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# IRRADIATION, ANNEALING, AND REIRRADIATION RESEARCH IN THE ORNL HEAVY-SECTION STEEL IRRADIATION PROGRAM*

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## SUMMARY

One of the options to mitigate the effects of irradiation on reactor pressure vessels (RPV) is to thermally anneal them to restore the toughness properties that have been degraded by neutron irradiation. This paper summarizes experimental results from work performed as part of the Heavy-Section Steel Irradiation (HSSI) Program managed by Oak Ridge National Laboratory (ORNL) for the U.S. Nuclear Regulatory Commission. The HSSI Program focuses on annealing and reembrittlement response of materials which are representative of those in commercial RPVs and which are considered to be radiation-sensitive. Experimental studies include (1) the annealing of materials in the existing inventory of previously irradiated materials, (2) reirradiation of previously irradiated/annealed materials in a collaborative program with the University of California, Santa Barbara (UCSB), (3) irradiation/annealing/reirradiation of U.S. and Russian materials in a cooperative program with the Russian Research Center-Kurchatov Institute (RRC-KI), (4) the design and fabrication of an irradiation/anneal/reirradiation capsule and facility for operation at the University of Michigan Ford Reactor, (5) the investigation of potential for irradiation-and/or thermal-induced temper embrittlement in heat-affected zones (HAZs) of RPV steels due to phosphorous segregation at grain boundaries, and (6) investigation of the relationship between Charpy impact toughness and fracture toughness under all conditions of irradiation, annealing, and reirradiation.

The materials used for these studies include various high-copper submerged-arc welds with either high or low Charpy upper-shelf energy,[1,2] a medium-copper plate of A533 grade B class 1 steel (HSST Plate 02),[3] various plate steels [A302 grade B, A302 grade B (modified), and A533 grade B class 1] for the temper embrittlement study, and two Russian welds representative of the VVER-440 and VVER-1000 type reactors.[4] The U.S. steels are generally designated Mn-Mo-Ni steels, while the Russian welds are similar to 1.5 Cr-0.5 Mo steels. With regard to radiation sensitivity, the U.S. welds are generally characterized primarily by relatively high copper and low phosphorous contents, while the Russian welds have relatively low copper but high phosphorous (VVER-440) or high nickel (VVER-1000) contents. However, there are some U.S. welds which have both relatively high-copper and high-nickel (>1.0 wt %) contents and these will be included in future HSSI investigations. With regard to concerns for potential temper embrittlement in the coarse-grain regions of U.S. base materials, five steels with various phosphorous contents (0.08 to 0.18 wt %) have been included in the temper embrittlement study. In the ORNL experiments, the U.S. materials were all irradiated in material test reactors at a nominal irradiation temperature of 288°C (550°F) to neutron fluences ranging from about 0.5 to 2.0 × $10^{19}$ n/cm$^2$ (1 MeV); the Russian welds were irradiated under similar

