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THERMAL RATCHETTING IN PIPES SUBJECTED TO INTERMITTENT THERMAL DOWNSHOCKS AT ELEVATED TEMPERATURES*

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ABSTRACT

Many of the structural design problems requiring inelastic analyses in high-temperature, liquid-metal-cooled reactor system components result from the frequent thermal transients that can occur. These transients can, if sufficiently severe, produce progressive inelastic deformations (ratchetting). This paper presents the results of two thermal ratchetting tests on straight sections of pipe. The pipes, each of which was machined from a well-characterized heat of type 304 stainless steel, were subjected to a series of thermal downshocks on their inner surface, followed by sustained periods under an internal pressure loading at a temperature of 1100°F. Testing was carried out in a special sodium test facility built for the purpose, and the outer surface strain histories were measured using high-temperature capacitive strain gages. The circumferential strain responses, which typify the inelastic behaviors, are presented.

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INTRODUCTION

Transient thermal loadings are an important design consideration in many high-temperature components. For example, power changes in liquid-metal fast-breeder reactors, particularly during shutdowns and scrams, can, because of the good heat-transfer characteristics of the sodium coolant, cause rapid temperature drops throughout the coolant system. These intermittent thermal downshocks can, in turn, produce progressive inelastic deformations (ratchetting) and significant creep-fatigue damage in the system components. Although a number of investigators have discussed simplified methods of estimating or bounding ratchetting strains (Refs. 1–5), a detailed evaluation of these effects requires that a detailed inelastic analysis be performed.

This paper presents the results of two thermal ratchetting tests on straight sections of pipe. The primary objectives of these tests were to: (a) provide carefully obtained ratchetting test data for evaluating basic inelastic analysis procedures; and (b) provide experimental data for verification and qualification of inelastic analysis computer programs by benchmark problem calculations.

The test specimens were 8-in.-diam x 0.375-in. wall pipe from a well-characterized heat (designated 9T2796) of type 304 stainless steel.* The tests, which were performed in a special high-temperature sodium test facility built for the purpose, each consisted of periodic thermal downshocks in the internal sodium temperature from 1100 to 800°F separated by sustained periods under internal pressure at 1100°F. Temperature distributions and outside surface strains were recorded during each test. Results are presented that typify the response of each specimen.

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*Representative inelastic properties of this heat of material are presented in the appendix of this booklet.

The remaining sections of this paper are arranged to facilitate use of the two pipe thermal ratchetting tests as benchmark problems. The problem descriptions are given in the first section. Included are the dimensions of the test specimens and the precise thermal and mechanical loading histories for each test. This information is intended to be sufficiently complete to allow the analyst to set up and carry out an inelastic analysis of each test. The second section briefly describes the sodium test facility, the test piece assembly, the test instrumentation, and the experimental approach. The experimentally measured results are given in the third section, and finally, the fourth section contains a brief discussion of the results.

PROBLEM DESCRIPTION

Each pipe test specimen was a 30-in.-long section of pipe having an outside diameter of 8.44 in. and a wall thickness of 0.375 in. The specimens were welded, after final annealing, to adjacent extensions of 8-in. stainless steel pipe of the same dimensions. The annealing heat treatment consisted of heating the specimens to 2000°F for 1/2 hr and then forced-air cooling rapidly to room temperature.

The nominal sodium temperature and pressure histories for each test are depicted in Fig. 1. In the first test (TTT-1), the normal sodium temperature and pressure were 1100°F and 700 psi respectively, during the long-term hold periods. The thermal downshock was from 1100 to 800°F at a nominal rate of 30°F/sec. Near adiabatic conditions were maintained on the outer surface of the specimen during each thermal transient. At 800°F, the internal pressure was removed, reapplied, and the temperature was slowly returned to 1100°F at a rate of 50°F/hr. The specimen was then held at 1100°F and subjected to the internal pressure of 700 psi for a period of 160 hr before the next transient was initiated. The total cycle time was 168 hr (one week), with approximately 2 hr spent at 800°F and 6 hr spent in heating from 800 to 1100°F. The first specimen was subjected to a total of 13 cycles.

The second specimen was subjected to a total of 23 cycles. The first five cycles consisted of a thermal downshock from 1100 to 800°F at a nominal rate of 22.8°F/sec. The internal pressure was 400 psi, and the hold period at 1100°F was 328 hr (total cycle time, two weeks). Following the initial five cycles, the conditions were increased in severity to match those used in the first test. Thirteen of these more severe cycles were imposed; finally, the original conditions were used for the final five cycles. The total test time for the second specimen was thus 33 weeks.

The idealized ramp transient shown in Fig. 1 was not actually obtained in the tests. The actual measured sodium thermal transients imposed on the pipe specimens are shown in Fig. 2. These transients were measured at the center of the test sections. They were reproducible from cycle to cycle and test to test, and they should be used as the thermal transients in any inelastic analyses.

The test facility in which the specimens were tested was designed to virtually eliminate piping reactions on the pipe ratchetting test assemblies. Thus, each test specimen can be analyzed as an infinitely long straight pipe with only the internal pressure loading acting in the axial direction.

TEST APPROACH

Figure 3 is a schematic diagram of the Thermal Transient Test Facility (TTTF) which was designed to subject a test specimen to internal pressures and intermittent thermal downshocks to produce thermal ratchetting. The principal sodium components, starting from the top and following the direction of sodium flow down to the drain tank, are the source tank, pipe nest, test piece assembly, orifice run, thermal capacitance tank, sodium shutoff valve, and the drain tank. The appropriate thermal transient is obtained by grading the temperature of the sodium in the pipe nest, from 800°F at the source tank to 1100°F at the test specimen. A high-pressure argon system is used to maintain the appropriate level of internal pressure in the test specimen during both the long-term hold periods at 1100°F and the thermal transients. The sodium shutoff valve is opened to initiate the thermal transient; the orifice run controls the rate of sodium flow during the transient; and the thermal capacitance tank mitigates the thermal shock before it reaches the high-pressure sodium shutoff valve.

