CONF-790736--2

A Fractographic Study Of A Thick Wall Pressure Vessel Failure

D. A. Canonico, R. S. Crouse and T. J. Henson

MASTER

ABSTRACT

A Heavy Section Steel Technology (HSST) Program sponsored by the Nuclear Regulatory Commission (NRC) and administered by the Oak Ridge National Laboratory (ORNL) is concerned with the safety and reliability of nuclear pressure vessels. Some of the testing involves pressurizing to failure simulated pressure vessels containing large fatigue sharpened flaws. These vessels are fabricated from SA533 grade B, Class 1 plate or SA508, Class 2 forgings.

The vessel described in this paper is identified as Intermediate Test Vessel 1 (ITV-1) and was fabricated of SA508, Class 2 Steel. It was tested to failure at 54°C (130°F). The gross failure appeared to be a brittle fracture although accompanied by a measured strain of 0.9%. Seven regions of the fracture were examined in detail and the observed surfaces were compared to Charpy V-notch (C_V) specimens of SA508, Class 2 steel broken at temperatures above and below the ductile to brittle transition temperature. Three samples from the vessel were taken in the region around the fatigue notch and four from areas well removed from the notch. All these were carefully examined both optically and by scanning electron microscopy (SEM).

It was established that early crack extension was by ductile mode until a large flaw approximately 500 mm long 83 mm wide was developed. At this point the vessel could no longer contain the internal pressure and final rupture was by brittle fracture.

Research sponsored by U. S. Department of Energy and Union Carbide Corporation under contract W-7405-eng. 26.

Submitted for presentation at the 12th Annual International Metallographic Society Technical Meeting at Tamiment, Pa., July 8-11, 1979.

A Fractographic Study Of A Thick Wall Pressure Vessel Failure

D. A. Canonico, R. S. Crouse and T. J. Henson

ABSTRACT

A Heavy Section Steel Technology (HSST) Program sponsored by the Nuclear Regulatory Commission (NRC) and administered by the Oak Ridge National Laboratory (ORNL) is concerned with the safety and reliability of nuclear pressure vessels. Some of the testing involves pressurizing to failure simulated pressure vessels containing large fatigue sharpened flaws. These vessels are fabricated from SA533 grade B, Class 1 plate or SA508, Class 2 forgings.

The vessel described in this paper is identified as Intermediate Test Vessel 1 (ITV-1) and was fabricated of SA508, Class 2 Steel. It was tested to failure at 54°C (130°F). The gross failure appeared to be a brittle fracture although accompanied by a measu . . strain of 0.9%. Seven regions of the fracture were examined in detail and the observed surfaces were compared to Charpy V-notch (C_V) specimens of SA508, Class 2 steel broken at temperatures above and below the ductile to brittle transition temperature. Three samples from the vessel were taken in the region around the fatigue notch and four from areas well removed from the notch. All these were carefully examined both optically and by scanning electron microscopy (SEM).

It was established that early crack extension was by ductile mode until a large flaw approximately 500 mm long 83 mm wide was developed. At this point the vessel could no longer contain the internal pressure and final rupture was by brittle fracture.

Research sponsored by U. S. Department of Energy and Union Carbide Corporation under contract W-7405-eng. 26.

Submitted for presentation at the 12th Annual International Metallographic Society Technical Meeting at Tamiment, Pa., July 8-11, 1979.

INTRODUCTION

The Oak Ridge National Laboratory has managed the Heavy Section Steel Technology (HSST) program and participated in the experimental work associated with it since its inception in 1966. The HSST program is concerned with the safety and reliability of nuclear pressure vessels. One facet of the program involves pressurizing 1-m diam by 2.5 m tall intermediate test vessels (ITV) to failure. Typically these vessels are fabricated from SA 533 Grade B Class 1 plate or SA 508 Class 2 forgings that are 150-mm thick, and each vessel is provided with a large fatigue sharpened (or hydrogen-charged electron beam) crack. Figure 1 provides a sketch of the ITVs that are being tested.

To date seven vessels have been tested. The test conditions and results of these tests are provided in Table 1. This series of ITV tests has provided a great deal of engineering and design information as well as affording the opportunity to thoroughly assess the failure mode of a vessel whose wall thickness approximates that in commercial nuclear pressure vessels. This paper will describe the procedure employed in the post-test examination of one ITV which was tested to failure at 54°C.

