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## Estimation of mechanical properties of cast stainless steels during thermal aging in LWR systems

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**ABSTRACT:** A procedure and correlations are presented for assessing thermal embrittlement and predicting mechanical properties of cast stainless steels under light water reactor operating conditions from known material information. The "saturation" fracture toughness of a cast stainless steel, i.e., the minimum value that would be achieved for the material after long-term service, is estimated from the chemical composition of the steel. Fracture properties as a function of time and temperature of service are estimated from the kinetics of embrittlement, which are also determined from chemical composition. The correlations successfully predict fracture toughness, Charpy-impact, and tensile properties of cast stainless steels from the Shippingport, Ringhals, and KRB reactors.

### 1 INTRODUCTION

After many years of service, cast stainless steels (SSs) used in valve bodies, pump casings, and piping in coolant systems of light water reactors (LWRs) suffer a loss in fracture toughness because of thermal aging. Thermal aging of cast SSs at reactor temperatures increases hardness and tensile strength and decreases ductility, impact strength, and fracture toughness of the material, and shifts the Charpy transition curve to higher temperatures. Investigations at Argonne National Laboratory<sup>1</sup> have shown that thermal embrittlement of cast SS components (ASTM Specification A-351 grades CF-3, CF-3A, CF-8, CF-8A, and CF-8M) can occur within the design lifetime of nuclear reactors. In general, CF-3 steels are the most resistant to thermal embrittlement, and CF-8M steels are the least resistant. The extent of thermal embrittlement increases with increased ferrite content. This paper presents a procedure and correlations for predicting Charpy-impact, tensile, and fracture toughness properties of cast SS components from known material information. Mechanical-property data for service-aged material from the Shippingport, Ringhals, and KRB reactors are used to validate the correlations.

### 2 ASSESSMENT OF THERMAL EMBRITTLEMENT

A procedure has been developed for assessing thermal embrittlement of cast SS components during reactor service from known material information. A flow diagram for estimating mechanical properties of cast SSs is shown in Fig. 1. A detailed description of the procedure and the correlations for predicting Charpy-impact, fracture toughness, and tensile properties of cast SS have been presented elsewhere.<sup>1-3</sup> When a certified material test record (CMTR) is available, the saturation room-temperature (RT) impact energy of

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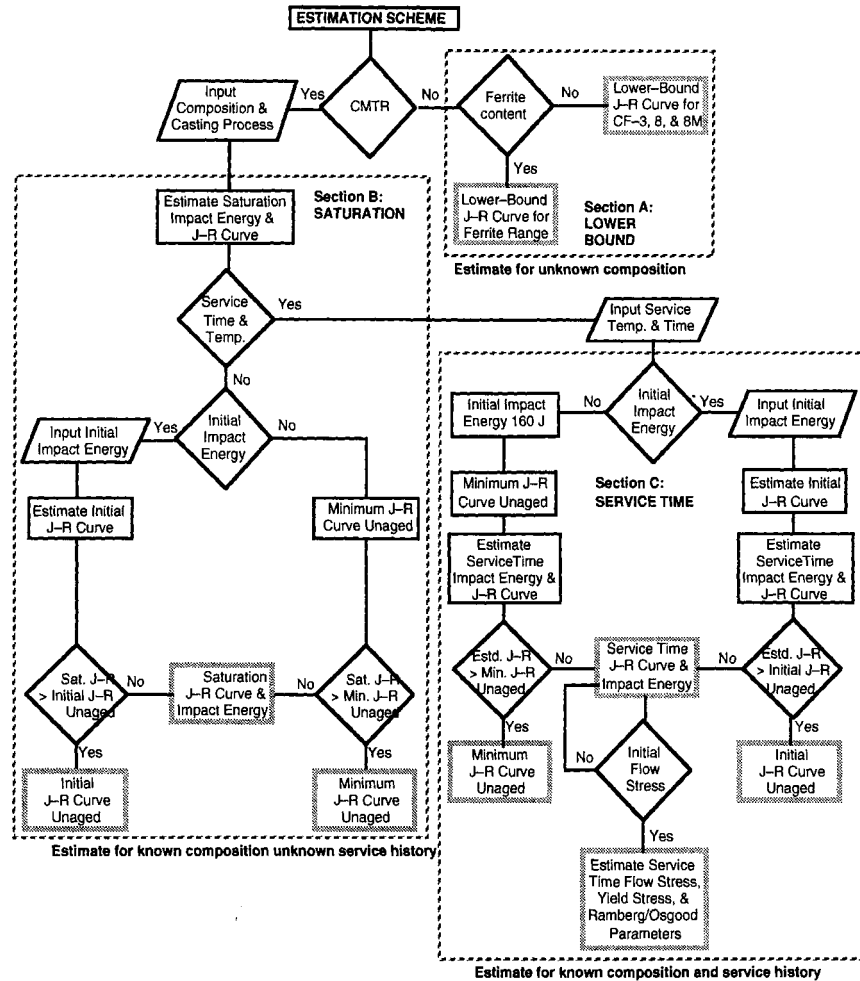


