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Stress-Intensity-Factor Influence Coefficients for Surface Flaws in Pressure Vessels

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STRESS-INTENSITY-FACTOR INFLUENCE COEFFICIENTS FOR SURFACE FLAWS IN PRESSURE VESSELS

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FOREWORD

The work reported here was performed at Oak Ridge National Laboratory (ORNL) under the Heavy-Section Steel Technology (HSST) Program, C. E. Pugh, Program Manager. The program is sponsored by the Office of Nuclear Regulatory Research of the U.S. Nuclear Regulatory Commission (NRC). The technical monitor for the NRC is Milton Vagins.

This report is designated HSST Program Technical Report 77. Prior reports in this series are listed below:

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STRESS-INTENSITY-FACTOR INFLUENCE COEFFICIENTS FOR SURFACE FLAWS IN PRESSURE VESSELS

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ABSTRACT

In the fracture-mechanics analysis of reactor pressure vessels, stress-intensity-factor influence coefficients are used in conjunction with superposition techniques to reduce the cost of calculating stress-intensity factors. The present study uses a finite-element code, together with a virtual crack extension technique, to obtain influence coefficients for semielliptical surface flaws in a cylinder, and particular emphasis was placed on mesh convergence (less than 1% error was sought in the results from any one mesh construction parameter). Comparison of the coefficients with those obtained by other investigators shows good agreement. Furthermore, stress-intensity factors obtained by superposition for a severe thermal-transient loading condition agree within 1% of the values calculated by a direct finite-element method.

Influence coefficients were calculated for three specific axially oriented semielliptical surface flaws. The first was a 2-m-long inner-surface flaw in a nuclear reactor pressure vessel with depth-to-wall-thickness ratios between 0.2 and 0.9. The second was an inner-surface flaw in the reactor vessel with a surface-length-to-depth ratio of 6 and with depth-to-wall-thickness ratios between 0.05 and 0.2. The third was a 1-m-long flaw on the outer surface of a test vessel with depth-to-wall-thickness ratios between 0.1 and 0.9. For the reactor vessel, separate coefficients were calculated for the cladding on the inner surface and for the base-material region. This allows for an accurate accounting of the effect of thermal stresses in the cladding on the stress-intensity factor for surface flaws that extend through the cladding into the base material.

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1. INTRODUCTION

An evaluation of pressurized-water reactor (PWR) pressure-vessel integrity during postulated overcooling accidents[1] requires the application

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of linear-elastic fracture mechanics (LEFM). This involves the calculation of stress-intensity factors (K_I) for both two-dimensional (2-D) and three-dimensional (3-D) surface flaws subjected to combined thermal and pressure loadings. Under these circumstances, a sufficiently accurate determination of K_I requires the use of finite-element (FE) analysis, an approach that has been developed and applied by numerous investigators (for examples see Refs. 2–6). However, computer costs for the direct FE analysis of cracks can be prohibitive when a large number of calculations must be made, as is the case for parametric, reactor transient, and probabilistic studies.

In the last several years, an alternative approach to the direct FE method has been promoted that makes use of superposition techniques and stress-intensity-factor influence coefficients[7-12] that correspond to simple basic load distributions on the crack face. The coefficients must be obtained from FE analyses of specific structures and flaws of interest; however, once available, the coefficients can be weighted by any actual crack-free stress distribution normal to the plane of the crack face and summed to obtain the total K_I value. Because only the predetermined influence coefficients and the crack-free stress distributions are necessary to calculate K_I, this alternative approach is particularly suitable for parametric studies of a specific PWR pressure vessel.

In this report, the use of influence coefficients with superposition techniques is described; mesh-convergence studies conducted to ensure reasonable accuracy for the influence coefficients are discussed; K_I values obtained by superposition for severe thermal-shock loading conditions are compared with values calculated with the direct FE method; coefficients are compared with those obtained by other investigators; and influence coefficients are calculated for three specific axially oriented, semielliptical surface flaws in a cylinder. Two of these flaws are on the inner surface of a PWR reactor pressure vessel, and the other is on the outer surface of a test vessel. One of the reactor vessel flaws has a length of 1.8 m (referred to as the 2-m flaw), while the other has a surface-length-to-depth ratio of 6 (6/1 flaw). The test vessel flaw has a surface length of 1.0 m (1-m flaw).

