Radiation Embrittlement of PWR Vessel Supports

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INTRODUCTION

Structural supports for most pressurized-water-reactor (PWR) pressure vessels are located in the cavity between the vessel and the biological shield and in some cases extend into the shield (Fig. 1). Within the cavity the fast neutron flux (ϕ) for energies $E > 1.0$ MeV is $\leq 2 \times 10^9$ neutrons/cm^2•s, and temperatures are <65°C. The corresponding calculated increase in the nil ductility transition temperature (NDTT) by 32 effective full-power years (EFPY), based on the radiation embrittlement data [1,2] available from materials testing reactors (MTRs) before 1987, is quite small, if the difference in the MTR and the PWR cavity fast neutron energy spectra is neglected.

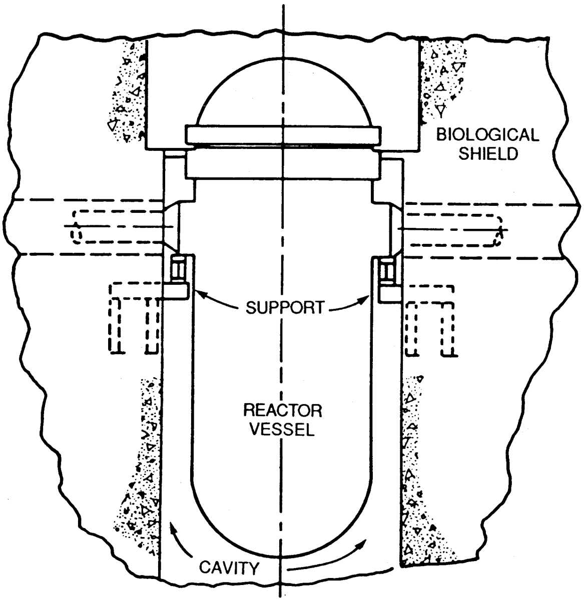

Fig. 1. PWR vessel support located in cavity between the vessel and biological shield.

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Early in 1978 it became apparent that the fast neutron spectrum above 0.1 MeV was much softer in the PWR cavity than in the MTRs. Because of this, and because neutrons with energies in the range of 0.1 to 1.0 MeV contribute to radiation damage, correlating the MTR embrittlement data with fast neutron fluence (Φ) for $E > 1.0$ MeV resulted in an underestimation of ΔNDTT for supports in the cavity.

Several studies pertaining to radiation damage of PWR vessel supports [3-6] were conducted between 1978 and 1987. During this period, apparently there was no reason to believe that low-temperature (<100°C) MTR embrittlement data, correlated with displacements per atom (dpa) for $E > 0.1$ MeV, were not appropriate for evaluating embrittlement of PWR vessel supports. However, late in 1986, data from the High Flux Isotope Reactor (HFIR) [7] vessel surveillance program [8,9] indicated that the embrittlement rates of the several HFIR vessel materials (A212-B, A350-LF3, A105-II) were substantially greater than anticipated on the basis of MTR data [9]. Further evaluation of the HFIR data suggested that a fluence-rate effect was responsible for the apparent discrepancy, and shortly thereafter it became apparent that this rate effect was applicable to the evaluation of LWR vessel supports. As a result, the Nuclear Regulatory Commission (NRC) requested that the Oak Ridge National Laboratory (ORNL) evaluate the impact of the apparent embrittlement rate effect on the integrity of light-water-reactor (LWR) vessel supports. Of course, the concern over radiation embrittlement is that it increases the potential for propagation of flaws, and this could lead to the failure of the supports.

The purpose of the study was to provide an indication of whether the integrity of reactor vessel supports is likely to be challenged by radiation-induced embrittlement before 32 EFPY. The scope of the evaluation included

1. correlation of the HFIR data for application to the evaluation of LWR vessel supports,
2. a survey and cursory evaluation of all U.S. LWR vessel support designs,
3. selection of two plants for specific-plant evaluation, and
4. a specific-plant evaluation of both plants to determine critical flaw sizes for their vessel supports.

This paper discusses items 1 and 2 and the specific-plant evaluation for one of the two plants selected in item 3.

HFIR VESSEL SURVEILLANCE DATA

HFIR [7] is a high-performance, light-water-cooled, low-temperature (50 to 70°C), research reactor at ORNL that began operation in 1965. Its stainless-steel-clad, carbon-steel, pressure vessel was designed for 20 EFPY, and a surveillance program was maintained to monitor the actual radiation-induced embrittlement [8]. Late in 1986, a reevaluation of the integrity of the vessel was commenced in an effort to extend the permissible life [9]. The surveillance data indicated that the embrittlement rate was significantly greater than had been anticipated on the basis of data obtained in the early 1960s from MTRs [1]. The neutron energy spectra and the irradiation temperatures for the HFIR surveillance specimens and for MTR specimens were believed to be essentially the same, and the materials were similar; however, the fast neutron flux (ϕ) in the MTRs was $\sim 10^5$ times that in the HFIR specimens. Thus, it appeared that the lower flux in HFIR was responsible for the relatively large amount of embrittlement per neutron; that is, there appeared to be a negative fluence-rate effect.