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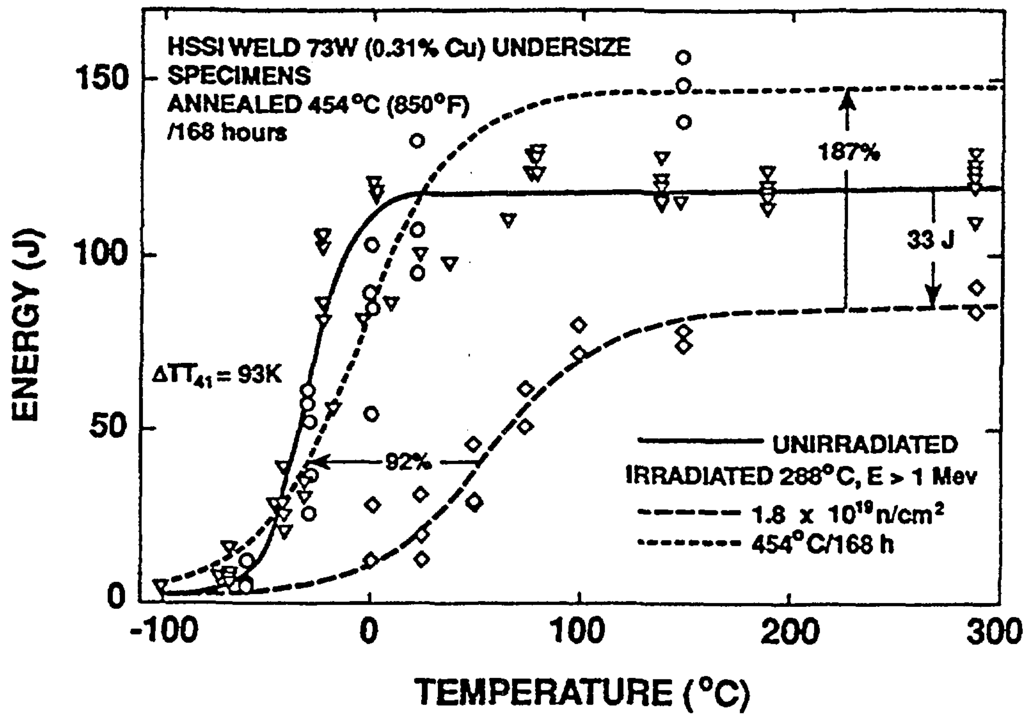
## HSSI PROGRAM HAS INVESTIGATED RECOVERY OF TOUGHNESS PROPERTIES BY THERMAL ANNEALING WITH FOUR MATERIALS

| MATERIAL | ANNEALING TEMPERATURE | ANNEALING TIME (HOURS) |
|---|---|---|
| WELD 73W UNDERSIZE | 343° C (650° F) | 168 |
| WELD 73W UNDERSIZE | 454° C (850° F) | 24, 96, 168, AND 336 |
| WELD 73W FULL SIZE | 343° C (650° F) | 168 |
| WELD MW NOZZLE | 454° C (850° F) | 168 |
| WELD MW BELTLINE | 343° C (650° F) AND 454° C (850° F) | 168 |
| PLATE HSST 02 | 343° C (650° F) AND 454° C (850° F) | 168 |

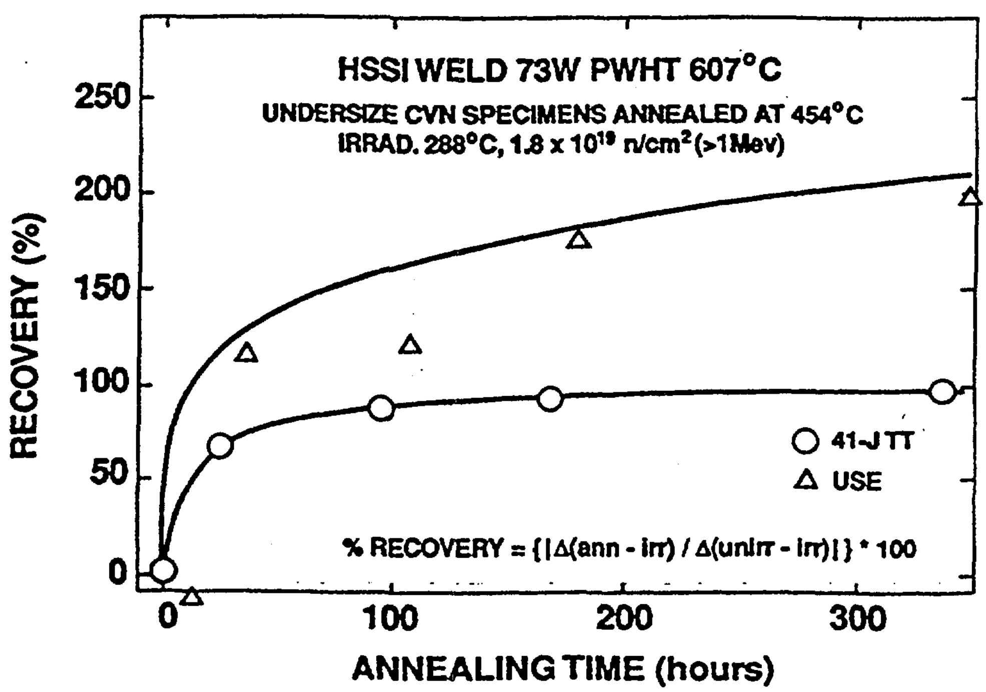
## CHEMICAL COMPOSITIONS OF MATERIALS USED IN ANNEALING STUDIES ARE TYPICAL OF RPV STEELS

