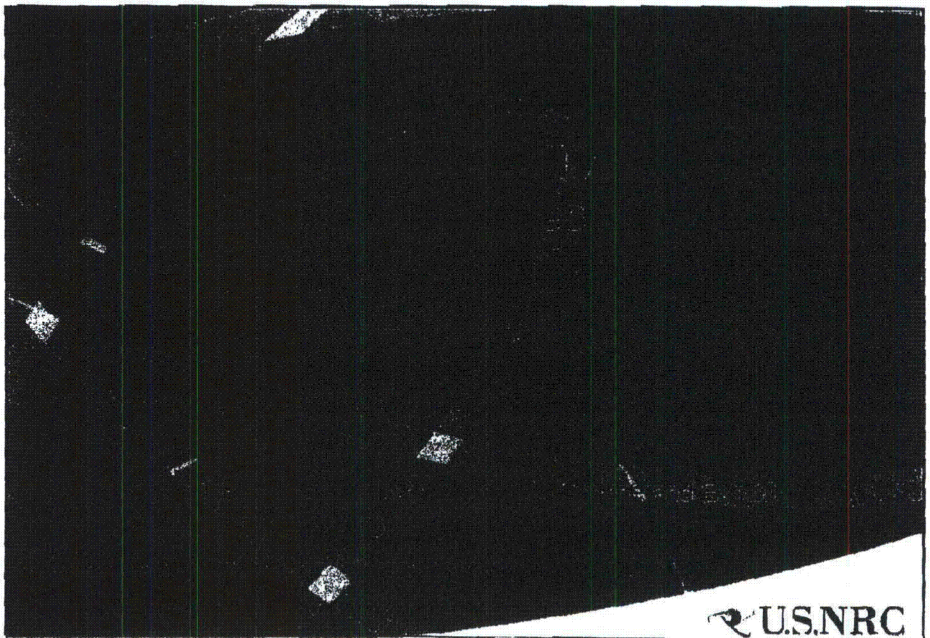

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The views expressed herein are those of the authors and do not reflect the views of the U.S. Nuclear Regulatory Commission.

Outline

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- Introduction and Motivation
- Analysis Methods
- Results
- Conclusion

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RG 1.161 and Appendix K

Overview

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- Regulatory Guide 1.161 and ASME Section XI, Nonmandatory Appendix K provide procedures for calculating adequate Charpy upper shelf energy to protect against ductile fracture of the vessel.
- The applied J-Integral is estimated from stress intensity factor equations.

$$K_{Ip}^{Axial} = (SF)\,p_a[1 + (R_i/t)](\pi a)^{0.5}\,F_1$$

$$a_e = a + \frac{1}{6\pi}\left(\frac{K_{Ip} + K_{It}}{\sigma_Y}\right)^2$$

$$F_1 = 0.982 + 1.006(a/t)^2$$

Re-evaluate using a_e, giving K_{Ip}' and K_{It}'

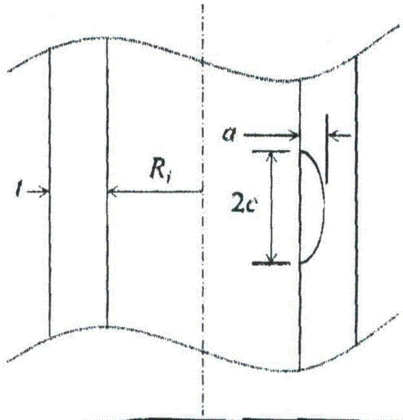
$$K_{It} = [(CR)/1000]t^{2.5}F_3$$

$$F_3 = 0.69 + 3.217(a/t) - 7.435(a/t)^2 + 3.532(a/t)^3$$

$$J = 1000\frac{\left(K_{Ip}' + K_{It}'\right)^2}{E'}$$

RG 1.161 and Appendix K
Overview

- Flaw geometry, a/c = 1/3



RG 1.161 and Appendix K
Motivation

- These stress intensity factor equations were derived for R/t = 10, which applies to pressurized water reactor vessels.
- Boiling water reactor vessels typically have R/t = 20.
- The thinner vessels are expected to be less susceptible to steep thermal gradients.
- This work further explores the validity of using the derived equations for the R/t = 20 case, through the use of independent methods of calculating stress intensity factor.

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Temperature Profiles

The Heat Equation

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- Parabolic partial differential equation: $\rho c_p \frac{\partial T}{\partial \tau} = \frac{1}{r}\frac{\partial}{\partial r}\left(kr\frac{\partial T}{\partial r}\right)$
- Boundary conditions: $q = h_c\left(T_f - T_s\right)$ for $r = R_i$ and all τ

  $q = 0$ for $r = R_o$ and all τ

  $T_f = T_0 - (CR)\tau$
- Initial conditions: $T = T_0$ for all r and $\tau = 0$

The Heat Equation

Solving Strategies for Temperature Profiles

- Finite element analysis
- Crank-Nicolson method
- Analytical solutions
- Resource: Kreyszig, Advanced Engineering Mathematics
- This work
  - Commercial engineering coding software with a built-in PDE solver
  - Skeel and Berzins, "A Method for the Spatial Discretization of Parabolic Equations in One Space Variable," SIAM J. Sci. and Stat. Comput.

