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Assessment of Thermal Embrittlement of Cast Stainless Steels

Prepared by
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O. K. Chopra and W. J. Shack

Abstract

A procedure and correlations are presented for assessing thermal embrittlement and predicting Charpy-impact energy and fracture toughness J-R curve of cast stainless steel components under light water reactor operating conditions from known material information. The "saturation" impact strength and fracture toughness of a specific 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 reactor service are estimated from the kinetics of embrittlement, which are also determined from chemical composition. A common "predicted lower-bound" J-R curve for cast stainless steels of unknown chemical composition is also defined for a given grade of steel, ferrite content, and temperature. Examples of estimating fracture toughness of cast stainless steel components during reactor service are presented.

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Nomenclature

C	Coefficient of the power-law J-R curve.
Cr_{eq}	Chromium equivalent for a material (wt.%).
C_V	Room-temperature "normalized" Charpy-impact energy, i.e., Charpy-impact energy per unit fracture area, at any given service and aging time (J/cm^2). The fracture area for a standard Charpy V-notch specimen (ASTM Specification E 23) is 0.8 cm^2. Divide the value of impact energy in J by 0.8 to obtain "normalized" impact energy.
$C_{V_{int}}$	Initial room-temperature "normalized" Charpy-impact energy of a material, i.e., unaged material (J/cm^2).
$C_{V_{sat}}$	Room-temperature "normalized" Charpy-impact energy of a material at saturation, i.e., the minimum impact energy that would be achieved for the material after long-term service (J/cm^2).
CMTR	Certified material test record.
J_d	Deformation J per ASTM Specification E 813-85 or E 1152-87 (kJ/m^2).
n	Exponent of the power-law J-R curve.
Ni_{eq}	Nickel equivalent for a material (wt.%).
P	Aging parameter, i.e., the log of the time of aging at 400°C.
Q	Activation energy for the process of thermal embrittlement (kJ/mole).
t	Service or aging time (h).
T_s	Service or aging temperature (°C).
α	Shape factor of the curve for the change in room-temperature Charpy-impact energy with time and temperature of aging.
β	Half the maximum change in room-temperature Charpy-impact energy.
δ_c	Ferrite content calculated from the chemical composition of a material (%).
Δa	Crack extension (mm).
Φ	Material parameter.
θ	Aging behavior at 400°C, i.e., the log of the time to achieve β reduction in impact energy at 400°C.
σ	Standard deviation for the fit to a data set.

In this report, all values of impact energy are considered to be for a standard Charpy-V-notch specimen per ASTM Specification E 23), i.e., 10 x 10-mm cross section and 2-mm V notch. Impact energies obtained on subsize specimens should be normalized with respect to the actual cross-sectional area and appropriate correction factors should be applied to account for size effects. Similarly, impact energy from other standards, e.g., U-notch specimen, should be converted to a Charpy-V-notch value by appropriate correlations.

SI units of measurements have been used in this report. Conversion factors for measurements in British units are as follows:

To convert from	to	multiply by
in.	mm	25.4
J*	ft-lb	0.7376
kJ/m^2	$in.-lb/in.^2$	5.71015
kJ/mole	kcal/mole	0.239

*When impact energy is expressed in J/cm^2, first multiply by 0.8 to obtain impact energy of a standard Charpy V-notch specimen in J.

Executive Summary

Cast stainless steels used in valve bodies, pump casings, piping, and other components in coolant systems of light water reactors (LWRs) suffer a loss in fracture toughness due to thermal aging after many years of service at temperatures in the range of 280–320°C (≈535–610°F). Thermal aging of cast stainless steels at these temperatures causes an increase in hardness and tensile strength and a decrease in ductility, impact strength, and fracture toughness of the material. The Charpy transition curve shifts to higher temperatures. Investigations at Argonne National Laboratory (ANL) and elsewhere have shown that thermal embrittlement of cast stainless steel components can occur during reactor operation. Therefore, an assessment of mechanical-property degradation due to thermal embrittlement is required to evaluate the performance of cast stainless steel components during prolonged exposure to service temperatures.

This report presents a procedure and correlations for predicting Charpy-impact energy and fracture toughness J–R curve of aged cast stainless steels (ASTM A 351) from known material information. Mechanical properties of a specific cast stainless steel are estimated from the extent and kinetics of thermal embrittlement. Embrittlement of cast stainless steels is characterized in terms of room-temperature Charpy-impact energy. The extent or degree of thermal embrittlement at "saturation," i.e., the minimum impact energy that can be achieved for the material after long-term aging, is determined from chemical composition of the steel. Charpy-impact energy as a function of time and temperature of reactor service is estimated from the kinetics of thermal embrittlement, which is also determined from the chemical composition. The initial impact energy of the unaged steel is required for these estimations. The fracture toughness J–R curve for the material is then obtained from correlations between room-temperature Charpy-impact energy and fracture toughness parameters. A common "predicted lower-bound" J–R curve for cast stainless steels with unknown chemical composition is also defined for a given grade of steel, range of ferrite contents, and temperature. Examples of estimating mechanical properties of cast stainless steel components during reactor service are presented.

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1 Introduction

Cast stainless steels (SSs) used in light water reactor (LWR) systems for primary pressure-boundary components such as valve bodies, pump casings, and primary coolant piping are susceptible to thermal embrittlement at reactor operating temperatures, i.e., 280–320°C (536–608°F). Thermal aging of cast SS at these temperatures increases hardness and tensile strength and decreases ductility, impact strength, and fracture toughness of the material. The Charpy transition curve shifts to higher temperatures. Investigations at Argonne National Laboratory (ANL)[1–3] have shown that thermal embrittlement of cast SS components (i.e., 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. Cast SS components with 10–15% ferrite may show significant thermal embrittlement. For example, the hot-leg elbow from the Ringhals 2 reactor showed poor fracture properties, e.g., room-temperature (RT) Charpy-impact energy of 36 J (≈26 ft·lb) and fracture toughness J_{IC} values of 150–330 kJ/m^2 (856–1884 in·lb/in^2).[3,4] The hot-leg elbow, constructed from CF-8M steel, was in service for ≈15 yr at 350°C and contained ≈12% ferrite.

An assessment of mechanical-property degradation due to thermal embrittlement is therefore required to evaluate the performance of cast SS components during prolonged exposure to service temperatures, because rupture of the primary pressure boundary could lead to a loss-of-coolant accident and possible exposure of the public to radiation. A procedure and correlations have been developed at ANL for estimating mechanical properties of cast SS components under LWR operating conditions from material information readily available in certified material test records (CMTRs). The procedure and correlations were published in NUREG/CR-4513, ANL-90/42 (June 1991).[5] 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 extent of thermal embrittlement at "saturation," i.e., the minimum impact energy that can be achieved for a steel after long-term aging, is determined from chemical composition of the steel. Charpy-impact energy as a function of time and temperature of reactor service is estimated from the kinetics of thermal embrittlement, which is also determined from the chemical composition. The fracture toughness J–R curve for the steel is then obtained from correlations between RT Charpy-impact energy and fracture toughness parameters. A common "predicted lower-bound" J–R curve for cast SSs of unknown chemical composition is also defined for a given grade of steel, ferrite content, and temperature.

This report presents a revised version of the procedure and correlations for estimating Charpy-impact and fracture toughness properties of cast SS components under LWR operating conditions. The differences between the correlations described in this report and those presented earlier are as follows:

- The correlations have been optimized by using a larger data base (e.g., ≈80 compositions of cast SS) and mechanical-property results on materials that were aged up to ≈58,000 h at 290–350°C (554–662°F). The earlier correlations were based on ≈45 compositions of cast SS and aging times up to 30,000 h. For the 80 compositions of cast SSs used in this

*In this report, grades CF-3A and CF-8A are considered equivalent to CF-3 and CF-8, respectively. The A designation represents high tensile strength. The chemical composition of CF-3A and CF-8A are further restricted within the composition limits of CF-3 and CF-8, respectively, to obtain a ferrite/austenite ratio that results in higher ultimate and yield strengths.

s[illegible]ly, estimates based on t[illegible] [illegible]orrelations yield conservative values of fracture to[illegible]ghness.

