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Effects of Radiation on Mechanical Properties of a Pressure Vessel Steel

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1) INTRODUCTION.

One of the crucial issues in the licensing process of a Nuclear Power Plant (NPP) is the safety evaluation of the Reactor Pressure Vessel (RPV) during its operating life.

To perform such an evaluation a fracture mechanics assessment of the RPV, in the presence of an assumed or existing flaw and operating stresses, is required.

The knowledge of the material toughness, during the life of the component, is needed to this purpose. Appendix A, Section XI and Appendix G, Section III of the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code contain respectively static and dynamic lower bound toughness curves (KIc,KIr), as a function of temperature, to be used in RPV structural integrity evaluation.

KIc and KIr curve are normalized to the material reference nil-ductility temperature (RTNDT)[1] that increases during the operation of the vessel due to the effects of neutron radiation. Surveillance programs are conceived to monitor material degradation. Small specimens, usually Charpy V-notch (CV), are loaded into the vessel, in capsules facing the core region, and are periodically withdrawn and tested to obtain complete Charpy V curves at different values of the integrated fast neutron flux (fluence).

The irradiated RTNDT is determined by adding the temperature shift between the unirradiated and irradiated CV curves, at the 41 J level, to the unirradiated RTNDT. The implicit assumption of this procedure is that the CV shift represents the shift of the KIc and KIr curves.

This paper presents the available results of an extensive research program that the Italian Committee for Nuclear Energy and Alternative Energies (ENEA) started in 1985.

The research had two primary objectives: (1) to characterize an SA508 Cl. 3 carbon steel ring forging produced in Italy as a prototype of a pressurized water reactor vessel and (2) to investigate the effect of various levels of neutron irradiation at temperatures near 280 C on the strength, toughness,

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[1] RTNDT is the highest of three temperatures: NDT, $T_{CV68}-33$, $T_{CV89}33$, where T_{CV68} is the temperature at which the CV energy in the transverse direction is 68 joules and T_{CV89} is the temperature at which the CV laterial expansion in the transverse direction is 0.89 mm.

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and ductile-to-brittle transition temperature of the forging. Irradiation temperatures were approximately 280 C and fluences ranged from approximately 1 E+19 to 5.5 E+19 n/cm^2.

For the first time crack arrest specimens of a base material been inserted in a capsule and irradiated.

A total of 40 tensile tests, 162 Charpy tests, 76 KId tests, 30 KIc (or JIc) tests, 17 crack-arrest tests were performed on unirradiated or irradiated material. Results from tensile, standard and pre-cracked specimens are reported in this paper. Additional tests are planned, including 9 crack arrest tests on irradiated material and 50 KIc tests on unirradiated and irradiated material.

The paper reports also comparisons among transition-temperature shifts measured and expected on the basis of some of the best-known empirical prediction equations.

Four laboratories have been involved in the investigation: ENEA CRE Casaccia, near Rome, Battelle Columbus Laboratories (BCL), Ohio, USA, and two laboratories of the Commissariat a l'Energie Atomique (CEA), namely Saclay and Grenoble in France.

ENEA, the sponsor of the entire program, has been performing mechanical testing of unirradiated materials. The other three laboratories have been performing testing of unirradiated specimens and irradiation, dosimetry, and mechanical testing of irradiated specimens.

The material is the SA 508 Cl.3 carbon steel, containing manganese and molybdenum as principal alloying elements. It is used for pressure vessel as well as for nozzles or flanges.

All tests specimens for the ENEA Irradiation Program were cut from material positioned at one quarter of the 300 mm thick ring forging. The orientation of the toughness specimens was C-R as defined in ASTM E399 standard (Annual book of ASTM standards. Vol. 3.01). Tensile specimens were aligned with the circumferential direction of the forging. Drop weight tests conducted on the material by the manufacturer indicated that the nil-ductility (NDT) temperature was -12.5 C, which is also the reference temperature nil-ductility transition temperature (RTNDT).

2) THE NEUTRON IRRADIATION.

