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NUREG/CR-3728
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Effect of Temperature on the Stress-Relaxation Response of a Pressure Vessel Steel

G. M. Goodwin
R. K. Nanstad

Prepared for the
U.S. Nuclear Regulatory Commission
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EFFECT OF TEMPERATURE ON THE STRESS-RELAXATION RESPONSE OF A PRESSURE VESSEL STEEL

G. M. Goodwin and R. K. Nanstad

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CONTENTS

EFFECT OF TEMPERATURE ON THE STRESS-RELAXATION RESPONSE OF A PRESSURE VESSEL STEEL*

G. M. Goodwin and R. K. Nanstad

ABSTRACT

Extensive cracking in the steam generator shells at Indian Point Station Unit 3 led to questions as to the effectiveness of the postweld heat treatment (PWHT) used during fabrication. A literature review revealed an absence of stress-relaxation data for the steels of interest, SA-302, grade B, and SA-533, grade B.

This investigation was undertaken to characterize the stress-relaxation response at various PWHT temperatures and to determine the correlation, if any, with other measurable properties, such as hardness. A novel technique utilizing a closed-loop thermal-mechanical simulator, the Gleeble 1500, was developed and used.

After producing a microstructure typical of a portion of the heat-affected zone (HAZ) of a weldment, we tested stress relaxation at eight temperatures, 482, 510, 538, 566, 593, 621, 649, and 677°C (900, 950, 1000, 1050, 1100, 1150, 1200, and 1250°F). We determined that 20 min (1200 s) was an adequate test time and that the magnitude of stress measured agreed with limited literature data for comparable materials. Substantial stress relaxation was noted at 593°C (1100°F) and above. Post-test hardness correlated very well with relaxation data.

BACKGROUND

In March 1982, the shells of the steam generators at Indian Point Station Unit 3 were found to have extensive cracking of the girth weld joining the upper cylinder to the transition cone.[1] One steam generator, number 32, had a through-wall crack. This weld was different from the other welds in the steam generators in that it was locally postweld heat treated (PWHT) rather than furnace heat treated. The shell material was identified as SA-302, grade B, low-alloy steel.

Failure analyses[2,3] identified the mode of cracking to be transgranular and characteristic of low-cycle corrosion fatigue. The girth weld heat-affected zone (HAZ) hardness was found to be HRC 39 to 41 (dph 382–402). Reheat treatment for 1 h at 538 and 593°C (1000 and 1100°F) reduced hardness to HRC 30 to 32 (dph 302–318) and HRC 28 to 29 (dph 286–294), respectively. These data imply the presence of commensurately high residual

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stresses in the girth weld, which were not relieved by the PWHT applied in fabrication of the vessel. These stresses could be additive to service stresses and could thus reduce the fatigue life.

An investigation was undertaken to characterize the stress-relaxation response of low-carbon manganese-molybdenum steel at various PWHT temperatures and to determine the correlation, if any, with other measurable properties, such as hardness.

MATERIALS

Actual material from the affected steam generators was not available for this study, so we tried to locate material with approximately the same composition. Table 1 shows the specification limits for SA-302 grade B and the actual steam generator material analysis, compared with the specification for SA-533 grade B and the analysis of plate 04 from the ORNL Heavy Section Steel Technology (HSST) Program.[4] The specifications for SA-302 grade B and SA-533 grade B differ only in nickel content, unspecified in SA-302 and 0.37–0.73 wt % in SA-533. The upper-shell material from steam generator 32 has a nickel content of 0.50 wt %, so it meets the specification limits for SA-533, grade B, and is, in fact, essentially

Table 1. Specification limits and chemical analyses of manganese-molybdenum pressure vessel steels

Element	Content (wt %)			
	SA-302 grade B		SA-533 grade B	
	Specification[a]	Indian Point[b]	Specification[a]	HSST 04[c]
Carbon	0.25 max	0.24	0.25 max	0.23[d]
Manganese	1.07–1.62	1.48	1.07–1.62	1.48
Phosphorus	0.035 max	0.011	0.035 max	0.009
Sulfur	0.040 max	0.019	0.040 max	0.015
Copper		0.01–0.09		0.12
Nickel		0.50	0.37–0.73	0.62
Chromium		0.11		0.14
Molybdenum	0.41–0.64	0.51	0.41–0.64	0.49
Silicon	0.13–0.45	0.25	0.13–0.45	0.25
Aluminum		0.01–0.09		0.03

[a]Product analyses, *ASME Boiler and Pressure Vessel Code*, IIA, 1983 edition.

