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Semi Annual Report
on
Wide Plate Crack Arrest Testing*

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Summary

To predict the behavior of a nuclear pressure vessel undergoing pressurized thermal shock, certain information on dynamic crack propagation and arrest is required. The purpose of the work described here is to provide such data on wide (1m) plates fracturing at temperatures in the upper shelf region. As the first NBS semi-annual report on this project, this document describes the initial efforts to prepare for and perform these tests. Design and fabrication of pull plates, tabs, completed specimen, temperature gradient systems, and data acquisition systems are described. Details of bend bar tests validating the planned, warm prestressing procedure are included. The effect of the imposed temperature gradient on the stress state in the wide plate specimen is calculated. Finally, the status of the first wide plate test WP-1.1 is discussed.

1. Introduction

To predict the behavior of a nuclear pressure vessel undergoing pressurized thermal shock, certain information on dynamic crack propagation and arrest is required. The purpose of the work described here is to provide such data on wide plates fracturing at temperatures up to the upper shelf region. Here are described the initial efforts to prepare for and perform these tests.

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*Trade names and companies are identified in order to adequately specify the experimental procedure. In no case does such identification imply recommendation or endorsement by the National Bureau of Standards, nor does it imply that the products are necessarily the best available for the purpose.

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Six single edge cracked tensile specimens are to be tested in a thermal gradient. The overall specimen configuration is shown in Figure 1. The edge-notched plates in the middle of the specimen have been supplied by ORNL. The pull plates and tabs have been designed and constructed by NBS. One consideration in the design of pull tabs was that the tabs must not fail at the pinholes. Design considerations for the choice of tab dimensions and mechanical properties are given in Section 2. The fabrication of the pull plates, tabs, and completed specimen are described in Section 3.

The specimen is to be fractured in a thermal gradient that, in the most extreme case, might extend from -150°F to 500°F across the 1 m specimen width. To establish this gradient, a heating and cooling system was constructed. Details of this system including testing of a prototype are discussed in Section 4.

The temperature gradient will cause a slight in-plane bending of the specimen. When a load is applied to this bent specimen, a moment results that will affect the stress state of the specimen. The magnitude of this effect is estimated in Section 5.

An important part of this study is data acquisition from the numerous strain gages, thermocouples, and timing wires that are mounted on the specimen. BCL is responsible for installing instrumentation for measuring crack velocity and acquiring the data from it. NBS is responsible for all other data acquisition. Low reactance bridges, wide range dynamic amplifiers, and high speed digital oscilloscopes will monitor the strain gage response to crack propagation and arrest. Details of the data acquisition system are given in Section 6.

To assure a meaningful crack run and arrest event, it is necessary to achieve a significant elevation in K above K_{IC}. The technique chosen by ORNL is warm prestressing and they have provided a suggested warm prestressing procedure. This procedure has been tried on two, full thickness bend bars with success. These tests and results are covered in Section 7.

Finally, the status of preparations for the first wide plate test WP-1.1 is discussed and best estimates of scheduling are given in Section 8.

2. Pinhole Design

Tests were run to assess the possibility of yielding at the pinholes in the tab. The configuration of a pinhole is shown in Fig. 2. The results of the tests are given in Table 1, where the symbols have the following meaning:

B	thickness of plate
W	width of plate
H	distance from pinhole to end of plate
D	diameter of pinhole
C	clearance, i.e., pinhole radius minus pin radius
σ_{YS}	yield strength of plate

Pinhole specimens were mounted in pin and clevis grips in a tensile testing machine and the load versus displacement was measured on a continuous record. The values listed in Table 1 for the observed load are those where the load-displacement record reached the 0.2% offset indicative of yielding at the pinhole.

A simple expression for yield load at a pinhole is given by

$$P = (2/\sqrt{3})\ BH\sigma_{YS} \qquad (1)$$

However, instead of using this equation we fitted the data from specimen numbers 5-13 by least squares to the expression

$$P = C_1\ BH\sigma_{YS} \qquad (2)$$

where the fitting parameter C_1 was found to be 1.136. The observed yield load is plotted versus the predicted yield load as the circles in Fig. 3. Included as squares are the data from specimen numbers 1-4. The data from specimen numbers 14-15 are included as stars.

An improvement over expression (1) for the yield load has been proposed by B.G. Johnson, Trans. ASCE 104, 314-339 (1939), as follows:

3. Fabrication of Pull Plates, Tabs, and Completed Specimen

For reasons of compatibility (both welding and mechanical), it was decided to construct the pull plates and tabs from the same type of steel as the ORNL wide plate specimens: A533B.

Once the steel was chosen, five steel companies were contacted and asked to submit bids for four plates having the following dimensions-two tab end plates each 1.524 m (60 inches) square, and .152 m (6 inches) thick and two pull plates each 1 m (39.37 inches) wide, 3.56 m (140inches) in length, and .102 m (4 inches) thick. American Alloy Plate of Houston, Texas was chosen to be the supplier. The mechanical properties, chemistry, and heat treatment, as reported by American Alloy Plate are shown in tables 2 and 3.

Following the procurement of the steel plates, the next step in the program was to find a welding company which could attach each tab end plate to the pull plate. This involved heavy section welding and requests for bids were sent to three companies which performed this type of work. Included in the bid were requests for the machining of a .425 m (16-3/4 inch) hole located in each tab end plate and the beveling of the plate adjacent to the welded region. Bids were received and examined. General Welding Works of Houston, Texas was chosen to perform the welding. Welding particulars, rod, wire, flux and certification of the welder all met with accepted nuclear construction codes. The welding rod was E10018 D2, the welding wire was F98-EF1-F1, and the flux was Oerliken OP121TT.

During the welding of the first tab end plate to the pull plate, difficulties were encountered. Initially it was decided, by General Welding, not to put a 26° bevel on the .152 m (6 inch) thick plate. This proved to be an error. When the welder began using the automatic welder, he found the wire holder and the .152 m (6 inch) plate not being beveled prevented him from making a good weld. It was decided to progress with hand welding the remainder of the task. Following the welding of the plates, a radiographic and UT examination was performed on the weld. Examination of the weld showed regions which were totally unacceptable. It was necessary to cut back on both plates, put a bevel on both pieces, and reweld using automatic techniques. Once the plate was rewelded, the plate was given an intermediate stress relief at 593°C (1100°F). The second tab end and pull plates were then welded using automatic welding

$$P = \frac{1}{2} DB\sigma_{YS} \left[3 \left(\frac{H}{D}\right) - \left(\frac{H}{D}\right)^2 - 2\left(\frac{C}{D}\right)\right] \qquad (3)$$

Therefore we also fitted the data from specimen numbers 5-13 to the expression

$$P = DB\sigma_{YS} \left[C_1 \left(\frac{H}{D}\right) - C_2 \left(\frac{H}{D}\right)^2 - \left(\frac{C}{D}\right)\right] \qquad (4)$$

where the fitting parameters were found to have the following values

$C_1 = 1.45$

$C_2 = 0.3$

$C_3 = 0.079$

The observed yield load is plotted versus the predicted yield load as circles in Fig. 4, and the data from specimen numbers 1-4 as squares. The data from specimen numbers 14-15 are included as stars.

