Fracture resistance of SA106B seamless piping and welds

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1 INTRODUCTION

Ontario Hydro has developed a leak-before-break (LBB) methodology for application to the large diameter heat transport piping for Darlington NGS A because of the difficulties encountered in attempting to provide pipewhip restraints and in recognition of the questionable benefits of providing such devices. This approach has been developed for pipe sizes which are equal to or greater than 21" nominal diameter (21" NPS).

Piping steels are expected to exhibit a stable crack extension behaviour with rising load up to the point of instability in the ductile uppershelf regime. Under these conditions, the application of structural integrity concepts that are based on crack initiation alone will be overly conservative. Thus the margin against failure must be determined under elastic plastic conditions by taking into account both crack initiation and stable crack growth. The Ontario Hydro leak-before-break approach is based on the J/T method.

The material value of J associated with crack extension which is also known as material resistance curve or a J-R curve is required for stability assessment. The nondimensionalised slope of a J-R curve at a given value of J is defined as tearing modulus (T). The margin against instability is determined from a J-T plot where J is plotted against T for the material and the structure. In this Darlington leak-before-break material test program J-R and J-T curves were determined from actual Darlington NGS-A large diameter heat transport piping, forgings, associated welds and heat affected zones. A total of 91 J-resistance curve tests were conducted. Sixty-three tensile tests were also performed to determine the stress-strain behaviour accurately. This paper is a brief summary of the J-R curve test results and major conclusions.

2 EXPERIMENTAL PROGRAM

The test program was designed to take into account the effect of various factors which influence fracture properties. The objective was to identify those factors which tend to lower resistance curves and apply the appropriate lower bound resistance curves that were obtained from this program, for structural analyses. Factors that were included in this project were:

Pipe size;
Heat of Piping Material;

Crack Plane Orientation;
Temperature;
Welding Effects.

Three different pipe sizes of seamless SA-106 Grade B were used (12, 22 and 24 inch NPS). Two SA-105 vesselet forgings were also tested. Vesselet is a trade name for a weld-in contour fitting. The test program utilized actual piping material from actual piping heats that were used in the construction of the Darlington heat transport system (Units 1 and 2). In the stability assessment of through circumferential (L-C) and longitudinal (C-L) flaws, J-Resistance curves in L-C and C-L crack plane orientations, respectively, are required. Specimens from SA106B and SA105 forgings were machined from both L-C and C-L orientation.

It is known that ductility of SA106B steel, as measured by the lateral contraction during a tensile test, shows a minimum value between 200°C and 300°C. Tensile tests were conducted in this temperature range and it was established that the lateral expansion of this material is minimum in the neighbourhood of 250°C. Therefore, 250°C was selected as the appropriate test temperature. These results will then be conservatively used for the appropriate operating temperature. In order to determine if there is any significant dependence of toughness on temperature over the temperature range, a temperature of 20°C was selected arbitrarily, as a lower bound of the lowest service temperature for the heat transport system.

Two different Ontario Hydro welding procedures (PN-108 and PN-232) were used for all welds within the scope of the LBB program. Each of these welding procedures for nuclear Class I piping, were included in the test program. These welding procedures are listed in Table I. Tests were conducted on the weld material and the heat affected zone (HAZ) material. The orientation of a crack in the weld and HAZ was in the L-C direction. Due to the V-shape of the weld preparation surface, the crack front in a HAZ specimen straddled the HAZ, parent and weld material. The measured HAZ toughness is therefore an average toughness.

3 TEST METHOD

Three different sizes of compact tension (CT) specimens, 1-1/4T, 1T and 3/4T, conforming to the geometry of the ASTM test procedure E813, Test for J_{Ic}, a Measure of Fracture Toughness were used. The sizes of the specimens were determined by the largest CT specimens that could be machined without flattening from the 24", 22" and 12" NPS pipe, respectively. All specimens were precracked and sidegrooved after precracking to ensure a straight crack front. The R-curves produced with a straight crack front extension exhibit slopes (dJ/da) lower than those produced with a non sidegrooved specimen. Sidegrooving also appears to produce a slightly lower (more conservative) value of crack initiation toughness.

Regarding specimen geometry, existing data indicate that fracture toughness specimens having approximately the same thickness as the pipe wall and without sidegrooves tend to model actual pipe behaviour most accurately. However, sidegrooved specimens will provide an acceptable lower bound J-resistance curve/1/. Also note that C-T specimens are bend type specimens. J-R curves from bend type specimens defines the lower bound estimate of J-capacity as a function of crack extension, and has been observed to be conservative in comparison with those obtained with tensile loading specimen configuration/2/. The specimen thicknesses were approximately 80% of the respective pipe wall thicknesses from which they were machined. Therefore, this test program will provide an acceptable lower bound J-resistance curve.