FRACTURE PROPAGATION

ITV-1 was fabricated from ASTM A 508 Class 2 steel.[1] Vessel testing was conducted in a facility designed and built for these specific tests (see Figure 2). The facility and testing procedure is described in an ORNL document.[2] The ITV-1 test resulted in the complete rupture of the vessel as shown in Figure 3. The fracture originated from an 203 mm long by 66 mm deep semi elliptical fatigue sharpened flaw and propagated to the top head in the upward direction and around the bottom hemihead in the downward direction. The upward propagation of the crack ran through the circumferential weld (shown in Figure 1) that joins the transition piece to the cylindrical test section and and terminated at the interface between the transition piece and the bolted-on cover plate. The downward propagation path was through the circumferential weld that joins the bottom hemihead to the center cylindrical test section. The crack continued around the bottom and terminated near the circumferential weld approximately 180^{o} from where it first entered the bottom hemihead.

This well-documented test allowed the complete evaluation of the vessel failure. The test temperature, 54^{o}C, is 56^{o}C above the drop weight nil ductility temperature (NDT) for the SA 508 Class 2 heat of steel from which ITV-1 was fabricated. Moreover, 54^{o}C is approximately the temperature of the onset of upper shelf for this heat of steel. Figure 4 contains the Charpy V-notch (C_V) curve for the 3/8 T and 5/8 T location for the ITV-1 steel.[3]

Although the vessel did undergo a strain of nearly 1%, the final fracture as observed immediately after vessel failure did not visually exhibit large shear lips and the initial observation was to conclude that the vessel had failed in a frangible mode. The "flat fracture" accompanied by a measured strain of nearly 1% was somewhat contradictory and it was decided that a fractographic study of the fracture surface was warranted.

Initially, an effort was made to extract fracture surface replicas with RTV rubber without disturbing the failed vessel. The rough texture of the fracture did not allow this nondestructive experimental approach and it was necessary to remove the fracture area from the vessel and subsequently saw it into pieces that could be handled in the scanning electron microscope. After considerable discussion concerning methods for removing the fracture surface from the failed vessel, it was concluded that oxyacetylene burning was the most expedient and least costly technique available. The flame cut was made approximately 8 in. away from the fracture surface. This distance is more than ample to assure no heat effect due to the flame cutting operation.[4] The fracture surface was protected during the flame-cutting. A photograph of the fracture surface prior to sawing is shown in Figure 5. The original fatigued flaw is quite evident. The circumferential weld that joined the bottom hemihead to the cylindrical test section is easily seen at the left side (A) of the photograph. (It is located at the change in contour.) The circumferential weld at the upper end of the cylindrical test section is not as evident; however, it, too, is located at the geometric change in section size the right side of the photograph.

FRACTOGRAPHY STUDY

Seven regions of the fracture surface shown in Figure 5 were studied. One is located in the transition piece, five are located in the cylindrical test section, and one is located in the hemihead. In order to relate the fracture morphology in ITV-1 to that exhibited by the same steel at the lower and upper Charpy V-notch (C_V) energy levels a SEM examination of C_V specimens was conducted. Figure 6 contains the results of the SEM study on C_V specimens whose precise test conditions are known. The steel from which the C_V specimens were prepared was SA-508 and was heat treated in precisely the same manner as the cylindrical test section. Specimens from the C_V curve shown in Figure 4 were used. A specimen tested at 59°C which absorbed 18 J of energy was used to illustrate brittle fracture appearance. A specimen tested at 50°C (4°C below the ITV-1 test temperature) which absorbed 112 J of energy was used to depict ductile behavior. Figure 6 shows the difference in appearance of a brittle and ductile fracture surface. Note the ribbon-like pocked appearance of the ductile failure. It is characterized by a dull appearance with surface contour somewhat akin to a classical cup-cone fracture of a ductile tensile failure. In contrast, the brittle fracture surface is faceted and both possess distinct characteristics that make each easily discernible.

The first ITV-1 specimen examined was from the region below the deepest point of the fatigue crack. Figure 7 shows two locations where specimens were taken and also illustrates the results of scanning electron microscopy studies of these fracture surfaces. Note the appearance of the surface of the two specimens is quite similar to that shown for the tough specimen (C_V energy of 83 ft-lb) in Figure 6. This region of the cylindrical test section exhibited a dimple fracture mode.

Figure 8 shows the results of the fractographic study from the region just adjacent to the fatigue crack. Two areas within this region were studied. (The corner of the flaw can be seen.) They, too, are similar in appearance to the ductile failures shown in Figure 6. This region also exhibited dimple (tough) fracture mode.