Each of the major sodium components is individually heated and controlled. The piping in the pipe nest is provided with separately controlled heater zones to establish the desired temperature gradients. The test piece is surrounded by a zone-controlled oven for maintaining the specimen at a uniform temperature during the hold periods.

The test piece assembly is shown in Fig. 4. The welds at either end of the 30-in.-long test section were made by a standard tungsten-inert-gas process using type 308 stainless steel filler metal. A relatively thin-walled bladder was mounted inside the test piece to reduce the amount of sodium required for the thermal transients.

Each test piece assembly was instrumented with 23 chromel-alumel thermocouples, the locations of which are shown in Fig. 4. Five thermocouples were located in the sodium annulus — one at the center, two 10 in. upstream from the center, and two 10 in. downstream from the center. Five thermocouples were embedded in the specimen wall and one was located on the outer surface at Section B-B in Fig. 4. These six thermocouples provided the temperature distribution through the wall as a function of time during the transients. Finally, to provide for an assessment of the uniformity of the specimen temperature at any time, six thermocouples were located on the outer surface at Sections A-A, 8 in. upstream and downstream from the midpoint.

The primary strain measuring devices used in each test were Boeing high-temperature capacitive strain gages (6), which were mounted in the circumferential and axial directions on the outer surfaces of the test pieces. These gages were backed up with Ailtech weldable resistance strain gages (model SG 425), strain-gage-based, air-cooled extensometers, and several pairs of tabs for gross "before and after" measurements with Demec mechanical extensometers at room temperature.

A photograph of the second specimen is shown in Fig. 5 with the instrumentation installed (the capacitive strain gages are protected by sheet-metal covers) and half of the test piece oven in place. Figure 6 shows one of the capacitive strain gages mounted in the circumferential direction and flanked by three Ailtech resistance gages. The basic gage length of the capacitive gage was 1 in., and the gage length of the resistance gages was 0.7 in.

Each of the thermal ratchetting tests was preceded by heating the specimen to 1100°F in steps. At discrete temperature levels a relatively low internal pressure was applied for strain gage calibration purposes. At 1100°F, the test was initiated with the application of the test pressure, followed by the first thermal transient. After the 1100°F hold period in the last test cycle, the pressure was removed and the test terminated.

During each thermal transient (from points a to b in Fig. 1), temperature and strain data were recorded every 0.2 sec by a high-speed data-acquisition system. During the heat-up periods (points d to e) and the hold periods (points e to f), data were recorded every 15 min.

During the hold periods an attempt was made to control the temperatures over the middle 20 in. of the 30 in. test section to 1100°F ± 5°F, both spatially and with time. However, in some hold periods the measured differences were as large as 20°F. During the most severe transients a gradient in the sodium temperature of about 25°F was consistently measured along the middle 20 in. length of the test sections. The internal pressure was maintained to within ±1% of the nominal value except during the actual transients. During the most severe transients the pressure dropped about 3% below 700 psi.

TEST RESULTS

Figure 7 shows the measured temperature distributions through the wall of the first specimen at various times after the initiation of the transient. Data for the first four cycles are shown. Also shown in the figure are predicted temperature distributions determined from a simple one-dimensional finite-difference transient heat conduction analysis. The predictions are based on the physical properties given in the appendix of this booklet for type 304 stainless steel and on the measured sodium transient shown in Fig. 2 for the first test. The heat transfer coefficient between the sodium and the pipe wall was taken to be 43.9 Btu/hr-in.^{2}-°F in the calculation.

The measured ratchetting behavior for the first pipe specimen is shown in Fig. 8, where the circumferential strain on the outer surface is plotted as a function of the accumulated hold time at 1100°F. Data points from two capacitive gages located 90° apart near the midlength of the 30 in. test section are shown. Initial pressurization data and data corresponding to the minimum strain during each transient are included.

Results for the second pipe specimen are shown in Fig. 9. Again the outside circumferential strain is plotted as a function of the accumulated hold time at 1100°F. Results from four capacitive gages are shown. Three gages were located 90° apart near the midlength of the 30 in. test section. The fourth gage was located on the weld at the upstream end of the test section. Data corresponding to the initial pressurization, to pressure changes made with each change in conditions, and to the final depressurization after the test are included, but the minimum strain values are not plotted in this case. Note that one of the four gage systems failed after 2920 hr of accumulated hold time, and another failed after 5032 hr.

DISCUSSION OF RESULTS

Consider first the temperature distributions through the wall of the first specimen. The agreement of the measured temperatures from cycle to cycle is good, and the measured response is in good agreement with the predictions.* This agreement lends credence to the temperature measurements and to the analyst's ability to enter an inelastic structural analysis of the pipe ratchetting specimens with the proper thermal loading.

The measured response of the first specimen (Fig. 8) indicates substantial ratchetting in the early cycles, but the incremental growth per cycle decreased continually with an increasing number of cycles. The second specimen (Fig. 9), on the other hand, exhibited an initial increment of growth during the first of

*The slight differences that are exhibited between the measured and predicted distributions in Fig. 7 are due largely to the actual transients being displaced, timewise, by a fraction of a second from the representative transient shown in Fig. 2.

the initial five cycles and little change thereafter. This marked difference between the first and second specimens is largely an indication of the strong influence that the primary pressure stress has on ratchetting behavior.

The 13 severe cycles in the second test produced incremental ratchetting, but never as much as the same cycles produced in the first specimen. Upon switching from the severe cycles back to the less severe cycles in the second test, the net response seemed to be an incremental decrease in strain. This behavior has also been observed in tests in Japan when severe cycles which produced ratchetting were followed by less severe cycles (7).

Comparisons of the results in Figs. 8 and 9 with the backup instrumentation measurements and with "before and after" mechanical measurements indicate that the gross strains measured by the capacitive gages are approximately correct.