- The sa[illegible]uration RT impact energy Cv_{sat} is estima[illegible] from two different correlations. For most [illegible]eats, the two methods give comparable estimates. For a few heats, however, one or the other set of expressions gives more accurate estimates. It is likely that minor differences in the composition and microstructure of the ferrite caused by differences in production heat treatment and possibly the casting process influence Cv_{sat} values. These factors cannot be quantified from the present data base. To ensure that the estimates are either accurate or conservative for all heats of cast SS within ASTM Specification A 351, the lower of the two estimated values is used for estimating the fracture properties.

- Different correlations are used to estimate the saturation RT impact energy Cv_{sat} for CF-8M steels with <10 and ≥10 wt.% Ni.

- Separate correlations are given for estimating fracture toughness J-R curves for static- and centrifugally cast SSs. Also, the correlation for estimating exponent n of the power-law J-R curve has been modified

- For CF-3 and CF-8 steels, the expression for estimating the activation energy for thermal embrittlement has been modified. The effect of Mo and Mn content has been omitted and the effect of C content has been added in the updated expression.

The criteria used in developing these correlations ensure that the estimated mechanical properties are adequately conservative for cast SSs defined by ASTM Specification A 351.* The correlations do not consider the effects of metallurgical differences that may arise from differences in production heat treatment or casting processes and therefore may be overly conservative for some steels. Mechanical properties are expressed in SI units (see Nomenclature for units of measure and for conversion factors for British units).

2 Assessment of Thermal Embrittlement

Mechanical properties of cast SSs during reactor service are estimated from the extent of thermal embrittlement for the material. The extent of thermal embrittlement is characterized by RT "normalized" Charpy-impact energy. A correlation for the extent of embrittlement at "saturation," i.e., the minimum impact energy that would be achieved for the material after long-term aging, is given in terms of chemical composition. Extent of thermal embrittlement as a function of time and temperature of reactor service is estimated from the extent of embrittlement at saturation and from correlations that describe the kinetics of embrittlement, which are also given in terms of the chemical composition of the steel. The fracture toughness J-R curve for the material is then obtained from the correlation between fracture toughness parameters and the RT Charpy-impact energy used to characterize the extent of thermal embrittlement.

*These correlations may yield nonconservative estimates of fracture toughness J-R curve for a few compositions of static-cast CF-8M steel that are very sensitive to thermal aging, i.e., those compositions of static-cast SS for which the estimated value of Cv_{sat} is <25 J/cm^2 (<15 ft·lb). These compositions should contain ≥25% ferrite. The existing data are not adequate to accurately establish the correlations between room-temperature Charpy-impact energy and fracture toughness parameters for estimated values of Cv_{sat} <25 J/cm^2.

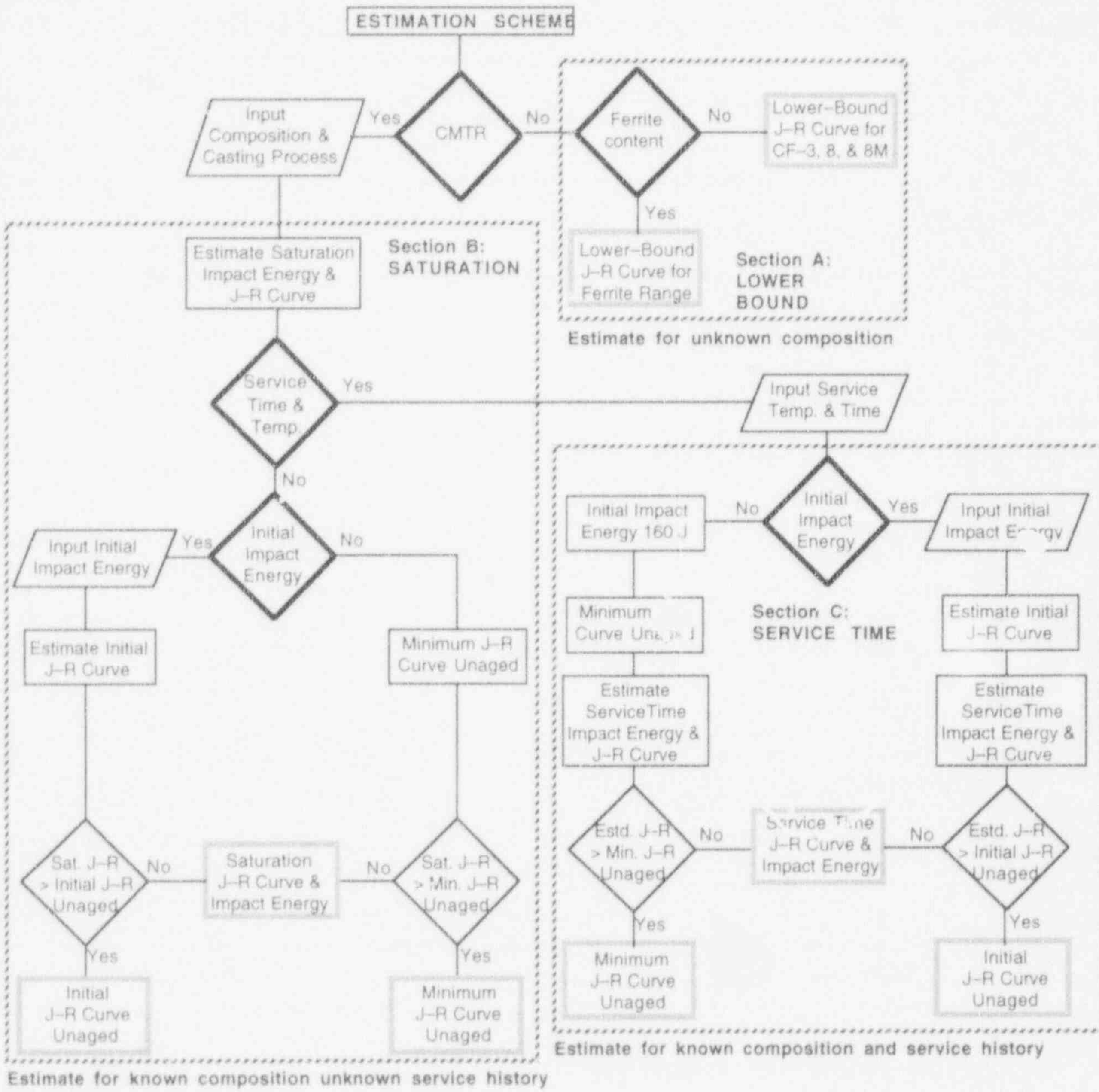

Figure 1. Flow diagram for estimating mechanical properties of aged cast SSs in LWR systems

A flow diagram for estimating Charpy-impact energy and fracture toughness J–R curve of cast SS components is shown in Fig. 1. The estimation scheme is divided into three sections on the basis of available information. In Section A, "predicted lower-bound" fracture toughness is defined for CF–3, CF–8, and CF–8M steels of unknown composition. When the ferrite content of the steel is known, a different lower-bound fracture toughness is defined for steels containing <10%, 10–15%, or >15% ferrite. Sections B and C present procedures for estimating mechanical properties when a CMTR is available. Section B describes the estimation of "saturation" impact energy and fracture toughness J–R curve. The only information needed for these estimations is the chemical composition of the material.