The third region investigated is just under the steel rope shown in Figure 5. On a macro scale this location exhibited a change in appearance and coloration. The dark "ductile" coloration seems to terminate in a V, with chevron lines, somewhat lighter in color, originating from this apex. This is usually indicative of an initiation site for fracture propagation. A fractographic study of this region (see Figure 9) was carried out. The first area studied was located close to the center of the fracture surface and was within an area that was visually similar to the regions shown in Figures 7 and 8. It has a fracture appearance (dimple mode) nearly identical to those previously shown. Therefore, this area is ductile (tough). The second area studied was outside the V-shaped area and in the more shiny, bright area. The SEM examination of this area revealed a clevage mode of failure similar to those seen for the low temperature (frangible) specimens seen in Figure 6. This area has undergone brittle failure.

Additional regions were studied that included regions approximately 76 mm from the circumferential welds in the top transition piece and the bottom hemihead. These regions exhibited cleavage fracture modes indicative of brittle failure.

INTERPRETATION OF RESULTS

An inspection of the exposed fracture surfaces showed that a shear lip of approximately 25-38 mm exists at both surfaces of the cylindrical test section. A sketch (Figure 10) was prepared showing the dimensional relationship of the various topographical aspects of the region around the manmade flaw. The dark tough region (dimple fracture mode, (see Figures 7,8 and 9) is approximately 520 mm long and 76 to 83 mm wide. Beyond this region the surface exhibits a cleavage fracture mode.

This SEM study proved that the fatigue crack grew by ductile tearing until the flaw approached 500 mm in length and 83 mm in width. This extension, because of the stronger and perhaps tougher at $54^{o}C$ surface material, was by internal tunneling. Slow crack propagation continued until the flaw became quite large and could no longer sustain the internal pressure which imposed a stress on the remaining vessel section that approached limit load. At this point fast fracture was initiated and crack extension was by cleavage mode.

SUMMARY

A study of the fracture surface of ITV-1 revealed a mixed mode of fracture. Initial crack growth is by ductile tearing. The growth was by tunneling and continued until the flaw size was such that unstable (plane strain) crack growth could occur. This results in a transition from ductile slow crack growth to brittle catastrophic failure. In summary, ITV-1 initially underwent ductile tearing. Final failure was rapid and fracture was by cleavage mode.

REFERENCES

1. 1964 Annual Book of ASTM Standards, Part 4, pp. 696-704, American Society for Testing and Materials, A508-68, 1964.

2. R. W. Derby, J. G. Merkle, G. C. Robinson, G. D. Whitman and F. J. Witt, "Test of Six Inch Thick Pressure Vessels, Series 1: Intermediate Test Vessels V1 and V2," ORNL 4895.

3. F. J. Witt, "Heavy Section Steel Technology Program Semi-Annual Progress Report," ORNL-4855 (Sept. 1973,), p. 39.

4. D. A. Canonico, "Technical Note: Depth of Heat-Affected Zone In Thick Pressure Vessel Steel Plate Due To Flame Cutting," Welding J. (N. Y.), 47 (9): 410-s and 419-s (Sept. 1968).

Table 1. Test Conditions and Results for the Intermediate Test Vessels

Vessel	Flaw Size, mm Depth	Flaw Size, mm Length	Test Temperature, °C	Charpy V. Notch Toughness at Failure site, J	Load Factor at Failure[a]	Remarks
2	64.3	211	0	54	2.87	Flaw on outside of SA5 Class 2 vessel. Flat of failure.
4	76.2	209	24	135	2.75	Flaw on outside of wel Mixed mode of failure.
9	30.5	(nozzle)	24	100	2.77	Flaw on inside of SA50 Class 2 vessel at nozzl Flat mode of failure.
1	65	208	54	108	2.96	Flaw on outside of SA5 Class 2 vessel. Mixed mode of failure.
3	53.6	216	54	170[b]	3.19	Flaw outside of weld. Mixed mode of failure.
6	47.5	133	88	170[b]	3.28	Flaw outside of weld. Shear mode of failure.
5	30.5	(nozzle)	88	NA	2.74	Flaw on inside of SA508 Class 2 vessel at nozzl Vessel leaked.
7	135	472	196	190[b]	2.20	Flaw on outside of SA53 Grade B Class 1 vessel. Largest flaw in all tests. Vessel leaked.

[a] Ratio of failure pressure to design pressure. Design pressure based on requirements of Section III Class 1 vessels in ASME Code.

[b] Upper shelf energy values.

