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MECHANICAL PROPERTIES TEST PROGRAM
ON STRUCTURAL MATERIALS
IN A SODIUM ENVIRONMENT

by

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ABSTRACT

This document describes in detail the ongoing and planned U. S. Test program on the mechanical properties of sodium-exposed Type 316 austenitic stainless and Fe-2 $\frac{1}{4}$ Cr-1Mo ferritic steels. The ongoing test program is based on (1) the Development Requirement Specifications (DRS) established by the DOE/Clinch River Breeder Reactor Project (CRBRP) Program Office, (2) the general need for the development of LMFBR structural-design criteria established by the Nuclear Systems Materials Handbook, and (3) the need for a fundamental understanding of materials behavior in a sodium environment, which is generic to LMFBR systems. The planned test program is an extension of work based on current knowledge of sodium chemistry and the influence of sodium purity on the mechanical properties of structural materials.

1. PHILOSOPHY OF CONDUCTING MECHANICAL TESTS IN SODIUM

In general, high-temperature environments produce long-term changes in the composition and microstructure of materials which can influence the mechanical properties. To achieve some understanding of the effect of various environments on material behavior, data are generally obtained on relatively thin mechanical-test specimens after exposure to the environment for times up to 10,000 h. In laboratory experiments, the material undergoes limited changes in composition and microstructure, which may or may not result in significant changes in mechanical behavior relative to results from unexposed material. The experiments are generally conducted on a single heat of material, and the chemistry of the environment is maintained in a range that may or may not be typical of the plant conditions. Since a combination of critical parameters (e.g., time, temperature, and sodium purity) is responsible for the observed property variations, the mechanical-property data obtained in these investigations are not amenable to quantitative extrapolation to other conditions.

As an example, mechanical properties of Types 304 and 316 stainless steel were improved¹ by exposure to sodium in which the oxygen and carbon concentrations were ~1.0 and 0.3-0.6 ppm, respectively, for time periods up to 5000 h at temperatures between 550 and 700°C. Similar beneficial effects have been observed² for Type 316 stainless steel exposed to sodium containing ~0.1 ppm carbon. However, the oxygen and carbon concentrations measured in the EBR-II reactor system are ~0.8 and 0.2 ppm, respectively. Much lower carbon levels in sodium are anticipated in larger reactor systems based on a comparative analysis of the FFTF and EBR-II systems.³ The low-cycle fatigue tests were conducted with a simple loading pattern. Data on the effect of complex loading, e.g., various hold times, are minimal.

Long-term tests are necessary to establish the threshold carbon levels in the steel and in the sodium environment above which the mechanical properties of the material are adversely affected. Information on the mass of carbon picked up by the steel (which depends on both the surface carbon concentration and the depth of carbon penetration) under various sodium-purity conditions is essential to establish long-term property trend correlations that are useful to reactor designers and operators.

II. SUMMARY OF AVAILABLE RESULTS

A number of qualitative conclusions can be reached based on results from mechanical-property test programs in the U. S. and elsewhere.

In the absence of carbon transfer, the effect of sodium environment on the tensile, creep-rupture, and low-cycle fatigue properties of Type 316 stainless steel is minimal. Preexposure of the steel for ~5000 h to sodium with a carbon concentration in the range 0.1-0.6 ppm has some beneficial effect on the tensile, creep-rupture, and low-cycle fatigue properties. However, the effect of longer exposure times and complex loading patterns (especially in fatigue) has not been established. On the other hand, if the carbon concentration in sodium falls below 0.05 ppm, where the steel can undergo decarburization, preexposure can result in degradation of the properties. Very limited data are available on crack propagation rates for Type 316 stainless steel exposed to a sodium environment.

The unstabilized Fe-2 $\frac{1}{4}$ Cr-1Mo steel can undergo decarburization upon exposure to a flowing-sodium environment. Since the mechanical properties of this steel are strongly influenced by the microstructure of the material, considerable research has been conducted to evaluate the relative effects of thermal aging and decarburization on the mechanical properties of the material in a sodium environment; only preliminary results are available.

