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MEMORANDUM

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cc: Richard Bass
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Subj: Embrittlement Trend Curve Modeling Activities Following Discussions held at UCSB on 6th and 7th November 2007

The purpose of this Memorandum is to inform you of some progress i have made in embrittlement trend curve modeling since our meeting in Santa Barbara in early November. Of the many notes i made for myself at the meeting, one note reinforced the idea that both flux (ϕ) and nickel can be expected to effect the fluence at which CRP saturates (Φ_{SAT}), so i took an action to see if i could arrive at an acceptable model having these features. I am pleased to report to you that i have, and that i can now provide to you the mathematical form of this model, an assessment of how it compares with the IVAR and RADAMO databases, and a comparison of how Ni and ϕ effects on Φ_{SAT} are treated in this new model vs. the model developed by Eason.

First, the functional form of the new model, which is referred to as Revised Model 9 (or RM-9), is detailed below. For convenience differences between RM-9 and RM-6(2) (which was the model recommended in the draft NUREG) are highlighted in yellow. In the final report i will provide a complete description of how RM-9 was arrived at, starting with RM-6(2).

$$\Delta T_{30} = \Delta T_{30(MD)} + \Delta T_{30(CRP)}$$

where

$$\Delta T_{30(MD)} = PF_{MD} \cdot CF_{MD} \cdot TF_{MD} \cdot \phi F_{MD} \cdot \Phi F_{MD}$$

$$PF_{MD} = \begin{Bmatrix} Weld = 6.7 \\ Plate = 8.1 \\ Forging = 4.75 \end{Bmatrix} \times 10^{-9} \qquad CF_{MD} = \left[1 + 35 \cdot P\right]$$

$$TF_{MD} = \left(\frac{T}{550}\right)^{-14.64} \qquad \phi F_{MD} = \left(\frac{Log10(\phi)}{10.7}\right)^{-3.44} \qquad \Phi F_{MD} = \sqrt{\Phi}$$

$$\Delta T_{30(CRP)} = PF_{CRP} \cdot CF_{CRP} \cdot TF_{CRP} \cdot \Phi F_{CRP}$$

$$PF_{CRP} = \begin{Bmatrix} Weld = 0.3 \\ Plate = 0.233 \\ Forging = 0.235 \end{Bmatrix}$$

$$CF_{CRP} = \left[f(Cu) + 2500 \cdot \text{MIN}\{0.32, \text{MAX}(0, Cu - 0.048)\} \cdot Ni \right]$$

$$f(Cu) = -115.8 + 530.8\sqrt{Cu}$$, subject to $0 \le f(Cu) \le 185$

$$TF_{CRP} = \left(\frac{T}{550}\right)^{-1.74} \qquad \Phi F_{CRP} = \left\{1 - \exp\left(\frac{-\Phi}{\Phi_{SAT}}\right)\right\}$$

$$\Phi_{SAT} = \left\{10 + 2.3 \cdot Ni + 11 \cdot \left(\frac{Log_{10}(\phi)}{10.7}\right)^5\right\} \times 10^{17}$$

RM-9 has T_{TOTAL} and T_{MAX} values of 7.44 and 0.89 (respectively), indicating that it provides an "acceptable" representation of the US-LWR surveillance data according to the criteria set forth in the draft NUREG that you are reviewing. To assess RM-9 relative to other data not directly used in fitting I compared the predictions of RM-9 to the IVAR data (at 290 °C) and the RADAMO data (at 300 °C and below $\Phi = 3\times10^{19}$ n/cm^2). The other document attached to this e-mail compares each individual data set to the RM-9 predictions (I apologize for the incorrect labels on the graphs – even though the lables say that Model RM-6(2) was used, ***in fact*** Model RM-9 was used to make the plots). The tables below summarize these comparisons, and also provide equivalent information on RM-6(2) for reference. These data suggest that RM-9 represents the IVAR and RADAMO data somewhat better than does RM-6(2). The most significant improvement is that RM-9 better predicts the CRP hardening magnitude of high copper steels, which were significantly over-predicted by RM-6(2).