| MATERIAL | COMPOSITION (WT%) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | C | Mn | P | S | Si | Cr | Ni | Mo | Cu | V |
| HSSI WELD 73W | 0.098 | 1.56 | 0.005 | 0.005 | 0.45 | 0.25 | 0.60 | 0.58 | 0.31 | 0.003 |
| MIDLAND BELTLINE WELD | 0.084 | 1.61 | 0.017 | 0.007 | 0.62 | 0.10 | 0.57 | 0.41 | 0.21-0.34 | 0.004 |
| MIDLAND NOZZLE WELD | 0.088 | 1.57 | 0.015 | 0.010 | 0.56 | 0.11 | 0.58 | 0.39 | 0.37-0.46 | 0.008 |
| HSST PLATE 02 | 0.23 | 1.55 | 0.009 | 0.014 | 0.20 | 0.04 | 0.67 | 0.53 | 0.14 | 0.003 |

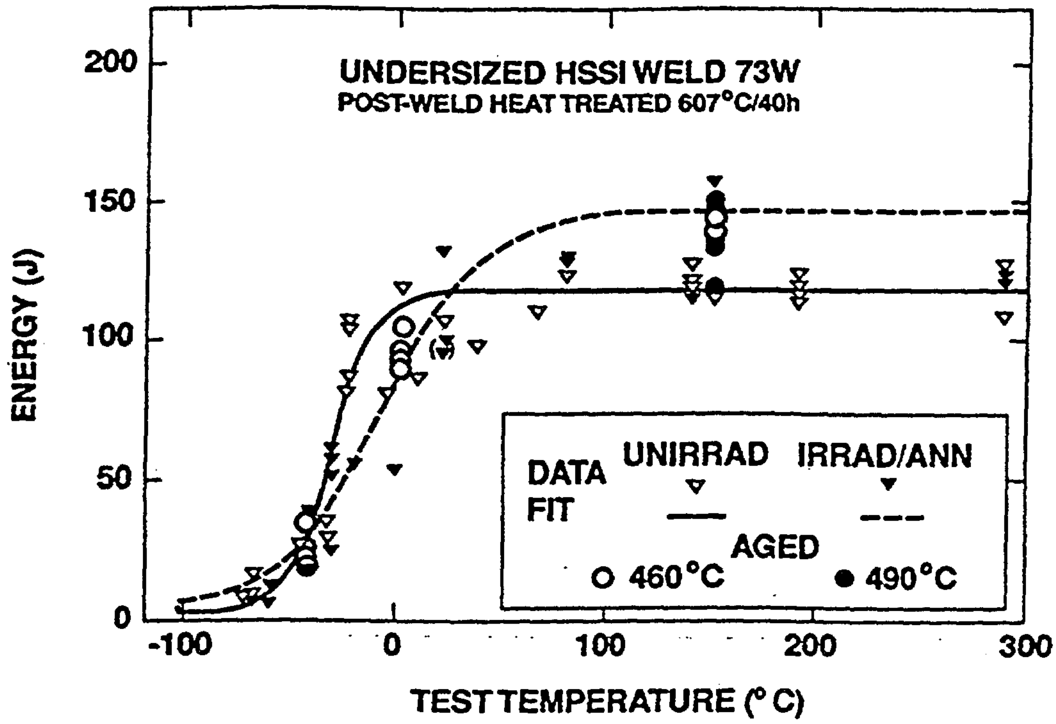
## ANNEALING OF HSSI WELD 73W AT 454°C FOR 168 HOURS RECOVERED 92% OF $\Delta TT_{41\text{-}J}$ AND 187% OF $\Delta$USE