III. ONGOING DOE-SPONSORED MECHANICAL TEST PROGRAM

A. Type 316 Stainless Steel

Three heats of Type 316 stainless steel are being used in present U. S. test programs, viz., heat 8092297 (reference heat), ARD heat 53835, and FFTF heat V87210. The ANL data reported at the Bensberg conference¹ were obtained on heat V87210. The Westinghouse ARD results² were from heat 53835, whereas most of the ORNL baseline data in air were generated on heat 8092297. The compositions of the three heats and the RDT Standard for this steel are given in Table 1.

TABLE 1. Composition (in wt %) of Type 316 Stainless Steel

Element	Heat Number			RDT Standards
	V87210	53835	8092297	
C	0.058	0.065	0.057	0.04-0.10
N	0.007	--	0.03	None
P	0.026	0.032	0.024	0.03 max.
S	0.011	0.024	0.019	0.03 max.
Cr	16.7	17.5	17.25	16.0-18.0
Ni	13.9	12.1	13.48	11.0-14.0
Mn	1.43	1.50	1.86	2 max.
Si	0.46	0.33	0.58	0.75 max.
Mo	2.84	2.29	2.34	2.0-3.0
Ti	0.04	--	0.02	None
Cu	0.06	0.11	0.10	None
Co	0.03	0.12	0.02	None

Test matrices for ongoing programs, which include tensile, creep-rupture, low-cycle fatigue, and creep-fatigue tests in a sodium environment with ~0.1 ppm carbon, are given in Tables 2-5. Tests are also being conducted to evaluate effects of radial holes on creep-rupture properties of Type 316 stainless steel in a sodium environment (Table 6).

TABLE 2. Tensile Tests on Type 316 Stainless Steel Plate
Material in a Sodium Environment

Test Temp., °C	Sodium Preexposure Times, h	No. of Specimens Tested in Sodium	No. of Control Specimens Tested in Air
482	0, 2000, 5000, 10000	10	7
538	0, 2000, 5000, 10000	12	3
593	0, 2000, 5000, 10000	$\frac{23^a}{45}$	$\frac{12}{22}$

^aIncludes three tests on welded specimens, six tests each on specimens with 0.15- and 0.10-in. (3.81- and 2.54-mm) gauge diameters, and three tests on specimens with radial holes.

TABLE 3. Creep-rupture Tests on Type 316 Stainless Steel Plate Material in a Sodium Environment

Test Temp. in Sodium, °C	Sodium Preexposure Time, h	Stress Levels, MPa	No. of Specimens ^a Tested in Sodium	No. of Control Specimens ^a Tested in Air
482	2,000	355,310,276,241	12	3
	5,000	355,310,276,241	12	
	10,000	355,310,276,241	12	
538	0	355,310,376,241	9	12
	2,000	355,310,276,241	12	3
	5,000	355,310,276,241	12	
	10,000	355,310,276,241	12	
593	0	355,310,276,241	14 ^b	12
	2,000	310,241	5 ^{b,c}	8
	5,000	355,310,241	19 ^{b,c}	8
	10,000	355,310,276,241	10	46
			129	

^aNominal gauge diameter of specimen is 0.25 in. (6.35 mm).^bIncludes three precycled specimens.^cIncludes three welded specimens and six specimens each with gauge diameters of 0.15 and 0.10 in. (3.81 and 2.54 mm).

TABLE 4. Low-cycle Fatigue Tests on Type 316 Stainless Steel Plate Material in a Sodium Environment

Test Temp. in Sodium, °C	Strain Rate, s ⁻¹	Sodium Preexposure Time, h	Strain Range, %	No. of Specimens ^a Tested in Sodium	No. of Control Specimens ^a Tested in Air
482	4 x 10 ⁻³	0	2,1,0.5,0.3	12	12
		2,000	2,1,0.5,0.3	12	3
		5,000	2,1,0.5,0.3	12	3
		10,000	2,1,0.5,0.3	12	
538	4 x 10 ⁻³	2,000	2,1,0.5,0.3	9	3
		5,000	2,1,0.5,0.3	9	3
		10,000	2,1,0.5,0.3	12	
593	4 x 10 ⁻³	0	2,1,0.5,0.3	8	12
		2,000	2,1,0.5,0.3	8 ^b	12
		5,000	2,1,0.5,0.3	17 ^b	12
		10,000	2,1,0.5,0.3	12	6
	4 x 10 ⁻⁴	5,000	1	2	3
	4 x 10 ⁻²	5,000	1	2	3
				127	72

^aNominal gauge diameter of specimen is 0.25 in. (6.35 mm).^bIncludes three welded specimens and six specimens each with 0.15- and 0.10-in. (3.81- and 2.54-mm) gauge diameters.