NA Not available - Test temperature is on charpy V notch upper shelf (135 J)

ORNL-DWG 70-320R2

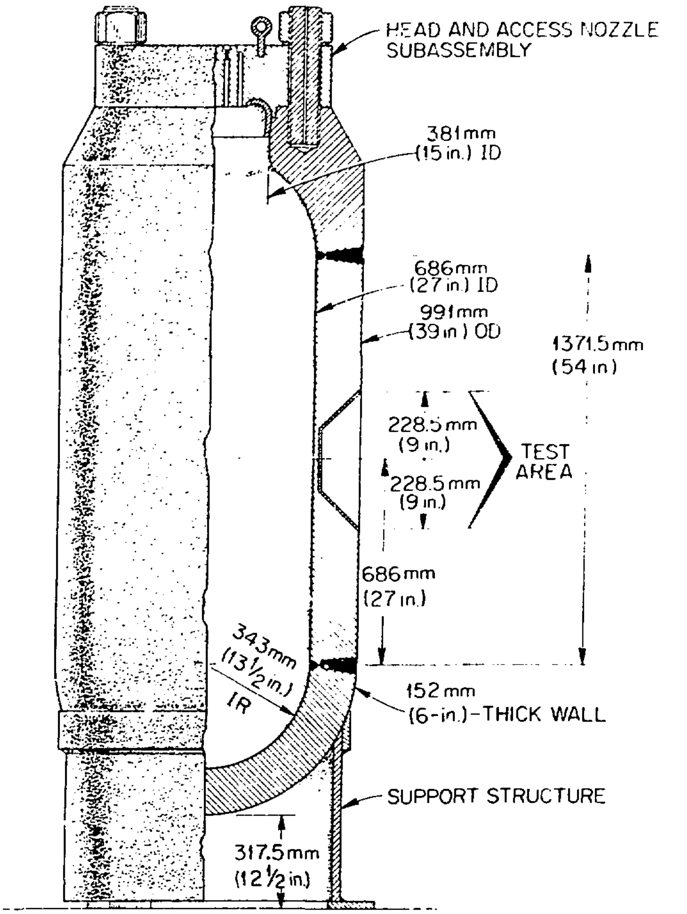

FIG. 1. A TYPICAL INTERMEDIATE TEST VESSEL (ITV). FROM TEST TO TEST THE FLAW LOCATION AND CONFIGURATION VARIED. (1 INCH = 0.0254 m)

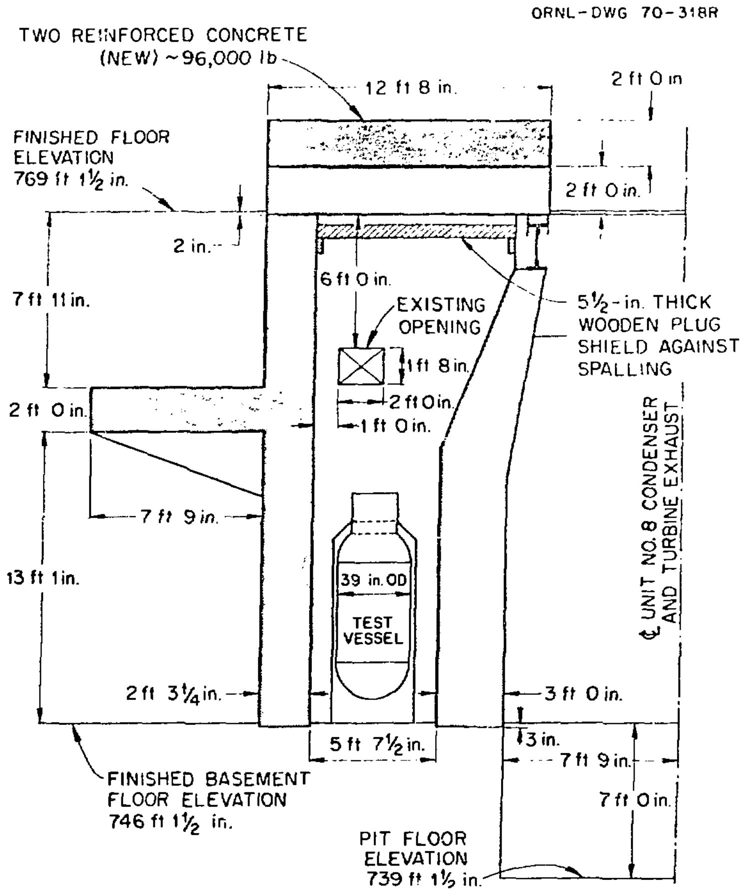

FIG. 2 PRESSURE VESSEL TESTING FACILITY. THE VESSEL WAS SURROUNDED BY REINFORCED CONCRETE. (1 POUND = 0.4536 KILOGRAMS; 1 FOOT = 0.3048 METERS; 1 INCH = 0.0254 METERS)

