**DOSE DEPENDENCE OF FRACTURE TOUGHNESS OF F82H STEEL** - M. A. Sokolov (Oak Ridge National Laboratory), G.R. Odette and T. Yamamoto (University of California, Santa Barbara), H. Tanigawa and N. Okubo (JAEA)

## OBJECTIVE

The objective of this work is to evaluate the fracture toughness of F82H RAFM steel irradiated to different doses in several capsules in the High-Flux Isotope Reactor (HFIR).

## SUMMARY

A large number of 3-point bend and DC(T) specimens of F82H RAFM steel were irradiated at 250-500$^{o}$C in capsules RB11, RB12, JP26 and JP-27 to doses from 3.5 to 22 dpa. These specimens were tested in the hot cell and results are reported here.

## TEST RESULTS

This report summarizes fracture toughness data determined after testing fracture toughness specimens that were irradiated in different capsules in the HFIR reactor. Two capsules, RB-11J and RB-12J, were irradiated in the HFIR removable beryllium positions with europium oxide ($Eu_2O_3$) thermal neutron shields in place for neutron spectrum tailoring. Specimens were irradiated up to 5 dpa at design temperatures of 300$^{o}$C (RB11J) and 500$^{o}$C (RB12J). Details of the irradiation conditions and the loading of the capsules can be found elsewhere [1].

The bottom and top sections of these capsules were loaded with disk-shaped compact tension [DC(T)] specimens that were used for fracture toughness characterization. These small (12.5 mm diameter and 4.6 mm thick) specimens were irradiated in each "low-" and "high-" irradiation temperature capsule to ~3.8 dpa. Irradiation temperatures were measured by thermocouples. In the low-temperature capsule, specimens were irradiated at an average temperature of 250°C; temperature variation during irradiation was within ±19°C for a given specimen. In the high-temperature capsule, all six specimens were irradiated at an average temperature of 377°C in the bottom part of the capsule; temperature variation during irradiation was within ±30°C for any given specimen.

In addition to DC(T) specimens, 1/3-size Charpy specimens both with regular V-notch (CVN) and precracked (PCVN) to a/W ratio of ~0.5 were irradiated in both capsules. Dimensions of the CVN/PCVN specimens were 3.3×3.3×25.4 mm$^3$ with a 0.51 mm deep 30°C V-notch and a 0.05 to 0.08 mm root radius. Charpy type specimens were irradiated in the middle sections of the capsules. In the “low-temperature” capsule, 1/3-size Charpy specimens were irradiated at an average temperature of 288°C to ~4.7 dpa. In the “high-temperature” capsule, 1/3 size Charpy specimens were irradiated at an average temperature of 509°C to ~4.8 dpa. See details in [2].

Capsule JP26 was irradiated in a target position up to 8 dpa. This capsule had three temperature zones, 300, 400, and 500$^{o}$C. Small three-point bend bar specimens were irradiated in each temperature zone of this capsule. The specimens were 1.65-mm thick, 3.3-mm wide, and 18 mm long. Capsule JP27 was irradiated in a target position up to 22 dpa. This capsule had two temperature zones, 300 and 400$^{o}$C. In this capsule newly designed multi-notch specimens were used for fracture toughness evaluation. Basically, it was the same 1.65-mm thick and 3.3-mm wide specimen as in capsule JP26, only instead of stacking two single-notch specimens one on top of the other, it was machined as one piece with three notches along the length of the specimen. That design helps utilize space in irradiation capsule compared to “regular” single-notch bend bars. The raw fracture toughness data from capsule JP27 are given in [3].

Specimens were tested in general accordance with the ASTM E1921 standard. Test temperatures were coordinated between JAEA, UCSB and ORNL based on available tensile data and direct hardness measurements on bend bars prior to the fracture toughness tests. The main goal of this study was to measure the reference fracture toughness transition temperature, $T_o$.

Thus the test temperatures were selected such that tests would be performed in the transition region where specimens would break by cleavage. Despite these efforts several specimens did not cleave. This highlights once again the very narrow temperature window that is available to generate meaningful results from these very small specimens. Moreover, in this report all data were analyzed using the ASTM E1921 procedure. ASTM standard E1921 utilizes the statistical-based size adjustment that takes into account crack length (thickness of specimen) as an adjustment parameter. No constraint-based adjustment has been performed in this report. However, it was shown recently [4] that a high degree of hardening may significantly reduce the usefulness of such small specimens for fracture toughness evaluation of highly irradiated steels.