TABLE 5. Creep-fatigue Tests on Type 316 Stainless Steel Plate Material in a Sodium Environment

No. of Specimens ^a	Test Temp., °C	Fatigue			Creep		Sequence
		Strain Range, %	No. of Cycles	Strain Rate, s ⁻¹	Stress Level, MPa	Time, h	
5 ^b	704	0.2 ^c	-	4 x 10 ⁻³	124	-	Fatigue with 0.5 h hold at 124 MPa in tension
15 ^d	593	2	50	4 x 10 ⁻³	345	F	Fatigue, then creep to failure
18 ^d	593	2	F	4 x 10 ⁻³	345	50	Creep, then fatigue to failure
3	593	2	-	4 x 10 ⁻³	345	-	Fatigue with 0.5 h hold at 345 MPa in both tension and compression
3	593	2	50	4 x 10 ⁻³	-	-	Fatigue, then tensile test to failure
$\frac{3}{47}$	593	-	-	-	345	50	Creep, then tensile test to failure

^aAll specimens preexposed to sodium for 5000 h at 593°C.

^bIncludes three specimens with radial holes.

^cMaximum stress = hold stress during creep test. If fatigue stress required to give 0.2% is greater than hold stress during creep, use reverse loading for the difference.

^dIncludes three air tests of samples aged in argon (5000 h at 593°C) and three tests each for welded specimens and specimens with 0.15- and 0.10-in. (3.81- and 2.54-mm) gauge diameter.

TABLE 6. Tests to Evaluate Effects of Radial Holes^a on Creep-rupture Properties of Type 316 Stainless Steel Plate Material in a Sodium Environment^b

Test Temp., °C	Stress Level, MPa	No. of Tests	
		Specimens with Radial Holes	Specimens without Radial Holes
593	248	3	-
704	124	3	3
704	97	3	3
Total specimens = 15			

^aRadial holes (3) of 0.070-in. (1.778-mm) diameter drilled in gauge area perpendicular to major axis and spaced at 120°C around circumference.

^bAll specimens to be exposed to 593°C sodium for 5000 h prior to testing.

TABLE 7. Composition (in wt %) of Fe-2½ Cr-1 Mo Ferritic Steels Used in DOE-sponsored Programs

Element	Heat Number	
	3P5601	C1005
C	0.12	0.09
N	0.0135	a
P	0.009	0.008
S	0.022	0.011
Cr	2.30	2.26
Ni	0.20	0.18
Mn	0.35	0.42
Si	0.27	0.22
Mo	0.96	0.96
V	-	<0.01
Ti	-	<0.01
Cu	-	0.10

^aNot available.

TABLE 8. Tensile Tests on Normalized Fe-2½ Cr-1 Mo Steel Exposed to a Sodium Environment

Test Temp., °C	Sodium-exposure Time, ^a h	No. of Tests
500	0	1
	2000	1
	4000 ^b	2
550	0	1
	2000	1
	4000 ^b	2
600	0	1
	2000	1
	4000 ^b	2
650	0	1
	1000	1
	3000 ^b	2
		16

^aSodium-exposure times are arbitrarily selected to achieve different decarburization depths. The times may be modified, if needed.

^bHalf the specimens will be thermally aged.

B. Unstabilized Fe-2½ Cr-1 Mo Ferritic Steel

Two heats of unstabilized Fe-2½ Cr-1 Mo ferritic steel, namely air-melted heat 3P5601 and ESR heat C1005, are used in DOE-sponsored programs. The compositions of the two heats are given in Table 7.

