UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D. C. 20555

NOV 11 1979

MEMORANDUM FOR: Harold R. Denton, Director
Office of Nuclear Reactor Regulation

FROM: Saul Levine, Director
Office of Nuclear Regulatory Research

SUBJECT: RESEARCH INFORMATION LETTER # 68 , "STRUCTURAL INTEGRITY OF WELD REPAIRED PRESSURE VESSELS"

1.0 Introduction

Under provisions of the ASME Boiler and Pressure Vessel Code, Section XI, "Rules for Inservice Inspection of Nuclear Power Plant Components," the procedures for the repair of flaws in a pressurized component of the primary coolant system of a light water nuclear reactor are specified. Section XI prescribes a procedure that may be used for such a repair where it is impractical to perform a post-weld high temperature heat treatment. This procedure, which employs the half-bead weld repair technique, is used in repairing new components and may be used for repair of pressure vessels and other nuclear components in service. It is not applicable to the repair of piping, and as of this date, no inservice vessels have been repaired using this procedure. This RIL describes the results of a test program to determine the adequacy of this technique. The results of this program show that, in general, the use of the half-bead welding technique, with no subsequent post-weld heat treatment in code acceptable pressure vessel material, leads to weldments that show excellent resistance to crack initiation and propagation. However, the results also lead to the judgement that in each situation in which a repair technique such as this is made without post-weld heat treatment, the adequacy of the weldment with regard to expected residual stresses and fracture toughness should be assessed.

2.0 Discussion

Six half-bead weld repairs were made in accordance with Section XI of the Code in 152-mm-thick vessels and cylinders fabricated of ASTM A533, grade B, class 1 steel plates; materials properties were determined; residual stresses were measured; and flawed vessels were tested to failure. Four of the welds were within the plate material and extended completely through the wall. Two half-thickness welds were adjoining both plate material and submerged-arc fabrication welds. The weldments in the cylinders were prototypical of three different repair welds in the Heavy-Section Steel Technology (HSST) Program intermediate test vessels V-7 and V-8. Details of the repairs are presented in Appendices I and II.

The prototypical weldments provided material for determining the properties of the base metal, fabrication weld metal, repair weld metal, and heat-affected zones (HAZs) of the test vessels. Detailed accounts of these properties are given in Appendices III, IV and V. Tensile properties of all regions except the HAZs were measured. From hardness measurements in all regions, it was determined that the tensile strength of the HAZ was substantially superior to that of other regions, which were generally equivalent to each other in strength.

Fracture toughness for all regions was determined by static tests of pre-cracked Charpy-V specimens and 25- and 51-mm-(1-inch and 2-inch)-thick compact specimens. HAZ material was consistently higher in toughness than any other material in the weldments, and the toughness of repair weld metal was approximately equal to that of the plate material.

Residual stresses induced by the repair welds were measured on the outside and inside surfaces of the vessels and cylinders by means of strain gauges attached before welding commenced. Additional measurements were made of the surface of vessel V-8 and on radial sections of the prototypical welds by means of the hole-drilling technique. Details of the measurements and results are found in Appendix VI. <u>Residual stresses varied from low values within the repair weld metal to values near yield just outside the weld-metal zone.</u>

3.0 Results

Three flawed intermediate vessel tests were conducted with repaired vessels. The first two tests were performed at upper shelf temperatures. In the third test, the vessel was cooled to as low a temperature as practicable in order to attain a low toughness state at the flaw size.

In test V-7A (reported in Appendix III), the vessel was pressurized under sustained gaseous loading with a flaw about 5.5-inches deep in the 6-inch vessel, remote from the place where the flaw for an earlier test (V-7) had been repaired by the half-bead technique. Both the V-7 and V-7A tests resulted in a leak without burst at a test temperature of about 90°C.

During the V-7A test, strains in the repair zone differed in magnitude from strains in base metal locations remote from both the flaw and the repair. Variances were insignificant, however, at pressures below about 110% of design pressure and the variances at higher pressure were probably a result of both the residual stresses from the repair and residual distortion from the earlier tests. In neither this nor the subsequent V-7A test were there any indications from strain or acoustic emission observations that this repair zone was in distress.

The V-7A test vessel was repaired and tested again (as V-7B, discussed in Appendix IV), with a duplicate large flaw as in V-7A, but this time with the sharp crack tip implanted in the HAZ of the second half-bead repair weld. As predicted, the residual stresses did not significantly alter the rupture pressure and the crack extension avoided the relatively tough HAZ. There was much greater axial tearing of the crack in V-7B than had been experienced earlier. Both the local residual stress field and the higher pressure attained in the V-7B test could have contributed to this, since the test data indicate that V-7B was as stable as V-7A at comparable pressures.

A new vessel, V-8, was prepared for the last (low temperature) test, the preliminary results of which are presented in Appendix V. The objectives of this test were (1) to demonstrate the behavior of a flaw in the residual stress field near a half-bead weld repair, and (2) to evaluate linear elastic fracture mechanics as a means of predicting the combined effects of residual stress and pressure stress on fracture. In order to realize the second objective, it was necessary to attain a low toughness condition in a region of high residual stress. The preliminary studies of the prototypical weldments indicated that the best site for the flaw was in the original fabrication weld metal of the vessel about 20 mm from the edge of the repair weld. A fatigue-sharpened flaw about half the vessel wall thickness was introduced by cyclic pressurization of the notch machined in the vessel in this location. During the test, the vessel was at about -20°C, at which temperature the flawed material toughness was about 100 $MN \cdot m^{-3/2}$. The crack ran rapidly (popped in) when the pressure reached 0.4 x design pressure, as predicted. It arrested as the tip of the crack reached a region of sufficiently low residual stress to reduce the stress intensity factor to its arrest value. A second pop-in was experienced at 0.96 x design pressure, at which time the vessel leaked. Test results suggest that the second arrest occurred, as did the first, at essentially constant pressure.