For model RM-9 (ignoring VVER data)

	Hi ϕ	**Medium ϕ**	**Low ϕ**	**Overall**
Under Prediction	6%	10%	19%	11%
OK Prediction	78%	81%	72%	77%
Over Prediction	16%	9%	9%	11%
Total Comparison data sets	69	58	57	184

For model RM-6(2) (ignoring VVER data)

	Hi ϕ	**Medium ϕ**	**Low ϕ**	**Overall**
Under Prediction (Low)	4%	9%	16%	9%
OK Prediction	74%	72%	70%	72%
Over Prediction (High)	22%	19%	14%	18%
Total Comparison data sets	69	58	57	184

Finally, it is interesting to compare the Φ_{SAT} function of RM-9, i.e.,

$$\Phi_{SAT} = \left\{10 + 2.3 \cdot Ni + 11 \cdot \left(\frac{Log_{10}(\phi)}{10.7}\right)^5\right\} \times 10^{17}$$

to the Φ_{SAT} function proposed by Eason, and to the Φ_{SAT} values in the IVAR database . Since Eason used a *tanh* rather than an exponential representation of the CRP fluence function some re-arrangement of Eason's equation is needed to make this comparison. In general a *tanh* function can be expressed as

$$g = \frac{1}{2} + \frac{1}{2}\tanh\left\{\frac{X - D}{C}\right\}$$

In Eason's fit the *tanh* takes the following form:

$$g(Cu_e, Ni, \phi t_e) = \frac{1}{2} + \frac{1}{2}\tanh\left[\frac{\log_{10}(\phi t_e) + 1.139Cu_e - 0.448Ni - 18.120}{0.629}\right]$$

So

$$X = \log_{10}(\phi t_e)$$
$$D = 18.12 - 1.139 \cdot Cu_e + 0.448 \cdot Ni$$
$$C = 0.629$$

Recalling that Φ_{SAT} is defined from the exponential function as the fluence at which 66% of the precipitation hardening has occurred, Φ_{SAT} can be related to the *tanh* parameters as follows:

$$\log_{10}(\Phi_{SAT(e)}) = D + \frac{C}{3}$$
$$\log_{10}(\Phi_{SAT(e)}) = 18.33 - 1.139 \cdot Cu_e + 0.448 \cdot Ni$$
$$\Phi_{SAT(e)} = 10^{18.33 - 1.139Cu_e + 0.448Ni}$$

Because Eason defines X in terms of an effective (i.e., flux modified) fluence, this last equation for $\Phi_{SAT(e)}$ is also expressed as an effective (i.e., flux modified) fluence. To convert $\Phi_{SAT(e)}$ to Φ_{SAT} so that comparison to RM-9 may be made the following conversion (from Eason) is needed:

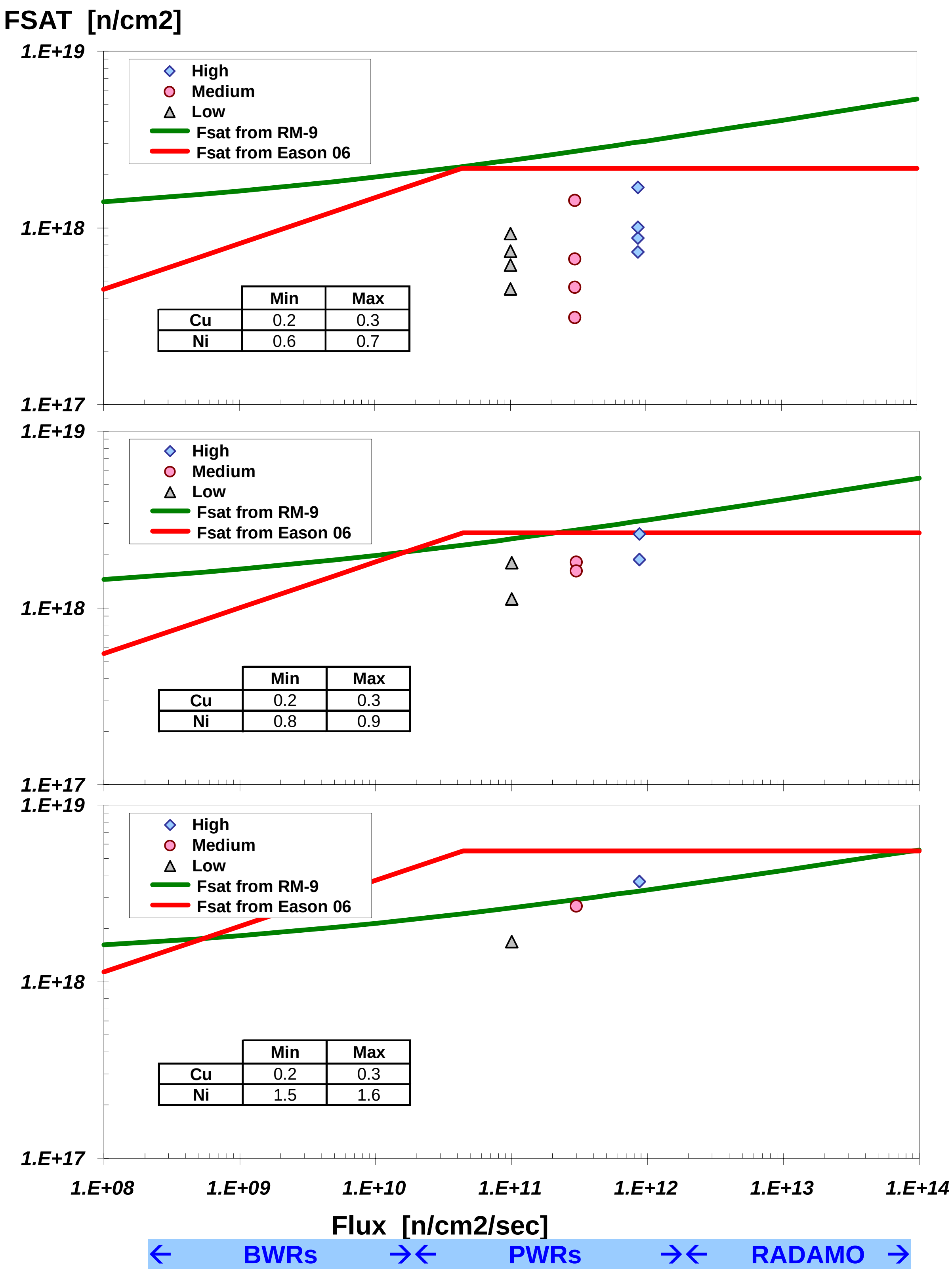
$$\phi t_e = \begin{cases} \phi t & for\ \phi \geq 4.39 \times 10^{10} \\ \phi t \left(\frac{4.39 \times 10^{10}}{\phi}\right)^{0.259} & for\ \phi < 4.39 \times 10^{10} \end{cases}$$