The main goal of the project was to investigate material radiation damage. Three test research reactors have been used to this purpose.

2.1) The OSIRIS reactor in Saclay.

The OSIRIS reactor is a pool reactor with a nominal power of 65 MW, managed by CEA. The neutron flux was around 1.15 E+13 n/cm^{2}s. The irradiation phase took only 10 days, at full power, to reach the target fluence of 1 E+19 n/cm^2.

Specimen capsules were instrumented with thermocouples and flux detectors. Copper and Cobalt detectors were used for fast and thermal flux respectively.

2.2) The MELUSINE reactor at Grenoble.

The Melusine reactor is a pool reactor with a nominal power of 8 MW, managed by CEA. The neutron flux in the specimens region had an axial parabolic shape with a peak value, in the middle, of 1.15 E+13 n/cm^{2}s and a lowest value, at both ends, of 0.6 E+13 n/cm^2.

For this reason different fluence levels were achieved along the capsule length. Specimens in the middle of the capsule experienced, after 1379 hours at full power, 5.5 E+19 n/cm^2 against 3.5 E+19 n/cm^2 for the border specimens.

2.3) The Ford Nuclear Reactor (FNR) at the University of Michigan.

The Ford Nuclear Reactor, a 2 MW pool reactor managed by University of Michigan, was selected by BCL for irradiation. An aluminium capsule was designed to contain specimens. The capsule was positioned in a region, close to the core, where the neutron flux was around 3 E+12 n/cm^{2}s. The irradiation phase took a total of 4677 hours at full power to reach an average final fluence of 3.7 E+19 n/cm^2.

3) TENSILE DATA.

Up to now 40 specimens have been tested in the not irradiated as well as in the irradiated conditions. Standard round specimens (ASTM E8 - 4 mm in diameter and 20 mm gage length) were used.

Irradiation increased both the tensile strength and the yield strength of the steel, but had little effect on either the uniform or total elongation (Ref. 1). Thus, in the absence of a notch, the energy absorbing capability of the material in tension was actually increased by irradiation.

Increasing the neutron fluence beyond 1 E+19 n/cm^2 produced virtually no additional strengthening of the steel.

Prior to irradiation, the tensile strength decreased continuously with increasing temperature, indicating that the steel had little susceptibility to dynamic strain aging (DSA) (Ref. 2). However, following irradiation, the tensile strength was found to increase as the temperature was raised from 150 to 290 C, indicating that the steel may be susceptible to DSA by neutron irradiation. Some serrations on the stress-strain curves at 200 and 250 C in the material irradiated to 3.5 E+19 n/cm^2 provide further evidence of DSA. This finding is in contradiction to some results reported by Murty (Ref. 3) who found that steels which were susceptible to DSA were made less susceptible by irradiation to a fluence of approximately 2 E+18 n/cm^2.

4) IMPACT TESTS.

Standard Charpy V-notch specimens were used. Tests were performed according to ASTM E23 (Annual Book of ASTM Standards - Vol. 3.01).

CV results on not irradiated material are shown in Fig. 1. The large amount of scatter, for example from 25 to 95 J at -50 C or from 50 to 150 J at -40 C, complicates the interpretation of unirradiated specimen results, particularly when the magnitude of the transition temperature shift had to be determined.

Moreover also results on irradiated material are characterized by a quite large scatter (see Fig. 1).

It came unexpected that, as shown in Fig. 1, data at 3.7 E+19 n/cm^2 were falling practically on the unirradiated data area.

At present no explanation has been found for this unusual behaviour. Data at 3.7 E+19 n/cm^2 were obtained at Westinghouse hot-cells facilities after irradiation in FNR.

The only difference can be ascribed to the neutron flux that is one order of magnitude lower in the FNR compared to the other two. A fluence rate effect and possibly the neutron spectrum could than be responsible for this behaviour. This particular aspect will be further investigated.

Data at 3.7 E+19 n/cm^2 were disregarded in the evaluation of the brittle to ductile transition temperature shifts to compare data at homogeneous fluence rate. Results are reported in the next section.

