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PRELIMINARY IRRADIATION TEST RESULTS FROM THE YANKEE ATOMIC ELECTRIC COMPANY REACTOR VESSEL TEST IRRADIATION PROGRAM

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ABSTRACT

The Yankee Atomic Electric Company test irradiation program was implemented to characterize the irradiation response of representative Yankee Rowe reactor vessel beltline plate materials and to remove uncertainties in the analysis of existing irradiation data on the Yankee Rowe reactor vessel steel. Plate materials each containing 0.24 w/o copper, but different nickel contents at 0.63 w/o and 0.19 w/o, were heat treated to simulate the Yankee vessel heat treatment (austenitized at 1800°F) and to simulate Regulatory Guide 1.99 database materials (austenitized at 1600°F). These heat treatments produced different microstructures so the effect of microstructure on irradiation damage sensitivity could be tested. Because the nickel content of the test plates varied and the copper level was constant, the effect of nickel on irradiation embrittlement was also tested. Correlation monitor material, HSST-02, was included in the program to benchmark the Ford Nuclear Reactor (U. of Michigan Test Reactor) which had never been used for this type of irradiation program. Materials taken from plate surface locations (vs. 1/4T) were included to test whether or not the improved toughness properties of the plate surface layer, resulting from the rapid quench, is maintained after irradiation. If the improved properties are maintained, pressurized thermal shock calculations could utilize this margin. Finally, for one experiment, irradiations were conducted at two irradiation temperatures (500°F and 550°F) to determine the effect of irradiation temperature on embrittlement. The preliminary results of the irradiation program show an increase in T_{30} shift of 69°F for a decrease in irradiation temperature of 50°F. The results suggest that for nickel bearing steels, the superior toughness of plate surface material is maintained after irradiation and for the copper content tested, nickel had no apparent effect on irradiation response. No apparent microstructure effect on irradiation response was noted and the HSST-02 material's response to irradiation was similar to results from power reactor and other test reactor experiments, thus qualifying the Ford Test Reactor for irradiation experiments such as those conducted for the Yankee Atomic program.

1.0 INTRODUCTION

The Yankee Atomic Electric Company test irradiation program was initiated to characterize the irradiation response of representative Yankee Rowe (YR) reactor vessel beltline plate materials and to remove uncertainties in the analysis of existing irradiation data for the YR reactor vessel. Clarification of the uncertainties associated with the response of the beltline plate material to irradiation temperature (500°F versus 550°F), microstructure/heat treatment variations (coarse vs fine grain), and nickel content (high vs low) were required. The microstructure variation was important because the YR vessel material apparently has a greater sensitivity to irradiation damage than the finer grained steels included in the data base for Regulatory Guide 1.99, "Radiation Embrittlement Of Reactor Vessel Materials" [1][1]. It was postulated that the reason for this extra sensitivity was due to microstructure.

The program also tested plate surface material whose initial Charpy 30 ft-lb fix temperatures (T_{30}) are generally lower (better toughness) than material from 1/4 thickness (1/4T) regions in the plate. This was done in an attempt to demonstrate that the toughness at the surface, for both unirradiated and irradiated materials, is superior to the toughness at the plate 1/4T depth. This demonstration, in turn, would show that the use of 1/4T, RT_{NDT} values for a surface flaw initiation event, such as pressurized thermal shock, is conservative.

2.0 TEST MATERIALS

2.1 Chemistry

The plate materials used in the YR reactor vessel irradiation test program are HSST-02 plate, which, because of its use in other test programs and power reactor surveillance programs, served as a correlation monitor material, an A302B plate (low Ni), designated YA9, and an A533B, Class 1 plate (high Ni), designated YA1. Both test plates contain the same copper level of 0.24 w/o. This allows the effects of nickel on irradiation damage to be accessed. The chemical compositions of the test plate materials are shown in Table I along with the chemical compositions of the YR reactor vessel plates they represent.

Table I Yankee Test Irradiation Program Materials' Chemical Composition

	Cu	Ni	C	Mn	Si	Mo	S	P	Chem. Factor*
YR Upper Shell	0.18	0.21	0.20	1.27	0.21	0.48	0.028	0.020	93.5
YA9	0.24	0.19	0.17	1.28	0.22	0.50	0.022	0.026	119.9
YR Lower Shell	0.20	0.63	0.19	1.18	0.20	0.48	0.026	0.016	150.5
YA1	0.24	0.62	0.25	1.40	0.23	0.59	0.011	0.008	173.9
HSST-02	0.17	0.64	0.23	1.39	0.21	0.50	0.013	0.013	128.0

* Chemistry Factors calculated in accordance with NRC Regulatory Guide 1.99, Rev. 02 [1].

