (hr)	TOTAL ELONGATION (%)	REDUCTION IN AREA (%)
5911	3125	1	A	1200	65,000	9.4	26.5	21.9
5911	3116	1	A	1200	55,000	49.6	27.4	21.2
5911	3094	1	A	1200	55,000	48.85	27.9	21.6
5911	3112	1	A	1200	47,000	206.5	17.3	17.1
5911	2838	3A	A	1200	47,000	120.75	27.17	21.1
5911	2952	3B	A	1200	47,000	181.0	23.48	20.7
5911	3099	1	A	1200	47,000	189.1	26.6	21.9
5911	3111	1	A	1200	40,000	413.7	17.3	16.7
5911	3126	1	A	1200	40,000	595.02	22.7	11.0
5911	2844	3A	A	1200	40,000	488.95	21.0	17.3
5911	2954	3B	A	1200	40,000	761.7	29.5	22.8
5911	3102	1	A	1200	40,000	706.3	29.2	25.4
5911	2093	1	A	1200	32,350	(1941.6)	(12.1)	
5911	3122	1	A	1200	32,350	1828.0	21.8	19.8
6252	2983	3	A	1200	32,350	2082.1	18.0	13.4
6252	2942	2+3B	A	1200	47,000	123.6	17.5	13.9
6252	2924	2	A	1200	40,000	647.25	21.2	15.6
6252	2943	2+3B	A	1200	40,000	622.2	14.88	14.0
6252	2933	2	A	1200	32,350	1813.3	(13.99)	14.0
5911	3123	1	B	1400	30,000	21.8	29.8	23.1
5911	3107	3A	B	1400	30,000	15.4	23.6	16.1
5911	2958	3B	B	1400	30,000	24.2	38.5	33.0
5911	3097	1	B	1400	30,000	17.65	19.2	14.3
5911	3110	1	B	1400	20,000	147.7	35.5	20.64
5911	2857	3A	B	1400	20,000	114.7	24.6	16.1
5911	2955	3B	B	1400	20,000	73.7	17.6	21.7
5911	3092	1	B	1400	20,000	113.5	25.3	16.2
5911	3118	1	B	1400	15,000	607.15	39.8	29.0
5911	3105	3A	B	1400	15,000	402.8	15.7	8.0
5911	2956	3B	B	1400	15,000	419.2	32.2	16.4
5911	3093	1	B	1400	15,000	654.7	24.8	13.2
5911	3120	1	B	1400	17,500			
5911	2957	3B	B	1400	17,500	153.3	29.3	17.3
5911	3095	1	B	1400	17,500	161.4	13.5	18.0
6252	3136	2	B	1400	30,000	7.3	12.1	10.2
6252	2947	2+3B	B	1400	30,000	10.0	13.1	12.0
6252	3133	2	B	1400	20,000	119.1	39.0	29.0
6252	3131	2A	B	1400	20,000	162.9	35.6	21.9
6252	2945	2+3B	B	1400	20,000	114.25	53.1	31.6
6252	3134	2	B	1400	15,000	636.5	46.7	37.7
6252	2946	2+3B	B	1400	15,000			
6252	3135	2	B	1400	17,500			
6252	3132	2A	B	1400	10,000	2553.1	14.1	
6252	2945	2+3B	B	1400	20,000	114.25	53.1	31.6