5) DYNAMIC TOUGHNESS TESTS.

PCCV specimens were tested according to a french standard similar to the Pressure Vessel Research Council / Metal Properties Council (PVRC/MPC) guidance.

Standard specimens were used for the PCCV instrumented dynamic tests, with an initial fatigue crack ranging from 45% to 55% of the thickness . The specimens were precracked in the linear elastic range, with a frequency of 20 Hz. Impact speeds ranging from 1 to 5 m/s, depending on the test temperature, were used in order to have enough energy to break the specimen and, at the same time, to minimize the effects of inertial loading.

When the specimen behaved elastically during the test, the fracture toughness KId were calculated using standard linear elastic formulas. When the specimen behaved in elastic-plastic fashion the test were evaluated using the method of the J integral (KJd) or the method of the equivalent energy (Kd*).

The large data scatter in the irradiated as well as in the not irradiated conditions does not allow, at present, the drawing of lower bound curves to estimate shifts of reference temperatures.

Fig. 2 shows pre-cracked Charpy V specimen results in terms of dial energy measured during the tests. Shifts at 41 J are reported in table 1.

6) REFERENCE TRANSITION TEMPERATURE INCREASE.

Hyperbolic tangent best-fit curves were drawn through experimental results shown in fig.1 and fig.2 in order to obtain shifts of CV and PCCV curves after irradiation.

Shifts of reference temperatures and drops of Upper Shelf Energy (USE) measured on the CV curves are reported in table 1, and compared to two prediction equations results. Regulatory Guide 1.99 Rev.2, issued by the American Nuclear Regulatory Commission (NRC) (Ref. 4) provides equations and plots to predict Reference Transition Temperature shifts and Upper Shelf Energy (USE) drops. Predictions from RG 1.99 Rev.2 are compared to the experimental CV shifts at 41J, with and without the "margin" proposed in the guide, and to the measured USE decreases. CV shifts read at 68J are compared to expected values according to a prediction equation developed at ENEA (Ref. 5).

7) CONCLUSIONS.

The paper presents intermediate results from a research program on neutron radiation damage in a pressure vessel steel (SA508) sponsored by the Italian Committee for Research and Development of Nuclear Energy and Alternative Energies (ENEA).

Tensile data show that the susceptibility of the steel to Dynamic Strain Aging (DSA) increases with neutron fluence.

Temperature shifts measured on Charpy V-notch energy curves have been compared to the results of two prediction equations. Regulatory Guide 1.99 Rev.2 equation, issued by American Nuclear Regulatory Commission (NRC), which is usually assumed to be conservative, is definitely not conservative in predicting irradiation effects for this forging. The ENEA equation, on the other hand, is conservative. A possible neutron flux and spectrum effect may be responsible for the large difference observed in CV energies between specimens irradiated in different reactors.

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TABLE 1 - Summary of transition temperature shifts

Fluence (E19 n/cm^2)	PCCV Tests Shift at 41J (C)	CV Tests Shift at 41J (C)	CV Tests USE Drop (%)	RG. 1.99 Rev.2 (with margin)		CV Tests Shift at 60J (C)	ENEA equation (with margin) (C)
				CV Shift at 41J(C)	USE drop (%)		
1.0	11	11	21	21 (39)	19	10	24 (64)
3.5	46	33	30	27 (45)	25	39	50 (90)
5.5		54	31	29 (47)	28	53	65 (104)