A single specimen technique documented in /2/ was utilized to determine the J-R curves. In this test method, crack length and crack extension were determined from elastic compliance measurements. These measurements were taken on a series of unloading/reloading segments spaced along the load versus load-line displacement record.

A personal computer was used for test control and data acquisition. A computer program was developed to control the loading and unloading sequences. A separate computer program was used to analyze the acquired data and plot final graphs.

The calculation of J_{Ic} is according to ASTM E813-81. J_{Ic} is defined by the intersection of a linear regression fit to the data, that fall within the 0.15 and 1.5 mm exclusion lines, with the blunting line. A J-R curve is established by fitting a curve through the experimental data points using a power law equation in the form

$$J = C_1 \ (\Delta a)^{C_2}$$

This equation has been used extensively to establish J-R curves for ferritic steels. An examination of the data showed that this equation provides an excellent fit through the experimental J-Δa data points for each experiment in this test program.

4 DISCUSSION OF RESULTS

The objective of this test program was to develop a comprehensive material data base for all product forms, heats of steels and weld procedures that have been used in the construction of large diameter Darlington heat transport circuit. At the end of the test program, it can be stated with confidence that this objective has been achieved. All test results are stored in a computerized data base.

4.1 Parent

Specimens from four product forms were tested. These were 24", 22" and 12" NPS Sch 100 pipes and SA105 forgings. Toughness values and J-resistance curves of these product forms depend on temperature and orientation. However, at a fixed temperature and at a fixed orientation toughness value (Figure 1) and J-resistance curves (Figures 2) lie within a narrow scatterband.

A general observation from all parent material results is that all precracked parent material specimens showed stable and ductile crack extension with rising load. There was no systematic variation of toughness with product forms or pipe sizes. At both test temperatures and specimen orientations all parent material specimens showed high J_{Ic} and rising resistance curves with crack extension.

Toughness values of pipes depend on the direction of crack extension relative to the pipe geometry. Tests using conventional Charpy specimens have shown that toughness of SA106B steel, as indicated by energy absorption, depends on specimen orientation/3/.

At 250°C, J_{Ic} and J-resistance curves in the circumferential direction were higher than those in the axial direction for all product forms. Changes in J_{Ic} values and J-resistance curves were comparable for the 24" and 22" NPS Sch 100 pipes and SA105 forgings (Figure 3). The 12" NPS Sch 100 pipe specimens showed the least reduction of toughness with orientation.

Toughness behaviour of high toughness – low strength C–Mn steels such as SA106B and SA105 forgings show a transition with temperature. An examination of load displacement curves and Charpy energy values indicated that these steels show an upper shelf toughness behaviour at 20°C. Specifically, load versus displacement behaviour of all specimens were highly ductile. All specimens exhibited high crack initiation toughness, stable crack extension and steeply rising resistance curves beyond J_{Ic}.

J_{Ic} and J-resistance curves at 250°C were lower than those at 20°C, which is characteristic of lower strength, high toughness structural steels (Figure 4). Reduction of material tensile stress with temperature will promote this behaviour.

4.2 Weld

Ontario Hydro has developed various welding procedures for the construction of Darlington PHT system. These procedures satisfy ASME Code requirements. The PN 108 and PN 232 weld procedures were used for all welds within the scope of the Darlington LBB project. Post weld heat treatment is required for these weld procedures. All tests on PN 108 and PN 232 weld and HAZ material at both test temperatures showed high J_{Ic}, stable crack extension and rising resistance curves, that is, general uppershelf toughness behaviour.

J_{Ic} values and J-resistance curves (Figure 5) for the weld and HAZ material of PN 108 and PN 232 procedures were higher than the corresponding parent material properties. Due to the geometry of weld preparation and the given thickness of pipes, the crack front in a HAZ specimen straddled the weld, HAZ and parent material. The measured HAZ J-resistance curves, therefore, lie between the weld and parent material resistance curves. Effect of test temperature on the toughness of PN 232 weld was similar to that observed in parent material tests in that J_{Ic} and J-resistance curves at 250°C were lower than those at 20°C. An uppershelf toughness behaviour was observed at both test temperatures.