The present correlations account for the degradation of mechanical properties due to thermal aging. They do not explicitly consider the initial fracture properties of the unaged material. It is possible that the estimations of saturation fracture toughness based on chemical composition are higher than the fracture toughness of the unaged material. Some cast SSs are inherently weak and may have poor fracture properties in the unaged condition. When information is available on either the initial fracture toughness of a material or the initial RT Charpy-impact energy for estimating fracture toughness, and when the J-R curve estimated from the chemical composition is higher than the initial fracture toughness of unaged material, the latter is used as the saturation J-R curve of the material. Such cast SSs are relatively insensitive to thermal aging, and the fracture toughness of the material would not change during reactor service. Furthermore, when no information is available on the initial fracture toughness of a material, the minimum fracture toughness of unaged cast SSs is used as a upper bound for the estimated fracture toughness; i.e., when the J-R curve estimated from the chemical composition is higher than the minimum fracture toughness of unaged cast SSs, the latter is used as the saturation J-R curve of a material.

Estimation of mechanical properties at any given time and temperature of service, i.e., service-time properties, is described in Section C. The initial impact energy of the unaged material is required for these estimations. If not known, the initial impact energy can be assumed to be 200 J/cm^2. However, similar to Section B, initial fracture toughness of the unaged material or the minimum fracture toughness of unaged cast SSs is used as a upper bound for the estimations.

2.1 Estimate for Steels of Unknown Composition: Lower-Bound Values

For cast SSs of unknown chemical composition within ASTM Specification A 351, the lower-bound fracture toughness J-R curve is defined for a given method of casting, material grade, and temperature. The J-R curve is expressed by the power-law relation $J_d = C(\Delta a)^n$, where J_d is deformation J per ASTM Specifications E 813-85 and E 1152-87, Δa is the crack extension, and C and n are constants. The lower-bound curve is based on the "worst case" material condition, e.g., >20% ferrite content. The cast SSs used in the U.S. nuclear industry generally contain <15% ferrite. The lower-bound fracture properties for a specific casting method and grade of steel may therefore be very conservative for most steels. More realistic estimates of lower-bound properties are obtained if the ferrite content of the steel is known. The ferrite content of a cast SS component can be measured in the field with a ferrite scope. The lower-bound J-R curves at RT and 290°C for static- and centrifugally cast CF-3, CF-8, and CF-8M steels with >15%, 10-15%, and <10% ferrite are shown in Figs. 2 and 3 and the values of the coefficient C and exponent n for the J-R curves are given in Table 1.

2.2 Estimate for Steels of Known Composition and Unknown Service History: Saturation Values

2.2.1 Charpy-Impact Energy

When a CMTR is available, the saturation RT impact energy of a specific cast SS is determined from chemical composition and ferrite content of the material. The ferrite content is calculated from chemical composition in terms of the Hull's equivalent factors[6]

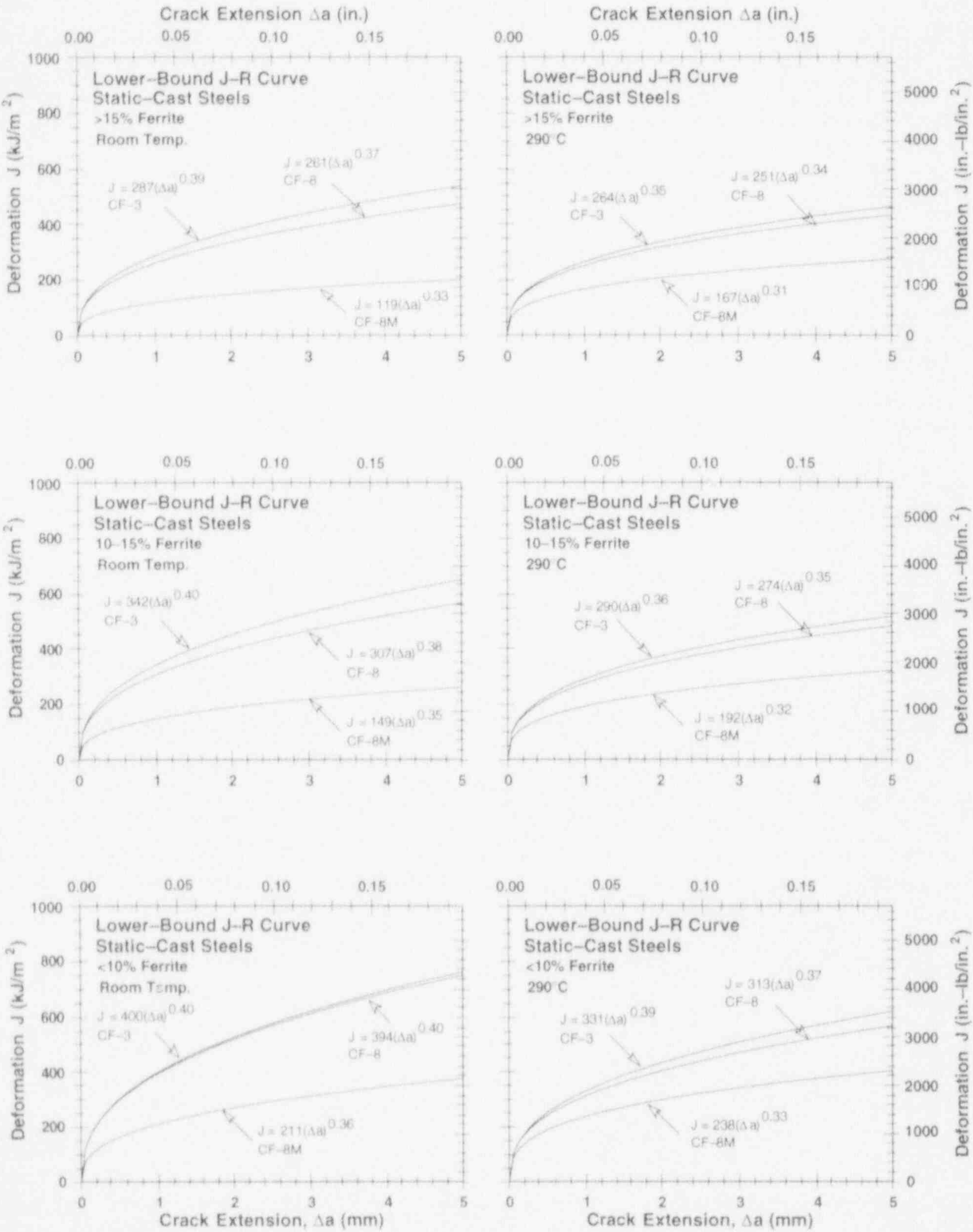

Figure 2. Lower-bound J-R curves at RT and 290°C for static-cast SSs with ferrite contents >15, 10–15, or <10%