[b]Check analysis of upper shell of steam generator 32, unit 3, Indian Point Nuclear Station.

[c]Check analysis of plate 04, HSST Program, reference four.

[d]Ladle analysis.

identical with HSST plate 04. Material from plate 04 was used for all the tests in this study. The presence of nickel in that amount indicates that SA-302, grade B (modified), the precursor specification to SA-533, grade B, was supplied for fabrication of the steam generator.

APPROACH

A brief review of the literature, including a very recent comprehensive compilation of stress-relaxation data[5] revealed an absence of data for manganese-molybdenum pressure vessel steels. The scope of this program precluded an extensive investigation using conventional methods, so a novel technique utilizing a closed-loop thermal-mechanical simulator, the Gleeble 1500, was developed and used.

The Gleeble 1500 is a computerized testing device, which precisely and independently controls thermal and mechanical operations on a bulk specimen. The specimen is heated by its resistance to the flow of electrical current, and mechanical loading is by a servo-hydraulic loop. The system is shown in Fig. 1.

Y-193784

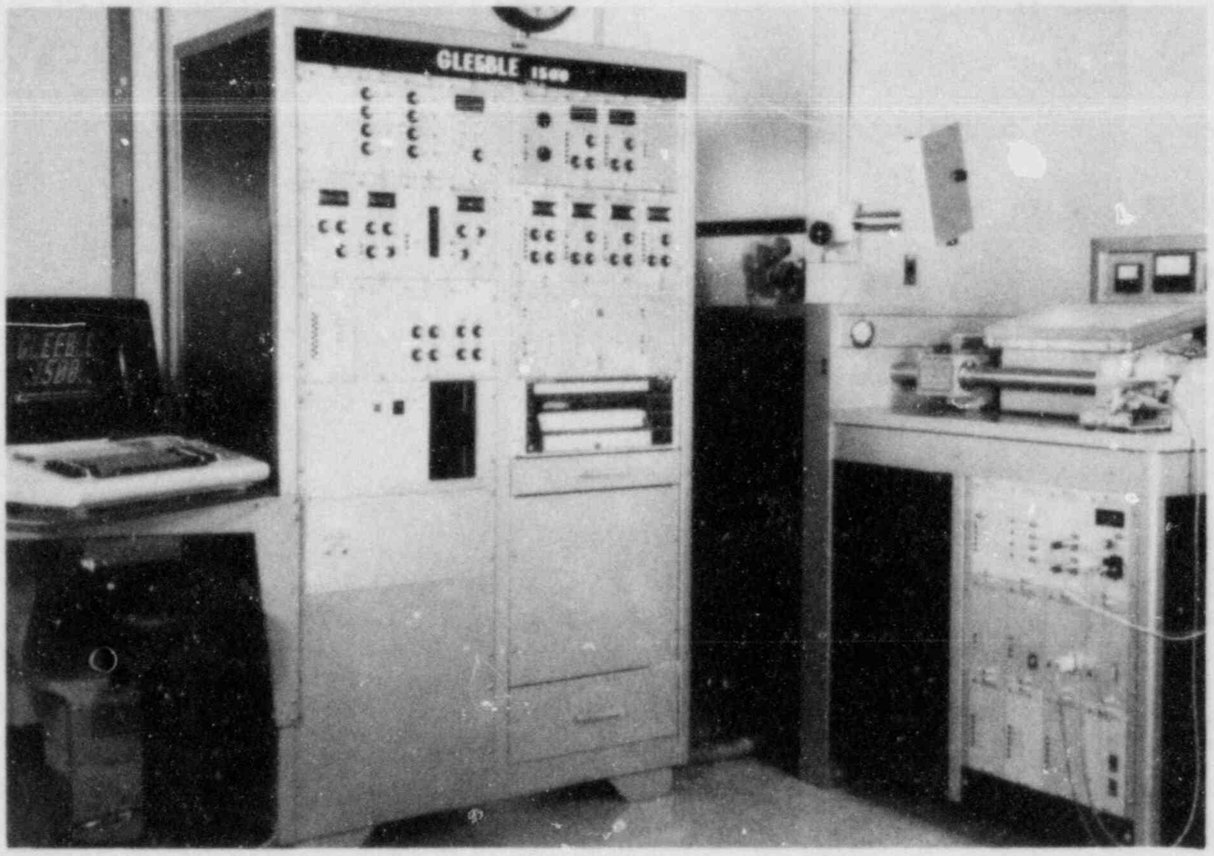

Fig. 1. Gleeble 1500 thermal-mechanical simulator.