The net strains from the two circumferential capacitive gages on the first specimen agree reasonably well although there does seem to be a consistent difference [gage 513 generally indicates more plastic (time-independent) strain and less creep (time-dependent) strain than gage 514]. The differences in the second specimen are more pronounced, particularly near the end of the test. These differences are thought to be real. A possible explanation is the significant variation in properties that has been found around the circumference of the 8-in. pipe product form which the ratchetting specimens were obtained. Also, although extreme care was taken to support the specimens so that negligible end reactions existed, it is possible that small reactions did reach the specimens. Although small, these could have a significant influence, particularly during creep periods.

ACKNOWLEDGEMENTS

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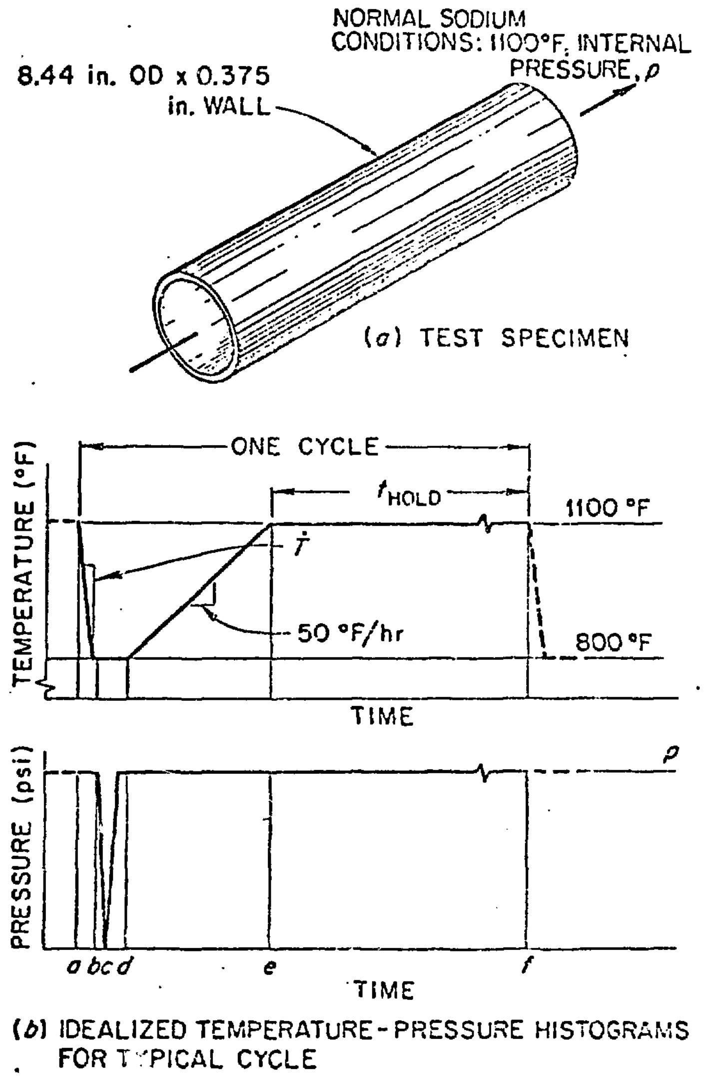

(c) SPECIFIC TEST CONDITIONS

$\dot{T}$ (°F/sec)	p, PRESSURE (psi)	t_{HOLD} (hr)	NO. OF CYCLES
SPECIMEN TTT-1:			
30	700	160	13
SPECIMEN TTT-2:			
22.8	400	328	5
30	700	160	13
22.8	400	328	5

Fig. 1. Nominal test conditions for first and second pipe thermal ratchetting tests (TTT-1 and TTT-2).

