Attachment 2

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PLANT SPECIFIC CHARPY SHIFT
MODEL FOR NINE MILE POINT UNIT 1
MPM-59401-NP
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Plant-Specific Charpy Shift Model for Nine Mile Point Unit 1

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Plant-Specific Charpy Shift Model

for Nine Mile Point Unit 1

prepared for

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Abstract

This report documents the development of a plant-specific Charpy shift model for Nine Mile Point Unit 1 (NMP-1). The plant-specific model is physically based and incorporates the important microstructural damage mechanisms which are now known and well understood. At fluences below ~2 x 10^{18} n/cm^2 (typical boiling water reactor (BWR) end-of-license (EOL) fluence), it is shown that there is no correlation of yield strength elevation or Charpy shift with bulk Cu content for the NMP-1 beltline materials. The analyses and data trends demonstrate that most BWRs operate below the fluence threshold for significant Cu precipitation. This results in a different functional form for the Charpy shift (ΔT_{30}) model than currently used in Regulatory Guide 1.99 (Revision 2) (RG1.99(2)). The Nuclear Regulatory Commission (NRC) model was based primarily on high fluence pressurized water reactor (PWR) data and there were very few surveillance data available in the BWR fluence range when the NRC model was developed. Depleted zone (cascade cores) damage is expected to be the primary damage component for BWRs. Since depleted zones are shearable defects, the Charpy shift has been shown to be proportional to the square root of fluence. The insignificant change in work hardening behavior exhibited by the tensile data confirm that shearable defects (mainly depleted zones) are the predominant microstructural feature resulting from neutron irradiation.

Based on knowledge of the important radiation damage mechanisms operating in the NMP-1 reactor pressure vessel (RPV) steel, criteria were established for defining the NMP-1 plant-specific data set from the larger NRC Power Reactor-Embrittlement Data Base (PR-EDB). Application of these criteria to the PR-EDB resulted in a data set containing 37 power reactor surveillance data points in addition to the 3 from NMP-1. Regression analyses yielded an accurate linear model of ΔT_{30} as a function of the square root of fluence. Application of the plant-specific model to NMP-1 will reduce the leakage/hydrostatic test temperature by ~41°F. This will reduce the in-service leak test duration by approximately eight hours for each future startup. In addition, outage scheduling flexibility will be increased as a result of the in-service leak tests being conducted below 212°F.

Executive Summary

Reactor pressure vessel (RPV) materials undergo a transition in fracture behavior from brittle to ductile as the test temperature of the material is increased. Charpy V-notch tests are conducted in the nuclear industry to monitor changes in the fracture behavior during irradiation. Neutron irradiation to fluences above ~5 x 10^{16} n/cm^2 causes an upward shift in the Charpy curve and in the ductile-to-brittle transition temperature (DBTT). The Nuclear Regulatory Commission (NRC) has developed a trend curve model and a calculative procedure for modelling the DBTT shift and this information is described in Regulatory Guide 1.99 (Revision 2) (RG1.99(2)). The nuclear industry tracks this shift through Charpy 30 ft-lb transition temperature measurements. At the time the RG1.99(2) model was developed, there were few surveillance capsule test results available for fluences in the boiling water reactor (BWR) operating range. Use of a data base which consists predominantly of pressurized water reactor (PWR) data has resulted in an overly conservative material behavior modelling for the Nine Mile Point Unit 1 (NMP-1) beltline plates. This report shows that with the large amount of data available today, a much more accurate plant-specific model can be developed for use in the BWR fluence range. The development of a Charpy shift (ΔT_{30}) model for a particular plant is anticipated in RG1.99(2), "To use the surveillance data from a specific plant instead of Regulatory Position 1, one must develop a relationship of ΔRT_{NDT} to fluence for that plant.". Therefore, the work documented in this report was undertaken to develop a plant-specific Charpy 30 ft-lb transition temperature shift (ΔT_{30}) model which can be applied to the NMP-1 beltline plates.

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1.0 Introduction

Ferritic pressure vessel materials undergo a transition in fracture behavior as a result of their body-centered-cubic (BCC) lattice structure. The Charpy V-notch test is used extensively in reactor pressure vessel (RPV) surveillance programs to characterize the effects of neutron fluence on the Charpy curve. Two key parameters which are monitored are the Charpy curve shift indexed at the 30 ft-lb level (ΔT_{30}) and the drop in the upper shelf energy (ΔUSE). Current regulations use the ΔT_{30} to determine the shift in the American Society of Mechanical Engineers (ASME) reference stress intensity factor (K_{IR}) curve. Therefore, pressure-temperature (P-T) operating curves are shifted to higher temperatures (reduced operating window) precisely in accordance with the Charpy curve shift. It is essential that accurate trend curve models (ΔT_{30} vs. fluence) be used to ensure that the P-T curves are appropriately calculated. In the case of Nine Mile Point Unit 1 (NMP-1), accurate representation of the actual material behavior is essential to determine whether in-service leak testing above 212°F is necessary. If it can be shown that in-service leak testing below 212°F is justified with adequate margins of safety, then substantial savings in outage time can be realized in the future.