The design of the tabs and pinholes are based on the following dimensions and materials properties:

B	152 mm	(6 in)
W	1524 mm	(60 in)
H	406 mm	(16 in)
D	431 mm	(17 in)
C	12.5 mm	(0.5 in)
σ_{YS}	621 MPa	(90 ksi)

Hence we find that the predicted yield load from Eq. (2) is 44 MN (9810 kips) and from Eq. (4) is 45 MN (10100 kips). These values are above the rated 27 MN (6000 kips) capacity of the NBS Universal Testing Machine. They are also above the value of 10.66 MN (2392 kips) anticipated for the first WP-1.1 test. Considering work hardnening as well leads to the conclusion that the above pinhole design is sufficiently conservative.

techniques. This weld was also given an intermediate stress relief. Both welds were radiographed and UT examined. Some flaws were found by General Welding and subsequently repaired.

The final radiographic and UT results for this finished welds were then sent to NBS for examination. The radiographs were examined by Dr.'s Placious and Polansky of the radiophysics group of NBS. In their examinations, they observed two very thin cracks in one weld. The cracks were about .0127 m (.5 inch) and .025 m (1 inch) in length. The depth was estimated, using film density techniques, to be no greater than .002 m (.080 inch). The radiograph from the other weld was examined and the observers reported that the weld appeared, in their estimation, to be quite good.

The length of the cracks were brought to the attention of C. Pugh and T. Bryan at Oak Ridge for the purpose of estimating the effects of these two cracks. It was calculated that this crack size should withstand a critical stress of 517 MPa (75 ksi). For the large specimen tested here, this stress corresponds to a fracture load in excess of 53 MN (12 X 10^6 lbs). It was decided not to have the cracks repaired and the welds were accepted. Both weldments were given the post weld stress relief of 607°C (1125°F) for 2 hours by General Welding.

Once the post weld stress relief was completed, the wide plate test specimen, already sent to General Welding by Oak Ridge, was welded to the pull plates. However, there was a change in the welding materials. The flux was Lincoln 860. The NBS welding engineer, Dr. T. Sievert, recommended that we use rod E7018 in the first pass and then EM12K. These changes reduced the possibility of weld cracking. The preheat temperature was the same, but the post weld heat treatment was done at 232°C (450°F) for at least 2 hours. There was no post weld stress relief at 607°C (1125°F). During the welding and post weld heat treatment, the temperature at the pre cracked region (that is in the specimen) was monitored by a contact thermocouple. The temperature in the pre cracked region did not exceed 142°C (285°F). As a precautionary measure, two .05 m (2 inch) by 2.5 m (8 foot) plates has been attached to the front and rear of the specimen to prevent the crack from being disturbed during the welding and subsequent shipment to NBS. Once the welding of the specimen was completed, General Welding radiographed and UT'ed the welds. The results were

sent to NBS for evaluation. Satisfied that the welds were acceptable, NBS authorized the entire specimen to be sent to NBS for testing. This authorization was given on August 29, 1984.

4. Design and Fabrication of Temperature Gradients System

For these tests, heating and cooling systems are required that are capable of producing a linear temperature distribution across the test specimen's width at the crack plane. Achieving and maintaining the temperature gradient must be accomplished by controlled heating and cooling of the plate surface only on the left and right edges of the specimen, while insulating the front and back surfaces. Thermal gradient readings of the plate must be taken during the warm prestressing and crack arrest test, requiring a data acquisition system for these measurements. Initially, NBS was requested to develop a system that could maintain a linear thermal gradient across the specimen width having a minimum temperature of -101°C (-150°F) at the cold edge (or notch edge) and a maximum temperature of 260°C (500°F) at the opposite hot edge. Although these were preliminary temperature requirements, and later modified, they were used as goals in the development of the heating and cooling systems. The major obstacle to overcome is the heat sink effect from the test specimen pull plates and test machine clevis devices. The thermal gradient may not be linear as a result of heat flow in the central portion of the pull plates. In order to maintain the desired linear thermal distribution within the area of interest ($a/W = 0.2$ to 0.8), the specimen edges may have to be heated or cooled beyond the required levels. Therefore, thermal systems are required that can achieve temperatures beyond those requested in the initial requirements.

For heating the hot edge of the specimen, electrical resistance strip-heaters were chosen. The strip-heaters are constructed of coiled nickel-chrome resistor wires embedded in a refractory material and sheathed in stainless steel. Each heating element measures 61 cm (24 in) in length and 3.8 cm (1.5 in) wide and has a maximum working temperature of 371°C (700°F). Either 2 or 3 heaters will be attached side by side, longitudinally along the edge of a test specimen. Heating and cooling will take place along a 2440 mm (8 ft) length centered about the notched

region of the specimen. The temperature will be maintained by powering each strip-heater separately through a variable transformer that is controlled by a temperature controller.

A system to achieve and maintain a temperature of -101°C (-150°F) on the cold edge of a specimen was designed using liquid nitrogen LN_2 as the coolant. A series of insulated chambers were constructed capable of either spraying gas and vaporizing liquid nitrogen onto the specimen surface or actually holding a reservoir of LN_2 in contact with the specimen edge. Through many modification and choices of building materials, a final design was reached. The cooling chamber is constructed of standard 2" by 6" building lumber. The sides of the chamber are fastened together with bolts through steel angle that is screwed to the wood. Leakage is prevented at the wood joints and specimen by squeezing either rubber hose or rubber tape between the interfaces. The chamber is mounted onto the edge of a specimen and clamped tightly to seal the contact areas. Cooling will be accomplished by pumping the LN_2 through a copper tube manifold affixed to the inside of the cooling chamber. The liquid or gas is sprayed across the specimen thickness at about 150 mm (6 in) intervals down the length of the chamber. Control of temperature is maintained by starting and stopping the flow of LN_2 into the cooling chamber with an electrically activated solenoid valve. The valve is opened and closed by a temperature controller having a thermocouple sensor to monitor the specimen temperature. Additionally, the flow rate of the LN_2 can be varied by pressure valves that control the output from the LN_2 tanks. Provisions are be available for filling the cooling chamber reservoir with LN_2 if that becomes necessary to obtain the low temperatures. The performance of the insulation material is also important for maintaining a linear thermal gradient. Two different materials were chosen for the cold and hot sides of the specimen. Styrofoam sheeting used in building construction was chosen to insulate the cold half of the plate up to about 93°C (200°F). The styrofoam insulation is in sheet form, 25.4 mm (1.0 in) thick, which can be stacked as needed for greater insulation. For temperatures on the specimen above 93°C (200°F), a mineral wool insulation blanket will be used. These blankets consist of a 50.8 mm (2.0 in) thick

insulation material with a 25.4 mm (1.0 in) wire mesh on both sides to retain insulation, form and heat resistance. The insulation is suitable for temperatures to 566°C (1050°F).

Thermal gradient readings of the test specimen will be taken during the course of the thermal and mechanical loading sequences. To acquire these readings, a data acquisition system capable of accessing at least 22 temperature sensors is required. The system that will be used for this test program consists of a data logger which can randomly access up to 40 channels that couple with an internal digital voltmeter. The data logger is interfaced with a computer for program control, data reduction and output. This system will be set up so that the thermal readings can be taken at the operator's request or at a given time interval and provide hard copy output and data storage.