5 VALIDATION OF TEST RESULTS

Since the material test program is pivotal to the Darlington LBB program, it was decided to validate the material test program by comparing six test results against tests conducted by an independent laboratory. Materials Engineering Associate of Lanham, Maryland was selected for conducting the validation tests because of their experience in conducting single specimen J-resistance curve tests for U.S. Nuclear Regulatory Commission/4/.

Three 2.5 cm thick compact tension specimens were machined by MEA and were tested at 250°C. All specimens were machined in the L–C orientation. Yield and UTS values were provided to MEA by Ontario Hydro.

In summary, the J_{Ic} and J-resistance curves obtained by OH and MEA on parent and weld materials (Figure 6) were comparable. There were no systematic variation or discrepancy between the tests conducted by two independent laboratories. This comparison provides an independent but indirect validation of transducer calibration, test method, crack length and J calculation procedures.

6 CONCLUSIONS

1. All product forms utilized in the construction of Darlington primary heat transport piping (24", 22" and 12" SA106B NPS Sch 100 pipes and SA105 forging) exhibited uppershelf toughness behaviour at 20°C and 250°C. All specimens from the above product forms showed high crack initiation toughness J_{Ic}, increasing resistance to crack extension and stable and ductile crack growth.
2. Toughness (J_{Ic} and J-Resistance curve) of parent materials depends on specimen orientations. Toughness of a pipe in the circumferential orientation was higher than the corresponding toughness in the axial direction. The effect of orientation on toughness was quantified.
3. For a given temperature and specimen orientation, toughness of various product forms was reasonably uniform.
4. All welds and heat affected zone materials within the scope of the Darlington Leak Before Break project exhibited uppershelf toughness behaviour at 20°C and 250°C. All specimens from weld and HAZ material showed high crack initiation toughness, J_{Ic}, increasing resistance to crack extension and stable and ductile crack growth.
5. The material test program was validated by comparing six test results against tests conducted by Materials Engineering Associates of Lanham, Maryland. The J_{Ic} and J-resistance curves obtained by Ontario Hydro and MEA were comparable.

REFERENCES

1. Report of the U.S. Nuclear Regulatory Commission Piping Review Committee, Nureg-1061, Volume 3.
2. Standard Test Method for Determining J-R Curves, 12th Draft. A proposed test method developed by the ASTM E24.08 Subcommittee.
3. "PVRC Recommendations on Toughness Requirements for Ferritic Materials", Welding Research Council Bulletin No. 175.
4. "Structural Integrity of Water Reactor Pressure Boundary Components", Annual Report for 1984. Edited by F.J. Loss, Materials Engineering Associate, NUREG/CR-3228, MEA-2051, Vol. 3.

Table I. Ontario Hydro Nuclear Weld Procedures

NPS (Inches)	Ontario Hydro Weld Procedure	Weld Process
24 22	PN 108	- GTAW root pass - SMAW fill up - for field and shop welding - PHWT performed
24 22	PN 232	- GTAW root pass - SMAW 2nd pass - SAW fill up - for shop welding only - PWHT performed