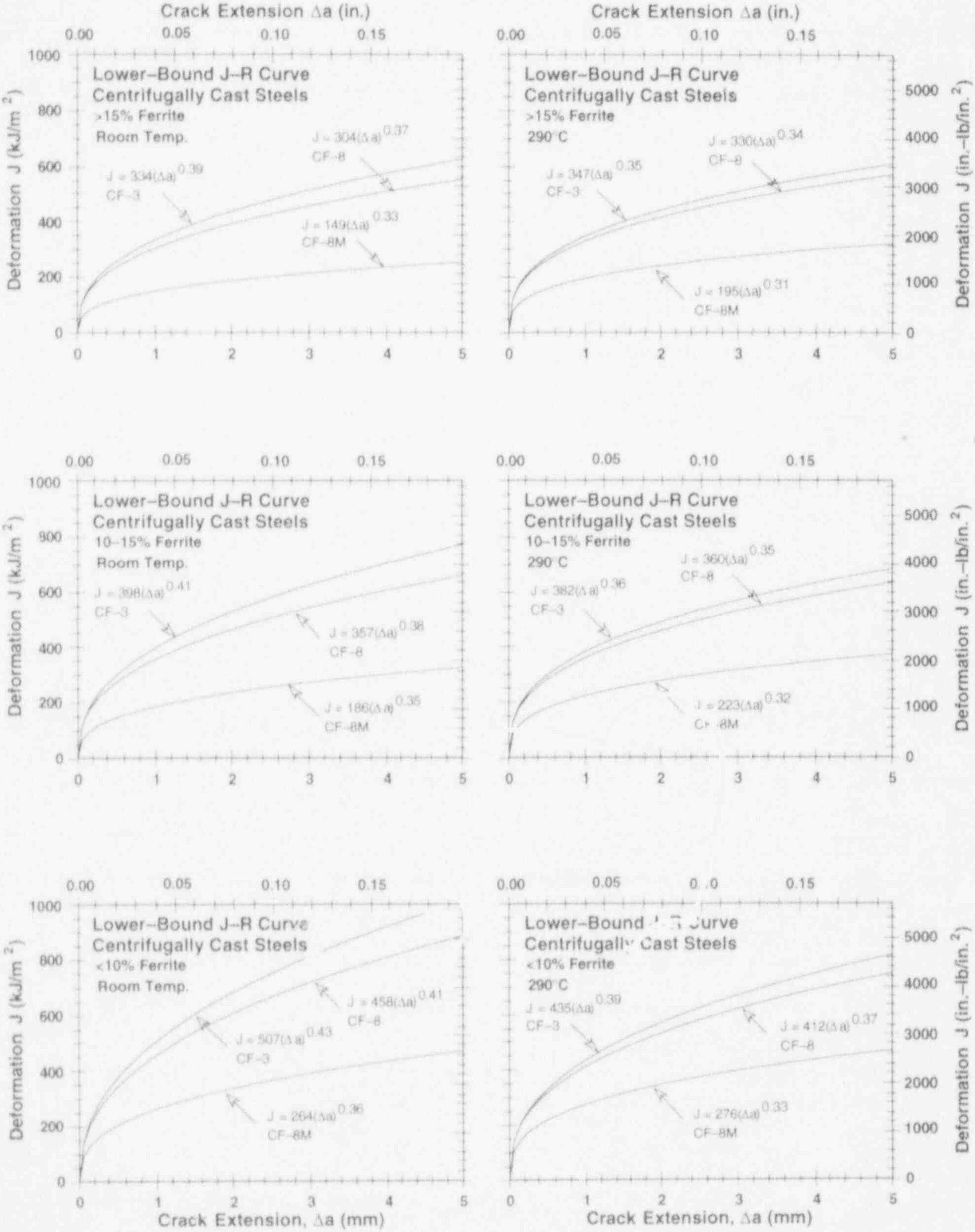

Figure 3. Lower-bound J-R curves at RT and 290°C for centrifugally cast SSs with ferrite contents >15, 10–15, or <10%

Table 1. Values of coefficient C and exponent n for lower-bound J-R curve for cast SSs

	Static-Cast				Centrifugally Cast			
	Room Temp.		290°C		Room Temp.		290°C	
Grade	C	n	C	n	C	n	C	n
Ferrite Content >15%								
CF-3	287	0.39	264	0.35	334	0.39	347	0.35
CF-8	261	0.37	251	0.34	304	0.37	330	0.34
CF-8M[a]	119	0.33	167	0.31	149	0.33	195	0.31
Ferrite Content 10–15%								
CF-3	342	0.40	290	0.36	398	0.40	382	0.36
CF-8	307	0.38	274	0.35	357	0.38	360	0.35
CF-8M	149	0.35	192	0.32	186	0.35	223	0.32
Ferrite Content <10%								
CF-3	400	0.40	331	0.39	507	0.43	435	0.39
CF-8	394	0.40	313	0.37	458	0.41	412	0.37
CF-8M	211	0.36	238	0.33	264	0.36	276	0.33

[a]The lower-bound J-R curve for static-cast CF-8M steels may not be applicable for some compositions of steel that contain ≥25% ferrite and are very sensitive to thermal aging. See footnote page 2.

$$Cr_{eq} = Cr + 1.21(Mo) + 0.48(Si) - 4.99 \quad (1)$$

and

$$Ni_{eq} = (Ni) + 0.11(Mn) - 0.0086(Mn)^2 + 18.4(N) + 24.5(C) + 2.77. \quad (2)$$

The concentration of N is often not available in the CMTR; if not known, it is assumed to be 0.04 wt.%. The ferrite content δ_c is given by

$$\delta_c = 100.3(Cr_{eq}/Ni_{eq})^2 - 170.72(Cr_{eq}/Ni_{eq}) + 74.22. \quad (3)$$

Different correlations are used to estimate the saturation RT impact energy of the various grades of cast SS. To ensure that the estimates are either accurate or conservative for all heats, the saturation RT impact energy for a specific cast SS is determined by two different expressions, and the lower value is used for estimating fracture properties. For CF-3 and CF-8 steels, the saturation value of RT impact energy C_{Vsat} is the lower value determined from

$$\log_{10} C_{Vsat} = 1.15 + 1.36\exp(-0.035\Phi), \quad (4)$$

where the material parameter Φ is expressed as

$$\Phi = \delta_c(Cr + Si)(C + 0.4N), \quad (5)$$

and from

$$\log_{10} C_{Vsat} = 5.64 - 0.006\delta_c - 0.185Cr + 0.273Mo - 0.204Si + 0.044Ni - 2.12(C + 0.4N). \quad (6)$$

For CF-8M steel with <10% Ni, the saturation value of RT impact energy C_{Vsat} is the lower value determined from

$$\log_{10}C_{Vsat} = 1.10 + 2.12\exp(-0.041\Phi), \tag{7}$$

where the material parameter Φ is expressed* as

$$\Phi = \delta_c(Ni + Si + Mn)^2(C + 0.4N)/5; \tag{8}$$

and from

$$\log_{10}C_{Vsat} = 7.28 - 0.011\delta_c - 0.185Cr - 0.369Mo - 0.451Si - 0.007Ni - 4.71(C + 0.4N). \tag{9}$$

For CF-8M steel with >10% Ni, the saturation value of RT impact energy C_{Vsat} is the lower value determined from

$$\log_{10}C_{Vsat} = 1.10 + 2.64\exp(-0.064\Phi), \tag{10}$$

where the material parameter Φ is expressed as

$$\Phi = \delta_c(Ni + Si + Mn)^2(C + 0.4N)/5; \tag{11}$$

and from

$$\log_{10}C_{Vsat} = 7.28 - 0.011\delta_c - 0.185Cr - 0.369Mo - 0.451Si - 0.007Ni - 4.71(C + 0.4N). \tag{12}$$

If not known, the N content in Eqs. 4–12 can be assumed to be 0.04 wt.%. The ferrite content δ_c used in developing Eqs. 4–12 was calculated from Hull's equivalent factors. Using δ_c values determined by methods other than Hull's may result in nonconservative estimates of mechanical properties. For example, estimations of ferrite content based on ASTM A 800/A 800M 84[7] are ≈20% lower than those obtained from Hull's method for ferrite levels >12% and are comparable for lower ferrite levels. Consequently, δ_c determined by the ASTM method for cast SSs with >12% ferrite may yield nonconservative estimates of fracture properties.

The correlations expressed in Eqs. 4–12 have been validated with Charpy-impact and fracture toughness data from service-aged cast SS components from the decommissioned Shippingport reactor; the KRB reactor in Gundremmingen, Germany; and the Ringhals 2 reactor in Sweden.[3] The correlations do not consider the effect of Nb and may not be applicable for Nb-bearing steels. Also, they do not differentiate between product form, i.e., static-cast or centrifugally cast materials.

*For all compositions of CF-8M steel, material parameter Φ was expressed as $\delta_c Cr(Ni+Si)^2(C+0.4N)/100$ in Ref. 5.

