PREDICTION OF RADIATION-INDUCED CHANGES IN FRACTURE TOUGHNESS K_{IC} FROM SMALL SPECIMEN TESTS

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ABSTRACT

A model has been developed for predicting the radiation-induced changes in the macroscopic measure of fracture toughness (K_{Ic} or K_{Id}) from changes in the microscopic or metallurgical fracture parameters σ_y (yield strength), σ_f^* (microcleavage fracture strength), and ρ_o (critical crack tip radius). Two different methods have been devised to determine these microscopic parameters from small specimen (Charpy V) tests. The model has been applied to the results of a typical nuclear pressure vessel surveillance program on A302B steel. The standard surveillance program provided Charpy energy curves and static fracture toughness for both the unirradiated and irradiated steel. An instrumented Charpy machine was used to obtain dynamic notched bend and fracture toughness data.

An equation of the form

$$K_{Id} = 2.9\ \sigma_{yd}\ [\exp(\sigma_f^*/\sigma_{yd} - 1) - 1]^{1/2} \sqrt{\rho_o}$$

was used to predict the dynamic fracture toughness of the irradiated material as a function of temperature from the surveillance results. For Charpy strain rates, it had previously been reported that $K_{Id}/\sigma_{yd} \approx 0.30$ at the nil ductility transition (NDT) temperature, and the same relation was observed for irradiated material. The implication of the study is that the standard Charpy V specimens available in reactor surveillance programs can be used to predict the dynamic fracture toughness behavior of irradiated pressure vessel steels.

1. INTRODUCTION

Reactor grade steels are brittle at low temperatures, tough at higher temperatures, and show intermediate behavior in between these extremes. The increase in toughness with temperature for low alloy steel allows large nuclear pressure vessels to be operated in temperature ranges where brittle fracture cannot occur. Knowing the relation between toughness and temperature for a particular vessel, it is possible to develop heating/pressurization/cooling plans for the vessel (Figure 1) to ensure that during startup and shutdown the vessel is operated in the tough region. Radiation embrittlement of the pressure vessel requires that the lower pressurization temperature be continually increased to remain in the tough region.

Since Figure 1 is derived from various test results on laboratory specimens, a thorough understanding of the factors that influence fracture toughness of irradiated materials is desirable. The toughness of reactor grade steels is generally evaluated in terms of the energy absorbed in a Charpy test (C_V), the energy per unit area absorbed in a dynamic tear (DT) test, or the fracture toughness K_{Ic} as measured in a sharp crack test. Figure 2 is a schematic diagram based on A302B and A533B reactor steels of the effect of notch radius ($\rho = 0.01$ inch on Charpy specimen, V, versus fatigue cracked, C), strain rate (slow versus impact) and large irradiation dose ($1\text{-}10 \times 10^{19}$ n/cm^2) on the toughness versus temperature curve. Increasing the specimen defect sharpness from a V-notch to a sharp crack produces a small but significant increase in brittleness in unirradiated steel tested under slow, 1 → 2, and rapid, 3 → 4, loading rates. Similar behavior has been noted in the irradiated condition. The increased brittleness appears as an approximately 50°F shift in the toughness curve to higher temperatures. The effect of increased loading rate (e.g., 1 → 3) generally appear as a shift in toughness curve of approximately 130°F for this particular class of steel irrespective of root radius (Barsom and Rolfe [1]). Neutron irradiation is able to produce shifts of all curves up to 300°F, 3 → 7 and 4 → 8, depending on dose. These shifts are often given in terms of the 30 ft.lb. V-notch temperature, which corresponds closely to the NDT in this particular steel, or a particular K_{Ic}/σ_y ratio such as 0.4, 0.6, etc.

As shown in Figure 2, the most dangerous case corresponds to that of a sharp crack that is dynamically loaded in an irradiated condition (C-D-I). Since there is always a possibility that a sharp fatigue crack could develop in a locally aged or embrittled zone (e.g., near a weld) and begin to propagate into a vessel, fracture safe design must assume the worst case and design on the basis of curve 8. Criteria based on NDT + X°F are often used for these purposes, where X depends on specimen thickness.

At the present time there is a real need to develop an inexpensive, reliable, and small specimen that can be used to measure and predict curve 8. The word "small" is important because there is not sufficient space in surveillance capsules to absorb large numbers of WOL or other standard fracture mechanics specimens. There is also a need to instrument the impacting system to obtain load-time data which can be converted to dynamic toughness (K_{Id}) data. We believe that the precracked Charpy V specimen offers the best alternative for nuclear surveillance on precracked specimens. This specimen can be tested on a conventional Charpy machine to which a dynamic load measuring system is easily added (Wullaert [2]).