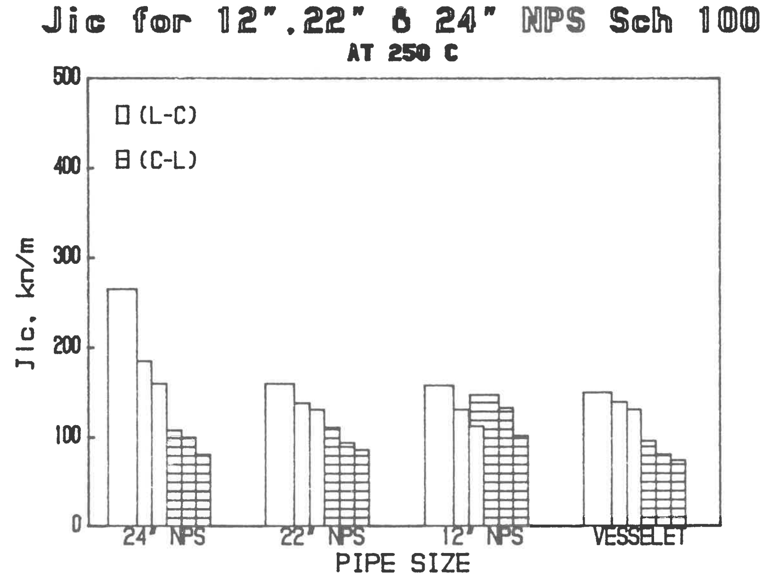

FIGURE 1

COMPARISON OF J_{IC} FOR VARIOUS PRODUCT FORMS

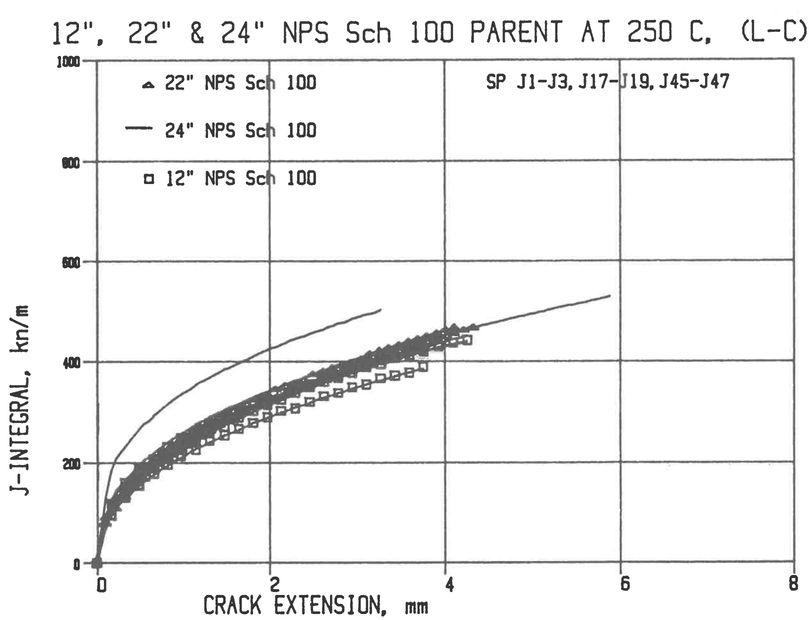

FIGURE 2

J-RESISTANCE CURVES FOR THREE PIPE SIZES

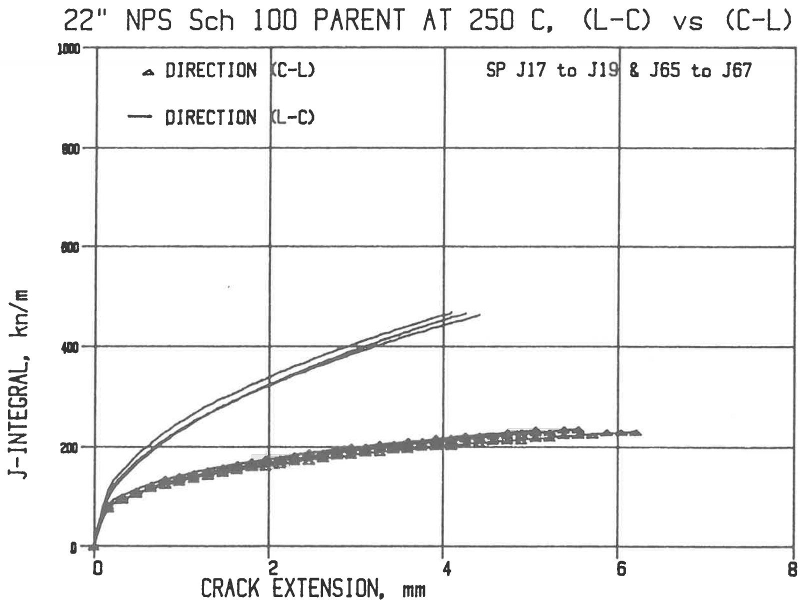

FIGURE 3

EFFECT OF ORIENTATION ON J-RESISTANCE CURVES

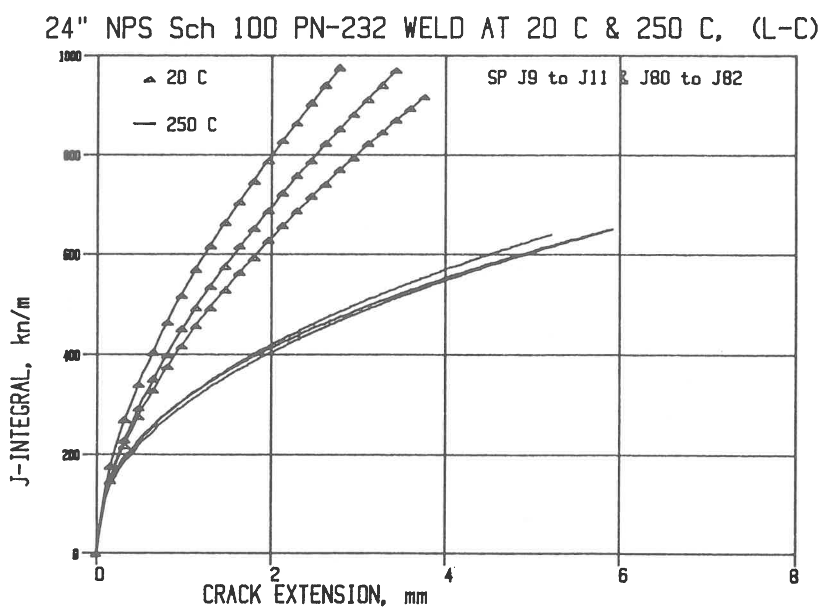