2.2.2 Fracture Toughness J–R Curve

The saturation fracture toughness J–R curve for a specific cast SS can be estimated from its RT impact energy at saturation, C_{Vsat}. The saturation fracture toughness J–R curve for static– and centrifugally cast steels is given by

$$J_d = a(C_{Vsat})^b(\Delta a)^n, \tag{13}$$

where the exponent n is given by

$$n = c + d(\log_{10} C_{Vsat}), \tag{14}$$

and the values of constants a, b, c, and d for different grades of steel and test temperature are given in Tables 2 and 3. The J–R curve at any intermediate temperature can be linearly interpolated from the estimated values of C and n at RT and at 290°C.

The correlations described in Eqs. 4–14 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 SSs may have low initial fracture toughness, and estimates from Eqs. 4–14 may be higher than the initial value. Some knowledge regarding the initial fracture toughness of the material is therefore needed to justify the use of the estimated fracture toughness.

The CMTR for a specific cast SS component provides information on chemical composition, tensile strength, and possibly Charpy-impact energy of the material; fracture toughness is not available in CMTRs. At temperatures between RT and 320°C, the minimum fracture toughness of unaged static-cast SSs can be expressed as

Table 2. Values of constants in Eq. 13 for estimating power–law J–R curve for cast SSs

	Static-Cast				Centrifugally Cast			
	Room Temp.		290°C		Room Temp.		290°C	
Grade	a	b	a	b	a	b	a	b
CF-3, CF-8	49	0.52	102	0.28	57	0.52	134	0.28
CF-8M	16	0.67	49	0.41	20	0.67	57	0.41

Table 3. Values of constants in Eq. 14 for estimating exponent n of power–law J–R curve for cast SSs

	Room Temp.		290°C	
Grade	c	d	c	d
CF-3	0.15	0.16	0.17	0.12
CF-8	0.20	0.12	0.21	0.09
CF-8M	0.23	0.08	0.23	0.06

$$J_d = 400(\Delta a)^{0.40}, \tag{15}$$

and of centrifugally cast SSs as

$$J_d = 650(\Delta a)^{0.43}. \tag{16}$$

When no information is available, these minimum fracture toughness J-R curves may be used as the initial fracture toughness of a cast material. The fracture toughness J-R curve for unaged material may also be obtained by using the initial RT Charpy-impact energy, C_{Vint}, instead of C_{Vsat} in Eqs. 13 and 14. However, Eqs. 15 and 16 are used as a lower bound for the initial fracture toughness of the material. When the estimation based on C_{Vint} is lower than the minimum fracture toughness J-R curve expressed in Eqs. 15 and 16, the latter is used as the initial J-R curve of the material.

When the initial f…cture toughness or initial RT Charpy-impact energy for estimating fracture toughness of a material is known, and when the J-R curve estimated from C_{Vsat} and Eqs. 13 and 14 is higher than the initial fracture toughness of unaged material, the latter is used as the saturation J-R curve of the material. Such cases represent low-fracture-toughness materials that are relatively insensitive to thermal aging, i.e., fracture toughness of the material would not change during reactor service.

When no information is available on either the initial fracture toughness or initial RT Charpy-impact energy for estimating fracture toughness of a material, the minimum fracture toughness of unaged cast SSs is used as the upper bound for the predicted fracture toughness of the aged material. In other words, if the J-R curve estimated from C_{Vsat} and Eqs. 13 and 14 is higher than the minimum fracture toughness of unaged cast SSs (i.e., Eqs. 15 and 16), the latter is used as the saturation J-R curve of a material.

2.3 Estimate for Steels of Known Composition and Service History: Service-Time Values

The RT impact energy as a function of time and temperature of aging of a specific cast SS is determined from its estimated RT saturation impact ene… C_{Vsat} and the kinetics of embrittlement. The decrease in RT Charpy-impact energy C_V with time is expressed as

$$\log_{10}C_V = \log_{10}C_{Vsat} + \beta\{1 - \tanh[(P - \theta)/\alpha]\}, \tag{17}$$

where the aging parameter P is defined by

$$P = \log_{10}(t) - \frac{1000Q}{19.143}\left(\frac{1}{T_s + 273} - \frac{1}{673}\right). \tag{18}$$

The constants α and β can be determined from C_{Vint} and C_{Vsat} as follows:

$$\alpha = -0.585 + 0.795\log_{10}C_{Vsat} \tag{19}$$

and

$$\beta = (\log_{10}C_{V_{int}} - \log_{10}C_{V_{sat}})/2. \quad (20)$$

If $C_{V_{int}}$ is not known, a typical value of 200 J/cm^2 (118 ft·lb) may be used. The value of θ varies with service temperature; it is 3.3 for <280°C (<536°F), 2.9 for 280–330°C (536–626°F), and 2.5 for 330–360°C (626–680°F). Activation energy for thermal embrittlement is expressed in terms of both chemical composition and the constant θ. The activation energy Q is given by

$$Q = 10\,[74.52 - 7.20\,\theta - 3.46\,Si - 1.78\,Cr - 4.35\,I_1\,Mn + (148 - 125\,I_1)\,N - 61\,I_2\,C], \quad (21)$$

where the indicators I_1 = 0 and I_2 = 1 for CF-3 or CF-8 steels and assume the values of 1 and 0, respectively, for CF-8M steels. Equation 21 is based on Charpy-impact data obtained from materials that were aged up to 58,000 h at 290–400°C (554–752°F) and is an updated version* of an expression presented earlier.[5] It is applicable to compositions within ASTM Specification A 351, with an upper limit of 1.2 wt.% for Mn content. Actual Mn content is used when materials contain up to 1.2 wt.% Mn; for steels containing >1.2 wt.% Mn, 1.2 wt.% is assumed. Furthermore, the values of Q predicted from Eq. 21 should be between 65 kJ/mole (15.5 kcal/mole) minimum and 250 kJ/mole (59.8 kcal/mole) maximum; Q is assumed to be 65 kJ/mole if the predicted values are lower, and 250 kJ/mole if the predicted values are higher.

The RT Charpy-impact energy of a specific cast SS as a function of service time and temperature can be obtained from estimated $C_{V_{sat}}$ (Eqs. 4–12) and the kinetics of embrittlement (Eqs. 17–21). The fracture toughness J-R curve is then obtained by using the estimated RT Charpy-impact energy C_V in Eqs. 13 and 14. However, depending on the available information, minimum fracture toughness of cast SSs (Eqs. 15 or 16) or initial fracture toughness of the unaged material is used as the upper bound for the estimations.

3 Conclusions

A procedure and correlations are presented for predicting Charpy-impact energy and fracture toughness J-R curve 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 extent or degree of thermal embrittlement at "saturation," i.e., the minimum impact energy that can be achieved for the material after long-term aging, is determined from chemical composition of the steel. Charpy-impact energy as a function of time and temperature of reactor service is estimated from the kinetics of thermal embrittlement, which is also determined from the chemical composition. The initial impact energy of the unaged steel is required for these estimations. The fracture toughness J-R curve for the material is then obtained from correlations between RT Charpy-impact energy and fracture toughness parameters. A common "predicted lower-bound" J-R curve for cast SSs with unknown chemical composition is also defined for a given grade of steel, range of ferrite contents, and temperature. Typical examples for estimating fracture properties of cast SS components during reactor service are described in the Appendix.

*The updated expression for CF-8M steel is essentially an optimized version of the earlier expression. For CF-3 and CF-8 steels, the effect of Mo and Mn content has been omitted and the effect of C has been added in the updated expression.