HFIR vessel shell material (A212-B) and beam-tube nozzle materials (A105-II and A350-LF3) were included in the HFIR vessel materials surveillance program. Surveillance specimens of A212-B were removed for testing after 15.0 and 17.5 EFPY, and A105-II and A350-LF3 specimens were removed after 2.3, 6.5, 15.0, and

17.5 EFPY. The corresponding ΔNDTT data [10] are compared in Fig. 2 [ΔNDTT vs Φ (E > 1.0 MeV)] with the MTR data [1] available at the time the vessel was designed. If it is assumed that spectrum and chemistry effects are not responsible for the incongruity of the several sets of data, the comparison indicates a fluence-rate effect.

To evaluate the effects of possible differences in chemistry and fast spectrum, HFIR archive A212-B material was recently irradiated in the Oak Ridge Research Reactor (ORR), a typical high-flux, low-temperature MTR, and the HFIR and ORR A212-B data were plotted as a function of dpa for E > 0.1 MeV (Fig. 3)

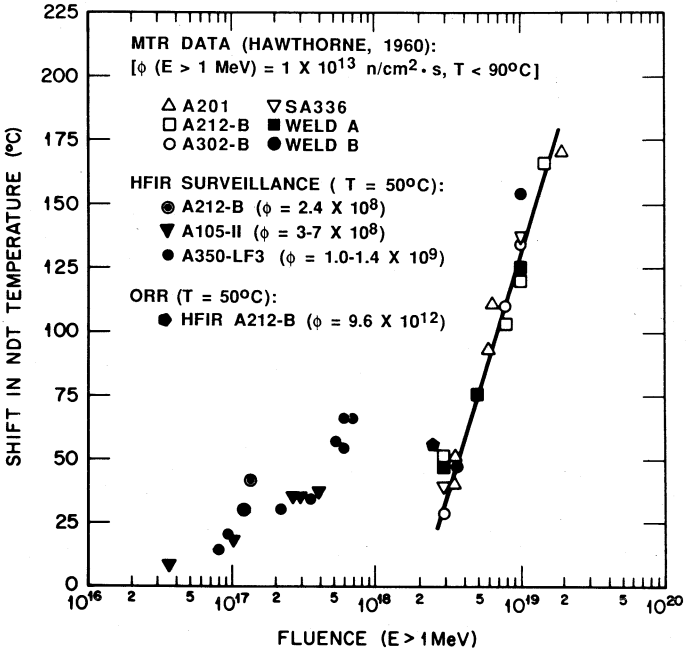

Fig. 2. Increase in NDTT with fast neutron fluence for irradition in HFIR (surveillance positions), ORR and MTR (Hawthorne, 1960).

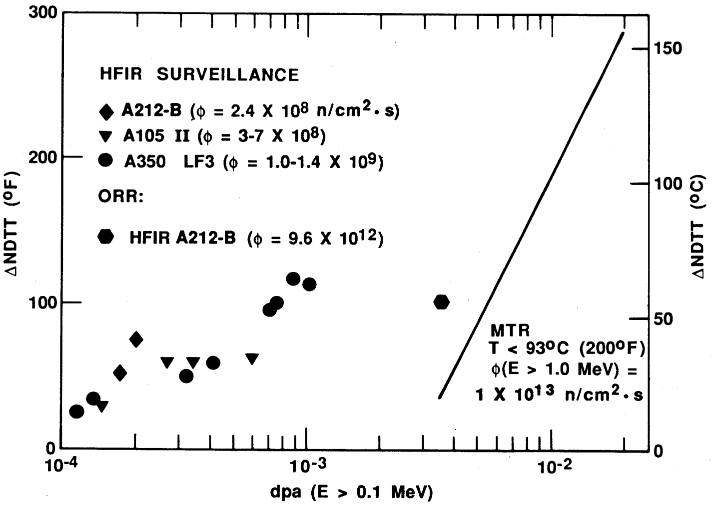

Fig. 3. Increase in NDTT with dpa for irradiations in HFIR (vessel surveillance positions), ORR, and MTR (Hawthorne, 1960).

as well as a function of Φ for E > 1.0 MeV (Fig. 2). Figure 2 shows the A212-B archive material (irradiated in the ORR) to be consistent with the MTR data, implying that the chemistry of the HFIR A212-B material is not significantly different from that corresponding to the MTR data (assuming that a difference in spectrum does not compensate for a difference in chemistry). Figure 3 shows that when the HFIR and MTR data are plotted as a function of dpa (E > 0.1 MeV), there is still evidence of a significant rate effect. Thus, the small differences in the HFIR and MTR fast spectra are not responsible for the incongruity in Fig. 2.

In the above discussion of a rate effect, only neutron energies $\geq$ 0.1 MeV were considered. Nanstad et. al., [11] and Mansur and Farrell [12] have suggested that lower energies, particularly thermal, may at least in part explain the relatively high embrittlement rates in HFIR. This possibility is being explored but was not considered in this study.