*PRETEST AGING TREATMENTS: A = 1080 hr AT 1200°F
B = 2080 hr AT 1400°F

( ) INDICATE SAMPLES ON TEST

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TABLE V

AI Test Results - ORR S-1 Controls

Uniaxial Stress Rupture

Heat Number	Specimen Number	Test Temp (°F)	Stress (psi)	Rupture Life (hr)	Total Elongation (%)	Reduction in Area (%)	Minimum Creep Rate (in./in./hr)
5911AW	3529	1400	20,000	138.9	23.0	22.7	1.2×10^{-3}
	3534	↓	↓	122.8	25.0	24.4	2.5×10^{-3}
	3536	1300	24,500	509	22.0	18.7	2.8×10^{-4}
	3541	1400	13,000	733	23	15.5	2.0×10^{-4}
	3542*	↓	↓	349.3	3	0	8.2×10^{-5}
	3545	1300	18,000	1664.8	18	6.5	5.3×10^{-5}
	3538**	1400	11,000	1222	16	11.0	7.7×10^{-5}
	3540	↓	↓	1596	20.0	19.0	9.1×10^{-5}
	4281	1200	50,000	45.6	17.0	15.3	9.9×10^{-4}
	4284	↓	35,000	448.2	11.0	13.9	9.1×10^{-5}
	4280	1400	20,000	94.4	18.0	15.3	1.7×10^{-3}
	4287		13,000	857.6	24.0	19.7	1.7×10^{-4}
	4285		11,000	1569.5	34.0	26.0	9.9×10^{-5}
	4286		11,400	1829	39.0	28.5	1.6×10^{-4}
	4282		10,000	2104	19	12.5	9.0×10^{-5}
↓	4283	↓	↓	2435	23	25.4	6.5×10^{-5}
6252AC	3912	1200	50,000	52.9	13.0	11.0	1.2×10^{-3}
	3915	↓	35,000	821.2	22	18.3	1.1×10^{-4}
	3911	1400	33,000	10.8	23	22.7	---
	3918		13,000	941.8	65	42.0	2.5×10^{-4}
	3916		11,000	1415	54	35.5	1.6×10^{-4}
	3917		12,000	1572	63	36.0	2.2×10^{-4}
	3913	↓	10,000	2504	50	35	1.0×10^{-4}
↓	3914		↓	2135	34	41.0	1.0×10^{-4}

* specimen damaged during loading

** specimen failed due to equipment malfunction

The uniaxial irradiated (2 x 10^{20} nvt thermal) data are presented in Table VI and compared with the unirradiated data in Figure 3. Tables IV, V, and VI shows that irradiation reduces the 1200°F rupture life of Hastelloy-N bar by about one decade. Figure 3 shows that irradiation and testing at 1400°F reduces the rupture life by a factor of from one to two decades. The reduction in rupture life is apparently less for the low stress, long-term tests (i.e., the stress-rupture life curves for the irradiated and unirradiated material tend to converge at low stress levels). For the 1400°F irradiation and test series, the specimens with higher ductilities were stressed at the lower stress levels, indicating a strain rate effect (high strain rate - lower ductility, low strain rate - higher ductility). Figure 4, a least-squares plot of strain to rupture (ductility vs. strain rate)shows the ductility to be inversely propertional to the strain rate. The strain to rupture is seen to decrease from about 3% to less than 1% as the creep rate is increased from about 10^{-5} in./in./hr to 10^{-2} in./in./hr. However, Figure 4 also shows considerable scatter in the data. More data points would be desirable to substantiate the slope of the line.

<u>ORR S-2 Results</u>

The biaxial stress-rupture control results are presented in Tables VII and VIII. There does not appear to be a significant difference in mechanical properties from heat to heat, either in the AI or ORNL tests. It may be noted the AI ductility values are apparently lower than the ductility in the ORNL tests. The thermal gradient applied in the ORNL tests greatly decreased the probability of rupture in a large percentage of the specimen area, particularly those areas most affected by cleaning, welding, and machining. Therefore, since a relatively smaller area was susceptible to failure at Oak Ridge, it is not surprising that higher ductility values would be derived from the ORNL tests. There is no reason to believe that AI ductility values might not be similar if such a thermal gradient had been imposed in the AI tests. It is noteworthy that most of the AI-tested specimens failed in a weld area. The control tests plotted in Figure 5 indicate that oxidation or nitriding did not contribute to a significant variation in biaxial stress-rupture life when compared to tests conducted in an inert atmosphere.

TABLE VI

UNIAXIAL STRESS RUPTURE PROPERTIES OF IRRADIATED HASTELLOY-N BAR (S8DR HEATS)