Calculation of Stresses

Pressure and Thermal Hoop Stresses

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- Pressure stresses in a thick-walled cylinder:

$$\sigma_{\theta\theta} = \frac{pR_i^2}{R_o^2 - R_i^2}\left[1 + \left(\frac{R_0}{r}\right)^2\right]$$

- Thermal stresses in a cylinder:

$$\sigma_{\theta\theta} = \frac{\alpha E}{1-\upsilon}\frac{1}{r^2}\left(\frac{r^2 + R_i^2}{R_o^2 - R_i^2}\int_{R_i}^{R_0} Tr\mathrm{d}r + \int_{R_i}^{r} Tr\mathrm{d}r - Tr^2\right)$$

Calculation of Stress Intensity Factor

Three Independent Methods

- American Petroleum Institute Standard 579-1:

$$\sigma(x) = \sigma_0 + \sigma_1\left(\frac{x}{t}\right) + \sigma_2\left(\frac{x}{t}\right)^2 + \sigma_3\left(\frac{x}{t}\right)^3 + \sigma_4\left(\frac{x}{t}\right)^4$$

$$K_I = \left[\sigma_0 G_0 + \sigma_1 G_1\left(\frac{a}{t}\right) + \sigma_2 G_2\left(\frac{a}{t}\right)^2\right]\sqrt{\frac{\pi a}{Q}} + \ldots$$

$$\left[\sigma_3 G_3\left(\frac{a}{t}\right)^3 + \sigma_4 G_4\left(\frac{a}{t}\right)^4\right]\sqrt{\frac{\pi a}{Q}}$$

$$Q = 1 + 1.464\left(\frac{a}{c}\right)^{1.65} \text{ for } a/c \le 1.0 \qquad Q = 1 + 1.464\left(\frac{c}{a}\right)^{1.65} \text{ for } a/c > 1.0$$

Calculation of Stress Intensity Factor

Three Independent Methods

- Fracture Analysis of Vessels – Oak Ridge (FAVOR) method:
  - Similar to the API-579-1 method, except that a 3rd order polynomial is used for the stress distribution.
- Newman and Raju for internal pressure:

$$K_I = \frac{pR_i}{t}\sqrt{\pi\frac{a}{Q}}\,F\left(\frac{a}{c},\frac{a}{t},\frac{R}{t},\phi\right)$$

Calculation of Stress Intensity Factor

Application of the Methods

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- API-579-1 and FAVOR methods:
  - Are based upon the principle of elastic superposition.
  - May be applied for multiple loading conditions, if:
    - All conditions are mode I and
    - The polynomial used to describe the stress fits the actual stress profile well.
- The Newman and Raju equation was derived only for internal pressure and should be used only for that case.

Inputs

Geometry, Material Properties, etc.

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Description	Value
Geometry	
t	0.16 m [0.51 ft]
R_i/t	20.6
a/t	0.1 to 0.8
a/c	1/3
Material Properties	
E	2.0×10^{5} MPa [4.2×10^{6} kip/ft^2]
ν	0.30
α	1.30×10^{-5} m/m/K [7.20×10^{-6} ft/ft/R]
k	38 W/(m-K) [22 BTU/(hr-ft-R)]
ρ	7770 kg/m^3 [486 lb$_m$/ft.^{3}]
c_p	536 J/(kg-K) [0.13 BTU/(lb$_m$-R)]
Thermal Loading Conditions	
h_c	5673 W/(m^2-K) [1000 BTU/(hr-ft^2-R)]
CR	0.02 K/s [100 R/hr]
T_0	561 K [1010 R]
Mechanical Loading Conditions	
p	19.0 MPa [396 kip/ft^2]

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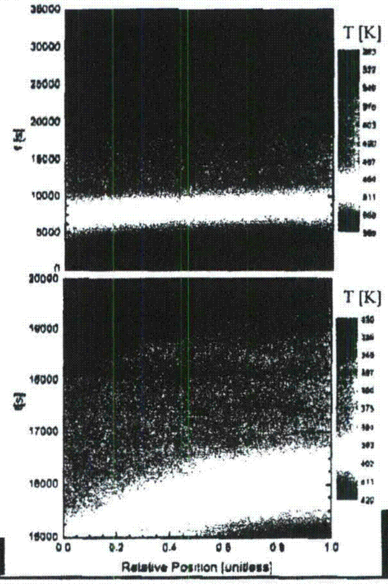
Temperature Distribution

Contour Plots



- Small gradients at the beginning and end of the cooldown.
- Highest gradient observed between 15 000 s and 20 000 s.