APPLICATION OF HFIR DATA TO VESSEL SUPPORT EVALUATION

The indicated embrittlement rate effect presumably applies to the supports of some LWR vessels because fast neutron fluxes, irradiation temperatures, and materials appear to be similar to those in HFIR. Temperatures of the supports range from ~250°C at the point of contact with the vessel to <65°C at a point of contact with the biological shield (65°C is the normal maximum permissible operating temperature of the concrete biological shield). The temperature of the HFIR vessel and surveillance specimens is ~50°C. Thus, presumably a portion of the support operates at a temperature close to that of the HFIR vessel.

Multigroup neutron transport calculations were performed recently for the vessel wall and the cavity of one boiling-water reactor (BWR) and three PWRs [13,14], and Table 1 summarizes the fast fluxes (E > 1.0 MeV) [as well as dpa rate (E > 0.1 MeV)] for the LWR cavities and the HFIR surveillance specimens. It is apparent that ϕ (E > 1.0 MeV) values for the PWR cavities are similar to those for the HFIR surveillance specimens (10^8 to 10^9 neutrons/cm^2·s), while that for the BWR is much less.

Table 2 summarizes LWR fast-flux data for E > 1.0 MeV (group A) and $0.1 \leq E \leq 1.0$ MeV (group B). These data indicate that the ratio of group A to group B fluxes is much less in the cavity than it is at the inner surface of the vessel wall (the result of inelastic scattering in the vessel wall). Thus, the fast flux (E > 0.1 MeV) in the LWR cavity is much softer than that at the location of the HFIR surveillance specimens. As suggested in the last section, to account for this difference in energy spectrum when applying the HFIR data to the evaluation of the supports in the cavity, the ΔNDTT data can be correlated

Table 1. Summary of fast neutron fluxes (E > 0.1 MeV)for cavities of "typical" LWR's and for HFIR surveillance specimens

Reactor[a]	ϕ(E > 1.0 MeV) (neutrons/cm^2·s)	dpa rate (E > 0.1 MeV) (s^{-1})
HFIR	2.4×10^8–1.4×10^9	3.7×10^{-13}–2.0×10^{-12}
GE (BWR)	2.8×10^7	6.3×10^{-14}
B&W (PWR)	2.1×10^8	6.8×10^{-13}
_W_ (PWR)	6.1×10^8	4.7×10^{-12}
CE (PWR)	1.8×10^9	5.0×10^{-12}

[a] Reactor designers: General Electric (GE), Babcock and Wilcox (B&W), Westinghouse (_W_),and Combustion Engineering (CE)

Table 2. Comparison of vessel and cavity calculated fluxes for "typical"BWR and PWR plants

Reactor	Neutron flux ($\text{neutrons/cm}^2 \cdot \text{s}$)					
	Vessel inner surface			Cavity		
	A[a]	B[a]	A/B	A	B	A/B
GE (BWR)	6.3×10^8	3.5×10^8	1.8	2.8×10^7	1.1×10^8	0.3
B&W (PWR)	5.8×10^9	7.4×10^9	0.8	2.1×10^8	1.6×10^9	0.1
W (PWR)	2.6×10^{10}	2.7×10^{10}	1.0	6.1×10^8	1.3×10^{10}	0.5
CE (PWR)	4.6×10^{10}	5.6×10^{10}	0.8	1.8×10^9	1.0×10^{10}	0.2

[a] A: $E > 1.0$ MeV
B: $0.1 \leq E \leq 1.0$ MeV

with dpa rate and dpa for $E > 0.1$ MeV instead of ϕ and Φ for $E > 1.0$ MeV, the assumption being made that most of the neutrons contributing to embrittlement have energies >0.1 MeV. A comparison of dpa rate ($E > 0.1$ MeV) for HFIR and the LWR cavities (Table 3) indicates that the maximum cavity dpa rate (5.0×10^{-12} s^{-1}) is about twice the maximum HFIR dpa rate (2.0×10^{-12} s^{-1}), while the maximum fast-flux values ($E > 1.0$ MeV) are about the same. This result indicates that some extrapolation of the HFIR data is necessary.

Application of the HFIR data to the LWR vessel supports requires extrapolation with regard to both dpa rate and dpa. Thus, correlations between ΔNDTT,

Table 3. Summary of calculated critical flaw depths for Trojan

Location on beam	Loading condition[a]	Flaw type	Critical flaw depth, a (mm)					
			7.48 EFPY[b]		32 EFPY			
			a/ℓ[c]		a/ℓ			
			0	0.1	0	0.1	0.2	0.3
Shield inner surface	A	Surface semi-ellipse	29	>32	21	>32		
	B		27	>32	20	32	>32	
	C		23	>32	17	25	>32	
Maximum bending moment	A	Surface semi-ellipse	29	>32	19	30	>32	
	B		27	>32	18	26	>32	
	C		22	>32	15	20	28	>32
Flange grout hole	A	Twin edge cracks	>50		41			
	B		>50		30			
	C		>50		11			

[a] A = DW + T + OBE, B = DW + T + SSE, and C = DW + T + SBLOCA.

[b] Corresponds to late 1988.

[c] Ratio of maximum depth (a) to surface length (ℓ).