The technique used in this study first involved producing a microstructure in the specimen typical of a portion of the HAZ of a weldment. This was done by imposing a thermal cycle on the gage section of the 6.3-mm-diam (1/4-in.) rod specimen with peak temperature and heating and cooling rates representative of a real weldment. The thermal cycle selected, shown in Fig. 2 and detailed in the appendix, has a peak temperature of 1093°C (2000°F) and a cooling rate approximately in the middle of the range investigated by Klumpes in his study of similar materials.[6] According to Lundin's results,[7] the curve should pass through a portion of the bainite nose on cooling, but the resulting untempered hardness, RC 48 (dph 489), suggests essentially 100% martensite.[8] The microstructures as received and untempered, that is, treated at 1093°C (2000°F) but with no stress relief, are shown in Fig. 3. The as-received (quenched and tempered) microstructure appears to be composed primarily of tempered bainite with possibly some retained austenite. We do not know from which depth in the 300-mm-thick (12-in.) plate the material was removed. The simulated HAZ microstructure is much finer because of the short time in the austenitization range; it consists primarily of martensite and lower bainite. More detailed microstructural investigations are planned with these materials. The detailed program for the thermal cycle is appended to this report.

After the simulated HAZ structure was produced and the specimen was cooled to room temperature, stress-relaxation testing was performed. Eight temperatures were used, 482, 510, 538, 566, 593, 621, 649, and 677°C, (900, 950, 1000, 1050, 1100, 1150, 1200, and 1250°F). The

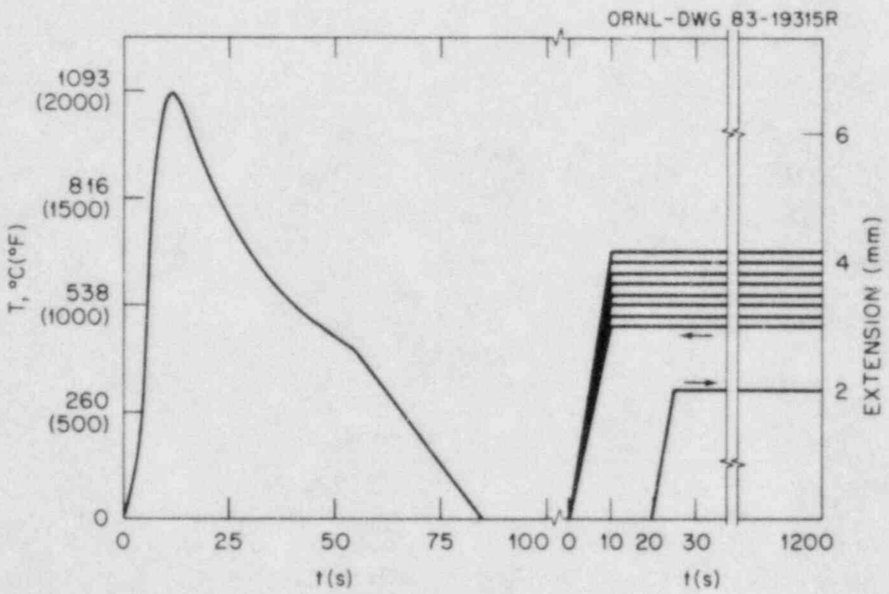

Fig. 2. Thermal-mechanical cycle used in stress-relaxation tests.

Y-194302

(*a*) 80 μm

Y-194301

(*b*) 80 μm

Fig. 3. Microstructure of SA-533, grade B, steel (*a*) as received, and (*b*) after exposure to 1093°C (2000°F) peak temperature thermal cycle.

program, which is shown schematically in Fig. 2 and detailed in the appendix, involves heating to the test temperature in 10 s, equilibrating 10 s, loading to 2 mm extension linearly in 5 s, and then holding at this extension for a minimum of 1200 s as the load decays.