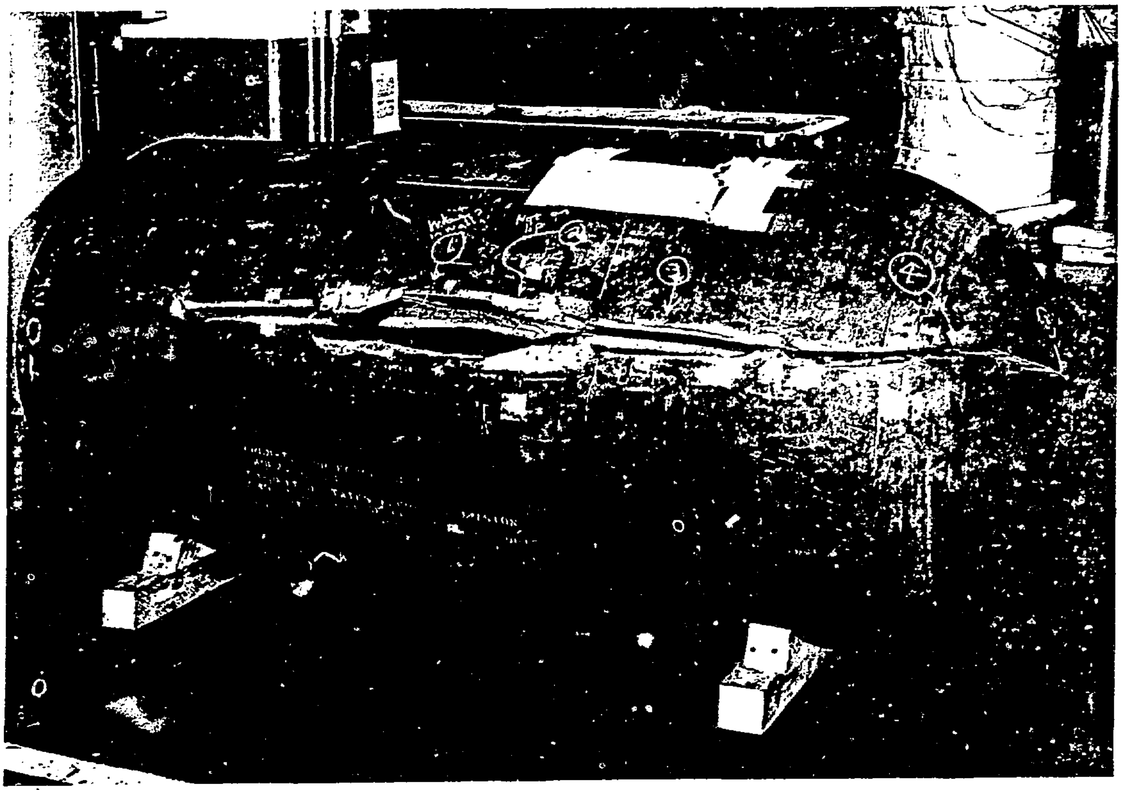

FIG. 3 INTERMEDIATE TEST VESSEL NO. 1 (ITV-1) AFTER HYDRAULIC TESTING TO FAILURE.