A model has been developed to predict the shape and position of the dynamic toughness curve, 8, on irradiated specimens from the data on unirradiated material, coupled with a knowledge of the effect of radiation on easily obtainable properties such as yield strength σ_y. This model is discussed below.

2. THE MODEL

In previous work (Malkin, Tetelman [3]) we have shown that brittle cleavage fracture develops in precracked specimens of low carbon steel when the tensile stress level in the plastic zone at the crack tip reaches a critical value, σ_f^*. If σ_y is the yield stress, then for a crack of root radius ρ

$$\left\{ \begin{matrix} K_{Ic}(\rho) \\ K_{Id}(\rho) \end{matrix} \right\} = 2.9\ \sigma_y\ [\exp(\sigma_f^*/\sigma_y - 1) - 1]^{1/2}\ \sqrt{\rho} \qquad \begin{matrix} (\sigma_f^* < 3.4\ \sigma_y) \\ (\rho > \rho_o) \end{matrix} \tag{1}$$

and for sharply cracked fracture toughness specimens

$$\left\{ \begin{matrix} K_{Ic} \\ K_{Id} \end{matrix} \right\} = 2.9\ \sigma_y\ [\exp(\sigma_f^*/\sigma_y - 1) - 1]^{1/2}\ \sqrt{\rho_o} \qquad \begin{matrix} (\sigma_f^* < 3.4\ \sigma_y) \\ (\rho \leq \rho_o) \end{matrix} \tag{2}$$

Structures and specimens containing sharp cracks of "infinitely" small root radius do not have infinitely small toughness, but actually are as tough as specimens containing cracks of finite root radius ρ_o. ρ_o is a measure of the extent of the process zone ahead of the crack over which the critical stress σ_f^* must exist.

Recent data indicate that ρ_o is independent of temperature and depends only on microstructure (Ensha, Tetelman [4]). σ_f^* is independent of temperature below about -100°F. At higher temperatures, as evaluated at high loading rates or in irradiated specimens, σ_f^* appears to increase slightly with increasing temperature. If σ_f^* and ρ_o are essentially independent of irradiation, the decrease in K_{Ic} with irradiation results solely from the increase in σ_y with irradiation, at least below and at the NDT temperature. Further studies are required to determine the nature of irradiation embrittlement at temperatures where fracture is initiated by a critical strain at the crack tip.

In order to determine the effect of irradiation on a curve of K_{Ic} (or K_{Id}) versus temperature, it is first necessary to determine values of ρ_o and σ_f^*. The former can be determined at some convenient low temperature (say -321°F) by making measurements of K_{Ic} and K_{Ic} (ρ = .01) from slow bend tests on precracked and standard Charpy specimens. ρ_o is then given by the relation (Tetelman, Wullaert, Ireland [5])

$$\rho_o = \left[\frac{K_{Ic}}{K_{Ic}(\rho)} \right]^2 (.01) \tag{3}$$

These measurements can also be made dynamically, in which case

$$\rho_o = \left[\frac{K_{Id}}{K_{Id}(\rho)} \right]^2 (.01) \tag{4}$$

For reactor grade A302B and A533B steels, ρ_o typically varies between 0.0016 and 0.0023 inch, so that ρ_o = .002 inch is a good approximation to use in preliminary design considerations.

The cleavage fracture stress σ_f^* is obtained by one of two methods. First, σ_y is measured at a temperature (say -321°F) where K_{Ic} and $K_{Ic}(\rho)$ are known. Then, knowing ρ_o, σ_f^* is obtained from either eq. (1) or eq. (2). A second procedure is diagrammed in Figure 3. Standard Charpy V-notch specimens are broken over a range of temperatures in either slow bending (slow bending case) or instrumented impact (dynamic loading). The loads to cause general yielding P_{GY}, and fracture, P_F(or P_{max}), are recorded. Below the temperature $T_{D(N)}$ fracture occurs before general yield so that the general yield load must be extrapolated, as shown by the dashed line. At the temperature T^*, where $P_F = 0.8\ P_{GY}$ in the notched specimen

$$\sigma_f^* = 2.18\ \sigma_y \tag{4}$$

Also for the standard Charpy V specimen

$$\sigma_y \simeq 33.3\ P_{GY} \tag{5}$$

when σ_y is in psi and P_{GY} is in pounds, so that

$$\sigma_f^*\ (\text{psi}) = 72.5\ P_{GY}\ (\text{pounds}) \qquad\qquad (T = T^*) \tag{6}$$

when the fracture load P_F is 80 percent of the (extrapolated) general yield load P_{GY}. Note that at T^* the fracture load P_F can be converted to K_{Id} and knowing P_{GY} (and hence σ_y) and ρ_o we can also get σ_f^* by the first procedure. Typically σ_f^* varies between 290 and 310 ksi for reactor grade steels so that $\sigma_f^* = 300$ ksi is a good approximation to use in preliminary design considerations.