HEAT NO.	SPECIMEN NO.	POSITION NO.	HEAT TREAT PROCESS	IRRADIATION AND TEST TEMPERATURE (°F)	STRESS (psi)	RUPTURE LIFE (hr)	TOTAL ELONGATION (%)	AVERAGE CREEP RATE (in./in./hr)
5911AW	2848	3	1	1200	32,350	144.3	0.86	5.9×10^{-5}
5911AW	2850	4	1	1200	40,000	43	0.83	1.9×10^{-4}
5911AW	2851	5	1	1200	47,000	12.8	1.68	1.3×10^{-3}
5911AW	2841	10	1	1400	8,000	834.4	1.77	2.1×10^{-5}
5911AW	2949	14	3B	1400	8,000	825.7	4.41	5.3×10^{-5}
5911AW	2842	11	1	1400	10,000	104.6	0.98	9.4×10^{-5}
5911AW	2951	16	3B	1400	10,000	55.2	1.34	2.4×10^{-4}
5911AW	2845	13	3A	1400	10,000	179.4	1.08	6.0×10^{-5}
5911AW	2840	9	1	1400	15,000	473	TEMP ERROR	
5911AW	2849	12	3A	1400	15,000	2.2	0.57	2.6×10^{-3}
5911AW	2950	15	3B	1400	20,000	0.45	0.58	1.3×10^{-2}
5911TH	2982	19	1	1400	8,000	365.2	1.45	4.0×10^{-5}
5911TH	2980	17	1	1400	15,000	2.1	0.87	4.1×10^{-3}
5911TH	2981	18	1	1400	20,000	1.0	0.67	6.7×10^{-3}
6252AC	2937	34	2	1200	47,000	18.5	1.50	8.1×10^{-4}
6252AC	2928	32	2	1200	32,350	220.6	1.70	7.7×10^{-5}
6252AC	2929	33	2	1200	40,000	23.5	0.97	4.1×10^{-4}
6252AC	2923	24	2	1400	12,500	24.1	1.55	6.4×10^{-4}
6252AC	2941	29	2 & 3B	1400	12,500	284.3	3.18	1.1×10^{-4}
6252AC	2922	23	2	1400	10,000	581.5	2.36	4.1×10^{-5}
6252AC	2932	26	2A	1400	10,000	289.8	1.12	3.9×10^{-5}
6252AC	2940	28	2 & 3B	1400	10,000	504.6	3.58	7.1×10^{-5}
6252AC	2920	22	2	1400	15,000	3.5	0.94	2.7×10^{-3}
6252AC	2930	25	2A	1400	15,000	0.7	0.32	4.6×10^{-3}
6252AC	2939	27	2 & 3B	1400	15,000	5.0	1.49	3.0×10^{-3}

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TABLE VII

AI TEST MATRIX: ORR S-2 CONTROLS

(1400°F BIAXIAL STRESS RUPTURE)

HEAT NO.	SPECIMEN NO.	HOOP STRESS (psi)	RUPTURE LIFE (hr)	TOTAL ELONGATION (%)	LOCATION OF RUPTURE
281-4-0143	5091	18,500	174	4.5	BE WELD
	5070	15,000	335	2.3	BE WELD
	5053	12,500	← FITTING FAILED →		
5911	6022	18,500	112	5.2	BE WELD
	6013	15,000	335	4.1	BE WELD
	6009	12,500	586	3.3	MAIN BODY
5911 (REDRAWN)	5056	18,500	112	4.3	1/4 in. ABOVE BE WELD
	5052	15,000	410	5.0	CLOSURE END
	5041	12,500	596	3.8	MAIN BODY

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TABLE VIII

HASTELLOY-N CONTROL SAMPLES
(1400°F ORR S-2 BIAXIAL STRESS RUPTURE)