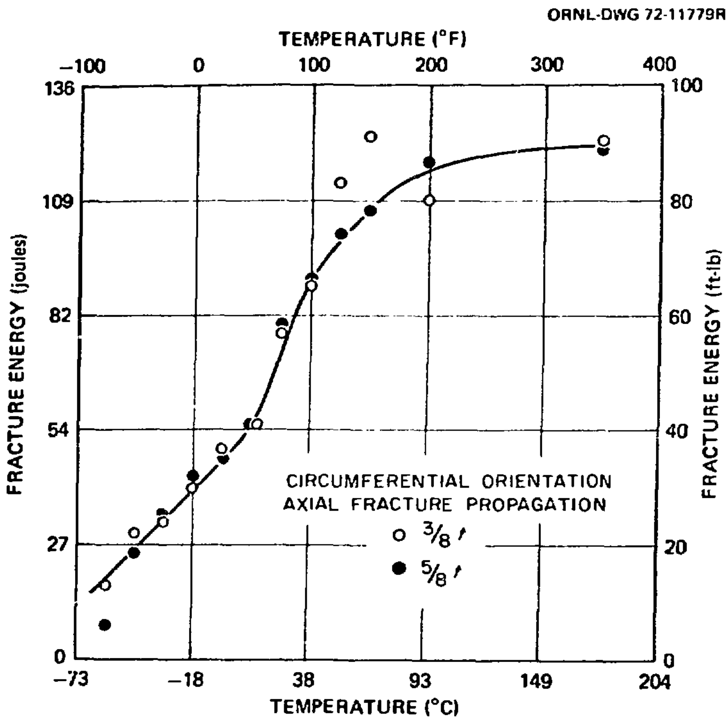

FIGURE 4. CHARPY V-NOTCH IMPACT TEST RESULTS OBTAINED FROM INTERMEDIATE VESSEL V-1, 152 mm THICK, ASTM A508, CLASS 2 FORGING.

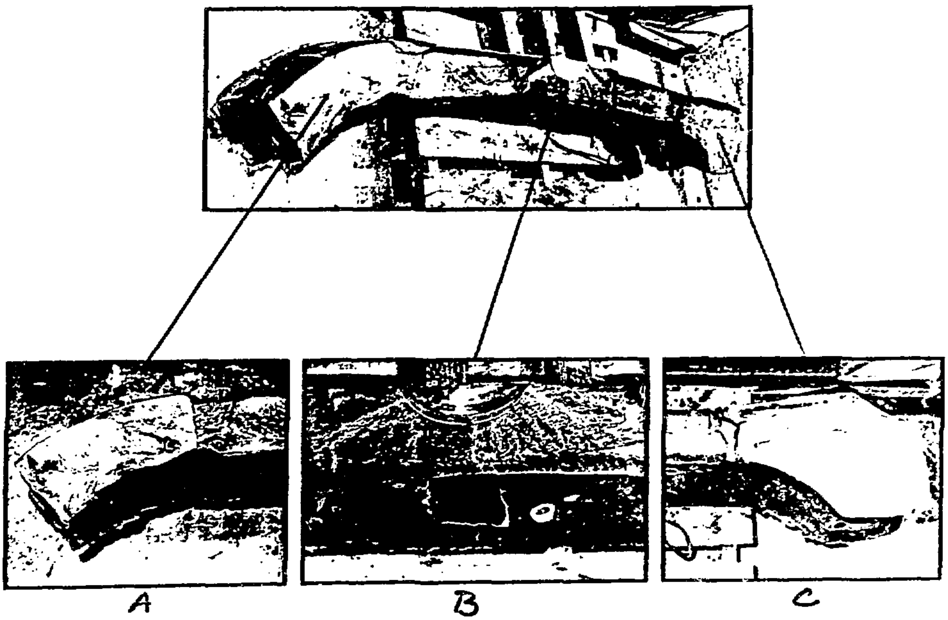

FIG. 5. THIS IS ONE HALF OF THE FINAL FRACTURE REMOVED FROM THE REST OF THE VESSEL. AREAS A, B AND C WERE CHOSEN FROM WHICH TO REMOVE SAMPLES FOR SCANNING ELECTRON MICROSCOPY.

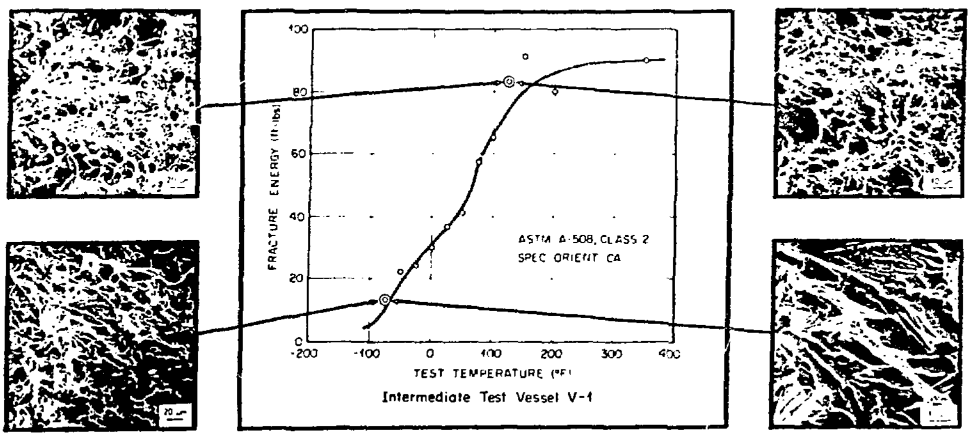

FIG. 6. CHARPY V-NOTCH TEST RESULTS. CAREFULLY CONTROLLED TOUGHNESS TESTS OF ITV-1 STEEL PROVIDED BASE LINE DATA FOR EVALUATION OF THE VESSEL TEST. (1 FOOT POUND 1.36 JOULES; $t_c=(t_F-32)/1.8$)