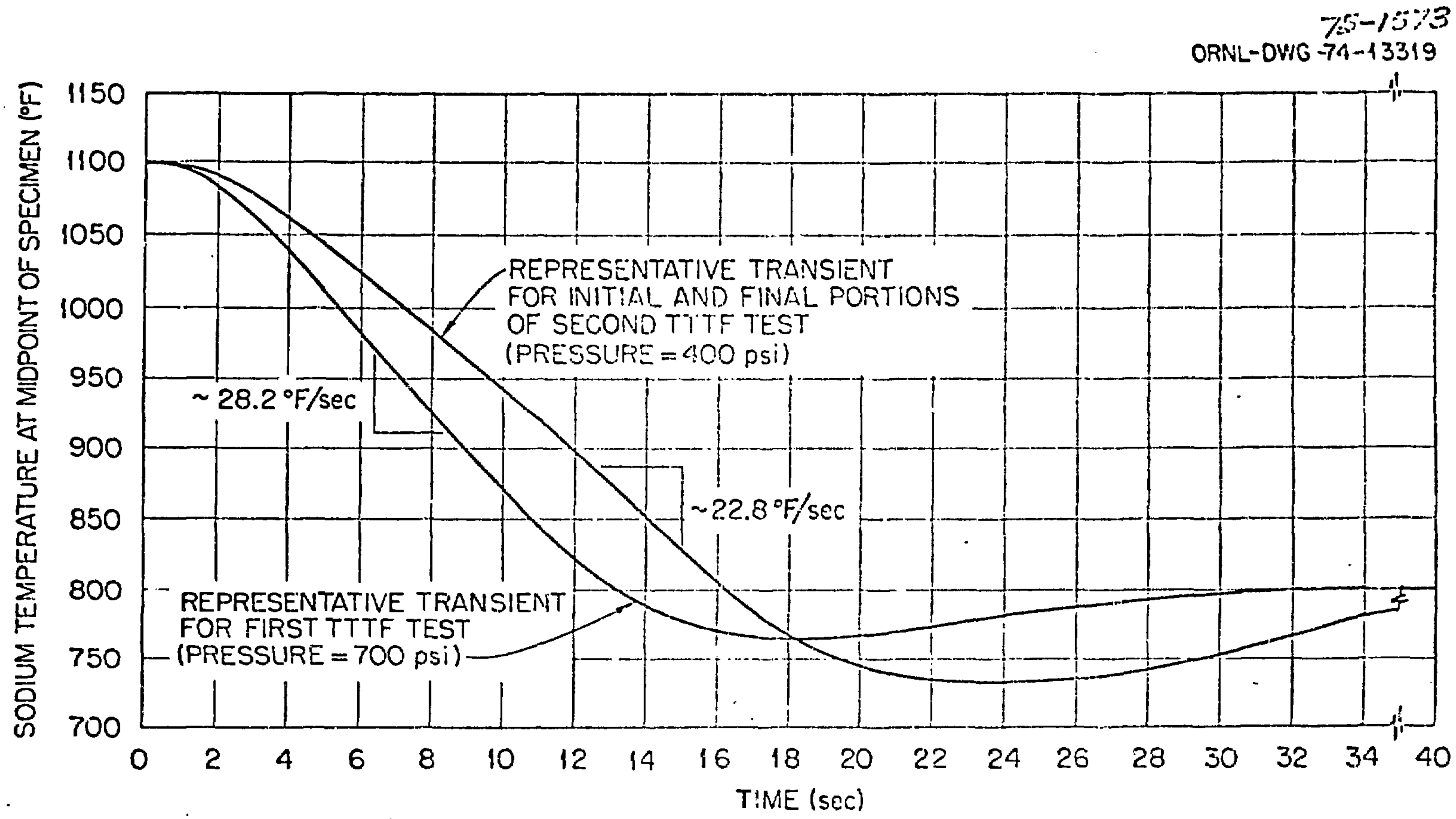

Fig. 2. Actual measured sodium temperature vs time from initiation of transients.

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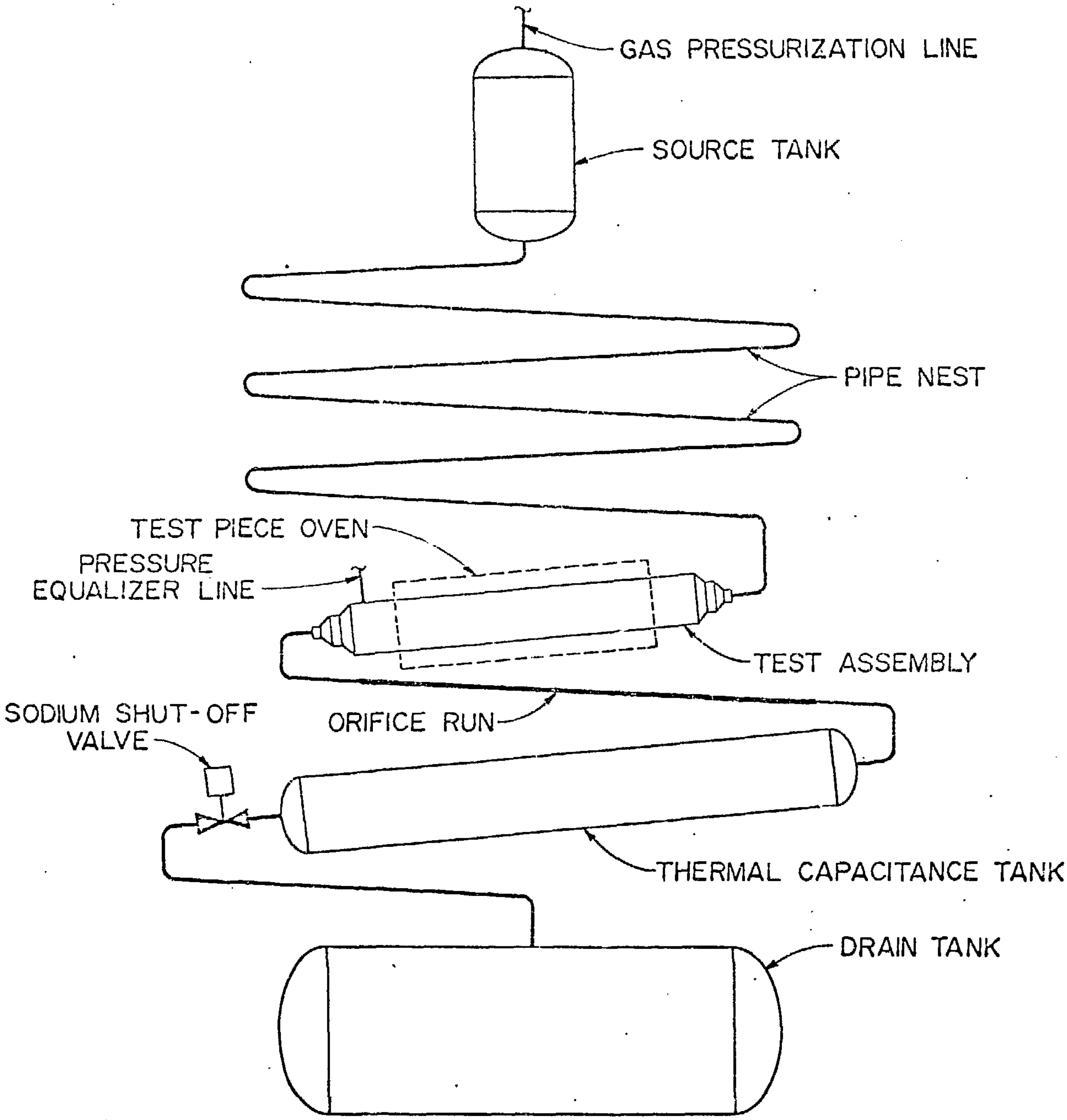

Fig. 3. Schematic of thermal transient test facility.

