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DISCUSSION

J. P. Higgins[1]—The proposed model appears to provide a useful approach for evaluating the effects of radiation on fracture toughness based primarily on mechanical property considerations; however, there are strong indications that certain trace element impurities have a strong effect on the radiation sensitivity of pressure vessel steels. The Naval Research Laboratory has identified copper and phosphorus as being particularly important. Does the proposed model account for minor variations in such trace impurities elements and their potential effect on radiation damage sensitivity?

R. A. Wullaert (authors' closure)—The instrumented Charpy test would be useful in determining whether the large radiation induced shift in the *DBTT* associated with high copper and phosphorous content is related to an enhanced radiation sensitivity of $\sigma_y{}^*$ or $\sigma_f{}^*$ or both. If the trace impurity elements are inhibiting the recovery of displacement defects, then a large increase in $\sigma_y{}^*$ and little change in $\sigma_f{}^*$ would be expected. However, if the trace impurities are producing a temper embrittlement type of behavior, a large decrease in $\sigma_f{}^*$ would be expected and the increase in $\sigma_y{}^*$ would be no greater than that for steels with low impurity element contents. Recent work at the Naval Research Laboratory[2] has shown that welds with a high copper content show a larger increase in hardness and *DBTT* than low-copper welds irradiated to the same fluence at 288 C. This indicates that at least part of the high radiation sensitivity of high copper content pressure vessel steels is related to the enhanced radiation sensitivity of the yield stress. The effect of trace impurity elements on the radiation sensitivity of $\sigma_f{}^*$ remains to be determined.

A. L. Bement[3]—The departure of the fracture load P_F from the maximum load P_{max} in region *4* of your Fig. 4 could result from either macroscopic lateral contraction of the specimen or ductile fracture. Can you distinguish the relative contribution of either process from your load-time traces alone? If so, should not a departure of P_F from P_{max} for lateral contraction prior to brittle fracture initiation be allowed for region *3*?

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[2] Hawthorne, J. R., Fortner, Edward, and Grant, S. P., "Radiation Resistant Experimental Weld Metals for Advanced Reactor Vessel Steels," submitted for publication in *The Welding Journal*, 1 Aug. 1970.
[3] Battelle-Northwest, Richland, Wash. 99352.

It is important in interpreting micrographs of ductile fracture surfaces to distinguish between features representing fracture under predominantly biaxial shear stresses and features representing regions subjected to significant hydrostatic tension components due to geometric restraints.

R. A. Wullaert (authors' closure)—For the class of steels studied, lateral contraction is about 1 to 2 percent at $T_{D(N)}$ and 6 to 8 percent at $T_{S(N)}$. This increase in plastic deformation through region *3* is an indication of the additional amount of strain hardening that is required to raise $\sigma_y{}^*$ to $\sigma_f{}^*$ to produce cleavage fracture. At $T < T_{S(N)}$, cleavage fracture occurs before the load reaches a zero slope, and thus the fracture load is the maximum load ($P_F = P_{\max}$). $T_{S(N)}$ corresponds to the temperature at which ductile tearing first occurs across the root of the notch. This ductile tearing has been observed to occur at the maximum load (zero slope). Figure 3 is a typical load-time (deflection) curve for temperatures above $T_{S(N)}$ where cleavage fracture can still occur. The fibrous crack initiated at $P_{\max}$ will sharpen and accelerate and eventually lead to cleavage fracture at the brittle fracture load P_F. As the temperature is increased above $T_{S(N)}$, the fracture will become 100 percent fibrous and a sharp drop in load will no longer occur. Thus in the initial part of region *4* where cleavage fracture occurs after fibrous initiation at the maximum load, $P_{\max} > P_F$.