To predict K_{Id} at higher temperatures or for <u>irradiated material</u>, it is then only necessary to measure P_{GY} with an instrumented Charpy machine using standard Charpy V specimens and obtain σ_y from eq. (5). Knowing σ_f^* and ρ_o as described above, K_{Id} is obtained from eq. (2) at all conditions (T, $\dot{\varepsilon}$, dose) for which σ_y is known.

3. APPLICATION TO CONNECTICUT YANKEE REACTOR SURVEILLANCE SPECIMENS

The value of this method lies in the fact that one K_{Id} measurement made on unirradiated material, coupled with a P_F [and hence $K_{Id}(\rho)$] measurement and a P_{GY} measurement on standard Charpy V specimens at T^*, are all that are required to specify the low temperature fracture toughness K_{Id} of a material (or K_{Ic} for static properties). Instrumented tests on standard <u>irradiated</u> surveillance specimens can then be used to determine P_{GY} and hence σ_y as a function of temperature for irradiated material. K_{Id} (irradiated) can then be obtained as a function of temperature from eq. (2). Figure 4 shows P_F (or P_{max}) and P_{GY} curves, along with the usual energy curves for the unirradiated and irradiated A302B base metal steel used in the Connecticut Yankee Reactor. Irradiation at 565°F to 2×10^{18} n/cm^2 (>1 Mev) has increased the NDT from -30°F to 5°F. Using the T^* method, we find $\sigma_f^* = 283$ ksi in the irradiated material. Assuming $\rho_o = 0.002$ inches, we obtain the (predicted) K_{Id} versus temperature curve shown in Figure 5. Also shown are static K_{Ic} values obtained from standard WOL specimens before and after irradiation. The predicted K_{Id} values are considerably lower than the measured K_{Ic} values confirming the strain rate sensitivity of the toughness of irradiated steel.

To obtain K_{Id} at higher fluences, it is only necessary to determine the radiation induced increase in σ_y (or P_{GY}). If the neutron dose changes from $(\phi t)_1$ to $(\phi t)_2$, σ_y increases and K_{Ic} (and K_{Id}) decrease, again assuming σ_f^* and ρ_o remain unchanged. If we compare the temperatures T_1 and T_2 at which the dynamic toughness is equivalent to some value, K_{Id}', we have

$$K_{Id}' = 2.9\ \sigma_y\ [T_1,(\phi t)_1][\exp\{\sigma_f^*/\sigma_y[T_1,(\phi t)_1]\ -1\}\ -1]^{1/2}\ \sqrt{\rho}\ =$$

$$2.9\ \sigma_y\ [T_2,(\phi t)_2][\exp\{\sigma_f^*/\sigma_y[T_2,(\phi t)_2]\ -1\}\ -1]^{1/2}\ \sqrt{\rho} \qquad (7)$$

and since ρ is a linear term on both sides of the equation, it drops out from further consideration. Thus, shifts in K_{Id} and K_{Ic} curves produced by irradiation will be equivalent whether measured on a standard Charpy V specimen (ρ = .01 inch) or a precracked specimen, provided the same reference temperature T_1 is used in both cases.

As a convenient reference temperature T_1, we choose the NDT which corresponds closely with the 30 ft.lb. temperature in irradiated steels. Recent studies on unirradiated material (Tetelman, Wullaert, Ireland [5]) indicate that at the NDT

$$\frac{K_{Id}}{\sigma_{yd}} \simeq 0.30 \qquad (T = \text{NDT}) \qquad (8)$$

for Charpy impact strain rates. From Figure 5, $K_{Id}/\sigma_{yd} = 0.27$ at the NDT for the irradiated steel, indicating that the same relation holds for irradiated material. We then find that the irradiation induced shift in NDT, as determined from a standard Charpy specimen (ρ = .01 inch) is equivalent to the shift in K_{Id} versus temperature curve, measured for the reference temperature where $K_{Id}/\sigma_{yd} = .30$.