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Appendix

Estimation of Fracture Properties of Cast SSs

The correlations described in this report can be used for assessing thermal embrittlement of cast SS components. The procedure involves a few simple steps. First, available information about the material and service condition is obtained from the CMTR; i.e., if known, determine the chemical composition, grade of steel, casting method, Charpy-impact properties, and time and temperature of service. Then, on the basis of available information, various schemes are used to estimate the fracture toughness J-R curve and Charpy-impact energy of the aged material. Typical examples for estimating fracture properties of cast SS components during reactor service are presented.

Example 1. *A centrifugally cast CF-8 pipe, 0.51 m nominal diameter, in service at 302°C (575°F) for 18 effective full power years (efpys). The following material information is also known.*

Measured Ferrite Content (%): 14.2

Only the lower-bound fracture toughness J-R curve can be estimated for this steel, because only the grade and ferrite content are known* and the chemical composition of the material is not known. The estimation scheme for this example involves one step and is shown in Fig. A-1. The lower-bound fracture toughness represents the minimum toughness that can be achieved after long-term aging by centrifugally cast CF-8 steels containing 10-15% ferrite.

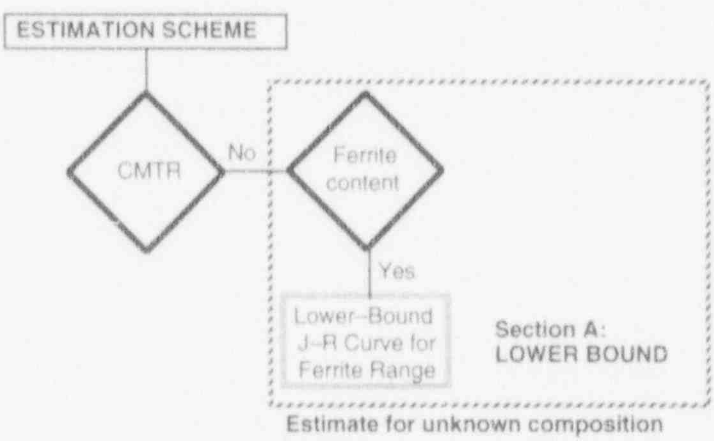

Figure A-1. Estimation scheme for Example 1

Step 1. From Table 1 the predicted lower-bound fracture toughness J-R curve for centrifugally cast CF-8 steel with 10-15% ferrite, at RT, is given by

$$J_d\ (kJ/m^2) = 357[\Delta a(mm)]^{0.38} \qquad (A-1.1)$$

*CF-8M steel and >15% ferrite are assumed if the grade and ferrite content of the steel are not known.

and at 290°C (554°F) by

$$J_d\ (kJ/m^2) = 360[\Delta a(mm)]^{0.35}. \qquad (A\text{-}1.2)$$

The J-R curve at a service temperature of 302°C can be linearly extrapolated from Eqs. A-1.1 and A-1.2. The curve at 302°C is not significantly different from that at 290°C and can be approximated as

$$J_d\ (kJ/m^2) = 360[\Delta a(mm)]^{0.35}. \qquad (A\text{-}1.3)$$

Example 2. *A static-cast CF-8 check valve in service at 282°C (540°F). The following material information is also known.*

Chem. Comp. (wt.%): Cr. 20.26; Mo. 0.01; Si. 1.45; Ni. 8.84; Mn. 1.10; C. 0.056; N. 0.041

Measured Ferrite Content (%): 10.4

RT Charpy-Impact Energy (J): 150.4

Only the saturation fracture properties can be estimated in this case, because the time of service is not known. The estimation scheme for this example is shown in Fig. A-2. The saturation fracture toughness represents the minimum toughness that can be achieved by this specific cast SS after long-term aging.

Step 1. The calculated ferrite content (Eqs. 1-3) is

$$\delta_c\ (\%) = 10.8.$$

Step 2. The material parameter Φ for CF-8 steel (Eq. 5) is 16.94. Saturation RT Charpy-impact energy in terms of Φ (Eq. 4) is 79.8 J/cm^2, and in terms of composition (Eq. 6), it is 58.8 J/cm^2. The lower of the two values is used for fracture toughness estimations; thus

$$Cv_{sat}\ (J/cm^2) = 58.8.$$

Step 3. The saturation fracture toughness J-R curve for static-cast CF-8 steel, at RT (Eqs. 13, 14 and Tables 2 and 3), is given by

$$J_d\ (kJ/m^2) = 407.8[\Delta a(mm)]^{0.41} \qquad (A\text{-}2.1)$$

and at 290°C, by

$$J_d\ (kJ/m^2) = 319.2[\Delta a(mm)]^{0.37}. \qquad (A\text{-}2.2)$$

The saturation fracture toughness J-R curve at a service temperature of 282°C is linearly interpolated from Eqs. A-2.1 and A-2.2. The curve at 282°C is not significantly different from that at 290°C and can be approximated as

$$J_d\ (kJ/m^2) = 319.2[\Delta a(mm)]^{0.37}. \qquad (A\text{-}2.3)$$

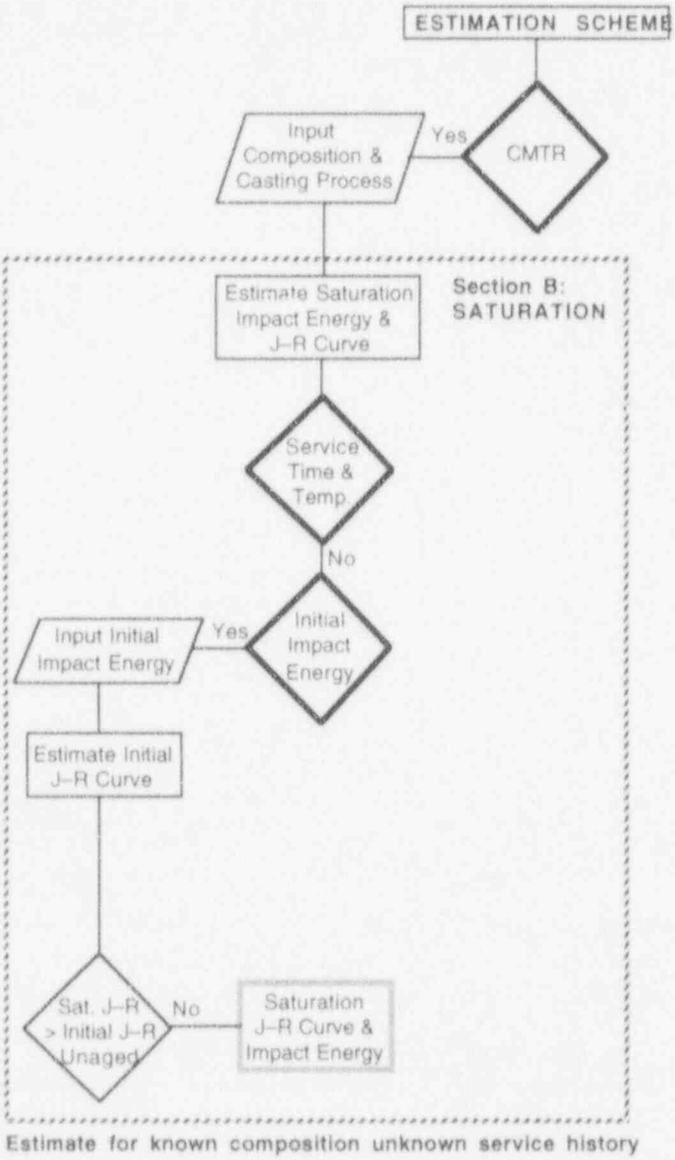

Figure A-2. Estimation scheme for Example 2

This corresponds to a J_d value of 579 kJ/m^2 (3306 in.·lb/in.^{2}) at 5-mm crack extension.