Certified type K (chromel-alumel) thermocouples were chosen for the temperature sensors. These thermocouples are bonded to a paper thin laminate backing that can be glued to the specimen surface using a thermally conductive epoxy adhesive. Two different epoxies are used depending on the temperature range that the thermocouple will encounter. Glue-on thermocouples have the advantage of simple application and do not require holes to be drilled into the specimen. A disadvantage however, is that temperature can be measured only at the surface of specimen. Two or three thermocouples will be mounted in 50.8 mm (2 in) deep holes to measure the internal temperatures and compare it with the surface.

To test the various heating and cooling systems that were developed, a test specimen mock-up was constructed. A steel plate with dimensions similar only in the width dimension to an actual specimen was used. However, since it is the thermal gradient across the specimen width that is measured, the width dimension was the most important to replicate.

A hot-rolled steel plate was chosen for the test specimen mock-up having the dimensions: 1830 mm (72 in) long, 1220 mm (48 in) wide, and 12.5 mm (1/2 in) in thickness. The extra 22 cm of width in excess of an actual test specimen's width was necessary for attaching the heating and cooling systems. The extra width provided about the same width of 101.6 mm (4.00 in) as the edge thickness of a test specimen. This simulated the approximate area of heating and cooling during an actual test. The mock-up plate was fastened in a support frame, mounted vertically in the

length direction and constrained only at the top and bottom. In this position, the two side edges were accessible for attaching the heating and cooling devices. For the mock up tests, 1220 mm (48 in) of the plate length, (610 mm (24 in) above and below the center line), was used for applying heat and cold to the two edges of the plate. The set-up is shown in Figure 5.

Four strip-heaters were bolted and clamped to the area of the plate to be heated. Two were placed adjacent to each other above the center line of the plate and two similarily placed below the center line. No covering or insulation was placed over the heaters. This placement allowed heating of an area approximately 1220 mm (48 in) in length and 80 to 100 mm (3 to 4 in) in width. The cooling chamber was constructed to spray liquid and gaseous nitrogen onto approximately the same area at the opposite edge of the plate. This arrangement left the center portion of the plate, approximately 1000 mm (39 in) wide, to simulate the test specimen.

An additional purpose of the mock specimen test, other than to test prototype heating and cooling systems, was to attempt to obtain a linear thermal gradient along the center line of the plate. To measure the thermal gradient, 17 thermocouples were attached to one side of the plate along the center line. Starting at the edge of the cooling chamber, the thermocouples were placed at 0, 10, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65, 70, 75, 80, 90 and 100 cm across the plate, ending at the edge of the strip heaters. As much of the exposed plate as possible was covered with insulation. A single layer of 25.4 mm (1.0 in) thick styrofoam insulation was placed on the cold areas of the plate. The hot side was covered with 12.5 mm (.5 in) thick Marinite insulation board covered with one sheet of the styrofoam. The Marinite board proved to be an inadequate insulator and will be replaced with mineral wool insulation blankets for the actual tests.

Although thermal systems were initially designed to maintain -101°C (-150°F) on the cold edge and 260°C (500°F) on the hot edge, the requirements for the first test are as follows: the temperature on the cold edge is -62.2°C (-80.0°F); the temperature at a/W = 0.2, is -17.0°C (1.4°F); the temperature at a/W = 0.45, is 39.5°C (103.1°F); and the temperature on the hot edge is 163.8°C (326.8°F). These new temperature restrictions were used in the mock specimen test. The computer outputs from the mock

test are shown in figures 6 and 7 and show the progression of the test. The test began with the plate in equilibrium at an ambient temperature of 78°F. Initially, heat transfer occurred at the plate edges, and with time moved towards the central portion of the plate. After 6.75 hours the test was stopped, the heaters and cooling chamber shut down. At that point, the thermal gradient was continuing to approach linearity at an extremely slow rate. Although perfect linearity was not achieved in the test, the results were reasonably good and no further tests were scheduled before an actual specimen test.

In the first actual test, heating and cooling systems similar to those tested on the mock-up specimen will be used. The major difference will be in the area of heating and cooling on the test specimen. This area will be doubled in length from 1200 mm (48 in) to 2440 mm (96 in). This increase in area required that the number of strip heaters used will increase from 4 to 8 or 10. A modified cooling chamber is also required. The new cooling chamber will similarily be increased in length to 2440 mm (96 in). It will now incorporate two seperate coolant manifolds, each controlled independently and supplied from seperate LN_2 tanks. The specimen and pull plates will be insulated as much as is feasible. With the increase in the heating and cooling areas and the results of the mock-up specimen test, we are confident that a nearly linear thermal gradient can be maintained in the specimen throughout the test sequence.

5. Effect of Temperature Gradient on Thermal Strain and Stress State

No Load Case

The effect of the temperature gradient on the configuration of the specimen was investigated. As shown in Fig. 8, the "notch-edge" of the test plate will be cooled to a temperature T_{min}, and the "crack arrest" edge will be heated to a temperature T_{max}. The extent of the temperature control along the height of the specimen is given by H_1. An attempt will be made to establish a constant temperature gradient between the edges over this region, resulting in a uniform strain. Hence, the hot edge will increase in length over the cool edge by an amount

$$\Delta H = H_1(T_{max} - T_{min})\alpha \qquad (5)$$

where α is the coefficient of instanenous thermal expansion. As a result the section of the specimen with the temperature gradient will bend thru and angle of

$$\theta = \Delta H/W \qquad (6)$$

where W is the specimen width. Fig. 1 shows that H_2 is the length of each pull-plate from the pinhole to the region of temperature control. Though this part of each pull-plate remains unstrained, each is tilted with respect to the vertical by an angle of $\theta/2$. Therefore the vertical between the two pinholes will be offset from the centerline of the specimen. This offset will be a maximum at the notch position and is given by

$$d = H_1\theta/8 + H_2\theta/2 \qquad (7)$$

Combining Eqs. (5), (6), and (7) we have

$$d = (H_1/8W)(H_1 + 4H_2)(T_{max} - T_{min})\alpha \qquad (8)$$

For the first wide-plate crack-arrest test WP-1.1 we have the following values

α	11×10^{-6}/°C
T_{min}	-62.2°C
T_{max}	163.8°C
W	1 m (39.4 in)
H_1	2.44 m (96 in)
H_2	3.70 m (145 in)

Hence we find from Eq. (4)

$$d = 13.1 \text{ (0.51 in)} \qquad (9)$$

With Load Case

If a load P is applied to the pinholes of the specimen, a stress will develop through the cross section of the specimen, given by

$$\sigma = (P/BW) - (Mx/I) \tag{10}$$

The first term is the average stress and the second term gives the stress variation due to the applied moment that results from the curvature of the specimen. The distance x is measured from the centerline of the specimen. The moment, which results from the applied load and the curvature offset, is given by

$$M = Pd \tag{11}$$

The moment of inertia for the plate (beam?) is given by

$$I = BW^3/12 \tag{12}$$

where B is the plate thickness. Combining (6), (7), and (8)

$$\sigma = (P/BW) \{1 - (12dx/W^2)\} \tag{13}$$

For a load of P = 10.65 MN (2392 kips) and a thickness B = 101.6 mm (4 in), this results in

$$\sigma = 103.5(1 - 0.00015\ x)\ \text{MPa} = 15(1 - 0.00386\ x)\ \text{ksi} \tag{14}$$

At the extremities of the plate $x = \pm W/2 = \pm 508$ mm (20 in). Hence,

$$\sigma = 103.5(1 \mp 0.077)\ \text{MPa} = 15(1 \mp 0.077)\ \text{ksi}$$

$$= 103.5\ \text{MPa} \mp 7.7\% = 15\ \text{ksi} \mp 7.7\%$$

6. Data Aquisition System

The specimen will be instrumented with thermocouples, strain gages and timing wires as recommended by ORNL and as shown in Figure 9. BCL will be responsible for installing and monitoring crack velocity instrumentation. NBS will handle all other data acquisition.