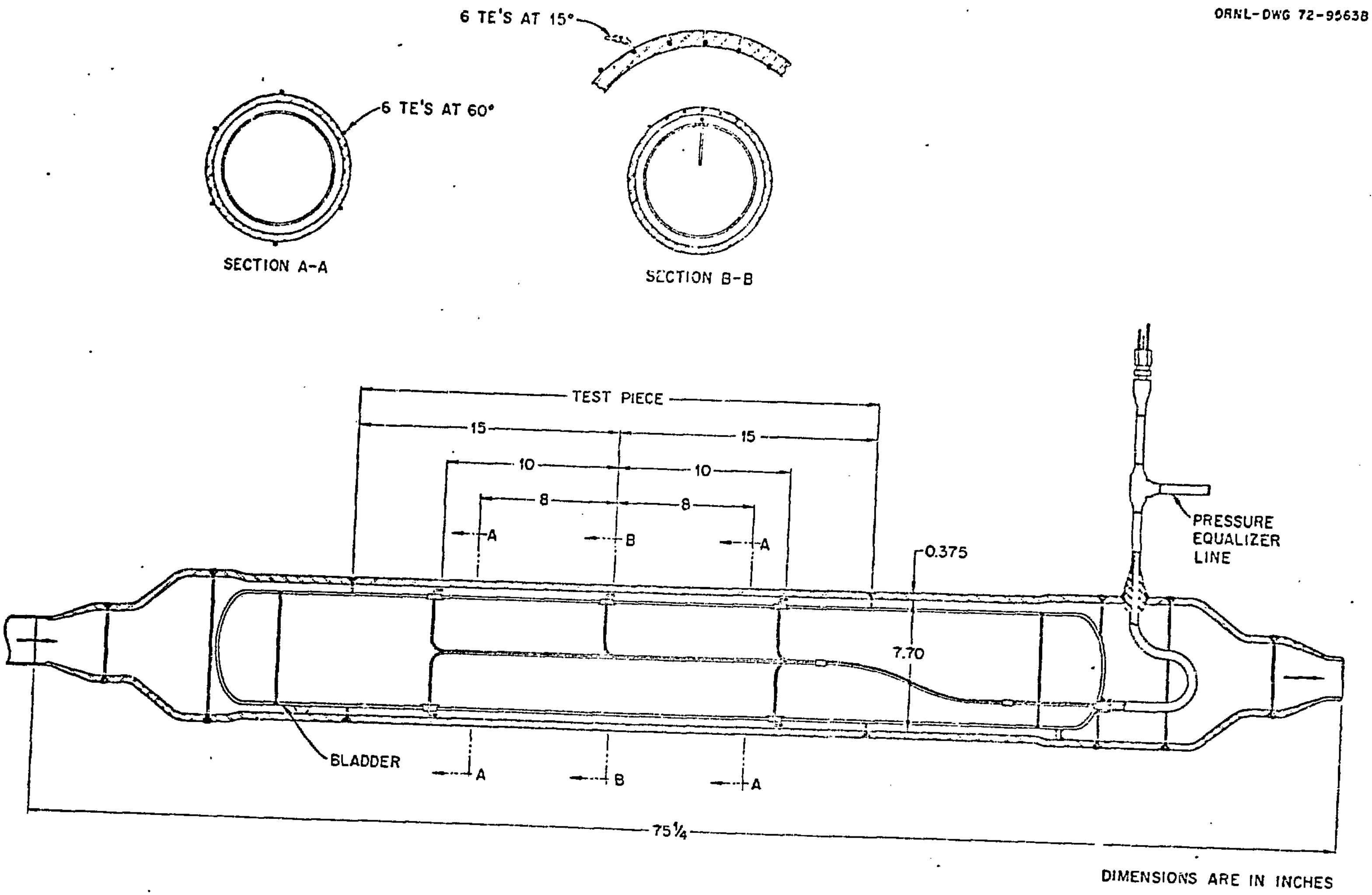

Fig. 4. Pipe thermal ratchetting test piece assembly.