Step 4. The initial RT Charpy-impact energy* is 150.4 J. The normalized value is obtained by dividing this value by the cross-sectional area of the Charpy-impact specimen, i.e., 0.8 cm^2.

$$C_{Vint}\ (J/cm^2) = 188.0.$$

Step 5. The initial J-R curve for the unaged material is the higher of either Eq. 15 or the J-R curve determined from Eqs. 13 and 14 using C_{Vint} instead of C_{Vsat}. The initial J-R curve at 282°C is not significantly different from that at 290°C and can be approximated as

$$J_d\ (kJ/m^2) = 441.9[\Delta a(mm)]^{0.41}. \qquad (A\text{-}2.4)$$

*In this report, all values of impact energy are considered to be for a standard Charpy-V-notch specimen (ASTM Specification E 23), i.e., 10 x 10-mm cross section and 2-mm V notch.

This corresponds to a J_d value of 855 kJ/m^2 (4881 in.·lb/in.^{2}) at 5–mm crack extension. Thermal aging decreases the fracture toughness of this steel from 855 to 579 kJ/m^2 in the fully aged condition.

Example 3. *A centrifugally cast CF–8M pipe, 0.51 m nominal diameter, in service at 291°C (555°F). The following material information is also known.*

Chem. Comp. (wt.%): Cr, 20.64; Mo, 2.05; Si, 1.02; Ni, 10.00; Mn, 1.07; C, 0.040; N, 0.151

Charpy–Impact Energy (J): *181.6*

This example is similar to the previous example and only the saturation fracture properties can be estimated because the time of service is not known. The estimation scheme for this example is shown in Fig. A-3. The saturation fracture toughness represents the minimum toughness that can be achieved by this specific cast SS after long–term aging.

Step 1. The calculated ferrite content (Eqs. 1–3) is

$$\delta_c\,(\%) = 8.8.$$

Step 2. The material parameter Φ for static–cast CF–8M steel with >10% Ni (Eq. 11) is [illegible]. Saturation RT Charpy–impact energy in terms of Φ (Eq. 10) is 40.4 J/cm^2, and in terms of composition (Eq. 12), it is 40.3 J/cm^2. The lower of the two values is used for fracture toughness estimations; thus

$$C_{Vsat}\,(J/cm^2) = 40.3.$$

Step 3. The saturation fracture toughness J–R curve for static–cast CF–8M steel, at a service temperature of 291°C (Eqs. 13, 14 and Tables 2 and 3), can be approximated as

$$J_d\,(kJ/m^2) = 259.5[\Delta a(mm)]^{0.33}. \qquad \text{(A-2.1)}$$

This corresponds to a J_d value of 441 kJ/m^2 (2520 in.·lb/in.^{2}) at 5–mm crack extension.

Step 4. The initial RT Charpy–impact energy is 181.6 J. The normalized value is obtained by dividing this value by 0.8 cm^2, the cross–sectional area of the Charpy–impact specimen.

$$C_{Vint}\,(J/cm^2) = 227.0.$$

Step 5. The initial J–R curve for the unaged material is the higher of either Eq. 16 or the J–R curve determined from Eqs. 13 and 14 using C_{Vint} instead of C_{Vsat}. The initial J–R curve, at 291°C is essentially the same as that at 290°C

$$J_d\,(kJ/m^2) = 527.0[\Delta a(mm)]^{0.37}. \qquad \text{(A-2.2)}$$

This corresponds to a J_d value of 956 kJ/m^2 (5459 in.·lb/in.^{2}) at 5-mm crack extension. Thermal aging decreases the fracture toughness of this steel from 956 to 441 kJ/m^2 in the fully aged condition.

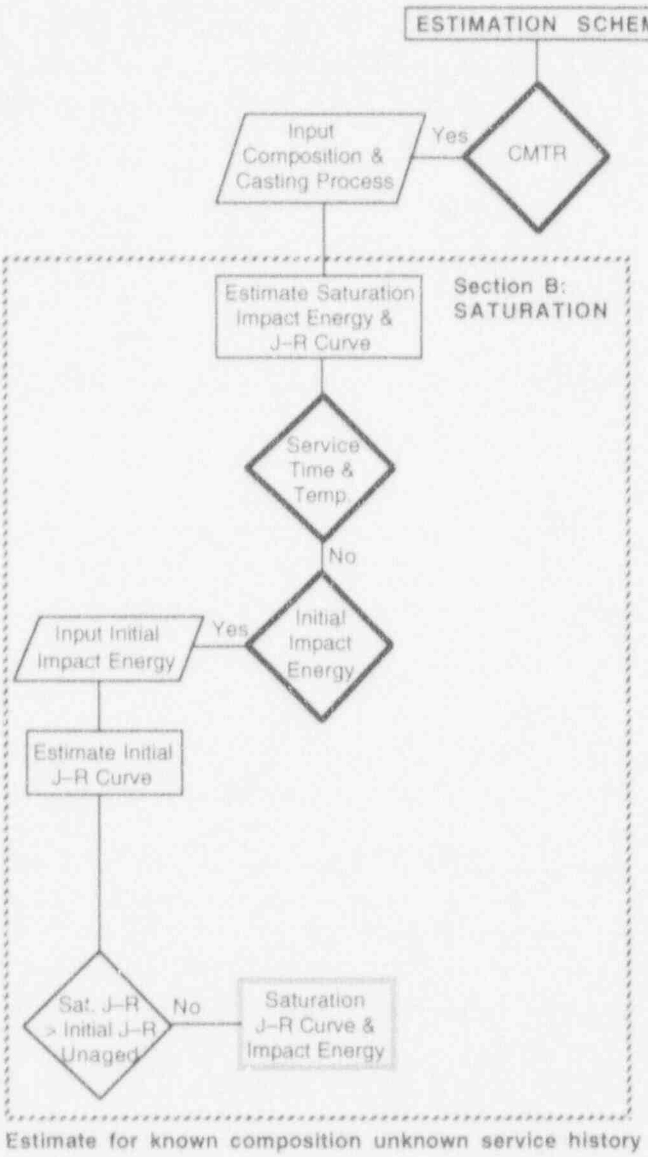

Figure A–3. Estimation scheme for Example 3

Example 4. *A static–cast CF–8M elbow, 0.66 m nominal size, in service at 325°C (617°F) for 9 efpys. The following material information is also known.*

Chem. Comp. (wt.%): Cr, 20.21; Mo, 2.09; Si, 1.03; Ni, 10.24; Mn, 0.77; C, 0.037; N, 0.044

Charpy–Impact Energy (J): 209.6

Service time, as well as saturation fracture properties, can be estimated in this case, because both chemical composition and service conditions for the material are known. The estimation scheme for this example is shown in Fig. A–4. The saturation fracture toughness represents the minimum toughness that can be achieved by this cast SS after long–term aging and the service time fracture toughness is the value after 9 efpys of service at 325°C.

Step 1. The calculated ferrite content (Eqs. 1–3) is

δ_c (%)= 16.1.

Step 2. The material parameter Φ for static-cast CF-8M steel with >10% Ni (Eq. 11) is 25.56. Saturation RT Charpy-impact energy in terms of Φ (Eq. 10) is 41.1 J/cm^2, and in terms of composition (Eq. 12), it is 62.9 J/cm^2. The lower of the two values is used for fracture toughness estimations; thus

C_{Vsat} (J/cm^2) = 41.1.

Step 3. The saturation fracture toughness J-R curve for this static-cast CF-8M steel, at RT (Eqs. 13, 14 and Tables 2 and 3), is given by

$$J_d\ (kJ/m^2) = 193[\Delta a(mm)]^{0.36} \quad \text{(A-4.1)}$$

and at 290°C, by

$$J_d\ (kJ/m^2) = 225[\Delta a(mm)]^{0.33}. \quad \text{(A-4.2)}$$

The saturation-fracture-toughness J-R curve at a service temperature of 325°C is linearly extrapolated from Eqs. A-4.1 and A-4.2 as

$$J_d\ (kJ/m^2) = 229[\Delta a(mm)]^{0.33}. \quad \text{(A-4.3)}$$

This corresponds to a J_d value of 389 kJ/m^2 (2224 in.-lb/in.^{2}) at 5-mm crack extension.