HEAT NO.	SPECIMEN NO.	PRESSURE (psi)	HOOP STRESS (psi)	RUPTURE LIFE (hr)	CREEP DUCTILITY (%)	AVERAGE CREEP RATE (in./in./hr)
281-4-0143	5069	2000	50,400	~0.1	17.2	1.7
281-4-0143	5057	1400	35,900	2.2	6.7	3.0×10^{-2}
281-4-0143	5097	1200	29,800	4.2	7.7	1.8×10^{-2}
281-4-0143	5068	1000	24,100	12.7	4.6	3.6×10^{-3}
281-4-0143	5098	850	21,100	15.5	9.6	6.2×10^{-3}
281-4-0143	5048	750	18,600	63.7	8.9	1.4×10^{-3}
281-4-0143	5072	600	14,900	153.2	8.2	5.3×10^{-4}
281-4-0143	5062	500	12,410	788.5	11.1	1.4×10^{-4}
281-4-0143	5078	400	9,930	2160.0	10.6	4.9×10^{-5}
5911	6025	2000	38,200	0.9	8.4	9.3×10^{-2}
5911	6016*	1400	27,200	30.1	6.7	2.3 c 10^{-3}
5911	6029	1400	27,100	5.0	3.9	7.8×10^{-3}
5911	6019	1000	19,400	30.3	9.4	3.1×10^{-3}
5911	6020*	750	14,500	61.2	0.9	DID NOT RUPTURE-LEAK IN SYSTEM
5911	6018	750	15,520	100.2	6.4	6.4×10^{-4}
5911	6026	750	14,500	343.5	9.0	2.6×10^{-4}
5911	6017*	600	11,610	160 9	7.6	TEMPERATURE RAN HIGH
5911	6012*	600	11,940	523.3	5.3	
5911	6014	600	11,630	334.7	7.63	2.3×10^{-4}
5911	6031	500	9,690	2974.5	4.6	1.5×10^{-5}
5911R	5127R	1400	36,600	0.4	9.1	2.3×10^{-1}
5911R	5126R	1200	31,400	5.85	4.4	7.5×10^{-3}
5911R	5057R	1000	26,300	19.8	8.2	4.1×10^{-3}
5911R	5050R	750	19,700	~86.9	8.2	9.5×10^{-4}
5911R	5049R	750	19,700	87.5	8.9	1.0×10^{-3}
5911R	5038R	675	17,730	20.9	7.8	3.7×10^{-3}
5911R	5130R	600	15,920	142.4	6.2	4.4×10^{-4}
5911R	5128R	500	13,180	372.5	7.8	2.1×10^{-4}
5911R	5123R	400	10,470	1731.7	6.8	3.9×10^{-5}
5911R	5054R	400	10,490	866.7	7.7	8.9×10^{-5}

*TEST RESULTS DEEMED NOT VALID BY ORNL.