The ongoing mechanical test programs, which include tensile, creep-rupture, and low-cycle fatigue tests on sodium-exposed specimens (~0.05 ppm carbon) in either the normalized or isothermally annealed conditions, are summarized in Tables 8-12. Tensile and creep-rupture tests are also being conducted on specimens with a postweld heat treatment; the conditions are outlined in Tables 13 and 14, respectively.

TABLE 9. Tensile Tests on Isothermally Annealed Fe-2½ Cr-1 Mo Steel Exposed to a Sodium Environment

Test Temp., °C	Sodium-exposure Time, ^a h	No. of Tests
482	0	2
	2000	2
	5000 ^b	4
	8000	2
538	0	2
	2000	2
	5000 ^b	4
	8000	2
593	0	4
	2000	2
	5000 ^b	4
	8000	2
		32

^aSodium-exposure times are arbitrarily selected to achieve different decarburization depths. The times may be modified, if needed.

^bHalf the specimens will be thermally aged.

TABLE 10. Creep-rupture Tests on Normalized Fe-2½ Cr-1 Mo Steel Exposed to a Sodium Environment

Test Temp., °C	Sodium-exposure Time, ^a h	No. of Tests
500	0	3
	2000	5
	4000 ^b	10
550	0	3
	2000 ^b	5
	4000 ^b	10
600	0	3
	2000 ^b	5
	4000 ^b	10
650	0	3
	1000 ^b	5
	3000 ^b	10
		<u>72</u>

^aSodium-exposure times are arbitrarily selected to achieve different decarburization depths. The times may be modified, if needed.

^bHalf the specimens will be thermally aged.

TABLE 11. Creep-rupture Tests on Isothermally Annealed Fe-2½ Cr-1 Mo Steel Exposed to a Sodium Environment

Test Temp., °C	Sodium-exposure Time, ^a h	No. of Tests ^b
482	0	6
	2000	6
	4000	6
	6000 ^c	12
538	0	6
	1000	6
	3000	6
	5000 ^c	12
593	0	6
	500	6
	2000	6
	5000 ^c	<u>12</u>
		<u>90</u>

^aSodium-exposure times are arbitrarily selected to achieve different decarburization depths. The times may be modified, if needed.

^bCreep tests will be conducted in the stress range 69 to 249 MPa.

^cHalf the specimens will be thermally aged.

TABLE 12. Low-cycle Fatigue Tests on Isothermally Annealed Fe-2½ Cr-1 Mo Steel in a Sodium Environment

Test Temp., °C	Sodium-exposure Time, ^a h	Tests at Strain Rate of $4 \times 10^{-3} \text{ s}^{-1}$	Tests at Dual Strain Rates of $4 \times 10^{-3} / 1 \times 10^{-5} \text{ s}^{-1}$	Total Number of Tests
482	0 ^b	5	5	10
	5,000 ^b	10	-	10
	10,000	5	5	10
	Calibration	3	3	6
538	0 ^b	5	5	10
	3,000 ^b	10	5	15
	6,000	5	-	5
	Calibration	3	3	6
593	0	5	5	10
	2,000 ^b	5	-	5
	4,000 ^b	10	5	15
	Calibration	3	3	<u>6</u>
				<u>108</u>

^aSodium-exposure times are arbitrarily selected to achieve different decarburization depths. The times may be modified, if needed.

^bHalf the specimens will be thermally aged.

TABLE 13. Tensile Tests for Isothermally Annealed Fe-2½ Cr-1 Mo Steel with Postweld Treatment, Exposed to a Sodium Environment

Test Temp., °C	Sodium-exposure Time, h	No. of Tests
482	0	1
	5000 ^a	2
538	0	1
	5000 ^a	2
593	0	1
	5000 ^a	2
		<u>9</u>

^aHalf the specimens will be thermally aged.

TABLE 14. Creep-rupture Tests on Isothermally Annealed Fe-2½ Cr-1 Mo Steel with Postweld Treatment, Exposed to a Sodium Environment

Test Temp., °C	Sodium-exposure Time, h	No. of Tests
482	0	5
	5000 ^a	10
538	0	5
	5000 ^a	10
593	0	5
	5000 ^a	10
		<u>45</u>

^aHalf the specimens will be thermally aged.