If σ_f^* and ρ_o are independent of irradiation, then shifts in K_{Id}/σ_{yd} curves depend only on shifts in σ_y. If the temperature dependence of yield strength is linear, then

$$\Delta T_{equiv} = \frac{\Delta\sigma_y\ \text{(irradiation)}}{d\sigma_y/dT} \qquad (9)$$

so that the irradiation induced shift of a given reference point depends on $d\sigma_y/dT$ as well as on $\Delta\sigma_y$ (Wullaert, Ireland, Tetelman [6]).

4. SUMMARY

A model has been developed which allows a thorough understanding of the factors that influence the fracture toughness of irradiated materials. The effects of temperature, strain rate, and radiation on fracture toughness are all taken into account. All the pertinent data required for the model can be obtained from standard Charpy V-notch specimens, except for one determination of K_{Ic} or K_{Id} on a sharply cracked specimen. The model provides an understanding of the correlation between radiation-induced shifts in transition temperature (NDT) and shifts in fracture toughness (K_{Ic}).

An implication of practical importance is the fact that the Charpy V specimen, upon which many engineering safety codes are based, can be used to predict dynamic fracture toughness behavior over a wide range of temperatures in the "frangible" region. The value of irradiated Charpy specimens, particularly in present nuclear pressure vessel surveillance programs, can be considerably enhanced by the use of the instrumented Charpy test and the present model relating the micro- and macro-aspects of fracture. The inclusion of precracked Charpy specimens in future surveillance programs would permit the direct measurement of K_{Id} as a function of temperature in addition to the usual Charpy energy transition information, thus combining the old and new approaches to fracture-safe design of nuclear pressure vessels.

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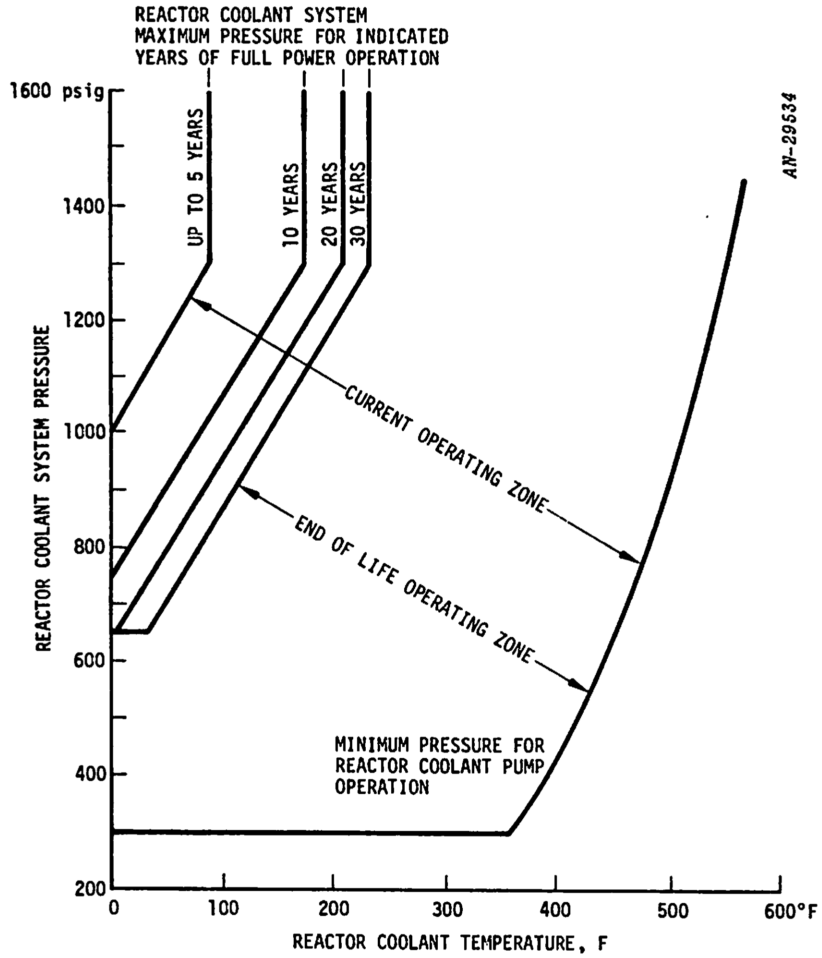

Figure 1. Typical Pressure-Temperature Relationship for Steady State Operation of a Pressurized Water Reactor. The Predicted Effect of Radiation After 10, 20, and 30 Years of Operation is Also Shown.