Figure 2. Flow diagram for estimating mechanical properties

a specific cast SS is determined from the chemical composition and ferrite content of the material. The ferrite content  $\delta_c$  is calculated in terms of the Hull's equivalent factor.<sup>4</sup> Different correlations are used to estimate the saturation value of RT impact energy\* ( $C_{V_{sat}}$ ) of the various grades of cast SS. To ensure that the estimates are either accurate or conservative for all heats,  $C_{V_{sat}}$  for a specific cast SS is determined from two different expressions, and the lower value is used to estimate fracture properties. For CF-3 and CF-8 steels,  $C_{V_{sat}}$  is the lower value determined from

$$(1) \quad \log_{10} C_{V_{sat}} = 1.15 + 1.36 \exp(-0.035\Phi),$$

$$(2) \quad \text{where} \quad \Phi = \delta_c(Cr + Si)(C + 0.4N);$$

$$(3) \quad \text{and from} \quad \log_{10} C_{V_{sat}} = 5.64 - 0.006\delta_c - 0.185Cr + 0.273Mo - 0.204Si + 0.044Ni - 2.12(C + 0.4N).$$

For CF-8M steel with <10% Ni,  $C_{V_{sat}}$  is the lower value determined from

$$(4) \quad \log_{10} C_{V_{sat}} = 1.10 + 2.12 \exp(-0.041\Phi),$$

$$(5) \quad \text{where} \quad \Phi = \delta_c(Ni + Si + Mn)^2(C + 0.4N)/5;$$

\* A "normalized" Charpy-impact energy, i.e., impact energy per unit fracture area, is used in this paper.

Table 1. Values of constants in Eqs. 13 and 14 for estimating power-law J-R curves for Static- and centrifugally cast stainless steels

Grade	Room Temperature				290°C			
	a <sup>a</sup>	b	c	d	a <sup>a</sup>	b	c	d
CF-3	49 (57)	0.52	0.15	0.16	102 (134)	0.28	0.17	0.12
CF-8	49 (57)	0.52	0.20	0.12	102 (134)	0.28	0.21	0.09
CF-8M	16 (20)	0.67	0.23	0.08	49 (57)	0.41	0.23	0.06

<sup>a</sup> Values of the constant a are different for centrifugally cast steels and are listed within parenthesis.

$$(6) \quad \text{and from} \quad \log_{10} C_{V_{\text{sat}}} = 7.28 - 0.011\delta_c - 0.185\text{Cr} - 0.369\text{Mo} - 0.451\text{Si} \\ - 0.007\text{Ni} - 4.71(\text{C} + 0.4\text{N}).$$