An extension of 2 mm was chosen to assure that yielding occurs at temperature. The standard Gleeble specimen is approximately 100 mm (4 in.) in length with threaded ends, but only the central portion (about 12 mm) is heated to temperature. The 2 mm extension is thus equivalent to about 2% strain overall or roughly 16% in the heated section, if it accommodates most of the deformation.

RESULTS AND DISCUSSION

The data obtained are given in Table 2 and shown graphically in Figs. 4 through 6. Initial stress σ_0 and relaxed stress after 1200 s σ_{20} were calculated by dividing the respective loads by the cross-sectional area measured after test. This takes into account the reduction of cross section by the loading and the presumably small additional reduction of area resulting from creep and relaxation during the test. This approach is validated by the observation that the highest test temperature, 677°C (1250°F), resulted in a total area reduction measured after test of only 8.6% at the midpoint of the specimen gage length. The total reduction includes loading and creep relaxation. This indicates a small effect of total cross-sectional area change on calculated initial stress, so the contribution of creep during test is very likely negligible.

Note from Fig. 4 that, for all temperatures, the 1200-s test duration is sufficiently long to permit the relaxation rate to become very low.

A thermal ramp test determined the temperature at which zero strength occurs, inferred to be the onset of melting, to be 1380°C (2516°F), so the test temperatures are approximately 0.46 to 0.57 times the absolute melting temperature.

The magnitude of the stresses measured agrees with British data on Cr-Mo-V steel,[9] which show 75.2 MPa (10.9 ksi) remaining stress after 1200 s at 704°C (1300°F) compared with 110.3 MPa (16.0 ksi) at 677°C (1250°F) in this study. The high values of initial stress at all temperatures confirm that loading to above yield strength was accomplished for all test conditions.

The relaxation data are shown in the conventional form, σ/σ_0 vs log time, in Fig. 5. No explanation is offered for the crossover of the data for 593 and 621°C (1100 and 1150°F), but it is apparent from the plot that 593°C is the temperature at which substantial stress relaxation begins.

Table 3 gives the hardness values measured on the tested specimens. Figure 6 compares the remaining stress after 1200 s, σ_{20}, with hardness as a function of test temperature. The correlation is excellent, and above 593°C (1100°F) both quantities are significantly reduced. Also shown on

Table 2. Stress relaxation in ASME SA-533, grade B, steel

(All tests performed on a Gleeble model 1500 after initial exposure to 1093°C (2000°F) peak temperature thermal cycle and cooled to room temperature; σ_0 = initial stress; σ_{20} = stress remaining after 1200 s)

Temperature		Stress [MPa (ksi)]		σ_{20}/σ_0 (%)	Time (s) to various fractions of σ_0								
(°C)	(°F)	σ_0	σ_{20}		0.9	0.85	0.8	0.75	0.7	0.6	0.5	0.4	0.3
482	900	440 (63.9)	345 (50.0)	78	26	161	661	>1200	>1200	>1200	>1200	>1200	>1200
510	950	449 (65.1)	348 (50.4)	78	15	85	451	>1200	>1200	>1200	>1200	>1200	>1200
538	1000	434 (63.0)	321 (46.5)	74	14	70	253	808	>1200	>1200	>1200	>1200	>1200
566	1050	439 (63.6)	321 (46.5)	73	12	42	132	468	>1200	>1200	>1200	>1200	>1200
593	1100	467 (67.7)	301 (43.6)	64	6	16	54	111	>1200	>1200	>1200	>1200	>1200
621	1150	416 (60.4)	234 (33.9)	56	8	22	42	71	131	615	>1200	>1200	>1200
649	1200	434 (63.0)	185 (26.8)	43	2	4	6	12	23	89	380	>1200	>1200
677	1250	438 (63.5)	110 (16.0)	25	0.5	1	2	4	8	22	72	192	549