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Figure 3

UNIAXIAL STRESS RUPTURE PROPERTIES OF HASTELLOY-N BAR AT 1400°F

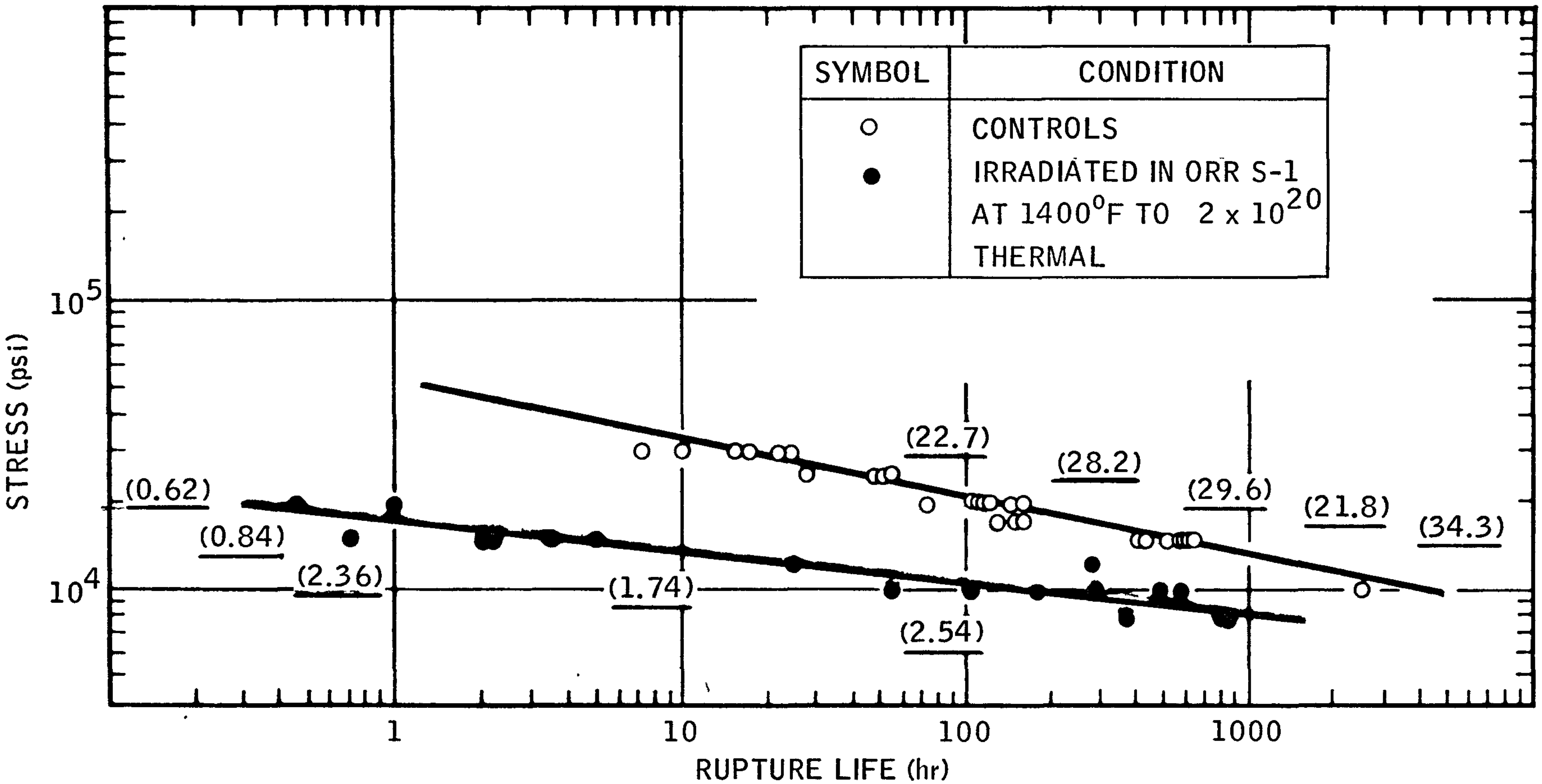

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Figure 4

POST-IRRADIATION STRAIN TO RUPTURE vs CREEP (1400°F)