Equations 5 and 6 are same for CF-8M steel with >10% Ni, and Eq. 4 is replaced by

$$(7) \quad \log_{10} C_{V_{\text{sat}}} = 1.10 + 2.64\exp(-0.064\Phi).$$

If not known, the N content can be assumed to be 0.04 wt.%. The RT impact energy of a specific cast SS as a function of time and temperature of aging is determined from its estimated  $C_{V_{\text{sat}}}$  and the kinetics of embrittlement. The decrease in RT Charpy-impact energy  $C_V$  with time is expressed in terms of the aging parameter P by equations

$$(8) \quad \log_{10} C_V = \log_{10} C_{V_{\text{sat}}} + \beta \left\{ 1 - \tanh\left(\frac{P - \theta}{\alpha}\right) \right\}$$

$$(9) \quad \text{and} \quad P = \log_{10}(t) - \frac{1000Q}{19.143} \left( \frac{1}{T_s + 273} - \frac{1}{673} \right),$$

where t is service time (h),  $T_s$  is service temperature (°C), Q is the activation energy for thermal embrittlement (kJ/mole), and the constants  $\alpha$  and  $\beta$  are determined from the initial impact energy  $C_{V_{\text{int}}}$  and the  $C_{V_{\text{sat}}}$  as follows:

$$(10) \quad \alpha = -0.585 + 0.795\log_{10} C_{V_{\text{sat}}}$$

$$(11) \quad \text{and} \quad \beta = (\log_{10} C_{V_{\text{int}}} - \log_{10} C_{V_{\text{sat}}})/2.$$

The value of  $\theta$  varies with service temperature; it is 3.3 at temperatures <280°C, 2.9 at 280–330°C, and 2.5 at 330–360°C. Activation energy Q for thermal embrittlement is expressed in terms of chemical composition and the constant  $\theta$  by the equation

$$(12) \quad Q = 10 [74.52 - 7.20\theta - 3.46\text{Si} - 1.78\text{Cr} - 4.35\text{I}_1\text{Mn} \\ + (148 - 125\text{I}_1)\text{N} - 61\text{I}_2\text{C}],$$

where  $\text{I}_1 = 0$  and  $\text{I}_2 = 1$  for CF-3 or CF-8 steels and are 1 and 0, respectively, for CF-8M steels. Equation 12 is applicable to compositions within ASTM A-351, with an upper limit of 1.2 wt.% for Mn content. Furthermore, Q is assumed to be 65 kJ/mole if the predicted value is lower, and 250 kJ/mole if the predicted value is higher. The fracture toughness J-R curve of a specific cast SS as a function of time and temperature of service is obtained from the estimated RT impact energy,  $C_V$ . The J-R curve for static- and centrifugally cast steels is given by

$$(13) \quad J_d = a(C_V)^b (\Delta a)^n,$$

$$(14) \quad \text{where} \quad n = c + d(\log_{10} C_V),$$

and the values of constants a, b, c, and d are given in Table 1. The J-R curve of the unaged material or at saturation is obtained by using  $C_{V_{\text{int}}}$  or  $C_{V_{\text{sat}}}$ , respectively, in Eqs. 13 and 14. Tensile yield and flow stresses, and engineering stress-vs.-strain behavior are estimated from the flow stress of the unaged material and the aging parameter P. The procedure and correlations have been described elsewhere.<sup>3</sup>

Table 2. Chemical composition of cast stainless steels from the Shippingport, KRB, and Ringhals reactor components

Mater. ID <sup>a</sup>	Composition, wt. %									Ferrite, %	
	C	N	Si	Mn	P	S	Ni	Cr	Mo	Calc.	Meas.
CA4 <sup>a</sup>	0.056	0.041	1.45	1.10	0.018	0.009	8.84	20.26	0.01	10.8	10.9
MA1 <sup>a</sup>	0.052	0.049	0.22	0.72	0.039	0.013	10.50	20.74	0.24	5.2	9.5
PV <sup>a</sup>	0.108	0.027	0.89	1.11	0.032	0.008	9.30	19.83	0.38	4.7	13.0
KRB <sup>b</sup>	0.062	0.038	1.17	0.31	—	—	8.03	21.99	0.17	27.7	34.0
Hot Leg <sup>c</sup>	0.037	0.044	1.03	0.77	0.022	0.008	10.60	20.00	2.09	13.0	20.1
Crossover <sup>c</sup>	0.039	0.037	1.11	0.82	0.020	0.012	10.50	19.60	2.08	12.3	19.8

<sup>a</sup> Hot-leg main valve MA1, and cold-leg check valve CA4 and pump volute PV from the Shippingport reactor in service for  $\approx 13$  y at 264°C for cold leg and at 281°C for hot leg.