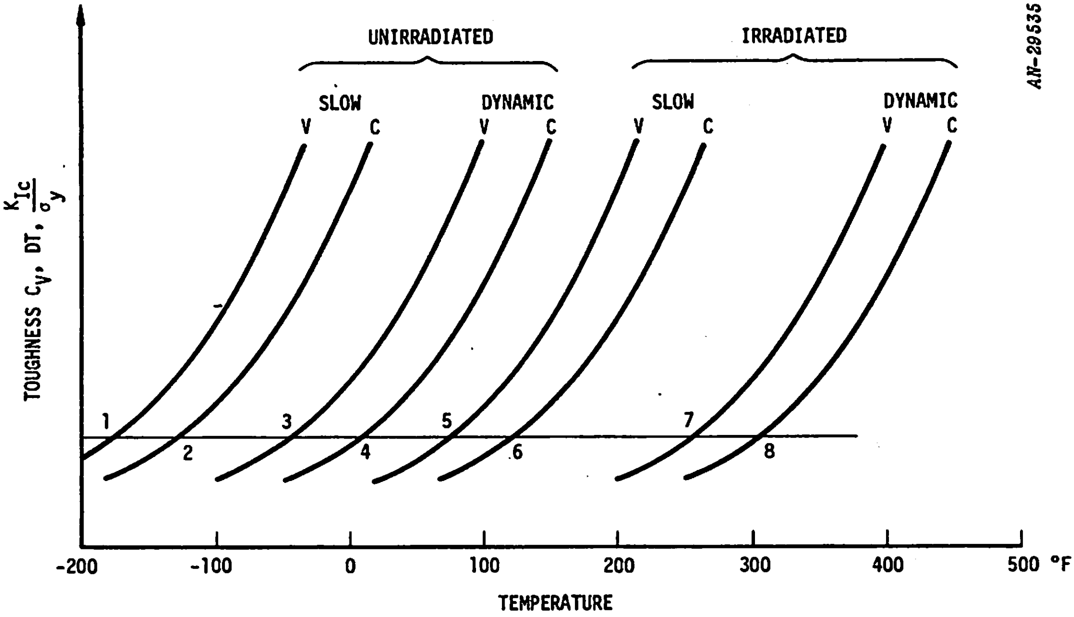

Figure 2. Schematic Diagram of the Effect of Notch Radius (Charpy, V,versus Fatigue Cracked, C), Strain Rate, and Radiation on the Toughness-Temperature Curve of a Pressure Vessel Steel.

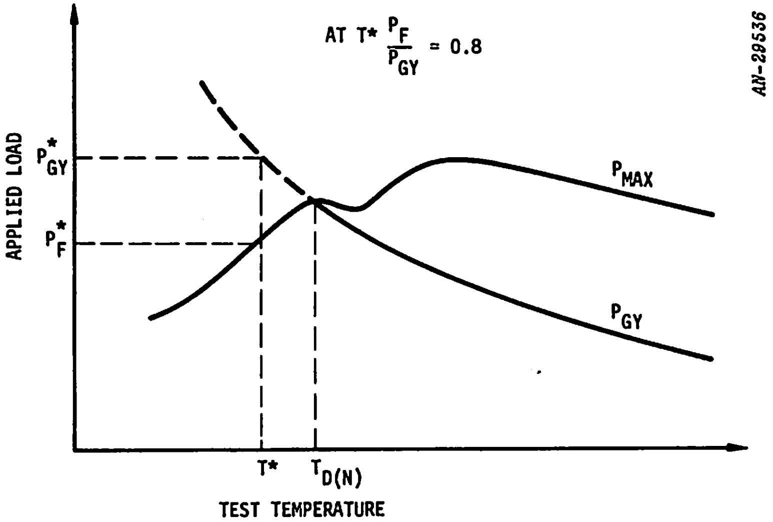

Figure 3. Typical Load-Temperature Curve for Notch Bending Showing Location of T^* and $T_{D(N)}$.