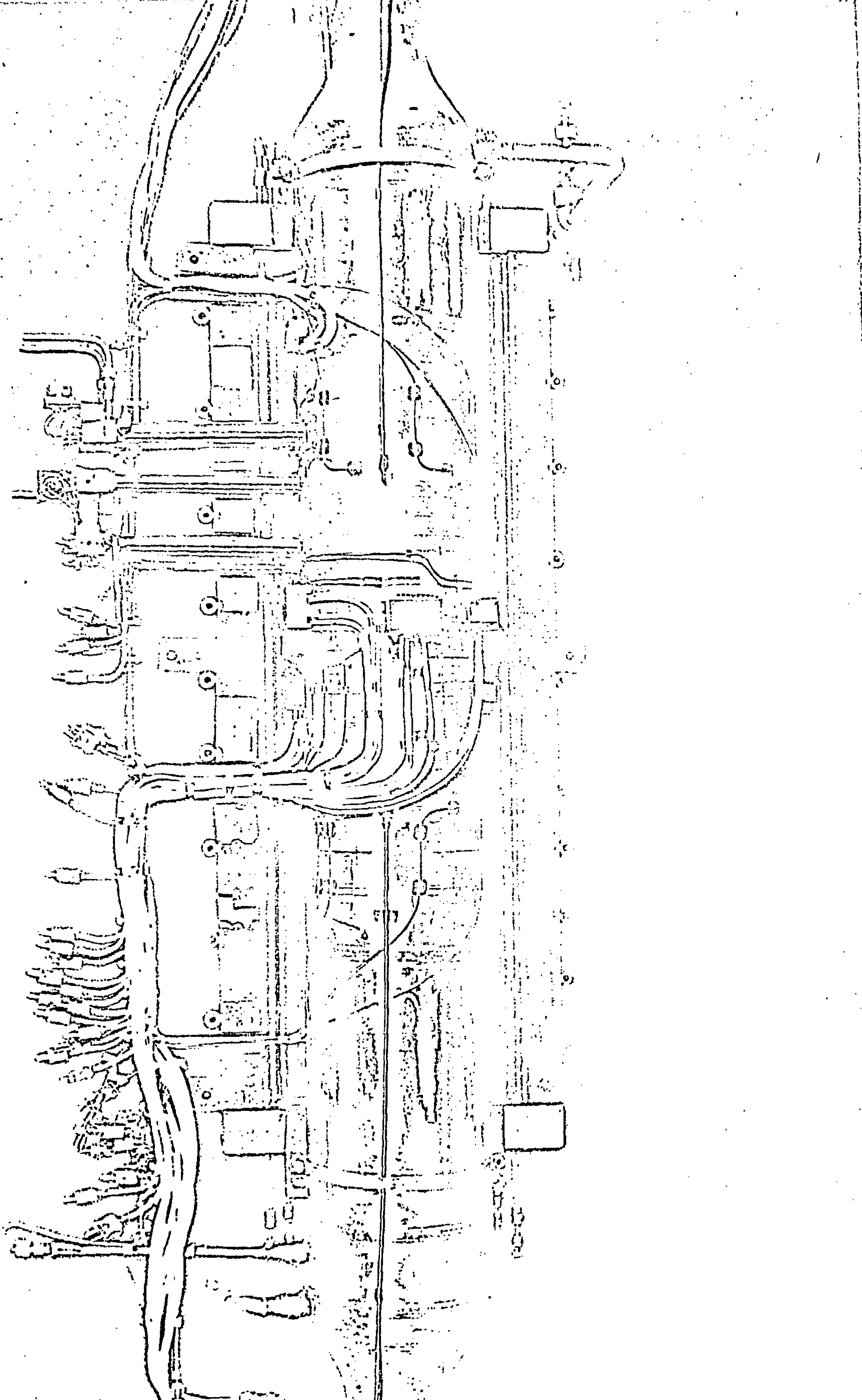

Fig. 5. Photograph of second test specimen with instrumentation installed and half of specimen oven in place.

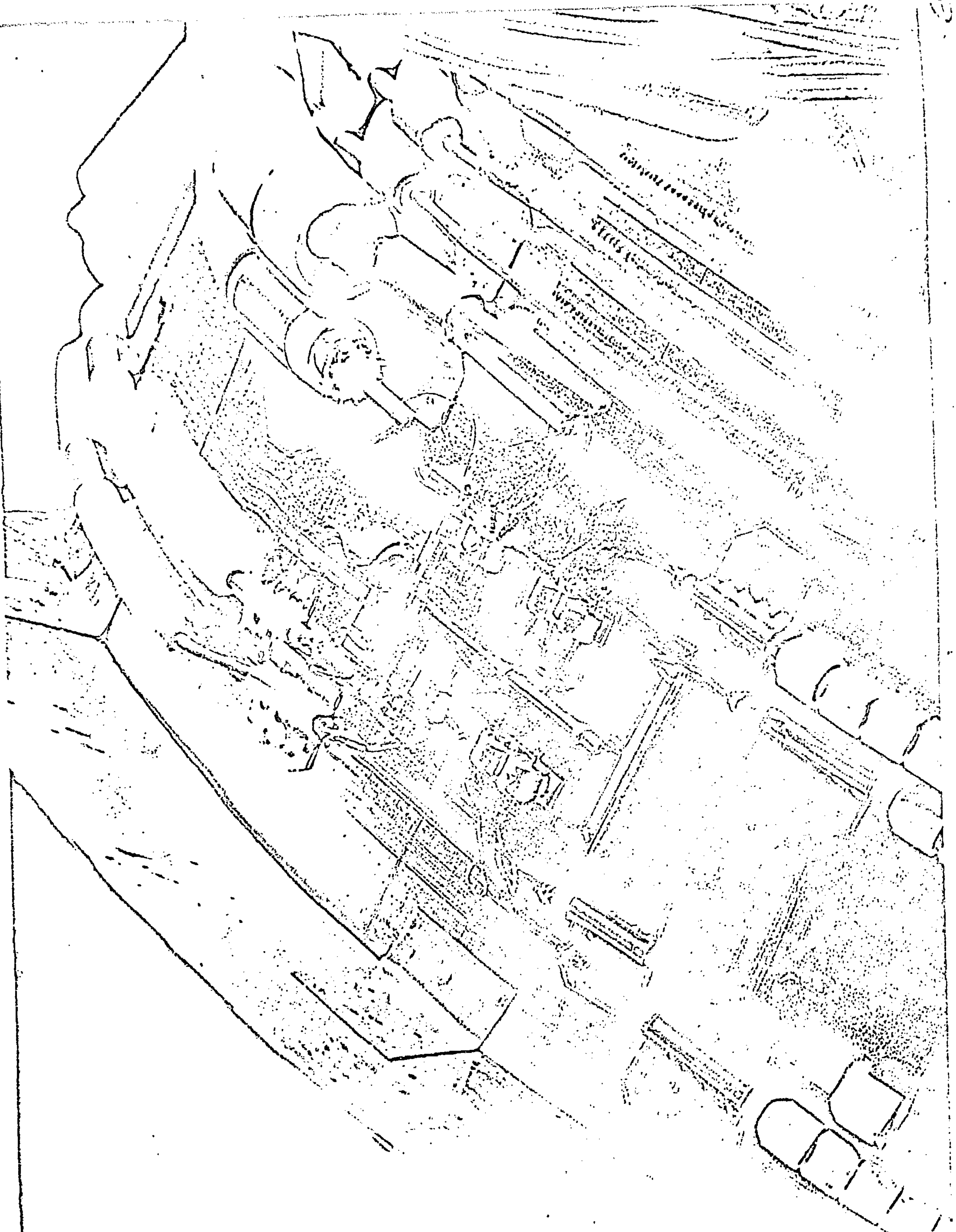

Fig. 6. High-temperature capacitive strain gage and weldable resistance strain gages side by side on second test specimen.