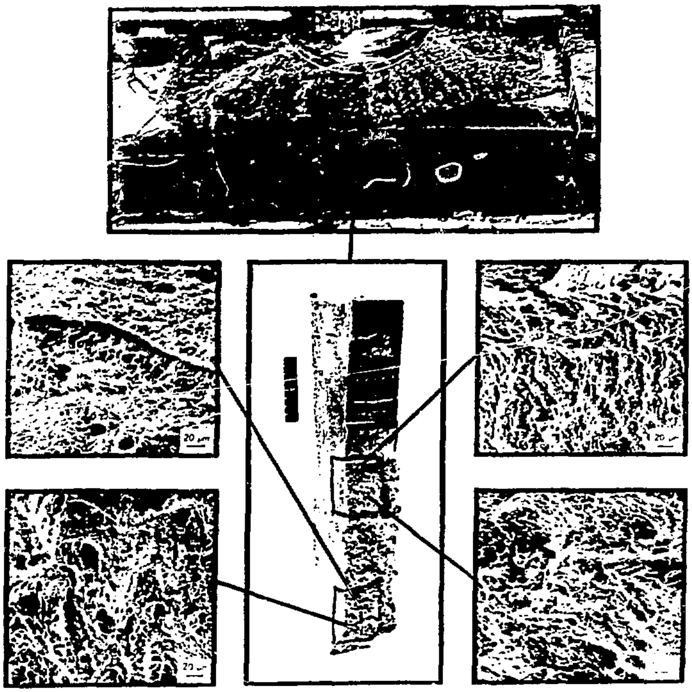

FIG. 7. FRACTOGRAPHIC SAMPLES WERE TAKEN FROM BELOW THE DEEPEST PENETRATION OF THE FLAW. THE FAILURE WAS IN THE DUCTILE MODE.

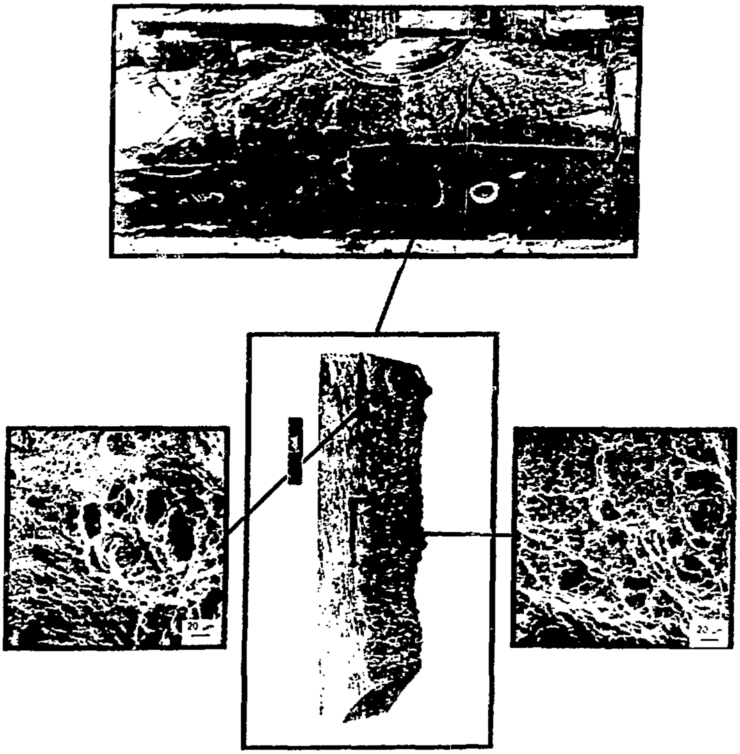

FIG. 8. THE REGION ADJACENT TO THE FATIGUE CRACK WAS STUDIED IN THE SEM. THIS AREA EXHIBITED ALL DUCTILE FAILURE.