2. SUPERPOSITION AND INFLUENCE COEFFICIENTS

The superposition technique, used in conjunction with the influence coefficients, makes use of the stresses in the uncracked structure, and, as discussed in Ref. 11 and illustrated in Fig. 2.1, only that portion of the stress distribution corresponding to the location of the crack face needs to be used. For an arbitrary stress distribution, such as that shown in Fig. 2.1, and for the case of a 2-D (long) flaw, the K_I value corresponding to the truncated stress distribution can be obtained by dividing the distribution into a reasonable number of equivalent forces on the crack face and then adding the K_I values corresponding to each of the forces. For convenience, normalized K_I values can be calculated for a number of individual unit loads along the crack face for all crack depths of interest (Fig. 2.2). These normalized K_I values, referred to as K_I^* and/or influence coefficients in these studies, can be weighted by any truncated stress distribution and added to obtain the total K_I value as indicated by Eq. (1).

$$K_I(a) = \sum_{i=1}^{n} \sigma_i \Delta a_i K_i^*(a_i', a) \quad , \tag{1}$$

where

Δa_i = an increment of about a',

$\sum_{i=1}^{n} \Delta a_i = a$,

a_i' = radial distance from open end of crack (cylinder surface) to point of application of unit load,

σ_i = average stress over Δa_i for equivalent problem,

K_i^* = stress-intensity factor per unit load applied at a_i' per unit length of cylinder,

n = number of points along length of crack for which K* values are available.

The K_i^* values are dependent on the nature of the structure in which the cracks reside. However, for a given structure, the same set of K_i^* values can be used for any stress distribution provided there are enough K_i^* values along the face of the crack to adequately represent the stress distribution. As indicated in Ref. 12, the authors have used no less than 6 K_i^* values for very shallow inner-surface flaws in thick-walled cylinders, and as many as 46 for deep flaws (these K_i^* values were calculated using the FE code FMECH[3]).

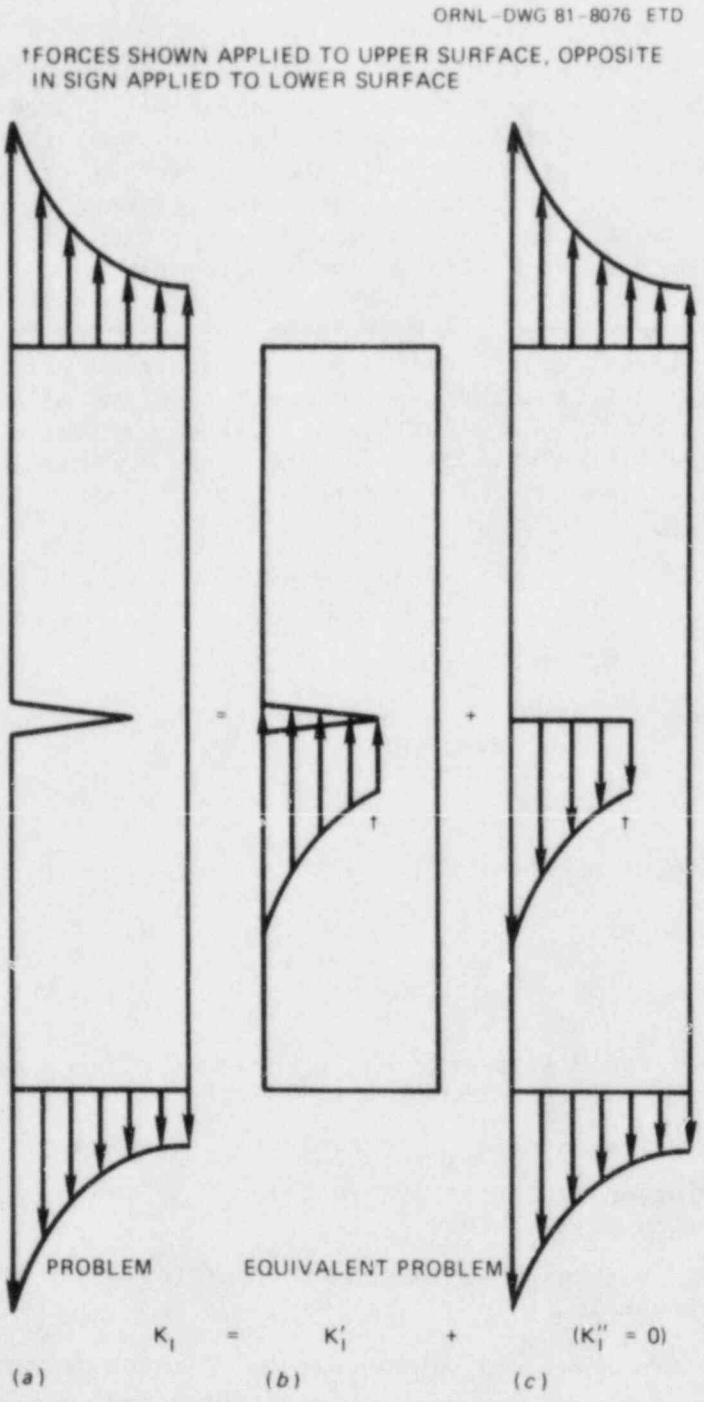

Fig. 2.1. Graphical representation of method for calculating K_I using equivalent problem.