4.0 Conclusions and Recommendations

The results of the half-bead repair studies in the HSST program are transmitted to the NRR staff to provide a confirmatory basis for future consideration of applications for in-service weld repairs. The studies have led to several conclusions that are pertinent to evaluations of component repair in nuclear power plants.

(1) The primary conclusion of this work is that the mechanical and fracture properties of the repair zone produced by the ASME-XI half-bead technique were adequate and in some respects superior to the original properties of the repaired test pieces.

(2) No deficiencies in metallurgical structure were found.

(3) The repair welds contained no significant defects as determined by on-line acoustic emission and magnetic particle inspection during welding, ultrasonic and radiographic examinations after welding including an ultrasonic examination 30 days after welding to check for delayed H_2 cracking, acoustic emission during the pressure test, and post-test destructive examination.

(4) Residual stresses in thick-section repairs exhibited high tensile peaks, approaching the yield stress in magnitude, adjacent to the weld at the surface at which the final weld passes were made.

(5) The combined effects of residual stress and pressure stress on crack initiation were substantially predicted in the intermediate vessel tests. In the case where linear elastic fracture mechanics was applicable, test V-8, the residual stress which was dominant was superimposed on the pressure stress to obtain an accurate prediction of crack instability. In the ductile shelf test, V-7B, large-scale yielding was present, and the strain contribution from the residual stress was not an important effect; in fact, it was neglected in the analysis. It follows that the relative effects of residual stresses on fracture strength diminish as the extent of yielding before fracture increases.

(6) In the transition temperature test, the arrest of the first crack advance occurred as the influence of the residual stress diminished, so that the net stress intensity was reduced to be equivalent to the arrest toughness of the weld metal in which the flaw resided.

(7) Residual stress appeared to have a major influence on the path of the flaw propagation in the transition temperature test, V-8, since the flaw moved out of the original longitudinal plane to deviate from the influence of maximum hoop stress to be oriented nearly perpendicular to its original plane on either end. In the ductile shelf test, V-7B, where the flaw was in the HAZ, it remained in that region most likely because of the inhomogeneity of the region and to some degree the residual stress.

(8) Fatigue crack growth proceeded more rapidly for the flaw in a residual stress field than for other flaws sharpened by fatigue.

In view of the influence of the residual stresses on the behavior of the vessels tested, it is recommended that either repair welding procedures should include additional provisions for reducing these stresses in repaired components, or acceptance of the half-bead weld repair technique be dependent upon a fracture analysis of the weldment (weld, HAZ, and local base material in the immediate area of the HAZ) which includes residual stresses of yield stress magnitude and carried out for temperature at RT_{NDT}. An alternative to the above two procedures would be the presentation of an acceptable analysis which fully defines the residual stress field and the effects that the maximum stresses found in such a field have upon the fracture toughness of the material at RT_{NDT} temperatures. This latter procedure should also take into account the effect of the required post-repair hydrostatic pressure test of 1.1 times design pressure.

The results of the studies described in this RIL reveal that the ASME Section XI weld repair technique will produce a repaired structure having a sufficiently high level of residual stresses that the structure could have an insufficient margin of safety against fracture. Thus, additional research is needed to perfect modifications to the present procedure so that residual stresses are minimized or eliminated in the repaired structure. RES notes that such a program is already underway under EPRI sponsorship; RES is following this work and will keep NRR informed of the progress. The final goal of the EPRI work is to perform a proof test of the recommended welding procedure using a realistic-sized structural model. EPRI and RES are currently negotiating an agreement whereby one of the HSST program intermediate test vessels will be used as the repair-weld vehicle for subsequent testing at Oak Ridge using the HSST intermediate test vessel facilities.

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Enclosures: See Attached Sheet

Enclosures:

Appendix I - W. D. Goins and D. L. Butler, Weld Repair of Heavy-Section Steel Technology Program Vessel V-7, EPRI NP-179 (ORNL/Sub/88242-76/1), Combustion Engineering, Inc., Chattanooga, TN, August 1976.

Appendix II - S. W. Wismer and P. P. Holz, Half-Bead (Temper) Repair Welding for Heavy-Section Steel Technology Program Vessels, ORNL/NUREG/TM-177, Oak Ridge National Laboratory, Oak Ridge, TN, June 1978.

Appendix III - R. H. Bryan et al., Test of 6-in.-Thick Pressure Vessels. Series 3: Intermediate Test Vessel V-7A Under Sustained Loading, ORNL/NUREG-9, Oak Ridge National Laboratory, Oak Ridge, TN, February 1978.

Appendix IV - R. H. Bryan et al., Test of 6-in.-Thick Pressure Vessels. Series 3: Intermediate Test Vessel V-7B, ORNL/NUREG-38, Oak Ridge National Laboratory, Oak Ridge, TN, October 1978.

Appendix V - R. H. Bryan, J. G. Merkle and G. D. Whitman, "Quick-Look Report on Test of Intermediate Test Vessel V-8 - Test of Flaw in Residual Stress Field," ORNL/SST-3, Oak Ridge National Laboratory, Oak Ridge, TN, August 2, 1978.

Appendix VI - G. C. Smith and P. P. Holz, Repair Weld Induced Residual Stresses in Thick-Walled Steel Pressure Vessels, ORNL/NUREG/TM-153, Oak Ridge National Laboratory, Oak Ridge, TN, June 1978.

See M. Vagins for copies of enclosures

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