The Nuclear Regulatory Commission (NRC) updated Regulatory Guide 1.99 and issued Revision 2 in May, 1988 (RG1.99(2)) [RG199]. Revision 3, which is expected to parallel the Revision 2 work in terms of technical approach and content, is currently being developed. The Revision 2 work involved several changes including: the separate treatment of welds and plates; the addition of Ni as a model variable; the removal of P from the Revision 1 model; and the inclusion of guidance for calculating neutron attenuation through the vessel wall based on a displacement per atom (dpa) basis. The final model adopted was based heavily on the work of two NRC contractors (Odette and Gutherie) [Ra84]. The Revision 2 model is based exclusively on the assumption that only hardening mechanisms (particularly Cu precipitation) contribute to the embrittlement trend [Od83] (hence the removal of the P term since P is a surface active element).

Research conducted over the past decade (and particularly over the past 5 years) has brought the physical basis for the NRC model into question [IGRDM4, IGRDM5, Ig92]. It is currently believed that spherical microvoids rarely form in vessel materials [ESER94, Au94, Ba92] (Odette's hardening theory postulates significant microvoid number densities [Ep84]). An energy minimization model [ESER94] shows that in iron it is more likely that vacancy clusters will collapse to loops or exist as a loosely connected collection of individual vacancies. Recent Atom Probe Field Ion Microscopy (APFIM) studies have shown the process of Cu precipitation to be much more complex than originally envisioned [Mi88a, Mi88b, Au94]. Several APFIM workers have reported "clouds" of solute atoms which include Ni, Mn, and Si, and these clouds occasionally are associated with Cu. Miller [Mi88a] has also reported P-rich regions and the precipitation of small rod-shaped spherical Mo_2C carbides in the ferrite matrix. The irradiation induced carbides are expected since there is a significant Mo concentration and Mo_2C is more stable than the Fe_3C produced during final heat treatment. However, little is known at present about the extent to which Mo_2C contributes to the total hardening.

With regard to non-hardening embrittlement, the British have recently demonstrated large Charpy shifts for tempered high P laboratory heats and verified the mechanism to be non-hardening embrittlement which results from transport of P to prior austenite grains [Mc94]. McElroy [Mc94] has also discussed grain boundary embrittlement in higher P Russian steels and MAGNOX welds. However, it is important to bear in mind that intergranular (IG) fracture has not been reported in the U.S. steels. This is most likely because the concentration of surface active elements at boundaries has not reached a critical level for fluences in the low 10^{19} n/cm^2 range. The U.S. light water reactor (LWR) surveillance programs should continue to examine Charpy fracture surfaces to ensure that IG fracture is not a problem.

Finally, the addition of a large amount of data to the NRC's Power Reactor-Embrittlement Database (PR-EDB) has shown that further sub-division of the data beyond that of plate and weld categories is needed. This point is more fully discussed later in this report. Further discussion concerning the physical mechanisms of neutron damage in RPV steels is also provided in the report sections which follow.

In light of these considerations, and the fact that the RG1.99(2) was developed using a data set with few boiling water reactor (BWR) fluence range data, a prudent approach is to develop a plant-specific trend curve for the NMP-1 beltline plates. Therefore, the focus of this report is strictly on the modified A302B (A302M) material. The model is referred to as "plant-specific" because the database was subdivided to a level which yields a data set which is representative of the A302M material in the NMP-1 beltline region.

2.0 Plant-Specific Database Development

The NRC's PR-EDB [PREDB94] was used as the primary source of data for model development. The PR-EDB is a collection of data from surveillance programs of commercial nuclear reactors (primarily U.S. reactors). The PR-EDB is one database contained within the NRC's Embrittlement Data Base (EDB) which also includes data from test reactor irradiations. While many useful insights can be gained from analysis of test reactor data, the current modelling effort focused solely on commercial reactor data since the goal is to produce a model which can be applied directly to NMP-1. The use of test reactor data would not, in general, be appropriate since there are widely varying flux, temperature, and neutron spectra in test reactor irradiations.