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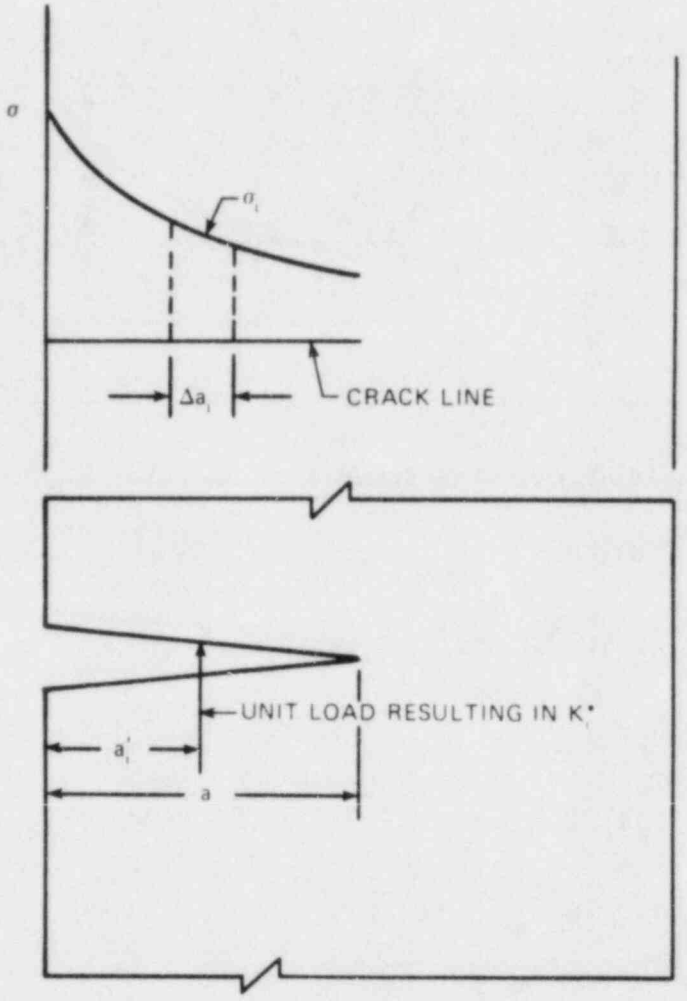

$$K_I(a) = \sum_{i=1}^{n} \sigma_i \, \Delta a_i \, K_i'(a', a)$$

Fig. 2.2. Method of calculating K_I using superposition principle.

The influence coefficients for 3-D flaws are obtained in a somewhat different manner. For these flaws, the truncated stress distribution is approximated with a polynomial as indicated by Eq. (2):

$$\sigma(a') = C_0 + C_1 \left(\frac{a'}{a}\right) + C_2 \left(\frac{a'}{a}\right)^2 + C_3 \left(\frac{a'}{a}\right)^3 , \qquad (2)$$

where $\sigma(a')$ is the stress normal to the crack plane at radial position a', and a' and a are defined in Fig. 2.3. The K_I values are calculated for each of the individual terms (stress distributions) in Eq. (2) and

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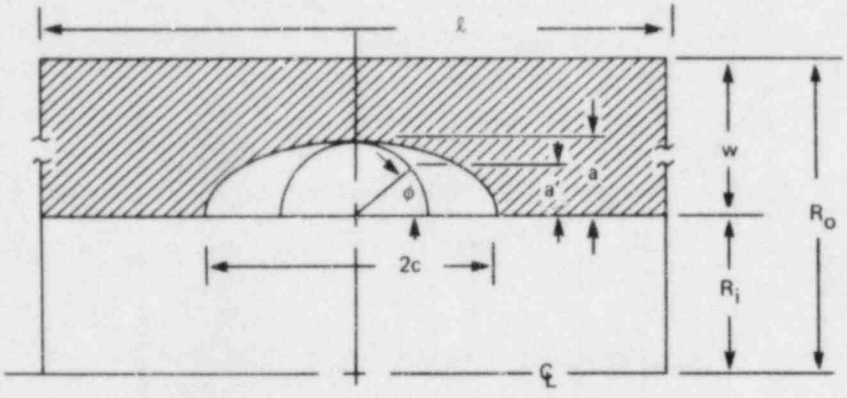

Fig. 2.3. Axially oriented semielliptical flaw on inner surface of cylinder.

are then added to obtain the total K_I value as indicated by Eq. (3):

$$K_I(a) = \sum_{j=0}^{3} K_{Ij}(a) = \sum_{j=0}^{3} C_j \sqrt{\pi a}\ K_j^*(a) , \qquad (3)$$

where

$$K_j^*(a) = K'_{Ij}(a)/(C'_j \sqrt{\pi a}) . \qquad (4)$$

Values of $K'_{Ij}(a)/C'_j$ are calculated for each of the normalized stress distributions corresponding to each term in Eq. (2) (see Fig. 2.4), using a 3-D finite-element analysis and an arbitrary value of C'_j, such as unity. The quantity $K_j^*(a)$ is referred to as the influence coefficient and, as indicated by Eq. (4), is dimensionless. Once the influence coefficients are obtained, they can be used with any values of C_j to obtain corresponding values of $K_I(a)$.