Thermal Stress Distribution

Hoop Stress Contour

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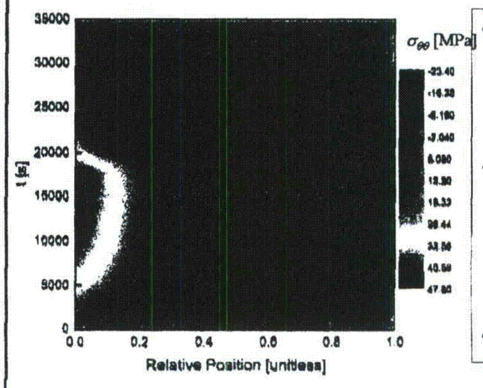

- Vanishing thermal stresses early and late in the transient.
- Highest magnitude stresses observed between 5 000 and 20 000 s.
- Tension at ID, compression at OD.

Stress Intensity Factor: Thermal

Time History

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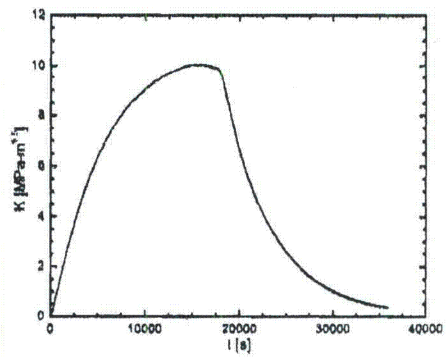

- API-579-1 method with a/c = 1/3, a/t = 1/4.
- Highest stress intensity factor observed at 14 000 s.

Stress Intensity Factor: Thermal

Comparison of Different Methods

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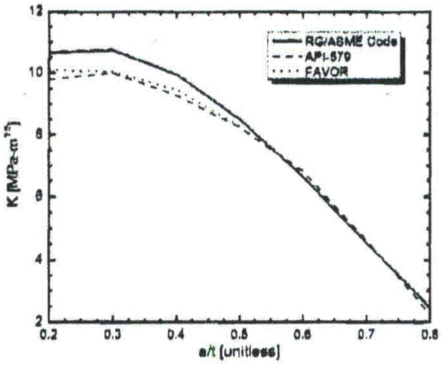

- Maximum K in the transient.
- RG/ASME Code equations bound API-579-1 and FAVOR methods for a/t < 0.55.
- Subsequent agreement.

Stress Intensity Factor: Thermal

Effect of Vessel Thickness

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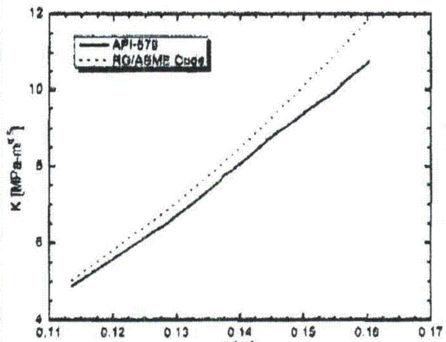

- RG/ASME Code equation conservatively bounds the API-579-1 method.

Pressure Stress Distribution

Hoop Stress

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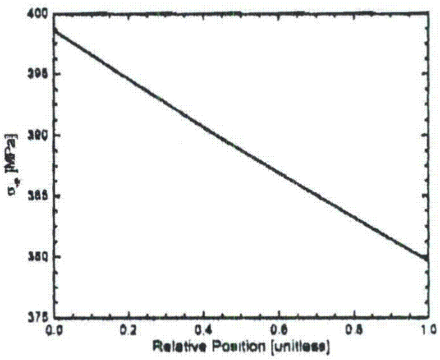

- Approximately linear distribution
- ID: ~400 MPa, OD: ~380 MPa

Stress Intensity Factor: Pressure

Comparison of Different Methods

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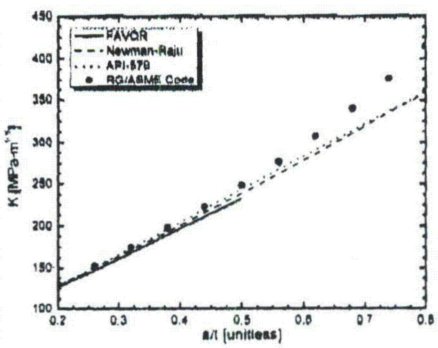

- Agreement up to a/t = 0.5.
- RG/ASME Code equation becomes increasingly conservative for a/t > 0.5.

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- The RG/ASME Code equations for estimating stress intensity factor under thermal and internal pressure loading conditions agree with or conservatively bound independent methods for R/t = 20.
- Reference: Conference Proceeding PVP2012-78229.