2.2 Heat Treatments

The microstructure of the YR reactor vessel plates was "coarse grained" [2] compared to the "finer" grain structure of modern vessel steels. The YR reactor vessel was heat treated at a high austenitizing temperature (1750°F/954°C) which produced a larger austenite grain size compared to modern steels austenitized at the lower temperature of 1600°F(871°C). The larger austenite grains affect the final microstructure of the steel upon quenching [3]. The plate surveillance data used to formulate Regulatory Guide 1.99 predictions on embrittlement is based on fine grain steels austenitized in the lower austenite temperature range.

To determine the difference in irradiation embrittlement between "coarse" and "fine" microstructures, portions of the surrogate YR reactor vessel test materials (YA1 and YA9) were heat treated at the higher austenite temperature and other portions were heat treated at the lower austenite temperature. The quench was a controlled water spray quench which was

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[1] The numbers enclosed in [] refer the reader to the list of references at the end of this paper.

previously qualified to produce the desired test microstructures.

The test specimens for "coarse" and "fine" microstructure tests were taken from a two inch region in the center of the respectively heat treated plates. The plates' were four and three-eights inches thick. The surface test specimens were taken from a 5/8 inch region at the surface of the coarse grain heat treated plate portions.

3.0 TEST IRRADIATION MATRIX

Six capsules containing test specimens of the materials were irradiated in a test reactor. The test matrix was designed to compare irradiation damage in high and low nickel materials (same copper content) and compare the irradiation effects for materials of various microstructures at fluences of 1.0, 3.0 and 5.0E+19 n/cm^2, E>1MeV. The matrix also allowed the 500°F vs 550°F temperature effects to be measured for various materials at $3X10^{19}$ n/cm^2 (E>1MeV). Finally, the inclusion of the HSST-02 material allowed the experiments to be benchmarked against existing data.

4.0 FNR IRRADIATIONS

The test capsules were irradiated in the L-67 fuel lattice position of the Ford Nuclear Reactor (FNR) at the University of Michigan in Ann Arbor, MI (USA). The FNR is a light-water-moderated and cooled, 2 MW pool type reactor. The measured flux for position L-67 is $5.6X10^{12}$ n/cm^2/s, E>1Mev. Each irradiation capsule assembly was instrumented with thermocouples. Capsule temperatures were controlled externally to ±15°F of the test temperature. Each capsule contained dosimetry wires.

5.0 PRELIMINARY RESULTS

5.1 Unirradiated Charpy V-notch Properties

Table II lists the unirradiated and irradiated Charpy V-notch data. All Charpy V-notch specimens were oriented parallel with the plate rolling direction with their notch perpendicular to the surface (ASTM, LT designation). The values in Table II (with the exception of YA1 surface material explained below) and the Charpy curves are based on Tanh fits to the test data and were computer generated using the EPRI Tanh Curve Fitting Routine, Version 1.8.

The effects of the various heat treatments can be seen by referring to the Table II, zero fluence values. For the YA9 material (low nickel), the surface and fine grain Charpy 30 ft-lb fix temperatures (T_{30}) are similar at approximately 5 ft-lbs and 8 ft-lbs, respectively. The corresponding upper shelf energy (USE) values are also similar. The YA9 coarse grain material, however, has a high initial T_{30} of 91°F and a lower USE (97 ft-lbs vs 112-114 ft-lbs). This difference is a direct result of the coarser microstructure. The YA1 (high nickel) material has three distinct T_{30} values; the YA1 surface material has the lowest value (T_{30} = -45°F), followed by the fine grain at -28°F and the coarse grain at +16°F. The YA1 USE values are similar for the heat treated coarse grain and surface material at 123 and 124 ft-lbs, respectively, but the USE is much higher for the fine grain microstructure (163 ft-lbs).

The unirradiated YA1 surface material produced anomalous Charpy results. Tests in the transition region showed substantial scatter such that one could draw two different Charpy curves. A metallurgical investigation was initiated to determine the cause for this variance (microscopic cracks in some specimens possibly), but no conclusions have been reached to date. A conservative (higher initial T_{30}) average of the data produces a T_{30} of -45°F versus a Tanh T_{30} value of -91°F. For further discussions of data in this paper, the initial T_{30} value for the YA1 surface material will be stated at -45°F.

5.2 Irradiation Test Results

The fluence values for the experiments are based on estimates derived from the known flux of the FNR core position, time of irradiation, and estimates based on dosimetry results. The reported fluences are accurate to within ±30% and are for neutron energies greater than one MeV (E>1MeV). The specimens irradiated to 5.0E+19 n/cm^2 have not been tested at this writing.