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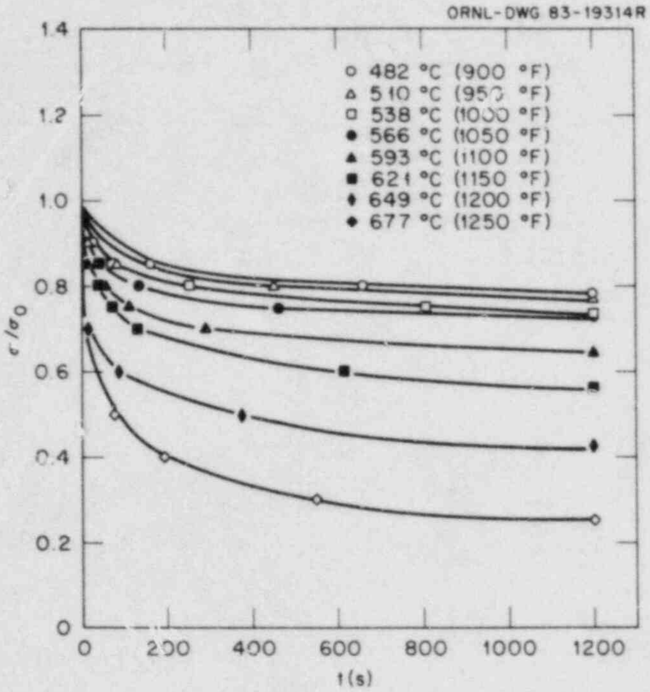

Fig. 4. Stress relaxation versus time for SA-533, grade B, steel.

ORNL-DWG 83-19312R

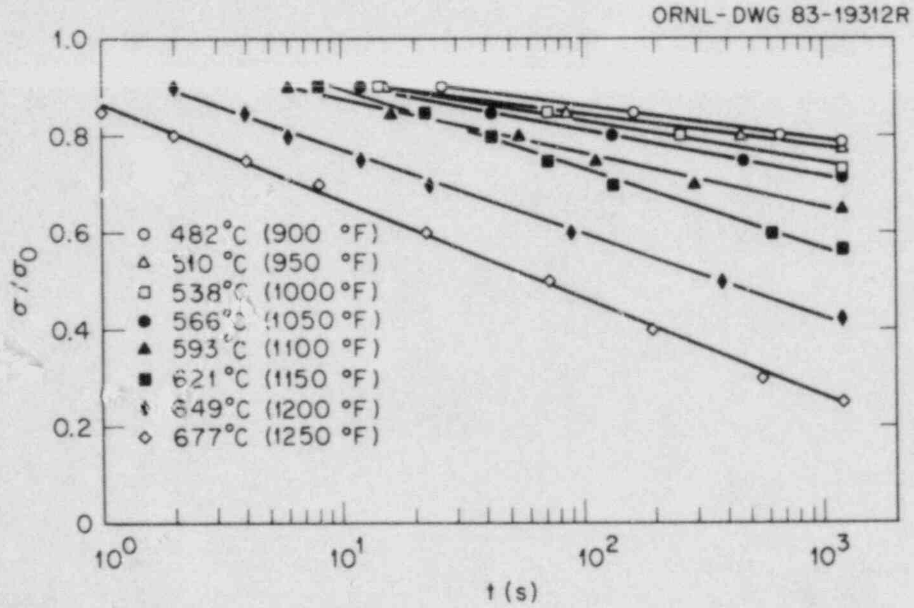

Fig. 5. Stress relaxation versus log time for SA-533, grade B, steel.