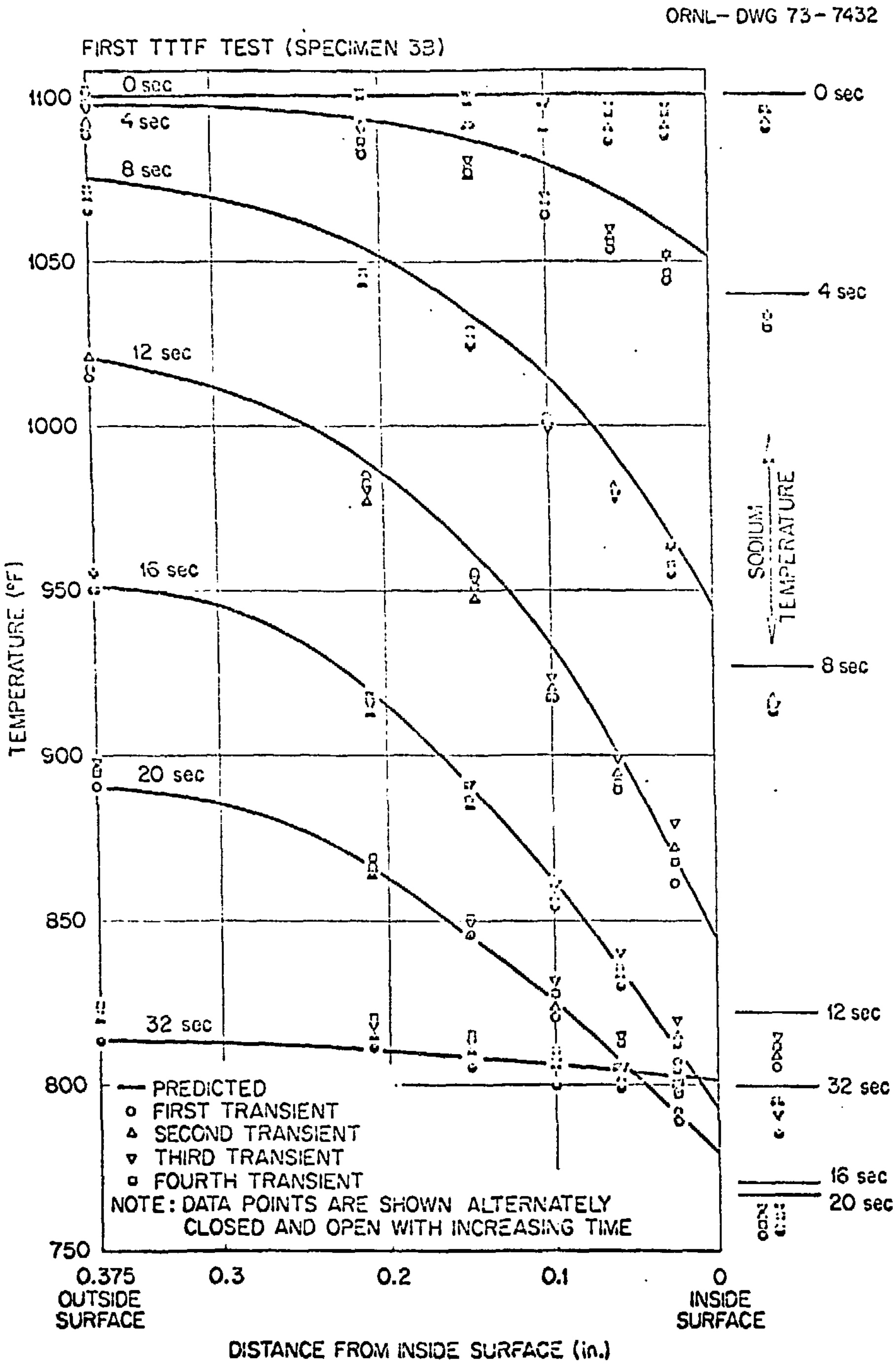

Fig. 7. Measured and predicted temperatures through wall of first test specimen at various times during the transient. Refer to Section B-B of Fig. 4 for thermocouple locations.

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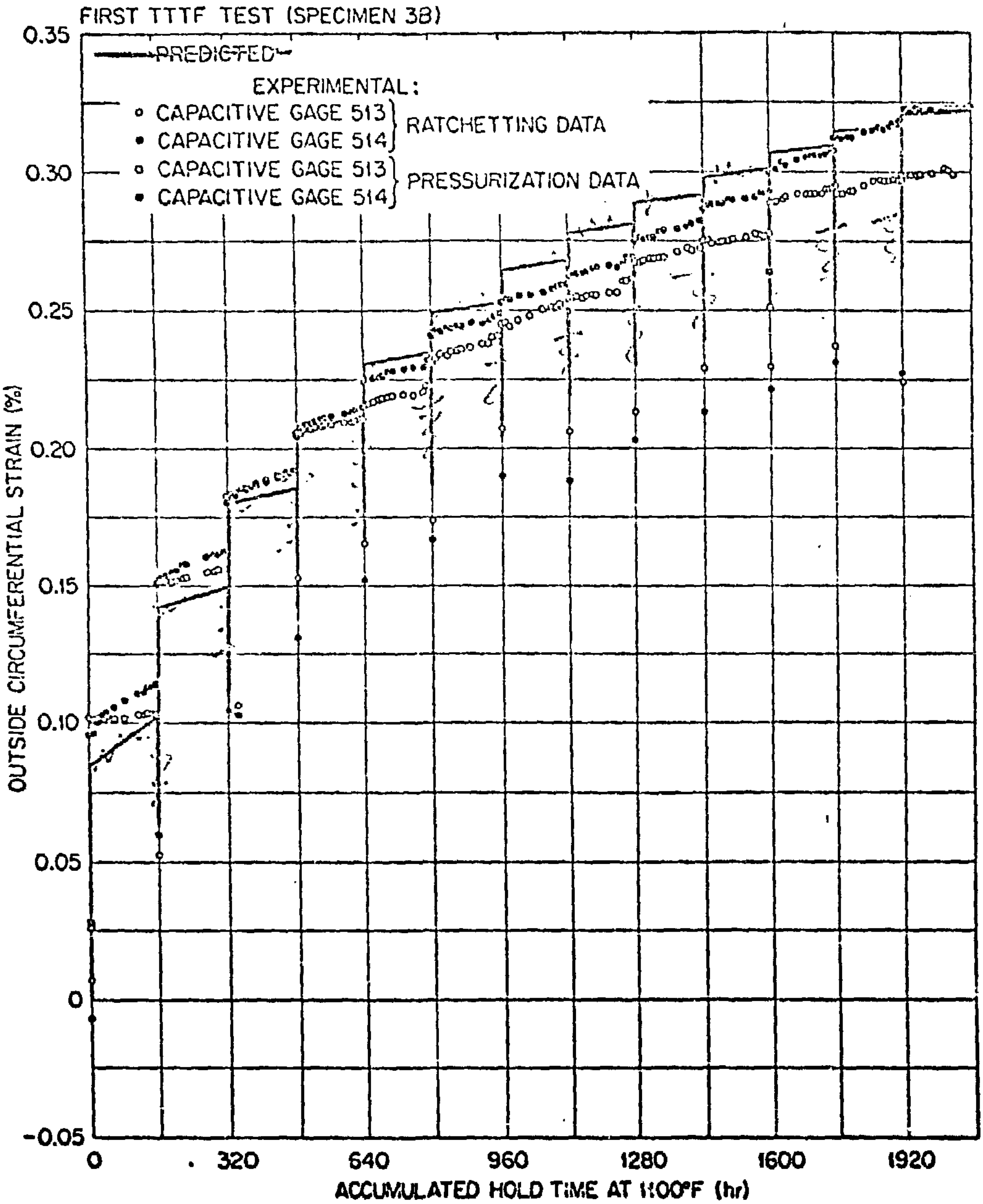