FIGURE 4

EFFECT OF TEST TEMPERATURE ON J-RESISTANCE CURVES

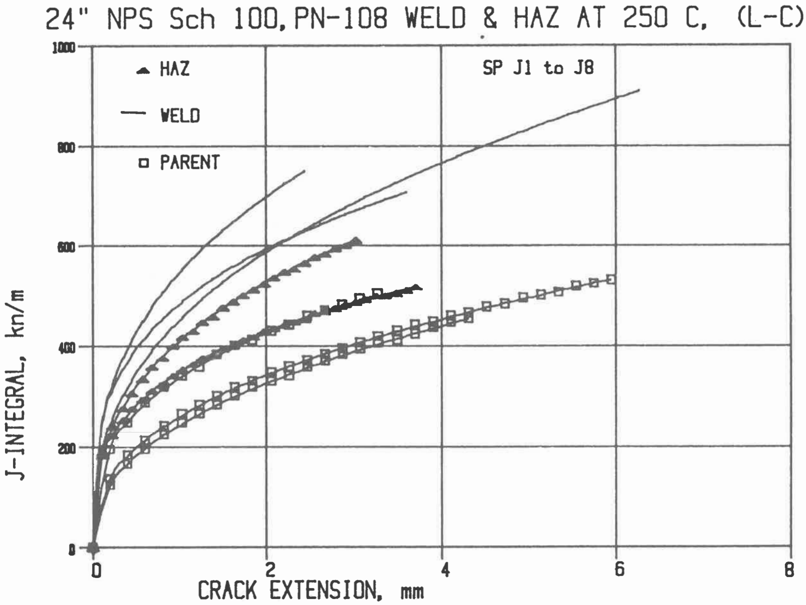

FIGURE 5

COMPARISON OF J-RESISTANCE CURVES FOR WELD, PARENT AND HAZ MATERIALS

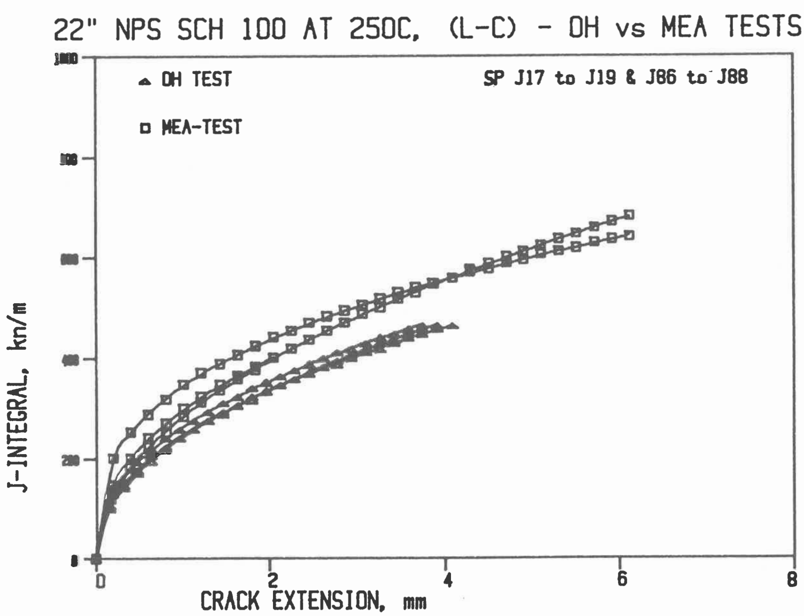

FIGURE 6

COMPARISON OF J-RESISTANCE CURVES BETWEEN OH AND MEA TESTS