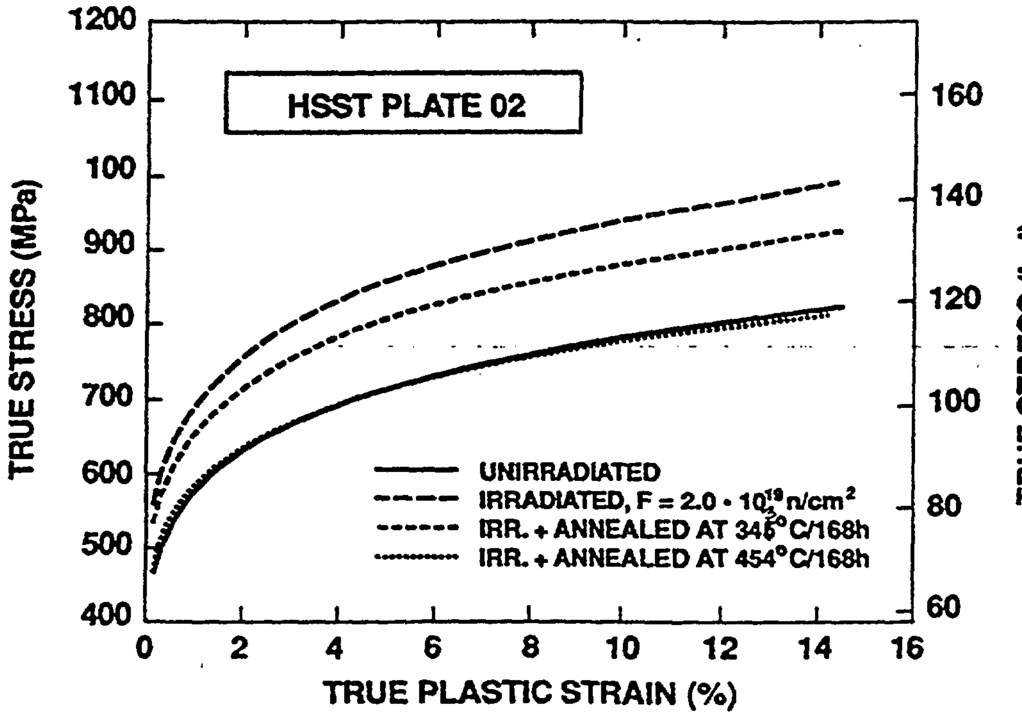

## UPON ANNEALING AT 454°C HSSI WELD 73W EXHIBITED RAPID RECOVERY OF TOUGHNESS AND DIMINISHING RETURNS OF TT AFTER 96 h, BUT USE CONTINUES TO INCREASE



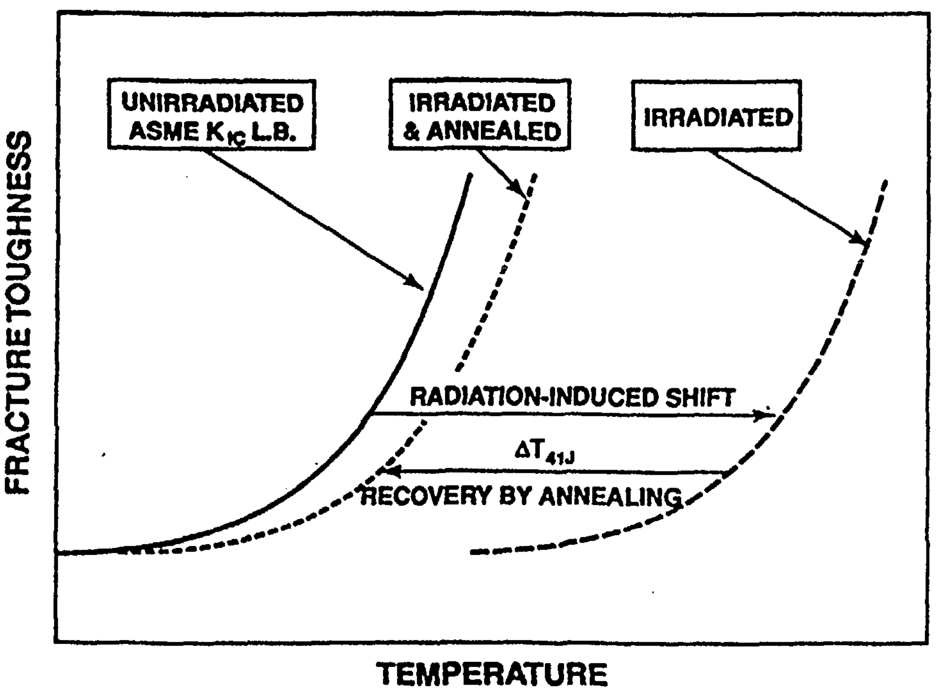
## AGING OF UNIRRADIATED HSSI WELD 73W AT 460 & 490°C INCREASED USE, BUT $TT_{41J}$ UNALTERED