One of the goals of fracture toughness evaluation of specimens in RB11J and RB12J was to compare data derived from relatively large DC(T) and smaller bend bar specimens. Unfortunately, post-irradiation evaluation of data from the capsules revealed that the RB capsule specimens were irradiated at different temperatures and to slightly different doses. Nevertheless, shifts of $T_o$ values derived from different specimen types provide a good description of the effect of irradiation temperature on embrittlement of F82H at 4-5 dpa, as shown in figure 1.

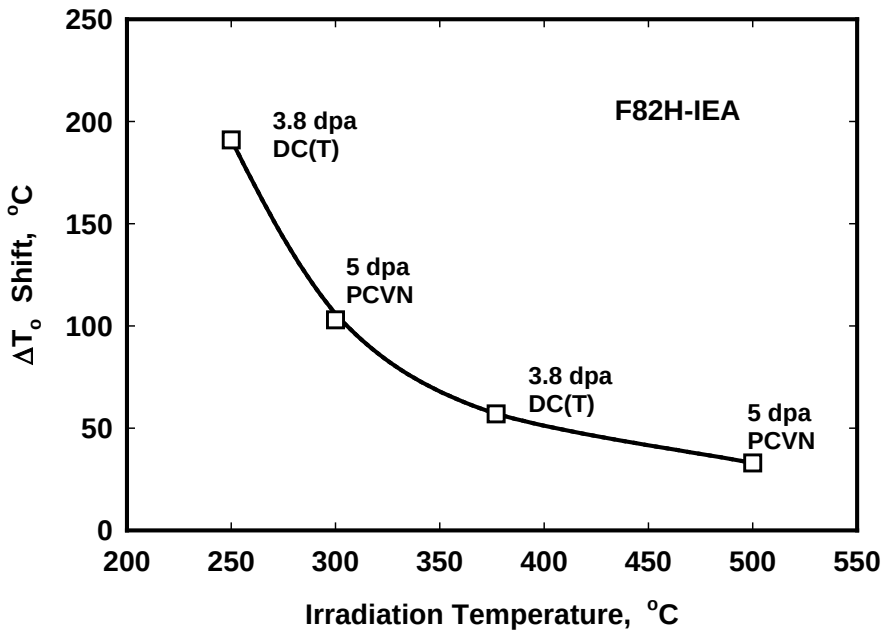


Figure 1. Fracture toughness transition temperature shifts from DC(T) and bend bars irradiated at different temperatures in capsules RB11J and RB12J.

As it was mentioned above, tensile specimens were also tested after irradiation in the same capsules so that hardening and embrittlement of F82H can be compared. Figure 2 illustrates the relationship between the shift of transition temperature and the increase of yield stress of F82H and some other RAFM steels. In addition to RAFM steels, the well-established database from low-alloyed reactor pressure vessel steels is also presented on this figure. The current data confirm previously observed trends for advanced RAFM steels to exhibit smaller amount of embrittlement (measured by shift of transition temperature) per unit of hardening (measured by yield stress increase) compared to low-alloyed RPV steels.