Step 4. The kinetics for thermal embrittlement of this steel, i.e., the activation energy Q, and aging parameter P corresponding to 9 efpys (78840 h) of service at 325°C (617°F) are estimated from chemical composition and service conditions.

θ = 2.9 for service temperatures of 280-330°C.

Q (kJ/mole) = 117.6 from Eq. 21 (with I_1 = 1 and I_2 = 0).

P = 3.752 from Eq. 18.

Step 5. The initial RT Charpy-impact energy is 209.6 J. The normalized value is obtained by dividing by the cross-sectional area of the Charpy-impact specimen, i.e., 0.8 cm^2.

C_{Vint} (J/cm^2) = 262.0.

Step 6. The initial J-R curve for the unaged material is the higher of either Eq. 15 or the J-R curve determined from Eqs. 13 and 14 using C_{Vint} instead of C_{Vsat}. In this example, the initial J-R curve at RT is obtained from Eqs. 13 and 14 as

$$J_d\ (kJ/m^2) = 667[\Delta a(mm)]^{0.42}; \quad \text{(A-4.4)}$$

and at 290°C as

$$J_d\ (kJ/m^2) = 481[\Delta a(mm)]^{0.38}. \quad \text{(A-4.5)}$$

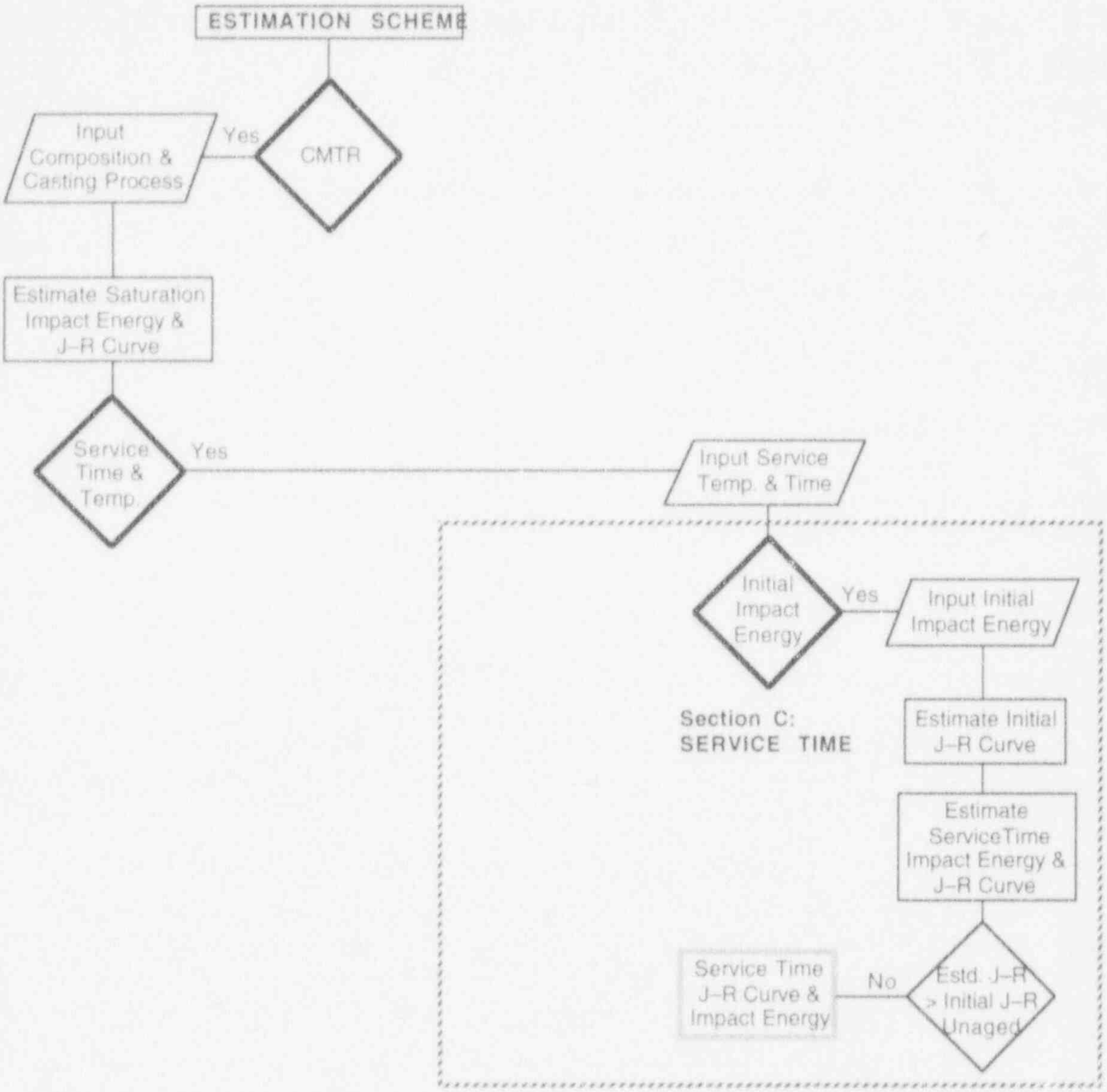

Figure A–4. Estimation scheme for Example 4

The initial-fracture-toughness J-R curve at a service temperature of 325°C is linearly extrapolated from Eqs. A–4.4 and A–4.5 as

$$J_d\ (kJ/m^2) = 456[\Delta a(mm)]^{0.37}. \qquad (A\text{–}4.6)$$

This corresponds to a J_d value of 827 kJ/m^2 (4723 in.·lb/in.^{2}) at 5-mm crack extension.

Step 7. The constants in Eq. 17 are obtained from Cv_{sat} and Cv_{int}.

$\alpha = 0.698$ from Eq. 19.

$\beta = 0.402$ from Eq. 20.

Step 8. Information from steps 2 and 7 are used to determine the Charpy-impact energy C_V after 9 efpys at 325°C.

C_v (J/cm^2) = 47.7 from Eq. 17.

Step 9. The service-time-fracture-toughness J-R curve for static-cast CF-8M steel, at RT, is given by

$$J_d\ (kJ/m^2) = 213[\Delta a(mm)]^{0.36} \tag{A-4.7}$$

and at 290°C, by

$$J_d\ (kJ/m^2) = 239[\Delta a(mm)]^{0.33}. \tag{A-4.8}$$

The service-time-fracture-toughness J-R curve at a service temperature of 325°C is linearly extrapolated from Eqs. A-4.7 and A-4.8 as

$$J_d\ (kJ/m^2) = 242[\Delta a(mm)]^{0.33}. \tag{A-4.9}$$

This corresponds to a J_d value of 412 kJ/m^2 (2350 in.-lb/in.^{2}) at 5-mm crack extension.

Thermal aging decreases the fracture toughness of this steel from 827 to 412 kJ/m^2 after 9 efpy of service at 325°C; the saturation fracture toughness in the fully aged condition corresponds to a J_d value of 389 kJ/m^2.

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10. SUPPLEMENTARY NOTES

11. ABSTRACT (200 words or less)
A procedure and correlations are presented for assessing thermal embrittlement and predicting Charpy-impact energy and fracture toughness J-R curve of cast stainless steel components under light water reactor operating conditions from known material information. The "saturation" impact strength and fracture toughness of a specific 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 reactor service are estimated from the kinetics of embrittlement, which are also determined from chemical composition. A common "predicted lower-bound" J-R curve for cast stainless steels of unknown chemical composition is also defined for a given grade of steel, ferrite content, and temperature. Examples of estimating fracture toughness of cast stainless steel components during reactor service are presented.

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