Mechanical-property evaluations of the Fe-2½ Cr-1 Mo ferritic steel are also being performed relative to requirements established for the CRBR steam generators. In this program, test specimens are decarburized to a desired carbon level, and mechanical tests are performed at 510°C. Tensile, uniaxial and biaxial creep-rupture, and strain-ratchetting tests on decarburized ferritic steel are summarized in Tables 15-18. Limited fatigue crack-growth tests are planned on the steel at 510°C, and these are listed in Table 19.

TABLE 15. Tensile Tests^a on Fe-2½ Cr-1 Mo Steel Decarburized in a Sodium Environment

Bulk Carbon Content in Steel, ppm	No. of Tensile Tests at Strain Rate of $6.7 \times 10^{-5} \text{ s}^{-1}$
950	2
850	2
750	2
950, ^b tT (750)	2
650	2
550	2
950, ^b tT (550)	2
450	2
350	2
950, ^b tT (350)	2
250	2
150	2
950, ^b tT (150)	2
	<u>26</u>

^aAll tests conducted at 510°C.

^bSame time at temperature as sample decarburized to level indicated in (), to isolate thermal aging effects.

TABLE 16. Uniaxial Creep Tests^a on Fe-2½ Cr-1 Mo Steel
Decarburized in a Sodium Environment

Bulk Carbon Content in Steel, ppm	Equivalent Stress Values, MPa		No. of Specimens
	Base Metal	Autogenous Welds	
950	120,130,150,172	130	5
650	120,130,150,172	130	5
950, ^b tT (650)	120,172		2
850	130		1
750	130		1
550	130		1
450	130		1
950, ^b tT (450)	130		1
800	-	130	1
500	-	130	1
300	-	130	<u>1</u> 20

^aAll tests conducted at 510°C.

^bSame time at temperature as sample decarburized to level indicated in (), to isolate thermal aging effects.

TABLE 17. Biaxial Creep Tests^a on Fe-2½ Cr-1 Mo Steel
Decarburized in a Sodium Environment

Bulk Carbon Content in Steel, ppm	Equivalent Stress Values, MPa	No. of Specimens
950	172,130,100,80	4
450	172,130,100,80	4
950, ^b tT (450)	172,130,80	3
850	130	1
750	130,100	2
950, ^b tT (750)	130	1
650	130,100	2
550	130	1
950, ^b tT (550)	130	1
350	130	1
250	130	<u>1</u> 21

^aAll tests conducted at 510°C.

^bSame time at temperature as sample decarburized to level indicated in (), to isolate thermal aging effects.

TABLE 18. Strain Ratchetting Tests on Fe-2½ Cr-1 Mo Steel Decarburized in a Sodium Environment

Test Temp., °C	Strain Range $\Delta\epsilon_t$, %	$\gamma = \sigma_a / \sigma_y$	Frequency, Hz	No. of Tests
RT	0.4	0,0.15,0.3,0.45	0.01	4
316	0.4	0,0.15,0.3,0.45	0.01	4
510	0.4	0,0.15,0.3,0.45	0.1	4
RT	0.8	0,0.15,0.3,0.45	0.01	4
		0.3	0.001	1
316	0.8	0,0.15,0.3,0.45	0.01	4
		0.3	0.001	1
510	0.8	0,0.15,0.3,0.45	0.01	4
		0.3	0.001	1
RT,	-	For yield strength, σ_y , determination		1
316,	-			1
510	-			1
				<u>30</u>

TABLE 19. Fatigue Crack-growth Tests on Fe-2½ Cr-1 Mo/I82 Material at 510°C

ΔK , MPa $\sqrt{\text{mm}}$ (Frequency 0.5 cpm)	No. of Tests in	
	Air	Sodium
166.3	1	1
151.2	1	
136.1	1	1
121.0	1	
105.8	1	1
90.7	1	1
75.6	1	1
60.5	1	1
	<u>8</u>	<u>6</u>