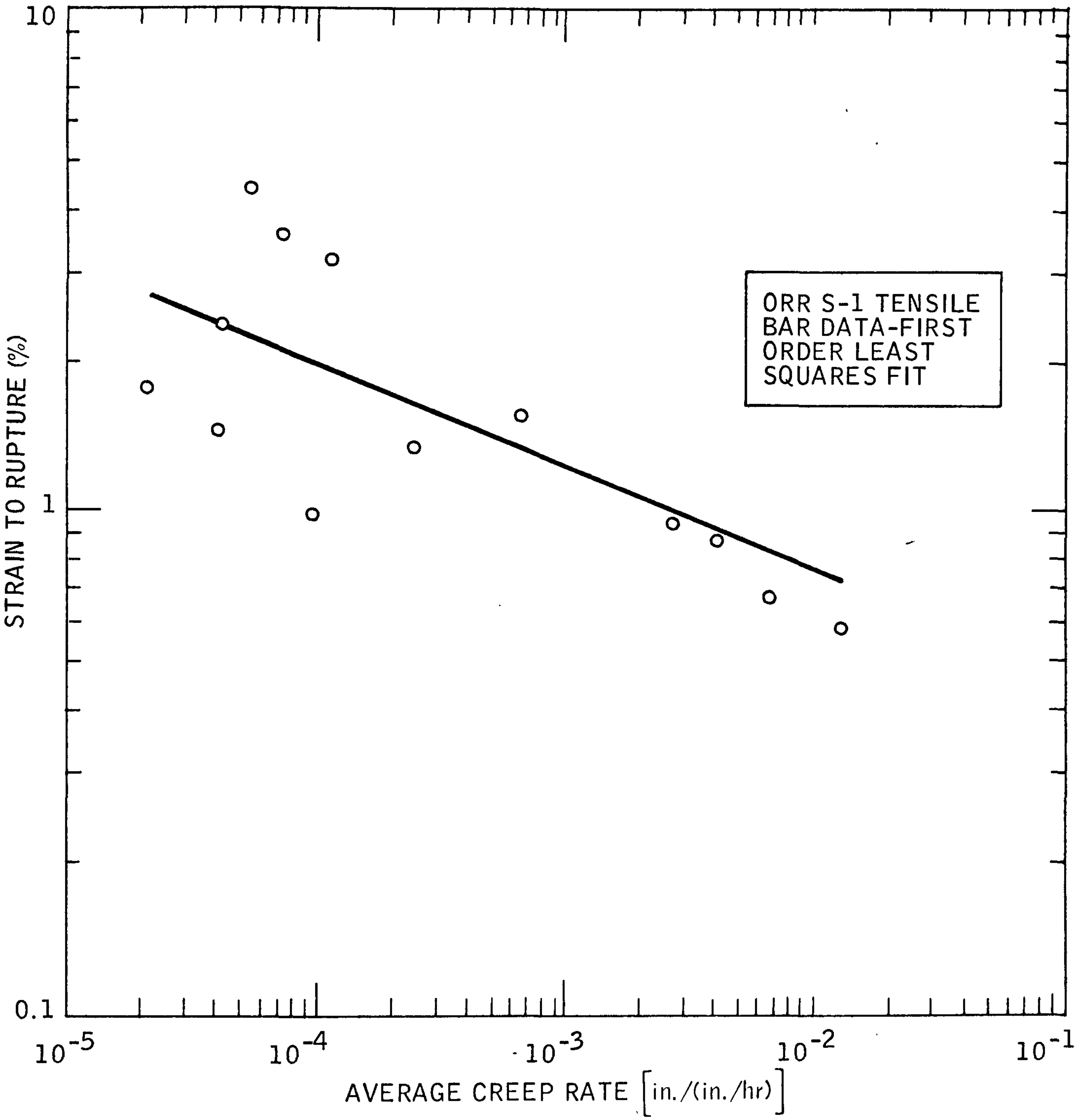

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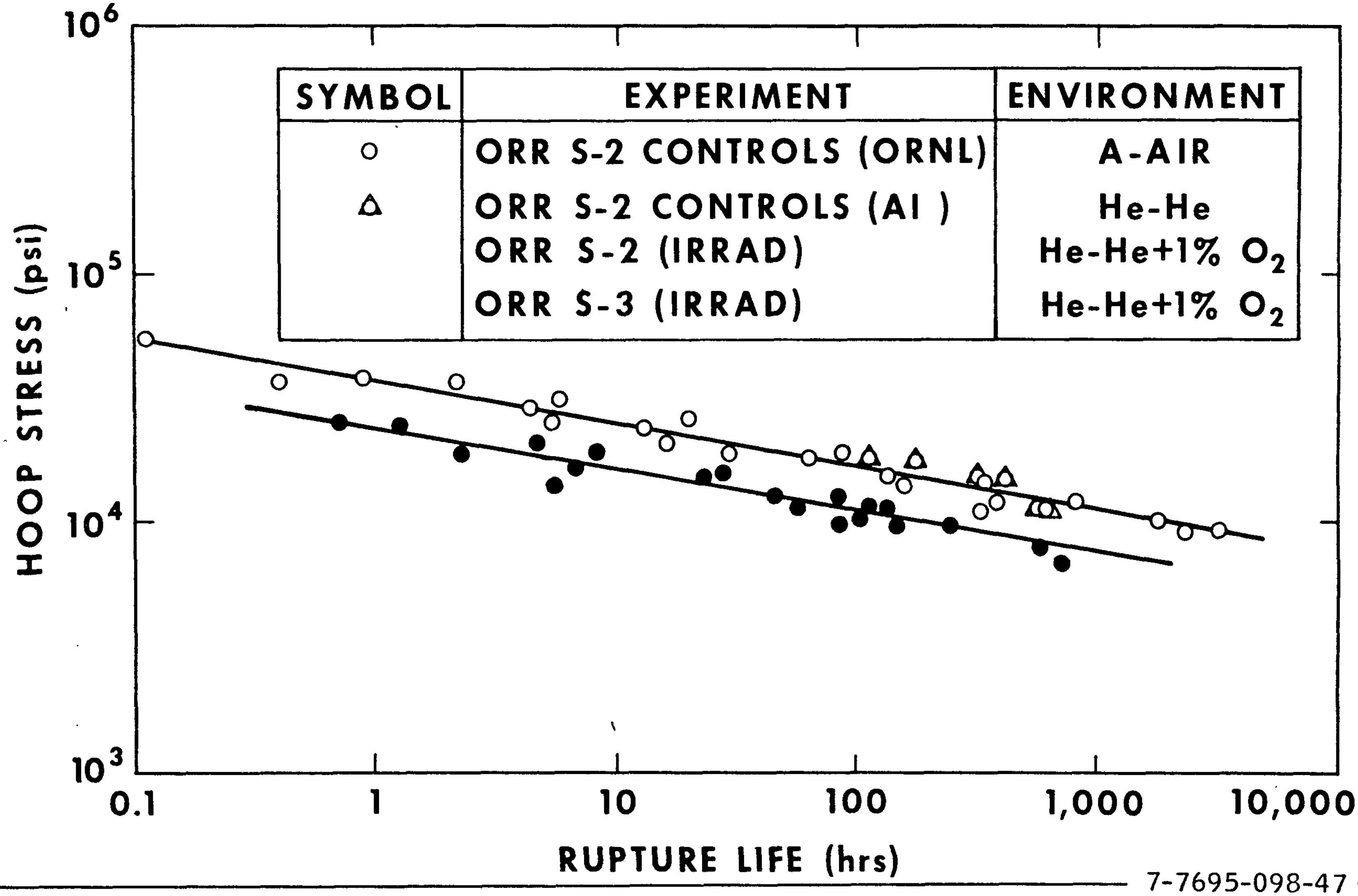
Figure 5