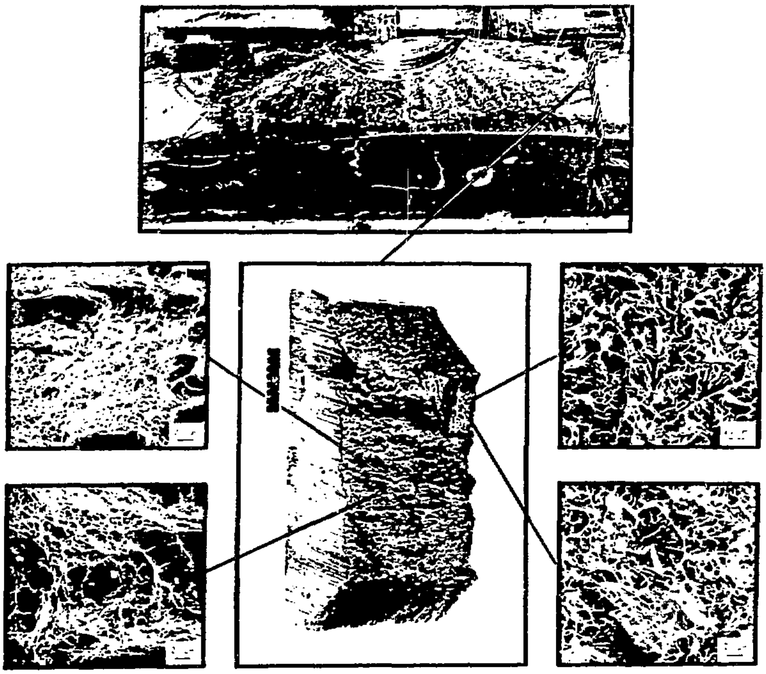

FIG. 9. FRACTOGRAPHIC SAMPLES AT THE POINT WHERE THE SURFACE APPEARANCE OF THE FRACTURE CHANGED SHOWED A TRANSITION FROM DUCTILE TO BRITTLE FRACTURE.

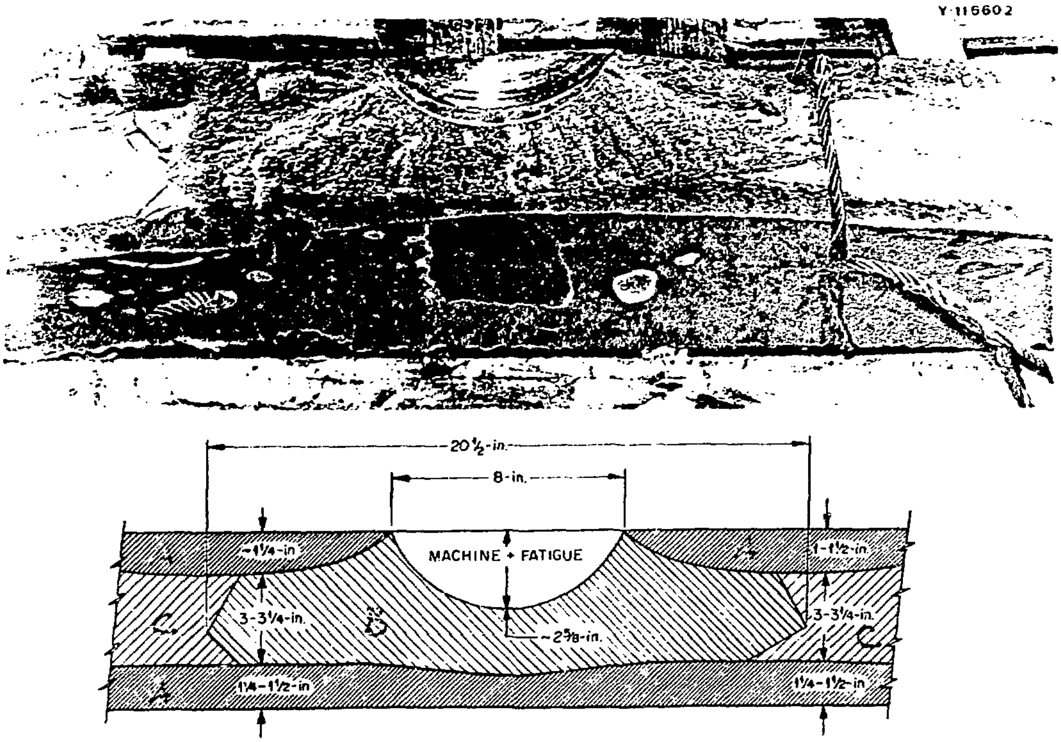

FIG. 10 THIS ILLUSTRATES THE LOCATION AND EXTENT OF THE VARIOUS TYPES OF FRACTURE SURFACES. A-SHEAR LIP, B-DUCTILE, C-CLEAVAGE. (1 INCH = 0.0254 METER)