Certified Type K (chromel-alumel) thermocouples will be placed at the points indicated in Figure 9 to determine the spacial variation in temperature in the specimen. Most of the thermocouples will be mounted on the surface of the specimen, but underneath the insulation. Two or three will be inserted into 50.8 mm (2 in) deep holes drilled adjacent to surface thermocouples. These will indicate the temperature difference between surface and internal temperature. All thermocouples will be monitored serially on a regular and frequent time basis during heating and cooling of the specimen to measure thermal gradients in the specimen. The data will be acquired by a data-logger/computer system and simultaneously printed out and recorded on magnetic tape to provide a thermal history of the specimen.

Strain gages (Micromeasurements Corp. designation CEA-06-250UW-350) will also be mounted basically as shown in Figure 9. In particular, a row of 8 strain gages will be mounted on each side of the crack plane. The centerline of these gages will be two inches from the crack plane. These paired gages will be mounted at the following a/W locations:

.344, .401, .457, .513, .569, .625, .681, .737

where "a" is the distance from the cracked side of the plate and "W" is the width of the plate (1 m).

Each pair of gages will form one arm of a full bridge circuit. The bridges used have been specially designed and constructed at NBS to have the lowest reactance possible. The outputs of the bridges are amplified by wide range, dynamic amplifiers designed and constructed by J.C. Moulder and J.C. Gerlitz of NBS in Boulder. Their gain is 113. The amplified signals are then fed to high speed digital oscilloscopes capable of resolving 0.5 μs. When the crack begins to move, it will break a conductive paint switch. The trigger setting of the oscilloscope monitoring this switch will be set by prototype fracture bars presently being

studied. Once triggered, this oscilloscope will trigger all the rest within 5 ns. All strain gages will then be monitored for 2 ms. Once the data has been acquired, it will be automatically recorded onto magnetic disks within seconds of the event and then off loaded to magnetic tape on the main computer for further analysis.

Besides the above temperature and strain data, the only other data will be the load at fracture. This will be read off the testing machine dial and will also be monitored digitally along with the thermocouple data.

7. Validation of Warm Prestressing Procedure for HSST Wide Plate Crack Arrest Test Program.

Before performing the first wide plate crack arrest test, three full thickness precracked bend bars were tested to demonstrate that the planned warm prestressing procedure was satisfactory. The bend bars were provided by the HSST program. ORNL had machined the specimens from the same plate stock as the wide plate specimens. ORNL also introduced sharp cracks into these specimens by hydrogen charging an electron beam weld at the root of the notch. ORNL also estimated the crack length using ultrasonic testing. The desired warm prestressing procedure was determined by ORNL. Testing of the bend bars was carried out in the Fracture and Deformation Division of NBS in Boulder, Colorado. Dr. V. Clark, Mr. D. McColsky, and Dr. D. Read, carried out the initial calculations of required loads, performed all of the testing reported here, and made photographs of the fracture surface. Their assistance and competent execution of the testing is gratefully acknowledged.

The relevant dimensions and actual (not UT) crack lengths of the three bars are given in Table 4. The spans for the three-point bend tests are also given in this table. Based on these dimensions, specimens 1 and 2 had been warm (50°C) prestressed to 131.8 and 138.2 MPa $\sqrt{m}$ (117.7 and 123.4 ksi $\sqrt{in}$), respectively. ORNL had requested a prestress of 131 MPa $\sqrt{m}$ (116.6 ksi $\sqrt{in}$). Thus, these specimens were warm prestressed at stress intensity factor levels very close to the desired value. The actual loading history is given in Table 5. The heating took about two hours and the specimen was allowed to thermally equilibrate for one-half hour prior to testing. The temperature was monitored using thermocouples on the

surface and inserted into holes drilled to the midplane of the specimen. After equilibration, the temperature on the surface and internally were within 1°C of each other.

After warm prestressing, the specimens were unloaded by 15%: to 112 MPa √m (100 ksi√in) in the case of specimen 1 and to 117.5 MPa √m (104.9 ksi √in) for specimen 2. At this point, the specimens were cooled to room temperature and dry ice was packed around the ends of the specimens. After about 6 to 7 hours the specimens had reached -17°C.

Reloading at 445 N/s (6 kips/minute) was started once the specimens had been at -17°C for one half hour. As noted in Table 2, specimen 1 broke in two just as it reached the warm prestressing load. No evidence of plasticity was apparent on the load-COD record. A photograph of the fracture surface is shown in Figure 10. Specimen 2 exceeded the warm prestressing load by 25% at the point of fracture. There was considerable non-linearity in the load-COD curve, indicating plasticity. The fracture surface is shown in Figure 11. It should be noted that, at about 110% of the prestressing load, the testing machine cut out. Specimen 2 had to be completely unloaded and reloaded to fracture. The unloading probably increased the required fracture load by introducing compressive residual stresses near the crack tip. Therefore, the actual fracture load would have been anywhere between 10 and 25% over the warm prestressing load had unloading not taken place.

Specimen 3 was not warm prestressed. It was simply cooled to -17°C, in the same manner as above, and loaded to fracture. This occurred at 85.4 MPa √m (76.2 ksi √in) and represents the K_{IC} at -17C for this material. Comparing this value with the 117.7 and 154.2 ksi√in required to break the warm prestressed specimens, significant K elevations are noted. Such K elevations are necessary to produce the long run and arrest events required for the wide-plate tests. The fracture surface of Specimen 3 is shown in Figure 12.

In conclusion, the bend bar tests have validated the warm prestressing procedure planned for the wide plate tests. Using warm prestressing K levels similar to those applied here, it is expected that fracture may commence at between 1.5 to 2 times K_{IC} at -17°C in the wide plate tests.

The stress intensity factors reported here were calculated from the following equation:

$$K_I = (t/t_n)^{.5}(1.5Ps/b^2t)(\pi a)^{.5}F(a/w)$$

where

t = full thickness

t_n = grooved thickness

P = load

s = span

b = width

a = total crack length

$F(a/w)$ = geometric factor

The geometric factors for s/b = 4 and 8 are given in The Stress Analysis of Cracks Handbook by H. Tada, P. Paris and G. Irwin published by Del Research Corp., Pennsylvania 1973. Geometric factors appropriate for the s/b ratios used here were obtained by linear interpolation.