Thus

$$\Phi_{SAT} = \Phi_{SAT(e)} \text{ for } \phi \geq 4.39\text{x}10^{10} \text{ n/cm}^2\text{/s}$$

$$\Phi_{SAT} = \frac{\Phi_{SAT(e)}}{\left(\frac{4.39 \times 10^{10}}{\phi}\right)^{0.259}} \text{ for } \phi < 4.39\text{x}10^{10} \text{ n/cm}^2\text{/s}$$

The graphs on the following page compare the variation of Φ_{SAT} with flux reflected by RM-9 and the Eason fit with three chemistry "slices" through the IVAR data as indicated by the small table on each plot (for both plots T = 290 °C, Mn is between 1 and 2 wt-%, and P is limited to 0.025 wt-% max). The Φ_{SAT} *vs*. ϕ curves are estimated at the Cu and Ni midpoints of each slice. It is relevant to note that the Φ_{SAT} *vs*. ϕ curves calibrated to the US-LWR surveillance data are both somewhat higher than is suggested by the IVAR data. Whether this difference is attributable to noise and/or inaccuracies in the US-LWR surveillance data or, in fact, reflects some different underlying mechanism in the US-LWR surveillance data (which exist over a much larger flux range than the IVAR data) is not determined from this analysis.


FSAT [n/cm2]
1.E+19
1.E+18
1.E+17
High
Medium
Low
Fsat from RM-9
Fsat from Eason 06
Min Max
Cu 0.2 0.3
Ni 0.6 0.7
Min Max
Cu 0.2 0.3
Ni 0.8 0.9
Min Max
Cu 0.2 0.3
Ni 1.5 1.6
1.E+08
1.E+09
1.E+10
1.E+11
1.E+12
1.E+13
1.E+14
Flux [n/cm2/sec]
BWRs
PWRs
RADAMO

In summary, RM-9 fits the US-LWR surveillance data as well as RM-6(2) while incorporating physically expected features in the Φ_{SAT} term better than RM-6(2) did. Consequently, RM-9 represents the IVAR and RADAMO data somewhat better (at fluences below $3x10^{19}$ n/cm^2) than did RM-6(2). Sadly, RM-9 does no better job at representing the high fluence data than did RM-6(2), so the same high fluence modification described in the draft NUREG would seem to be needed for RM-9 as well.

Based on this assessment i would appreciate it if you would consider RM-9 as the recommended model (with the high fluence modification), instead of RM-6(2) as stated in the draft NUREG.