Fig. 8. Measured circumferential ratchetting strains on the outer surface of the first pipe thermal ratchetting test (TTT-1). The data shown are from capacitive strain gages located 90° apart near the midlength of the pipe specimen.

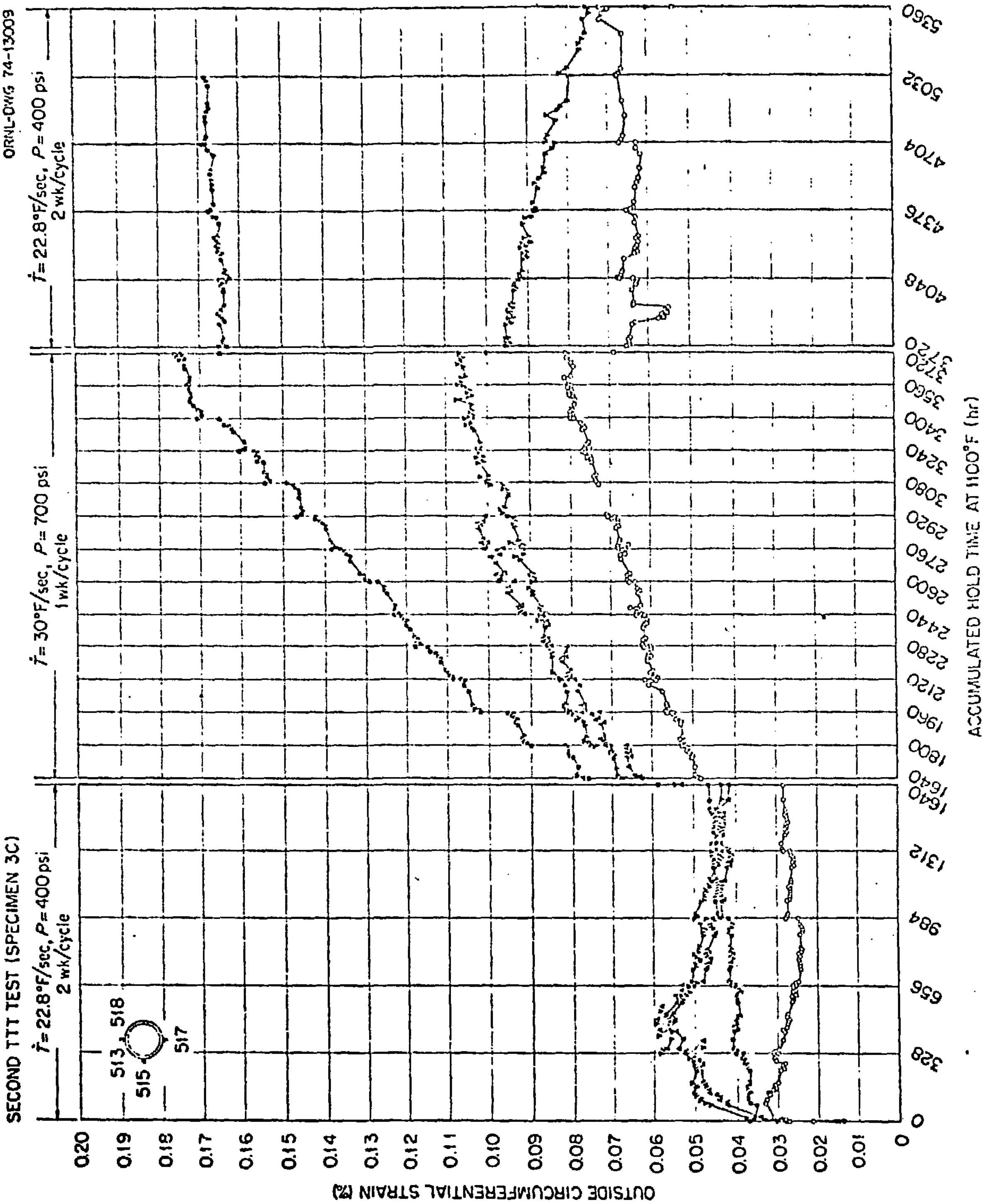

Fig. 9. Measured circumferential ratchetting strains on the outer surface of the second pipe thermal ratchetting test (TTT-2). The solid data points shown are from three strain gages near the midlength of the specimen as shown in the inset. The open data points are from a gage located on the circumferential weld at the upstream end of the test piece (the left end in Fig. 4).