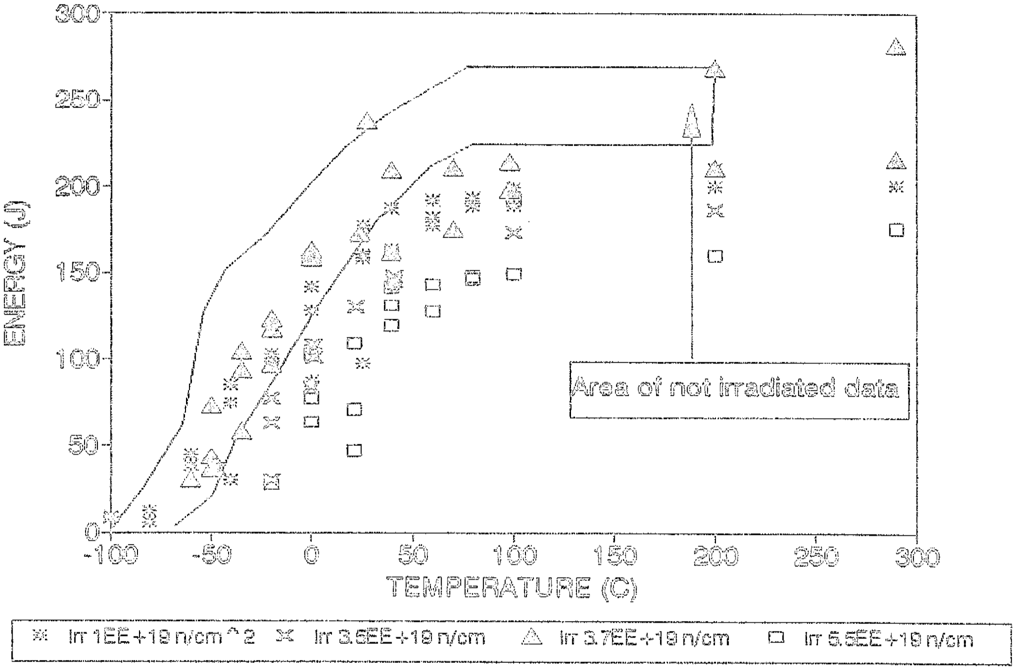

Fig.1 - CV results in the not irradiated and irradiated conditions

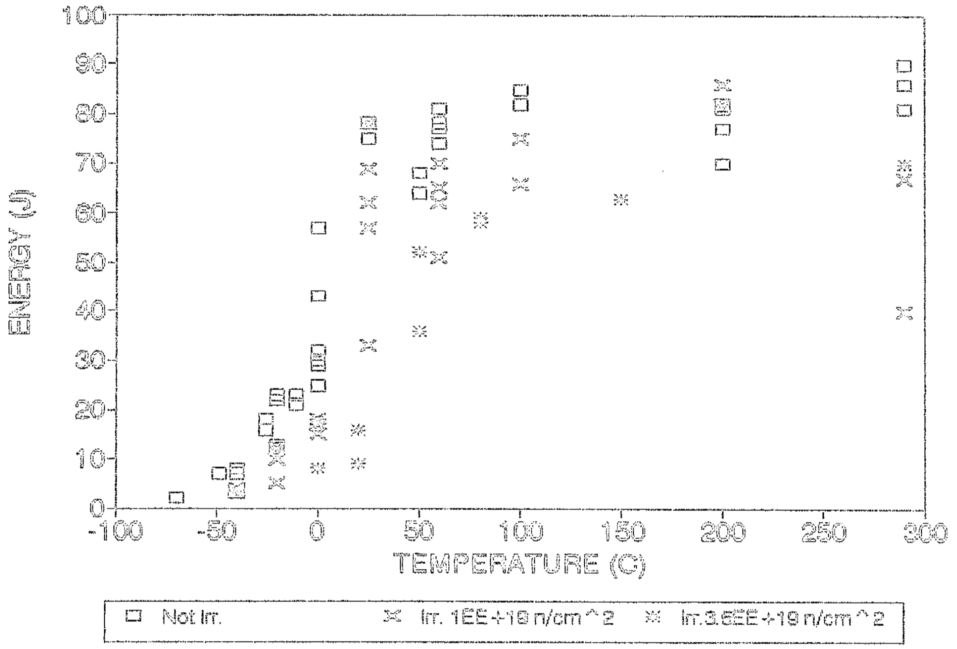

Fig.2 - PCCV results in the not irradiated and irradiated conditions