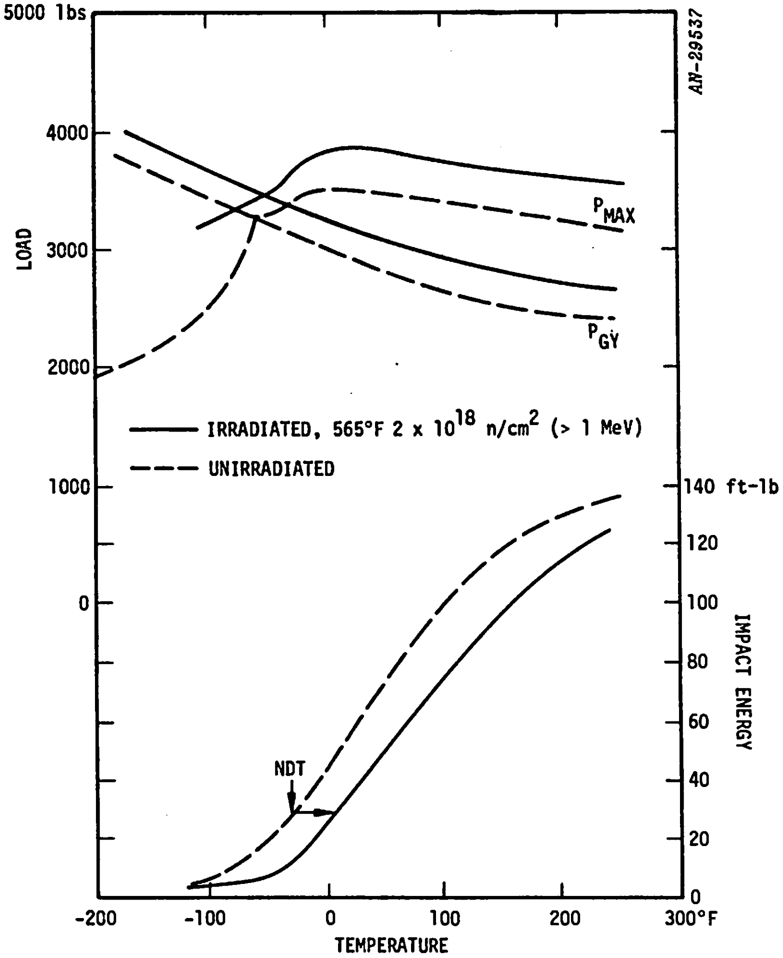

Figure 4. Comparison of Instrumented Charpy Data for Unirradiated and Irradiated A302B Steel from the Connecticut Yankee Surveillance Program (Base Metal Plate W9807-2).

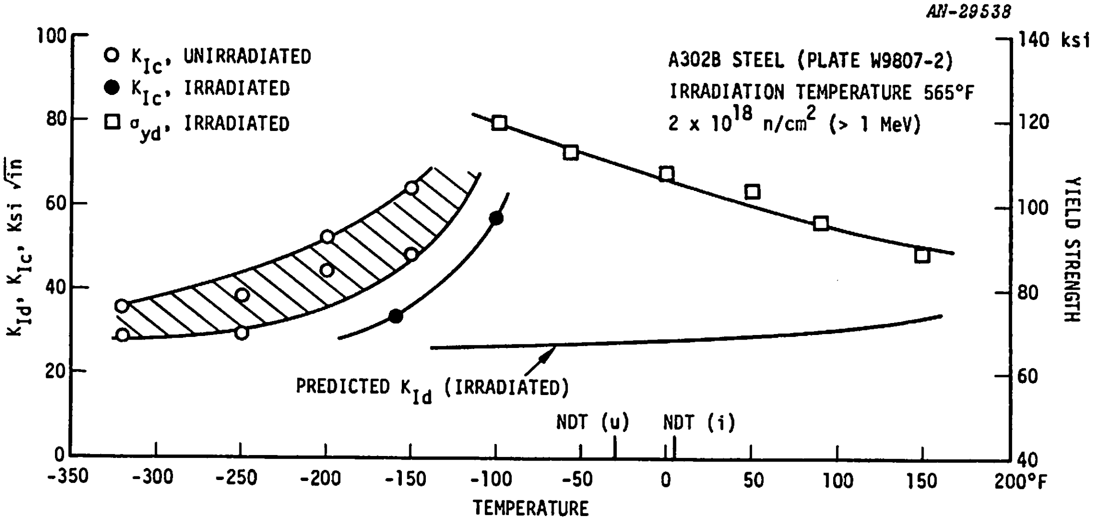

Figure 5. Effect of Radiation and Strain Rate on the Fracture Toughness-Temperature Curve for A302B Steel. Static Toughness Measured on WOL Specimens from Connecticut Yankee Surveillance Program. Dynamic Toughness Predicted from Instrumented Charpy V-Notch Tests.