5.2.1 Temperature Effect Experiment

Two capsules containing YA1 coarse and fine grain materials and HSST-02 material were irradiated simultaneously in the L67 core position to a fluence of 2.8E+19 n/cm^2. One capsule was held at 500°F while the other was maintained at 550°F. The 500°F irradiated Charpy V-notch specimens demonstrated greater T_{30} shifts than the 550°F irradiated specimens. The YA1 fine grain T_{30} shift was greater by 50°F; the YA1 coarse grain T_{30} shift was greater by 77°F; and the HSST-02 shift was greater by 80°F when compared to the 550°F data (using Tanh derived data). The average temperature effect for these materials is 69°F.

The HSST-02 Charpy data compared well with existing 550°F irradiated data [4] for the HSST-02 material. This observation indicates that the FNR is capable of generating reproducible results for steel irradiations.

5.2.2 Results of 500°F Irradiations:

In terms of shift there is an apparent effect of nickel for the coarse grain materials in that the YA1 (high nickel) material has a greater shift than the YA9 (low nickel) material at both fluences. This is only observed with the coarse grain materials, however, it is not apparent when the absolute, irradiated T_{30} values are compared. The opposite effect is seen at 1.0E+19 n/cm^2 fluence for the high (YA1) and low nickel (YA9) surface materials. Surface data for the high nickel, YA1, material at 3.0E+19 n/cm^2 is not available, but the YA1 fine grain and coarse grain materials (high nickel) fall within the same shift group as the low nickel (YA9) materials at 3.0E+19 n/cm^2. This observation suggests that any nickel effect for these .24 w/o Cu containing materials is negligible. See Figure 1.

In terms of the irradiated, final T_{30} values (Figure 2), the high nickel (YA1) surface and fine grain materials retain superior toughness after irradiation compared to the other materials. At 1.0E+19 n/cm^2, the surface material T_{30} value is very low and at 3.0E+19 n/cm^2, the YA1 fine grain material retains the lowest T_{30} value. Another interesting trend is that the separation for the YA9 surface and coarse grain T_{30} values (absolute, not shift) decreases at higher fluences. The unirradiated T_{30} values for the YA9 coarse grain and surface material were significantly different at +91°F and +5°F, respectively.

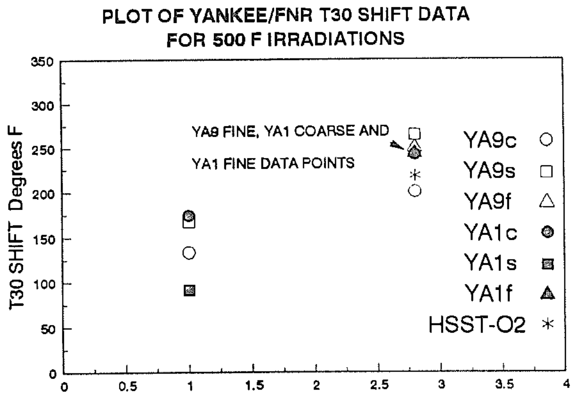

Figure 1

c - coarse, s - surface, f - fine

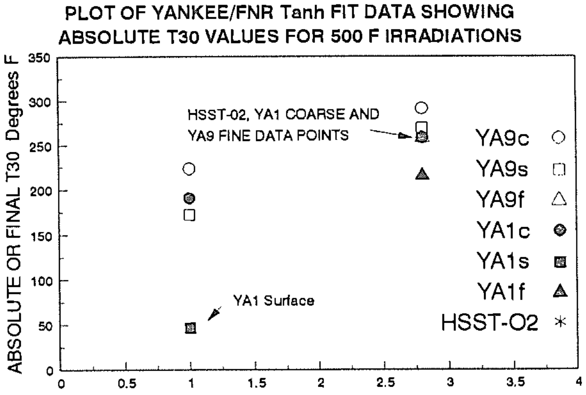

Figure 2

c - coarse, s - surface, f - fine

6.0 CONCLUSIONS

The assumption regarding microstructure was that the coarse grain material would be more sensitive to irradiation damage. The results of this test matrix do not support this assumption. The YA1 surface material shows superior toughness after irradiation based on its lower final T_{30} value. Testing of the specimens irradiated to 5.0E+19 n/cm^2 will provide further information regarding this phenomenon. If the higher fluence results show improved toughness at the surface, compared to 1/4T properties, then this will demonstrate that use of 1/4T properties is indeed conservative for predicting crack initiation in pressurized thermal shock evaluations.

No apparent microstructure effect on the irradiation response of the materials tested is evident, although the high nickel, YA1 material did show a surface material effect.