8. Status of Wide Plate Tests

As can be seen from the preceeding sections, all of the preparatory work has been completed in the 6 months since this project began. Fine details of strain gage data acquisition are being checked out in preparation for the arrival of the first test specimen WP 1.1. Arrival is expected in the last week of August or the first week of September. The clevises are being installed in preparation for the test. When the specimen arrives, it will be mounted in the testing machine as soon as possible. Instrumentation, thermal gradient system, and insulation will be attached after mounting the specimen. If possible, the warm prestressing will be preformed by the second or third week of September. Under these circumstances, WP-1.1 will take place in the second or third week of September. Since this is the first test, it is possible that instrumentation may take more than three days. In this case, a delay of one week might occur. In any case, WP-1.1 should be completed during September. WP-1.2 should follow the first test by about 2 or three weeks unless some difficulties are encountered in the first test that must be remedied

before WP-1.2. Nevertheless, it is expected that these tests will be history by the time of the Twelfth Water Reactor Safety Research Information Meeting at NBS in October.

List of Tables

1. Results of pull out tests on specimens containing pinholes.
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Table 1.

Specimen	Specimen - Dimensions				Clearance	^{o}YS	Observed Load	
Number	B, mm (in)	W, mm (in)	H, mm (in)	D, mm (in)	C, mm (in)	MPa (psi)		(lbs)
1	9.53 (0.375)	76.2 (3)	25.4 (1)	25.4 (1)	0	331 (48000)	71000	(15950)
2	" "	63.5 (2.5)	" "	" "	0	345 (50000)	83300	(18700)
3	6.35 (0.25)	102 (4)	" "	" "	0	386 (56000)	69900	(15675)
4	9.53 (0.375)	" "	" "	" "	0	352 (51000)	95500	(21450)
5	2.13 (0.084)	63.5 (2.5)	" "	" "	0	242 (35000)	15200	(3410)
6	" "	76.2 (3)	" "	" "	0	" "	"	"
7	" "	102 (4)	" "	" "	0	" "	14700	(3300)
8	" "	127 (5)	" "	" "	0	" "	"	"
9	2.95 (0.116)	38.1 (1.5)	12.7 (0.5)	12.7 (0.5)	0	214 (31000)	9550	(2145)
10	" "	44.5 (1.75)	" "	" "	0	" "	9800	(2200)
11	" "	50.8 (2)	" "	" "	0	" "	"	"
12	" "	57.2 (2.25)	" "	" "	0	" "	8800	(1980)
13	4.75 (0.187)	50.8 (2)	12.2 (0.48)	13.5 (0.53)	(0.3125)	780 (113000)	51500	(11559)
14	50.8 (2)	1327 (54)	355 (14)	410 (16.125)	(0.125)	897 (130000)	2.14 x 10^6	(4800000)
15	63.5 (2.5)	" "	" "	" "	"	690 (100000)	"	"

Table 2. Mechanical properties and heat treatment for the A533B, Class 2 steel used for the tab ends and pull tabs in the wide plate tests. Manufacturers reported results.

Melt Number: E18832
Slab Number: C275 (4")
: C274 (6")

Ultimate tensile strength:	(4")	105950 psi	730 MPa
" " " :	(6")	111500 psi	768 MPa
Yield point:	(4")	86600 psi	596.7 MPa
" " :	(6")	92500 psi	637.3 MPa
Elongation, 2", % :	(4")	20.0	
" "	(6")	19.0	
Reduction of Area:	(4")	48.0	
" :	(6")	37.5	

ASIM A533B, Class 2: Specifications	Tensile strength: 90-115 KSI (620-792 MPa) Yield strength, min: 70 KSI (482 MPa) Elong. 2", min %: 16
Heat Treatment:	All material 927°C (1700°F) for 1 hour per inch of thickness, quenched. Tempered at 632°C (1170°F) for 1 hour per inch of thickness.

Table 3. Chemistry results for the steel used for the tab ends and pull tabs. The steel is identified as A533B, Class 2, quenched and tempered. The results are in weight percent.

Element	Mill Report	ASTM A533-84 Specification
Carbon, (max)	.23	.25
Manganese	1.31	1.15-1.50
Phosphorus, (max)	.011	.035
Sulfur, (max)	.020	.040
Silicon	.35	.15-.40
Chromium	.18	NR
Nickel	.60	.40-.70
Molybdenum	.53	.45-.60

Table 4. Specimen Dimensions

Specimen Number	Loading* Span, mm (in)	Width, b, mm (in)	thickness t, mm (in)	total side groove depth, mm (in)	total crack + length, a, mm (in)
1	813 (32.0)	141 (5.55)	102 (4.00)	25.4 (1.00)	51.8 (2.04)
2	813 (32.0)	152 (6.00)	102 (4.00)	24.6 (0.97)	49.8 (1.96)
3	813 (32.0)	152 (6.00)	102 (4.00)	25.9 (1.02)	49.3 (1.94)

* Three point bend.

+ Includes machined notch depth.

Table 5. Loading History

Specimen Number	WPS* Load+ MN (kips)	WPS* K_I MPa $\sqrt{m}$ (ksi$\sqrt{in}$)	Reduced Load+, MN (kips)	Reduced K_I MPa $\sqrt{m}$ (ksi$\sqrt{in}$)	Fractureζ Load+, MN (kips)	Fractureζ K_I MPa $\sqrt{m}$ (ksi$\sqrt{in}$)
1	0.404 (90.6)	131.8 (117.7)	0.343 (77.0)	112.0 (100.0)	0.404 (90.6)	131.8 (117.7)
2	0.533 (119.6)	138.2 (123.4)	0.453 (101.7)	117.5 (104.9)	0.666 (149.5)	172.7 (154.2)
3	0	0	0	0	0.328 (73.7)	85.3 (76.2)

* Warm prestressing at 50°C.

\+ All loading at 445 N/s (6 kips/min).

ζ Fracture took place at -17°C.

Figure 1. Overall specimen configuration and approximate dimensions in centimeters.

Figure 2. Configuration of pinhole indicating meaning of symbols.

Figure 3. Observed yield load versus yield load predicted from equation 2.

Figure 4. Observed yield load versus yield load predicted from equation 4.

Figure 5. Test specimen mock-up with cooling, heating, and instrumentation systems attached.

Figure 6. Temperature as a function of position along mock-up specimen at start of test.

Figure 7. Temperature as a function of position along mock-up specimen after 6.75 hours of cooling and heating.

Figure 8. Effect of temperature gradient on configuration of specimen. Note in plane bending.

Figure 9. Suggested locations of thermocouples and strain gages on ORNL specimen. Dimensions in centimeters.

Figure 10. Fracture surface of bend test specimen #1.

Figure 11. Fracture surface of bend specimen #2.

Figure 12. Fracture surface of bend test specimen #3.