IRRADIATED HASTELLOY N BIAXIAL STRESS RUPTURE PROPERTIES AT 1400°F



7-7695-098-47

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CONCLUSIONS:

1) Processing variables did not significantly affect the mechanical properties of Hastelloy-N.

2) No significant difference in short-time (irradiated or unirradiated) tensile properties could be distinguished between heats 5911 and 6252.

3) Irradiation (2 x 10^{20} nvt thermal) reduces the 1200°F UTS from about 65 - 80 ksi to about 48 - 52 ksi; the 1200°F YS was decreased from about 36 - 40 ksi to about 30 - 34 ksi; and elongation at fracture was decreased from 15 - 45% to 5 - 11%.

4) Irradiation (2 x 10^{20} nvt thermal) reduces the 1400°F UTS from 45 - 51 ksi to 32- 34 ksi; the 1400°F YS was increased slightly from about 26 - 33 ksi to 34 kwi; and elongation at fracture was decreased from 8 - 26% to 1 - 1½%.

5) Although no discernible difference between heats was observed in either the irradiated or unirradiated ORNL tests, the AI tests indicated that the 1400°F creep ductility was greater for heat 6252 than heat 5911. This phenomenon was attributed to microsegregation. It may be noted that some of the heat 6252 specimens did exhibit greater ductility at 1400°F, but uniaxial scatter prevented a definite conclusion in the ORNL tests.

6) Irradiation reduces the 1200°F rupture life of Hastelloy-N by about one decade.

7) Irradiation (2 x 10^{20} nvt) reduces the 1400°F uniaxial rupture life of Hastelloy-N by from one to two decades.

8) The ductility was apparently dependent upon strain rate; the elongation of Hastelloy-N decreased from about 3% to less than 1% when the strain rate was increased from about 10^{-5} in./in./hr to 10^{-2} in./in./hr.

9) The ORNL biaxial control specimens exhibited greater ductility than the AI biaxial control specimens but this difference was attributed to test procedure variation, not an inherent difference in material properties.

RECOMMENDATIONS:

An interesting phenomenon which deserves further investigation was the contribution of microsegregation to greater ductility in heat 6252. A detailed investigation of the history of this heat to determine how the microsegregation was produced might well be beneficial. If the microsegregation can be reproduced, further tests of material with this microstructure would be desirable to determine the extent of ductility increase that could be expected.

It is also recommended that low stress, longer rupture life ($>$2000 hour) tests be conducted to further define the strain rate effect observed in these tests.

REFERENCES:

(1) Allaria, G. G., "ORR S-2 Irradiated Hastelloy-N Biaxial Stress-Rupture Data," NAA-SR-TDR-12457 (June 2, 1967).

(2) Krupp, W. E., "Low Cycle Fatigue Tests of Irradiated Hastelloy-N (ORR S-2)," NAA-SR-TDR-12553 (To be published).

(3) Wunderlich, J. W., "Reverse Bend Fatigue Tests of Unirradiated S8DS Strip Specimens at 1400°F," NAA-SR-TDR-12558 (To be published).

(4) Lee, S. K., "Tensile and Stress-Rupture Tests of S8DS Hastelloy-N Heats - ORNL Verification Tests," NAA-SR-TDR-12550 (To be published).