The YA9 (low nickel) material data show a merging of Charpy properties as the fluence increases. This behavior suggests that while initial properties can vary in the low nickel steel, due to heat treatment, the radiation damage causes the material to approach a "saturation level." If the initial Charpy properties are poor, the properties do not seem to deteriorate at the same rate as the finer grain or differently heat treated material.

Finally, the results of this test program did not explain the higher sensitivity of the YR reactor vessel plate material to irradiation damage. Fabry [5] believes that this anomaly may be due to the use of the Charpy T_{30} fix point. Fabry has demonstrated that when percent shear is used to measure the Charpy shift, the Yankee data behaves the same as other data on this type of steel (A302B) and the steel is not more sensitive to irradiation damage. This issue also warrants further investigation.

7.0 REFERENCES

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8.0 ACKNOWLEDGMENTS

This test program was conducted on an expedited schedule in order to answer questions about the Yankee Rowe reactor vessel. The program was conceived in September of 1990. The fact that test materials were identified and obtained, heat treated, machined into specimens, and irradiated and tested within eighteen months, between September 1990 and February 1992, is a tribute to all who participated in this endeavor. The principal author expresses his appreciation to the staff at B&W Nuclear Technologies, Lynchburg, VA; Babcock & Wilcox in Mt. Vernon, IN; and to the staff at MEA, Lanham, MD. We thank the folks at the Ford Nuclear Reactor for letting us in the reactor and for adjusting their schedule to meet ours. Thanks also go out to those who assisted us in obtaining the test materials and to Len Steele, Albert Fabry and Dieter Pachur who provided insight for this program.

Table II FNR TEST RESULTS OF YANKEE SURROGATE MATERIAL FROM Tanh FITS

500 F IRRADIATION DATA

MATERIAL	FLUENCE E+19 n/cm2	T30 F	T30 SHIFT F	T50 F	T50 SHIFT F	USE FT-LBS	% USE DROP	50 % SHEAR F	DELTA SHEAR F	35 MLE F	35 MLE SHIFT F
YA9	0.00	90.8	0	109.9	0	97.3	0	101.3	0	93.5	0
COARSE	1.00	223.9	133.1	272.1	162.2	67.49	30.6	241.9	140.6	238.9	145.4
	2.80	291.5	200.7	364.2	254.3	63.28	34.9	301.6	200.3	312.9	219.4
	5.00										
YA9	0.00	5.1	0	36.4	0	112.22	0	55.3	0	23.9	0
SURFACE	1.00	172.3	167.2	226.4	190	83.72	25.3	215.6	160.3	197.2	173.3
	2.80	269.7	264.6	322.7	286.3	71.78	40.4	283.9	228.6	294	270.1
	5.00										
YA9	0.00	7.9	0	35.8	0	114.31	0	56.3	0	22.5	0
FINE	2.80	257.6	249.7	300.5	264.7	64.48	43.6	260.6	204.3	274.3	251.8
YA1	0.00	16.4	0	54.1	0	122.55	0	81.4	0	39.4	0
COARSE	1.00	190.8	174.4	222.7	168.6	87.14	28.8	216.6	135.2	210.1	170.4
	2.80	258.9	242.5	326.2	272.1	81.31	33.6	282.3	200.9	295.6	256.2
	5.00										
YA1 *	0.00	-45.0	0	-33.5	0	124	0	-23.5	0	-80	0
SURFACE	1.00	46.3	91.3	90.8	124.3	85.82	30.7	82	105.5	73.1	153.1
	5.00										
YA1	0.00	-27.8	0	10.3	0	162.7	0	45.5	0	-4.1	0
FINE	2.80	215.4	243.2	256.9	246.6	95.87	41	243.8	198.3	240.4	244.5
HSST-02	0.00	40.2	0	72.8	0	118.05	0	91.3	0	56.9	0
	2.80	258.8	218.6	306.7	233.9	83.67	29.1	260.6	169.3	277.1	220.2
550 F IRRADIATION DATA											
YA1	0.00	16.4	0	54.1	0	122.55	0	81.4	0	39.4	0
COARSE	2.80	182.8	166.4	241.5	187.4	84.7	30.8	227.4	146	213.3	173.9
YA1	0.00	-27.8	0	10.3	0	162.7	0	45.5	0	-4.1	0
FINE	2.80	165.6	193.4	200.5	190.2	106.58	34.5	198.8	153.3	193.1	197.2
HSST-02	0.00	40.2	0	72.8	0	118.05	0	91.3	0	56.9	0
	2.80	178.6	138.4	244.5	171.7	98.53	16.5	210	118.7	213.1	156.2

NOTE: ALL CV DATA FOR 1E+19 N/CM2 NOT RECEIVED
* T30 DATA BASED ON CURVE FIT VS TANH