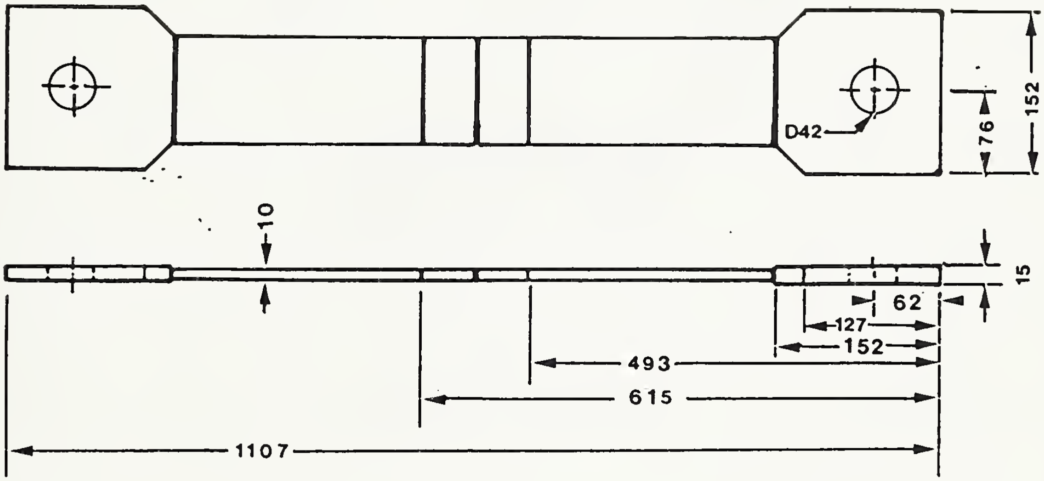

Figure 1. Overall specimen configuration and approximate dimensions in centimeters.

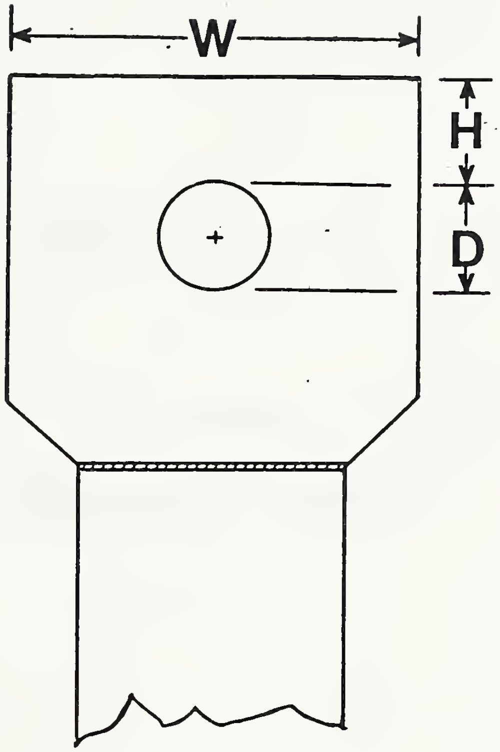

Figure 2. Configuration of pinhole indicating meaning of symbols.

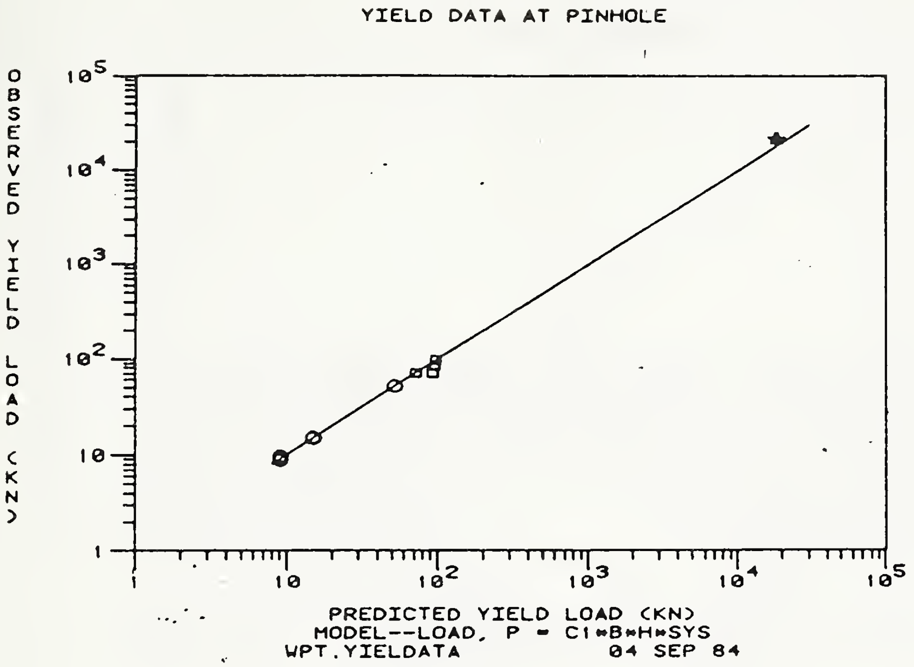

Figure 3. Observed yield load versus yield load predicted from equation 2.

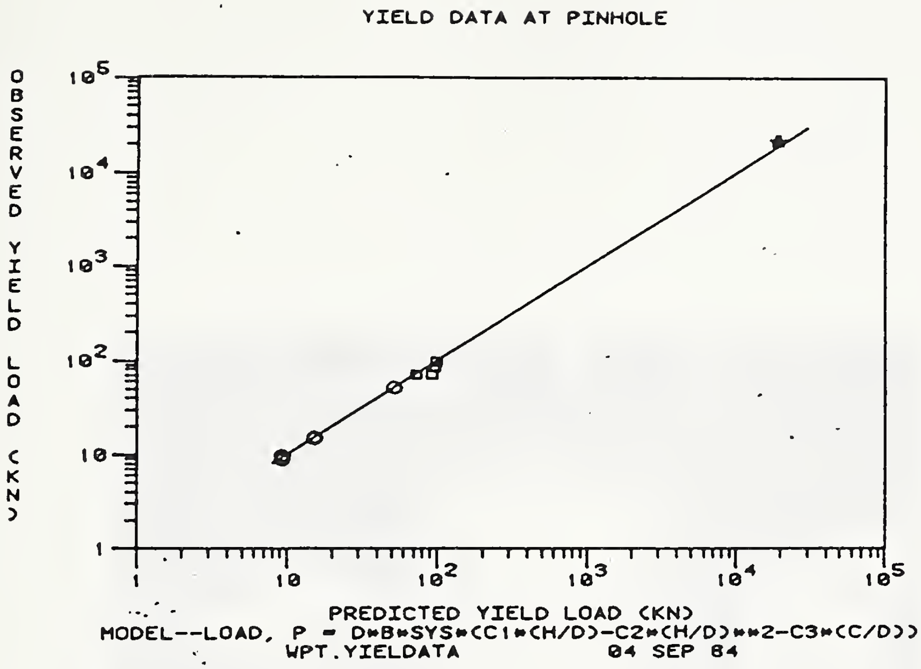

Figure 4. Observed yield load versus yield load predicted from equation 4.