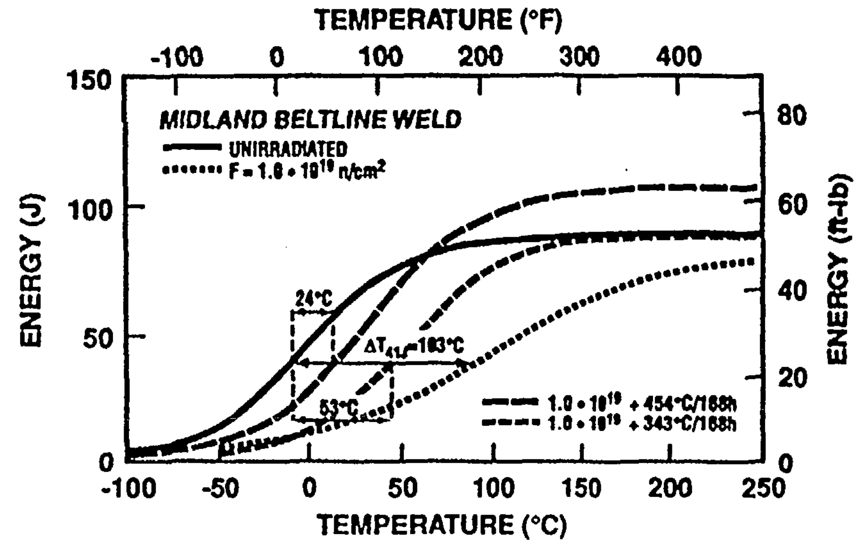

## TRUE STRESS - TRUE PLASTIC STRAIN CURVES FROM AUTOMATED BALL INDENTATION TESTS INDICATE RECOVERY OF RADIATION HARDENING FOLLOWING THERMAL ANNEALING