<sup>b</sup> Recirculating pump cover plate from the KRB reactor in service for  $\approx 8$  y at 284°C.

<sup>c</sup> Hot-leg and crossover-leg elbows from the Ringhals 2 reactor in service for  $\approx 13$  y at 325°C for hot leg and at 291°C for crossover leg, and at hot standby for  $\approx 2$  y at 303°C for hot leg and 274°C for crossover leg.

### 3 ESTIMATION OF MECHANICAL PROPERTIES

The procedure and correlations presented in Section 2 have been used to estimate Charpy-impact, tensile, and fracture toughness properties of service-aged materials from the Ringhals, KRB, and Shippingport reactor components.<sup>5</sup> The chemical composition of the cast stainless steels is given in Table 2. Some materials were aged further in the laboratory at 320, 350, and 400°C to validate the estimates of  $C_{Vsat}$  and kinetics of thermal embrittlement. The estimated and measured impact energies for some of the materials are plotted in Fig. 2 as a function of aging time at different temperatures. The estimates were obtained from assumed as well as experimental values of  $\theta$ . The estimated impact energies show very good agreement with the experimental data. The predicted values of  $C_{Vsat}$  also are in excellent agreement with the measured values.

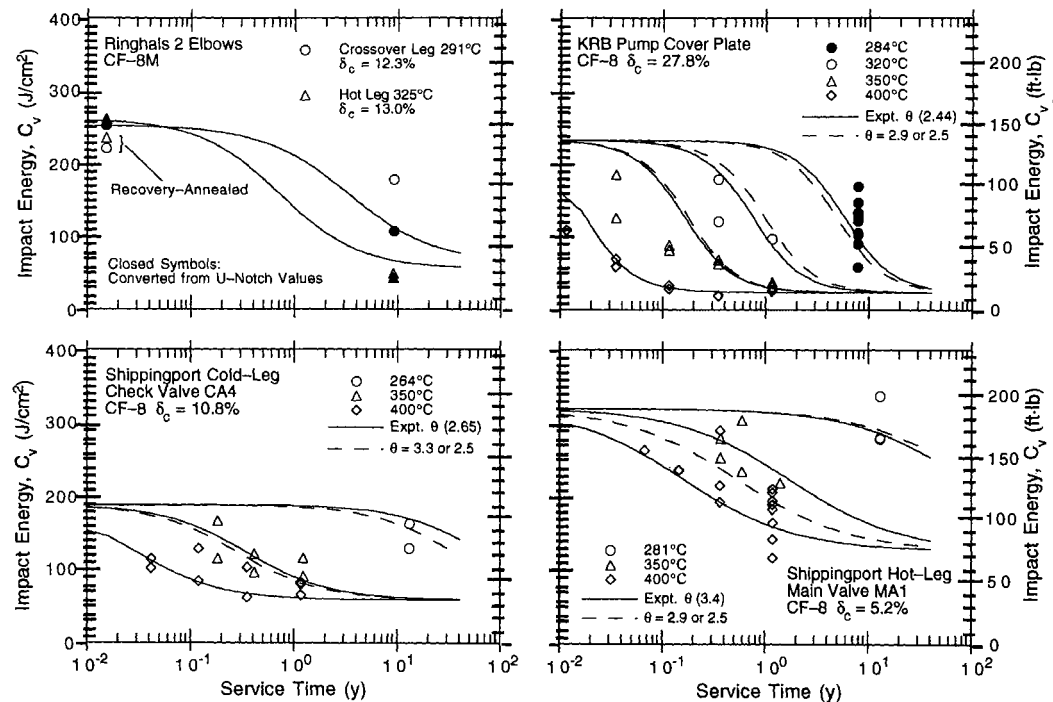


Figure 2. Variations of estimated and measured room-temperature Charpy-impact energy with service time for cast stainless steel from the Ringhals, KRB, and Shippingport reactors