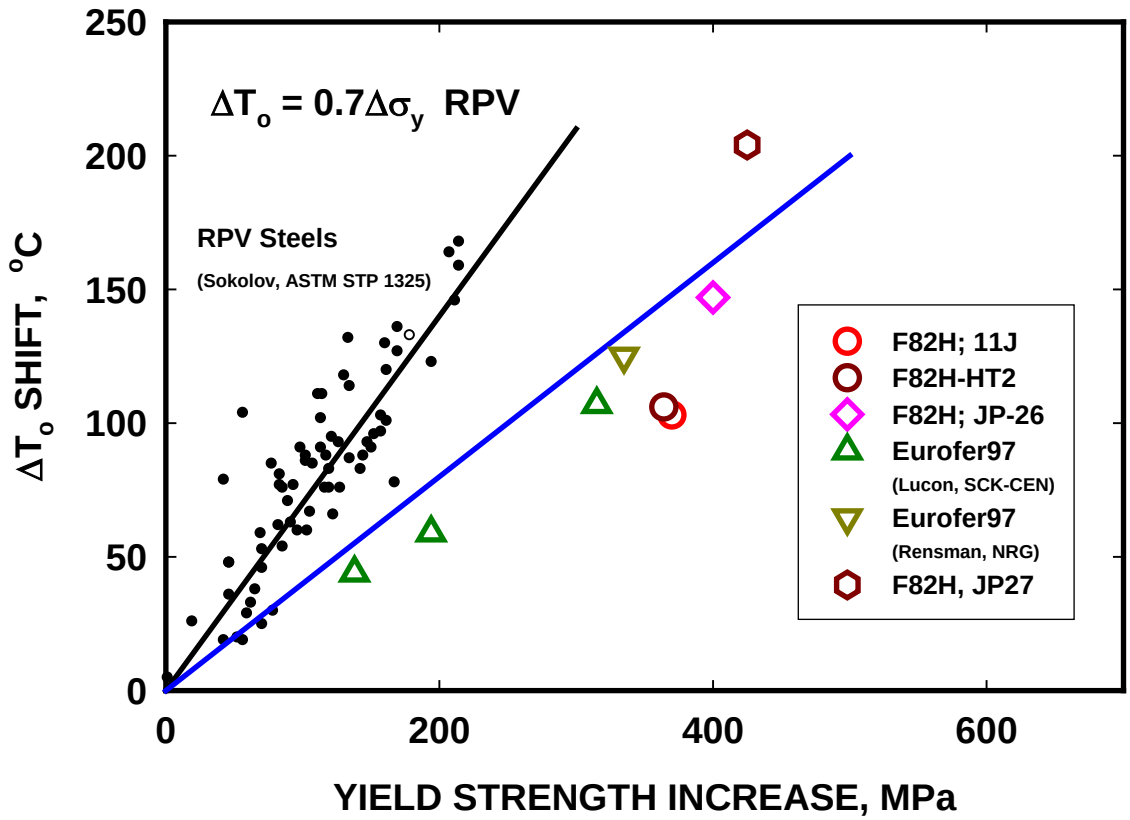


Figure 2. Comparison of shifts of fracture toughness transition temperature and yield strength increase for F82H and other RAFM and RPV steels.

Figure 3 summarizes the latest trend in shift of fracture toughness transition temperature of F82H steel at different irradiation temperatures for neutron doses up to ~20 dpa.

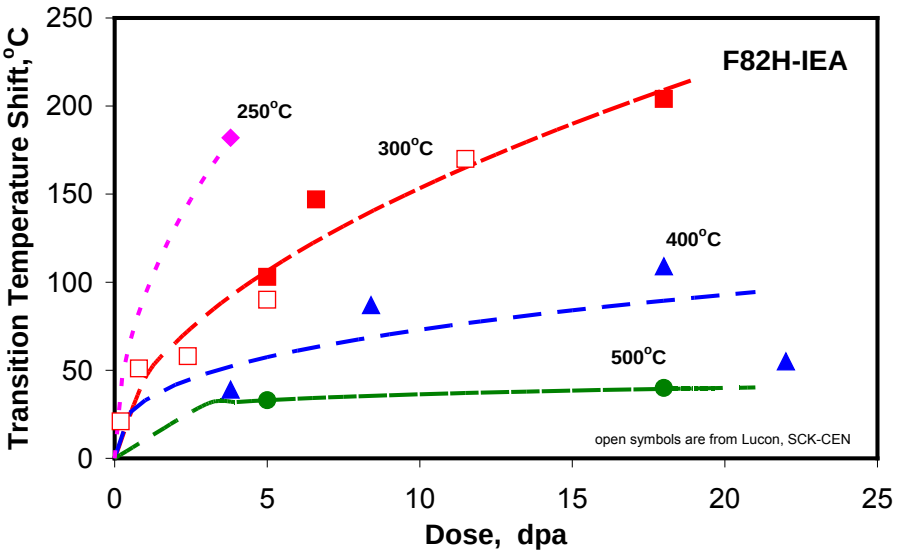


Figure 3. Fracture toughness transition temperature shift vs dose at different irradiation temperatures.

It appears that at 500°C F82H exhibited a very small shift of transition temperature that is insensitive to dose. At 400°C, the shift of transition temperature tend to saturate at ~100°C after ~ 10 dpa. However, data at 300°C do not show saturation in the shift of transition temperature, at least up to ~20 dpa. This somewhat contradicts the trend of increase of yield strength of F82H that appears to saturate at ~10-15 dpa. Future experiments with higher irradiation doses will clarify the trends.

REFERENCES:

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[2] M. A. Sokolov, R. L.Klueh, G. R.Odette, K.Shiba, and H.Tanigawa, in *Effects of Radiation on Material: 21st International Symposium, ASTM STP 1447,* 2003.

[3] M.A. Sokolov, "RESULTS OF FRACTURE TOUGHNESS TESTS OF SEVERAL RAFM STEELS IRRADIATED IN JP-27 CAPSULE IN HFIR," in Fusion Materials Semi-Annual Progress Report for Period Ending December 31, 2008, pp.49-51 *DOE/ER-0313/45.*

[4] T. Yamamoto, G.R. Odette, and M.A. Sokolov, "On the Fracture Toughness of Irradiated F82H: Effects of Loss of Constraint and Strain Hardening Capacity" in proceedings of ICFRM-14, in publication.