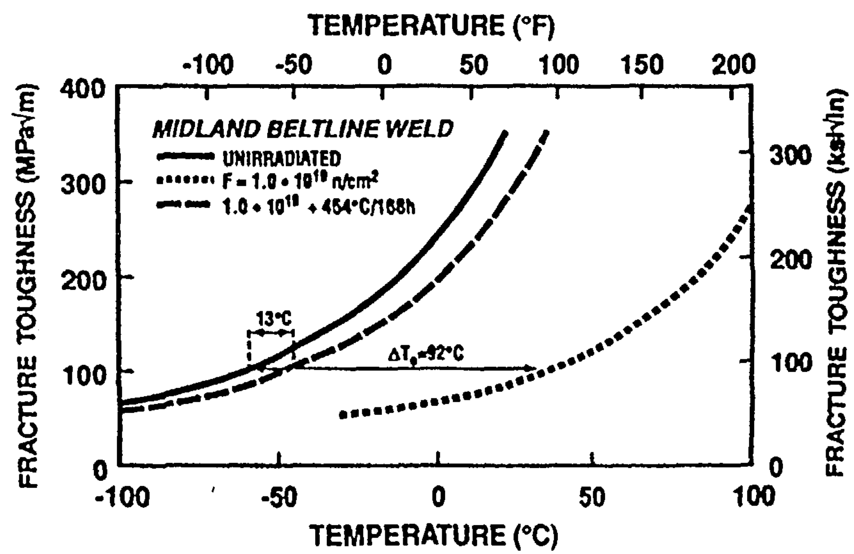


## IS RECOVERY OF TRANSITION CHARPY AND FRACTURE TOUGHNESS COMPARABLE?

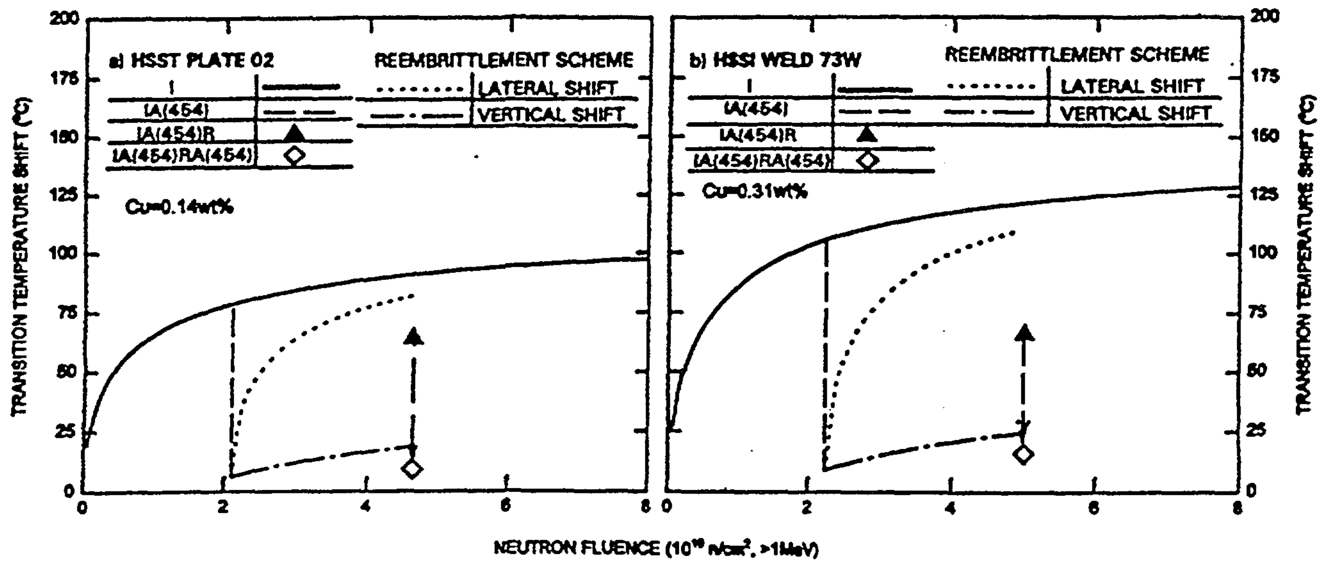



## FOR MIDLAND BELTLINE WELD ANNEALED AT 454°C FOR 168h, RESIDUAL CHARPY AND $K_{Jc}$ SHFTS ARE COMPARABLE

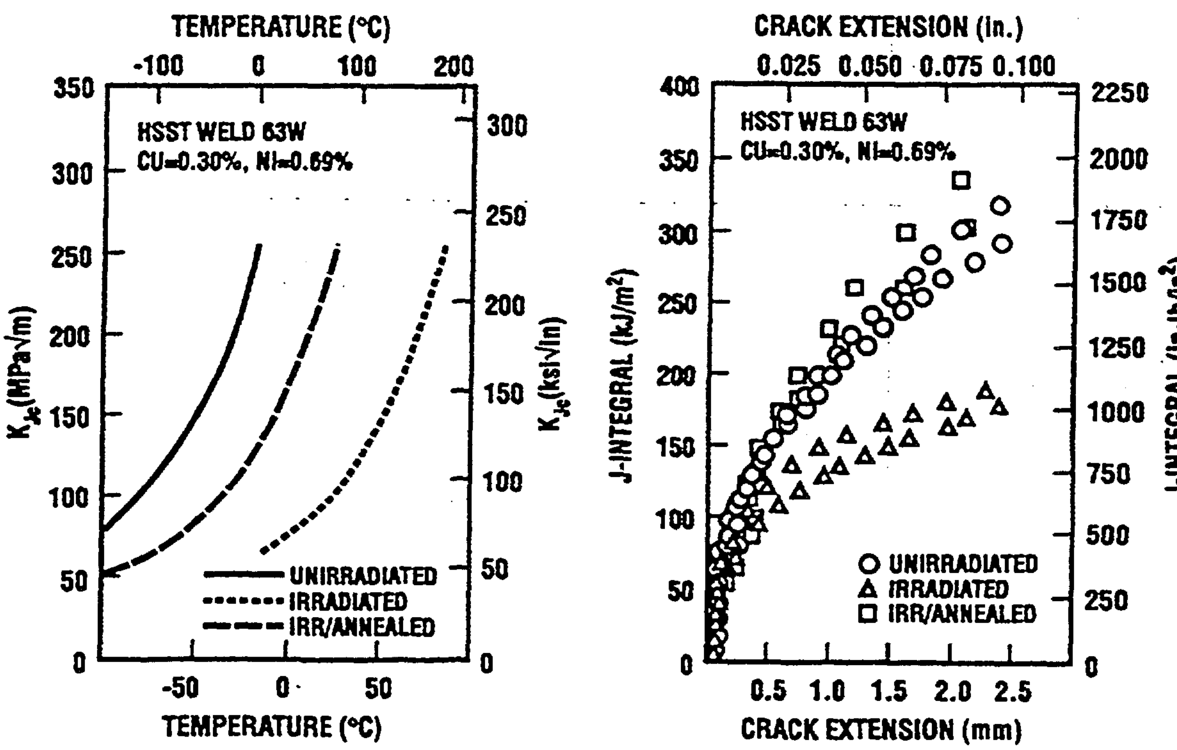


## REEMBRITTLEMENT RATES FOR HSST PLATE 02 AND HSSI WELD 73W ARE CONSERVATIVE RELATIVE TO THE "LATERAL SHIFT" PREDICTION




## RECOVERY OF TEARING RESISTANCE EXCEEDED $K_{Jc}$ RECOVERY FOR HIGH-COPPER LUS WELD AFTER ANNEALING AT 454°C/168h



## IRRADIATION, ANNEAL, AND REIRRADIATION RESULTS SHOW GENERAL AGREEMENT WITH CURRENT MODELS, BUT PAUCITY OF FRACTURE TOUGHNESS DATA EXIST (CONTINUED)

- IN GENERAL, EXPERIMENTAL RESULTS FROM ORNL AND ELSEWHERE TEND TO SUPPORT THE LATERAL SHIFT METHOD FOR PREDICTION OF REIRRADIATION EMBRITTLEMENT, BUT PAUCITY OF FRACTURE TOUGHNESS DATA UPON BOTH ANNEALING AND REIRRADIATION PROVIDE HIGH UNCERTAINTIES
- DETAILED MICROSTRUCTURAL ANALYSIS OF EXISTING SPECIMENS EXPOSED TO VARIOUS CONDITIONS WOULD PROVIDE INVALUABLE INSIGHT TO UNDERSTANDING OF MECHANISMS LEADING TO RE-EMBRITTLEMENT
- HSSI PROGRAM CONTINUES TO INVESTIGATE RESPONSE OF RPV STEELS TO ANNEALING AND REIRRADIATION TO INCLUDE DESIGN AND FABRICATION OF AN IRRADIATION-ANNEAL-REIRRADIATION CAPSULE AND FACILITY FOR OPERATION AT THE UNIVERSITY OF MICHIGAN FORD REACTOR