IV. GENERAL RECOMMENDATIONS AND ADDITIONAL TEST PROGRAMS

Most of the ongoing programs encompass a narrow range of sodium-purity conditions. It is imperative that the mechanical behavior of the materials be established under a wider range of sodium-purity conditions to assess the influence of off-normal situations on the performance of structural components. Realistic evaluations of the extent of contamination of the sodium by carbonaceous material should be made to establish the upper bound for the carbon level in reactor-sodium systems. When this has been determined, experiments should be performed in which Type 316 stainless steel specimens are exposed to sodium containing the appropriate carbon concentrations and subsequently creep-rupture or low-cycle fatigue tested. A minimum test matrix for this type of program is given in Table 20.

TABLE 20. Creep-rupture and Low-cycle Fatigue Tests on Type 316 Stainless Steel Exposed to Sodium Containing 1.0-2.0 ppm Carbon

Test Temp., °C	Sodium-exposure Time, h	Number of Tests	
		Creep-rupture	Low-cycle Fatigue
500	3,000	6	5
	5,000 ^a	12	10
	10,000 ^a	12	10
550	3,000	6	5
	5,000 ^a	12	10
	10,000 ^a	12	10
600	3,000	6	5
	5,000 ^a	12	10
	10,000 ^a	12	10
650	3,000	6	5
	5,000 ^a	12	10
	10,000 ^a	12	10
		120	100

^aHalf the specimens will be thermally aged.

Also, mechanical-test data on specimens that have been exposed for long periods of time to sodium of "normal" purity are required to verify the beneficial effects of sodium observed in short-term tests and to aid in long-term extrapolations of the results. The recommended test matrix for this program is listed in Table 21.

TABLE 21. Long-term Creep-rupture and Low-cycle Fatigue Tests on Type 316 Stainless Steel Exposed to Sodium of "Normal" Purity

Test Temp., °C	Sodium-exposure Time, h	Number of Tests ^a	
		Creep-rupture	Low-cycle Fatigue
500	10,000	12	10
	20,000	12	10
	30,000	12	10
550	10,000	12	10
	20,000	12	10
	30,000	12	10
600	10,000	12	10
	20,000	12	10
	30,000	12	10
650	10,000	12	10
	20,000	12	10
	30,000	12	10
		144	120

^aHalf the specimens will be thermally aged.

Very limited data are available on the effect of sodium on high-cycle fatigue properties of Type 316 stainless steel. A few long-term tests, in which the anticipated high-cycle fatigue life is $\sim 10^8$ cycles, are proposed (see Table 22). These tests will establish whether the enhanced life derived from a sodium environment can be used in evaluations of thermal-stripping problems in upper-core internals.

TABLE 22. High-cycle Fatigue Tests on Type 316 Stainless Steel in a Sodium Environment

Test Temp., °C	Fatigue Life, N_f	No. of Tests
550	10^8	4
600	10^8	4

V. COST ESTIMATES

The present mechanical-test programs at various laboratories were initiated within the past six years, and consequently, no overall manpower estimate was made. However, based on past experience with the maintenance of specimen-exposure facilities and the performance of mechanical tests in and out of sodium, manpower estimates are presented in Table 23 for the recommended future programs.

TABLE 23. Manpower Estimates for Newly Recommended Test Programs

Test (Identified by Table No.)	Effort, Man-years				
	FY 1980	FY 1981	FY 1982	FY 1983	FY 1984
20	3	5	5	3	
21	3	3	4	5	
22	3	5	3	-	-

The DOE contractors responsible for various facets of the mechanical-test program are listed in Table 24.

TABLE 24. DOE Contractors Responsible for Various Test Programs

Mechanical-property Test (Identified by Table Nos.)	DOE Contractor
2-6	Westinghouse Advanced Reactors Division, Waltz Mill, PA
8-14	Argonne National Laboratory, Argonne, IL
15-19	General Electric Company, San Jose, CA
20-22 ^a	

^a Recommended programs.

VI. SUMMARY

Details of the ongoing DOE-sponsored mechanical-property test programs were described. Additional programs relevant to LMFBR design and operation were proposed, and manpower estimates for the work were provided.

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