The fracture toughness J-R curves for the various materials after reactor service were estimated from Eqs. 13 and 14. The correlations described in Eqs. 1-14 account for the degradation of mechanical properties of typical heats of cast SS. They do not consider the initial fracture properties of the unaged material. Some heats of cast SS may exhibit a low initial fracture toughness, and the estimated J-R curve may be higher than the initial fracture toughness J-R curve. When the estimated J-R curve is higher than the initial fracture toughness J-R curve, the latter is used as the J-R curve of the material.

Examples of estimated and experimental fracture toughness J-R curves at room temperature and at 290°C for cast SS components in the unaged or recovery-annealed condition, after service, and at saturation (i.e., aged 10,000 h at 400°C), are shown in Fig. 3. The estimated J-R curves either show good agreement, or are lower (30-50%) than the experimental results. The somewhat conservative estimates are expected for some compositions of cast SS; the criteria used in developing the estimation scheme ensure that the estimated mechanical properties are adequately conservative for cast SS as defined by ASTM A-351. They do not consider the effects of metallurgical differences that may

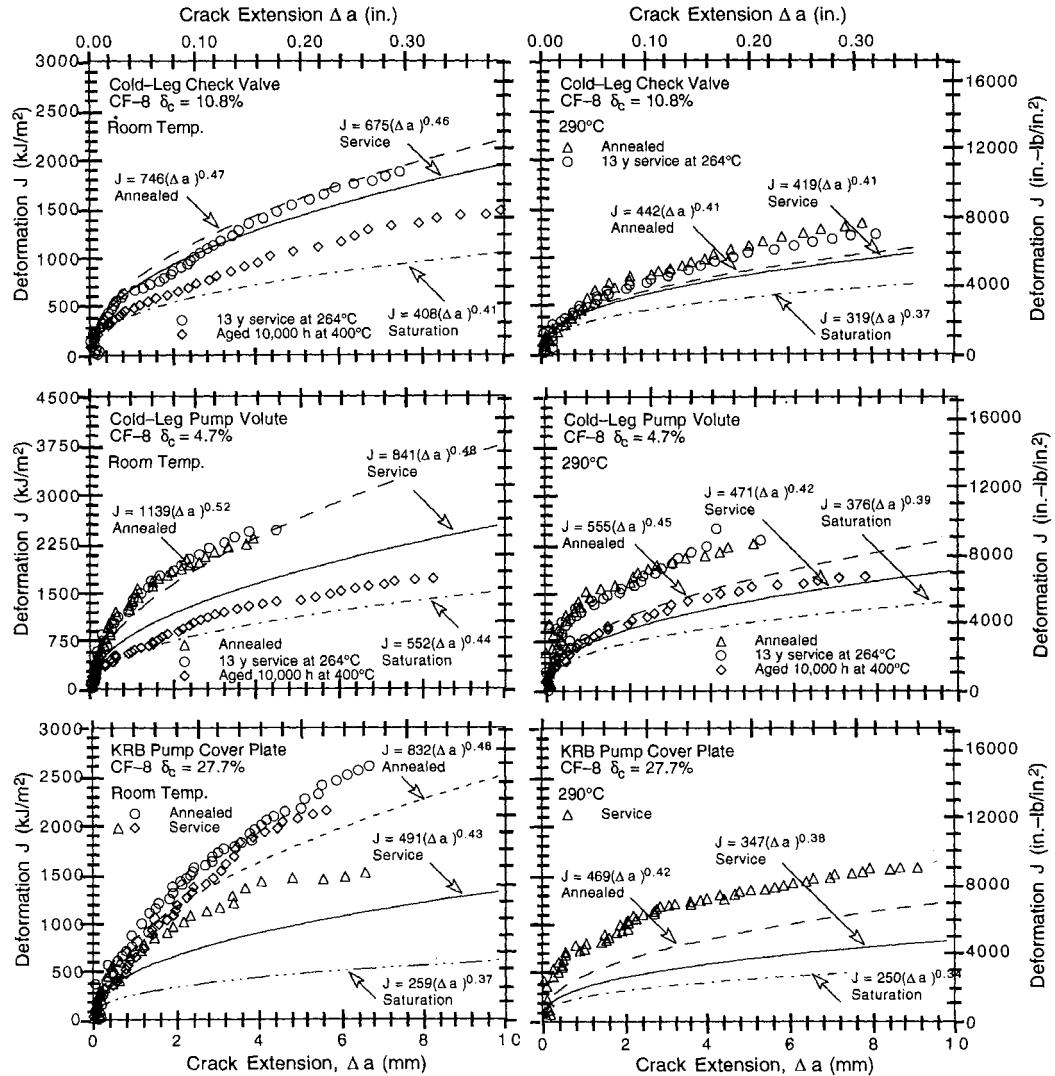


Figure 3. Estimated and measured fracture toughness J-R curves at room temperature and 290°C for materials from the Shippingport and KRB reactors