The version of the PR-EDB (Version 2) used in this study contains the following Charpy data:

- 252 capsules from 96 reactors
- 207 heat affected zone (HAZ) Charpy curves (98 different HAZs)
- 227 weld Charpy curves (105 different welds)
- 524 base material Charpy curves (136 different base materials)

2.1 Database Scrub

Since the goal of the present work is to develop a Charpy shift plate model for NMP-1, the first step was to delete weld and HAZ data from the PR-EDB files. The NMP-1 data were then corrected (the NMP-1 data in the current PR-EDB does not reflect the material mix-up resolution) and data for several plants (ex., Oyster Creek) were verified for accuracy in cases where surveillance reports were readily available at MPM Research & Consulting. Inconsistencies, such as temperature and energy units, were then corrected in the PR-EDB files containing the plate data.

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3.0 Analytical Model

This section of the report reviews neutron damage mechanisms and provides the basis for the physically based model. The discussion is limited to damage mechanisms which are relevant to the A302M material. The objective is to develop the proper functional form for least-squares regression using the U.S. LWR PR-EDB.

3.1 Defect Production

3.2 Chemical/Microstructural Variables

Steels for RPV plates, such as A302M and A533B, are 0.23C steels with about 1.35Mn, 0.5Ni and 0.5Mo (weight percents). In addition, their levels of impurities or tramp elements are generally 0.01-0.02P, 0.01-0.02S and 0.1-0.3Cu [Kh80]. These impurities can have dramatic effects on mechanical behavior depending in part on the processing of the steels. To produce the heavy plate needed for RPVs, the steels are generally cast into large ingots which, after cooling, are hot rolled or forged into thick plates which are then re-austenitized, quenched, and tempered. The plates are then welded into the vessel and the final structure is stress-relief annealed and furnace cooled.

3.3 Hardening Mechanisms

Extensive LWR, Liquid Metal Fast Breeder Reactor, and fusion reactor databases have established that exposure of all metals to fast neutron fluxes results in an increase in the yield strength of the material. In the case of ferritic steels irradiated to high fluences, the yield strength is observed to increase, the ultimate tensile strength (UTS) increases the same as the yield strength, or for some steels modestly, and the ductility (measured as total or uniform elongation in a tensile test or reduction of area) is reduced. Neutron irradiation increases the strength of a metal in two ways:

- Source Hardening - it increases the stress required to start a dislocation moving within the slip system.

- Friction Hardening - once the dislocation is moving, it will be impeded by obstacles close to or lying in the slip plane.

In BCC metals, the pre-existing matrix C atmospheres are very effective in pinning dislocations prior to the application of stress, and the depleted zones formed at LWR fluence levels would not be expected to significantly affect the source hardening. Therefore, we focus attention on friction hardening in the discussion which follows.

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3.4 Summary

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4.0 Charpy Shift Modelling

Examination of the ΔT_{30} and ΔUSE trends with fluence and composition indicate that the A508 forgings should be modelled as a separate sub-division of the database. Accordingly, in the report sections which follow, the A302B, A302M, and A533B materials are grouped together for development of the NMP-1 material-specific model.

4.3 Regression Analysis

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5.0 Summary and Conclusions

6.0 References

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7.0 Nomenclature

Å	=	angstrom
AA	=	atomic absorption
APFIM	=	Atom Probe Field Ion Microscopy
ASME	=	American Society of Mechanical Engineers
BCC	=	body-centered cubic
BWR	=	boiling water reactor
$\Delta\sigma_{flow}$	=	change in flow stress
DBTT	=	ductile brittle transition temperature
DPA	=	displacements per atom
EDB	=	Embrittlement Data Base
EOL	=	End-of-License
HAZ	=	heat affected zone
ICPS	=	inductively coupled plasma spectrometry
IG	=	Intergranular
K_{IR}	=	ASME reference stress intensity factor curve
LWR	=	Light Water Reactor
NMP-1	=	Nine Mile Point Unit 1
NMPC	=	Niagara Mohawk Power Corporation
NRC	=	Nuclear Regulatory Commission
P-T	=	Pressure-Temperature
PR-EDB	=	Power Reactor-Embrittlement Database
PWR	=	pressurized water reactor
ΔRT_{NDT}	=	neutron induced shift in ASME nil-ductility reference temperature
RB	=	Russell/Brown
RG1.99(2)	=	Regulatory Guide 1.99 (Revision 2)
RPV	=	reactor pressure vessel
RT	=	room temperature
ΔT_{30}	=	Charpy curve shift indexed at the 30 ft-lb
ΔUSE	=	drop in the upper shelf energy
USE	=	upper shelf energy
UTS	=	ultimate tensile strength
XRF	=	x-ray fluorescence

Appendices

Appendix A

Procedures For Evaluation of The Power Reactor Embrittlement Data Base

Part I Data Base Evaluation

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Part II Data Analysis for PR-EDB (Version 2)

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Appendix B

Important Chemical and Microstructural Variables in RPV Neutron Damage Modelling for A533B, A302B, and A302B Modified Steel

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