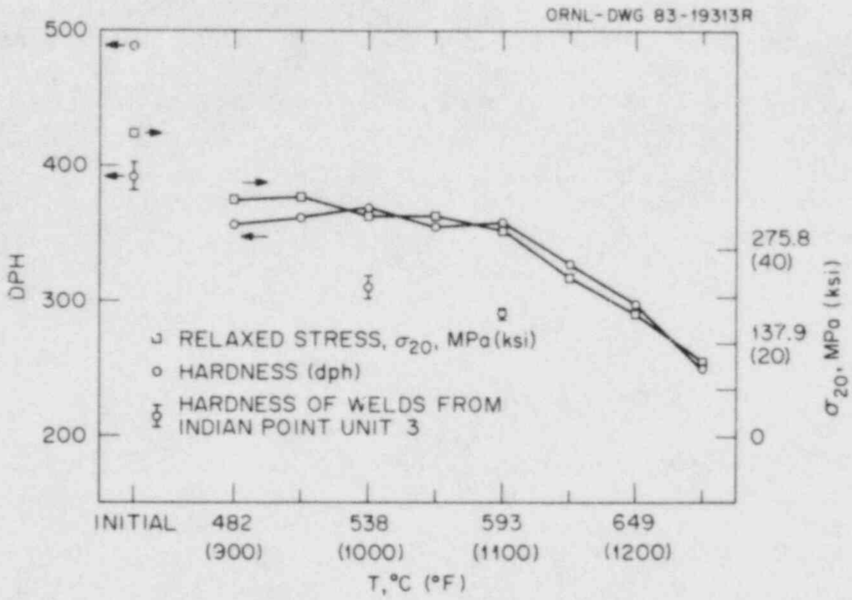

Fig. 6. Hardness and relaxed stress versus temperature for SA-533, grade B, steel.

Table 3. Hardness of stress-relaxation specimens

(Average of three readings made with Kentron diamond pyramid microhardness tester)

Test temperature (°C)	Test temperature (°F)	Hardness (dph)
Untempered		489
482	900	356
510	950	362
538	1000	369
566	1050	355
593	1100	358
621	1150	328
649	1200	298
677	1250	250

the plot are the average initial stress σ_0 [439.9 MPa, (63.8 ksi)], the untempered hardness (489 dph), and the peak HAZ hardness measured on the failed steam generator, as removed from service (382–402 dph) and after heat treating 1 h at 538°C (1000°F) (302–318 dph) and at 593°C (1100°F) (286–294 dph).

Optical metallography showed no observable changes in microstructure from the untempered condition [Fig. 3(*b*)] for any of the stress-relaxation test conditions.

CONCLUSIONS

On the basis of this study, we can make the following statements. The Gleeble 1500 can be successfully used to assess stress-relaxation behavior. For the material of interest [SA-302, grade B (modified with 0.5 Ni); SA-533, grade B] and the temperatures studied, 482 to 677°C (900–1250°F), a test can be accomplished in 1200 s relaxation time. The magnitude of stresses measured agrees with the very limited literature data. Substantial stress relaxation occurs at 593°C (1100°F) and above. Posttest hardness correlates very well with the relaxation data. Although toughness was not addressed in this investigation, the high hardness of the service weld and of the lower temperature stress-relaxation specimens indicate that it would be prudent to characterize the toughness of these materials as a function of PWHT temperature.