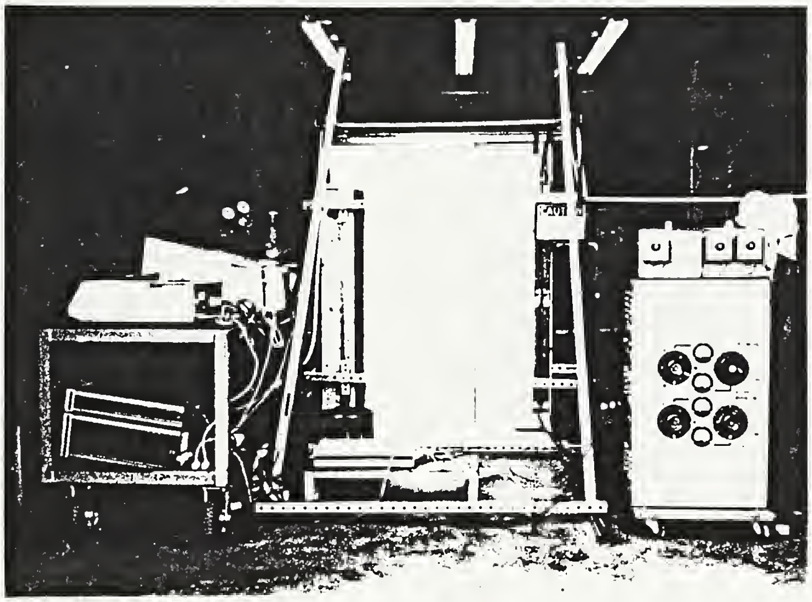

Figure 5. Test specimen mock-up with cooling, heating, and instrumentation systems attached.

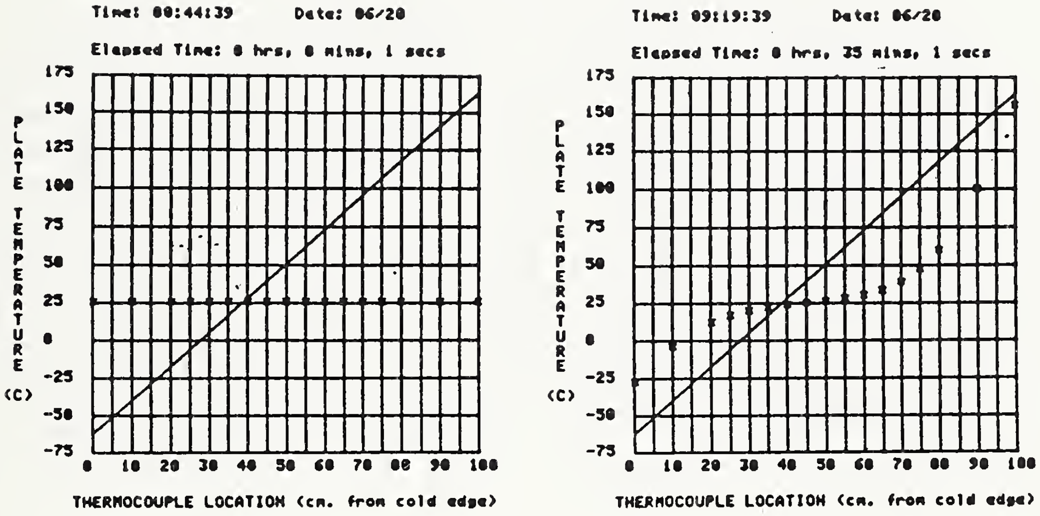

Figure 6. Temperature as a function of position along mock-up specimen at start of test.

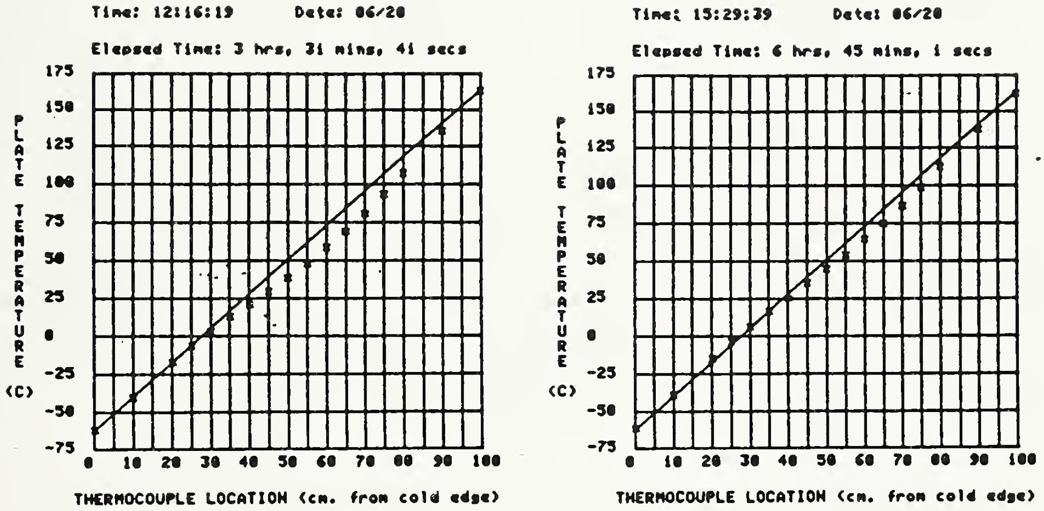

Figure 7. Temperature as a function of position along mock-up specimen after 6.75 hours of cooling and heating.

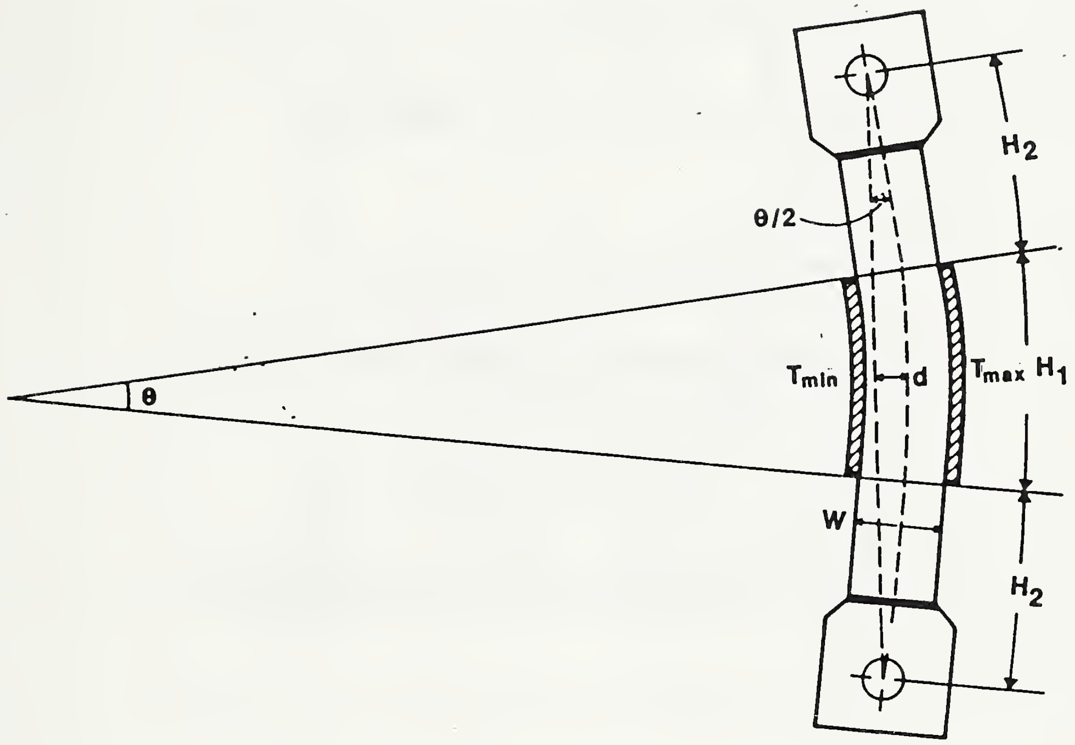

Figure 8. Effect of temperature gradient on configuration of specimen. Note in plane bending.