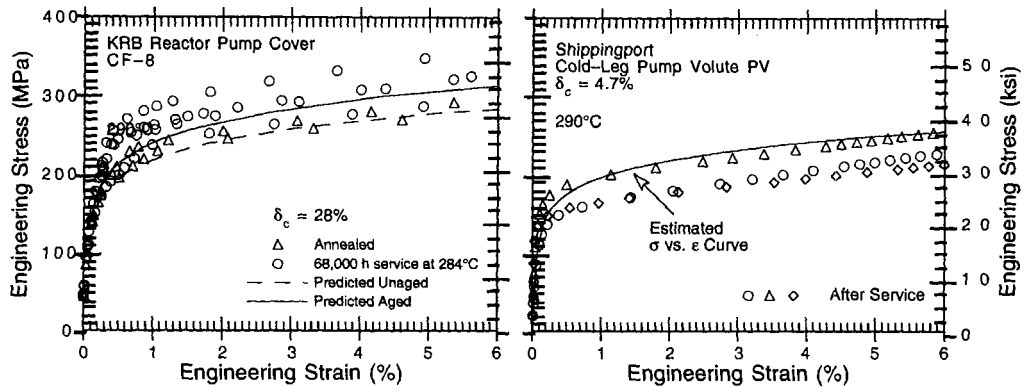


Figure 4. Estimated and measured tensile stress-vs.-strain curves at 290°C for service-aged material from the Shippingport and KRB reactor components

arise from differences in production heat treatment or casting processes and, therefore, may be overly conservative for some steels.

The changes in tensile flow stress and engineering stress-vs.-strain behavior of the various cast SSs were estimated from the tensile properties of the unaged material and the kinetics of thermal embrittlement. The estimated values show good agreement with the experimental data.<sup>3</sup> Estimated and measured engineering stress-vs.-strain curves at 290°C for material from the KRB pump cover plate and Shippingport pump volute are shown in Fig. 4.

#### 4. CONCLUSIONS

A procedure and correlations are presented for predicting Charpy-impact energy, fracture toughness J-R curves, and tensile properties of aged cast SSs (ASTM A 351) from known material information. Mechanical properties of a specific cast SS are estimated from the extent and kinetics of thermal embrittlement. Embrittlement of cast SSs is characterized in terms of RT Charpy-impact energy. The correlations successfully predicted the mechanical properties of service-aged cast SSs from the Shippingport, Ringhals 2, and KRB reactor components.

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