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Appendix

GLEBBLE PROGRAM FOR THERMAL CYCLES

The programs detailed in this appendix are the actual thermomechanical programs use to produce the simulated heat-affected zone and to perform the stress-relaxation tests.

```
* THIS IS A THERMAL CYCLE PROGRAM TO SIMULATE A HEAT AFFECTED ZONE IN STEELS.
* ACTUAL TEMPERATURE-RED CURVE; PROGRAMMED TEMPERATURE-BLACK CURVE.
* CHART SPEED - 10 CM/MIN. ; BOTH CHANNELS SET AT 2V.
* 2000 DEG. C FULL SCALE.
* SEPT.21,1983 ; RWR
MECHANICAL RANGE = 0 - 10
PT.         TIME       TEMP  MODE    MECH    NO. OF  RETURN     CONTROL
                                             LOOPS   POINT    SWITCHES ON
0001 | 000:01.000 | 0000 |      | 00.000 | ---- | ----   | 2
0002 | 000:01.000 | 0000 |      | 00.000 | ---- | ----   | 0,2
0003 | 000:01.000 | 0020 |      | 00.000 | ---- | ----   | 0,2
0004 | 000:01.000 | 0057 |      | 00.000 | ---- | ----   | 0,2
0005 | 000:01.000 | 0125 |      | 00.000 | ---- | ----   | 0,2
0006 | 000:01.000 | 0222 |      | 00.000 | ---- | ----   | 0,2
0007 | 000:01.000 | 0389 |      | 00.000 | ---- | ----   | 0,2
0008 | 000:01.000 | 0645 |      | 00.000 | ---- | ----   | 0,2
0009 | 000:01.000 | 0844 |      | 00.000 | ---- | ----   | 0,2
0010 | 000:01.000 | 0953 |      | 00.000 | ---- | ----   | 0,2
0011 | 000:01.000 | 1023 |      | 00.000 | ---- | ----   | 0,2
0012 | 000:01.000 | 1064 |      | 00.000 | ---- | ----   | 0,2
0013 | 000:01.000 | 1089 |      | 00.000 | ---- | ----   | 0,2
0014 | 000:00.500 | 1093 |      | 00.000 | ---- | ----   | 0,2
0015 | 000:00.500 | 1091 |      | 00.000 | ---- | ----   | 0,2
0016 | 000:01.000 | 1071 |      | 00.000 | ---- | ----   | 0,2
0017 | 000:01.000 | 1057 |      | 00.000 | ---- | ----   | 0,2
0018 | 000:02.000 | 0997 |      | 00.000 | ---- | ----   | 0,2
0019 | 000:02.000 | 0936 |      | 00.000 | ---- | ----   | 0,2
0020 | 000:02.000 | 0874 |      | 00.000 | ---- | ----   | 0,2
0021 | 000:02.000 | 0826 |      | 00.000 | ---- | ----   | 0,2
0022 | 000:02.000 | 0783 |      | 00.000 | ---- | ----   | 0,2
0023 | 000:02.000 | 0745 |      | 00.000 | ---- | ----   | 0,2
0024 | 000:02.000 | 0710 |      | 00.000 | ---- | ----   | 0,2
0025 | 000:02.000 | 0678 |      | 00.000 | ---- | ----   | 0,2
0026 | 000:05.000 | 0601 |      | 00.000 | ---- | ----   | 0,2
0027 | 000:05.000 | 0541 |      | 00.000 | ---- | ----   | 0,2
0028 | 000:05.000 | 0494 |      | 00.000 | ---- | ----   | 0,2
0029 | 000:10.000 | 0418 |      | 00.000 | ---- | ----   | 0,2
0030 | 000:30.000 | 0000 |      | 00.000 | ---- | ----   | 0,2
0031 | 000:02.000 | 0000 |      | 00.000 | ---- | ----   |

 END OF TABLE
```

*THIS IS A LOAD RELAXATION PROGRAM ON A A-533 MATERIAL FOR G.M. GOODWIN.
*RED CURVE,ACTUAL TEMP.,SET AT 2V.; BLUE CURVE,STROKE,SET AT 2V.
*GREEN CURVE,FORCE OR LOAD,SET AT 5V. CHART SPEED-4 CM/MIN..
*SEPT.21,1983 ; RWR
MECHANICAL RANGE = 0 - 10

PT.	TIME	TEMP	MODE	MECH	NO. OF LOOPS	RETURN POINT	CONTROL SWITCHES ON
0001	000:08.000	0000		00.000	----	----	1,2,3
0002	000:02.000	0000		00.000	----	----	0,1,2,3
0003	000:10.000	0649		00.000	----	----	0,1,2,3
0004	000:10.000	0649		00.000	----	----	0,1,2,3
0005	000:05.000	0649		00.200	----	----	0,1,2,3
0006	030:00.000	0649		00.200	----	----	0,1,2,3
0007	000:02.000	0000		00.200	----	----	

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16. ABSTRACT (200 words or less)

Extensive cracking in the steam generator shells at Indian Point Station Unit 3 led to questions as to the effectiveness of the postweld heat treatment (PWHT) used during fabrication. A literature review revealed an absence of stress-relaxation data for the steels of interest, SA-302, grade B, and SA-533, grade B.

This investigation was undertaken to characterize the stress-relaxation response at various PWHT temperatures and to determine the correlation, if any, with other measurable properties, such as hardness. A novel technique utilizing a closed-loop thermal-mechanical simulator, the Gleeble 1500, was developed and used.

After producing a microstructure typical of a portion of the heat-affected zone (HAZ) of a weldment, we tested stress relaxation at eight temperatures, 482, 510, 538, 566, 593, 621, 649, and 677°C (900, 950, 1000, 1050, 1100, 1150, 1200, and 1250°F). We determined that 20 min (1200 s) was an adequate test time and that the magnitude of stress measured agreed with limited literature data for comparable materials. Substantial stress relaxation was noted at 593°C (1100°F) and above. Post-test hardness correlated very well with relaxation data.

17. KEY WORDS AND DOCUMENT ANALYSIS	17a. DESCRIPTORS

17b. IDENTIFIERS/OPEN-ENDED TERMS

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