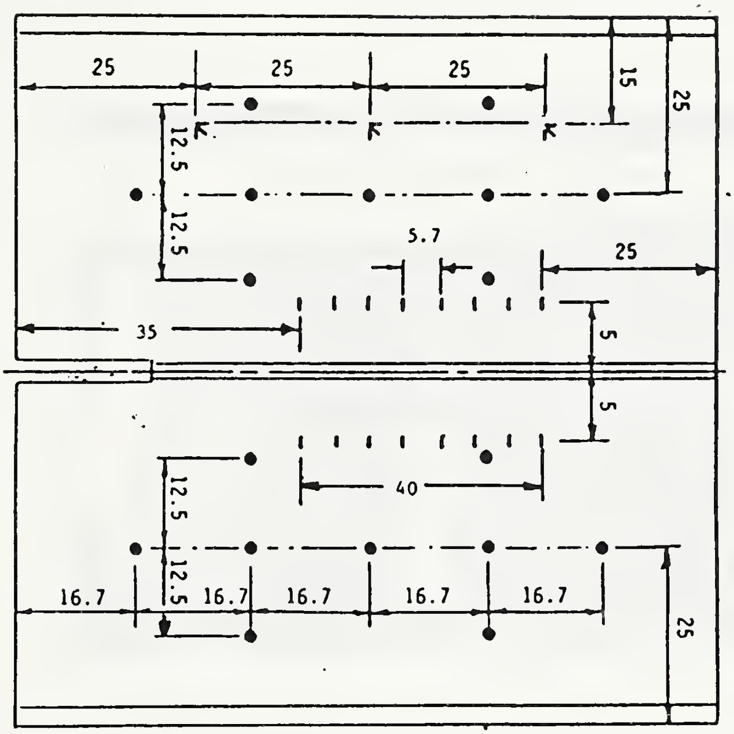

Figure 9. Suggested locations of thermocouples and strain gages on ORNL specimen. Dimensions in centimeters.

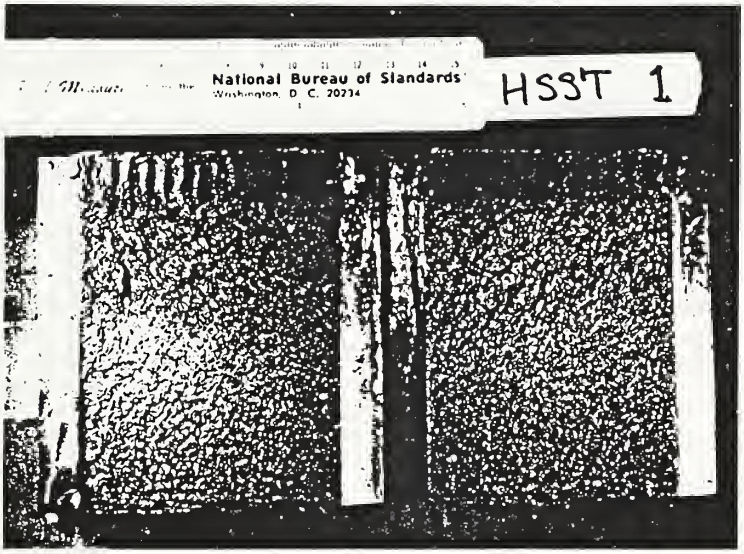

Figure 10. Fracture surface of bend test specimen #1.

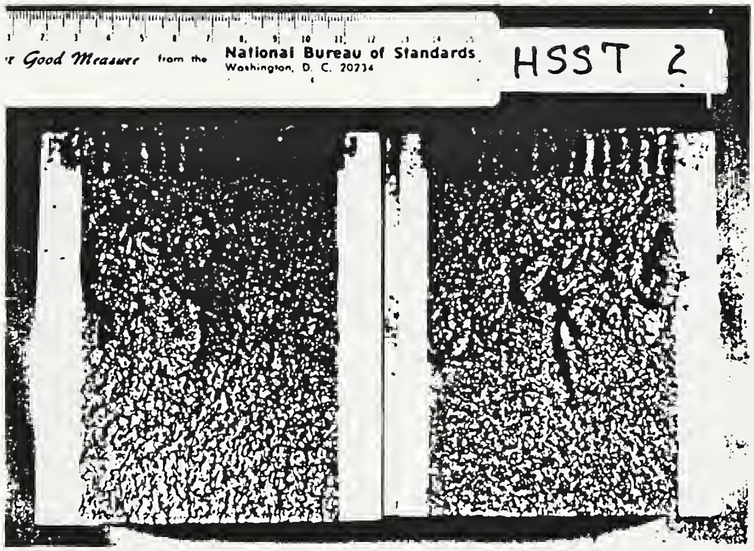

Figure 11. Fracture surface of bend specimen #2.

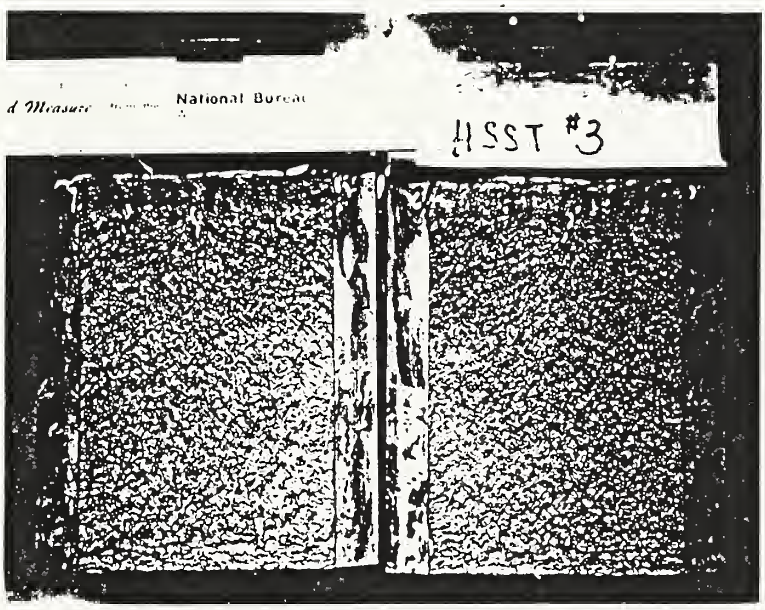

Figure 12. Fracture surface of bend test specimen #3.