For 3-D flaws, $K_j^*(a)$ values can be calculated for several points along the crack front, in which case Eq. (3) becomes

$$K_I(\phi) = \sum_{j=0}^{3} C_j \sqrt{\pi a}\ K_j^*(\phi) , \qquad (5)$$

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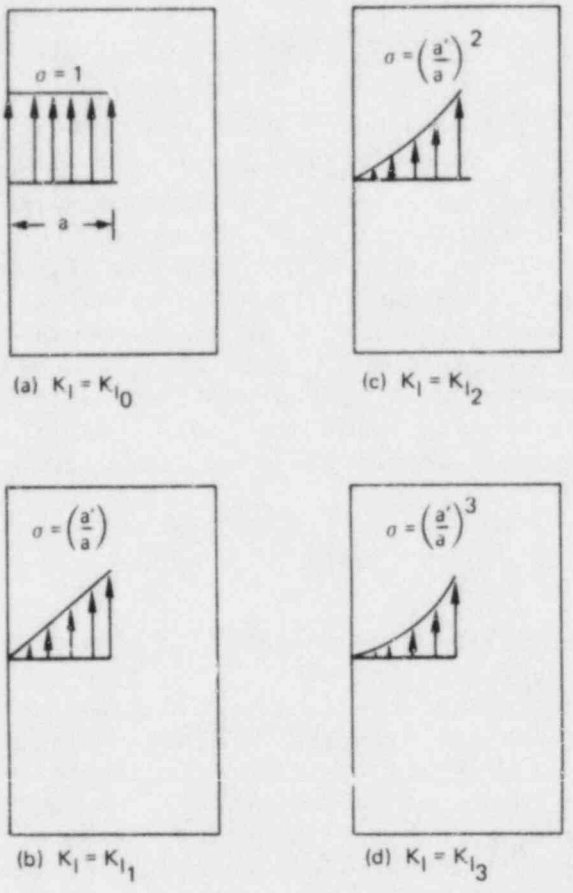

Fig. 2.4. Crack-surface loading cases for determining 3-D flaw influence coefficients.

where ϕ is the elliptical angle denoting the point on the crack front, and the crack-depth notation (a) has been dropped.

3. CALCULATION AND EVALUATION OF INFLUENCE COEFFICIENTS FOR SPECIFIC 3-D FLAWS

3.1 Computer Codes

For the present study, K_j^* was computed using the three-program system, ORMGEN[13] -ADINA[14] -ORVIRT,[15] which addresses linear or nonlinear fracture in 2- or 3-D crack configurations. ORMGEN automatically generates a complete 3-D finite element model of the cracked structure and creates data files that have formats compatible with ADINA, which is a structural analysis program. ADINA was modified to allow the application of the crack-face loads shown in Fig. 2.4. Special elements that introduce the appropriate stress singularity are used along the crack front.

ORVIRT acts as a postprocessor of the conventional ADINA analysis. It employs a virtual crack-extension technique for the calculation of energy release rates at specified points along the crack front.

3.2 Mesh Design

Figures 3.1 and 3.2 illustrate a typical ORMGEN mesh design for a semielliptical surface flaw and show the mesh in the plane of the flaw and in a plane normal to the fracture surfaces. For this particular design, the number of elements in the azimuthal and axial directions, the number of rings of elements in the ligament from the crack front to the outer wall, the number of elements along the crack front, and the number of elements through the cladding must be included. A geometric progression factor was used with the first three categories of elements.

3.3 Mesh Convergence Studies

In the process of calculating the influence coefficients, careful attention was paid to using adequately converged FE meshes and appropriate cylinder lengths. The number of elements in each category of elements was increased, one category at a time, to the point where the addition of one element in a single category changed the value of K_I by less than 1%. The resultant converged meshes for a 90°, half-length segment of the cylinder had ~8700 degrees of freedom.

Convergence of the K_I values was examined at all points along the crack front, except for the case in which the number of elements along the crack front was varied; for this case, only the K_I value at the deepest point was examined. Also, because convergence was more sensitive to details of the mesh design for the deeper flaws, most of the mesh convergence studies were based on rather deep flaws ($a/w = 0.8$).

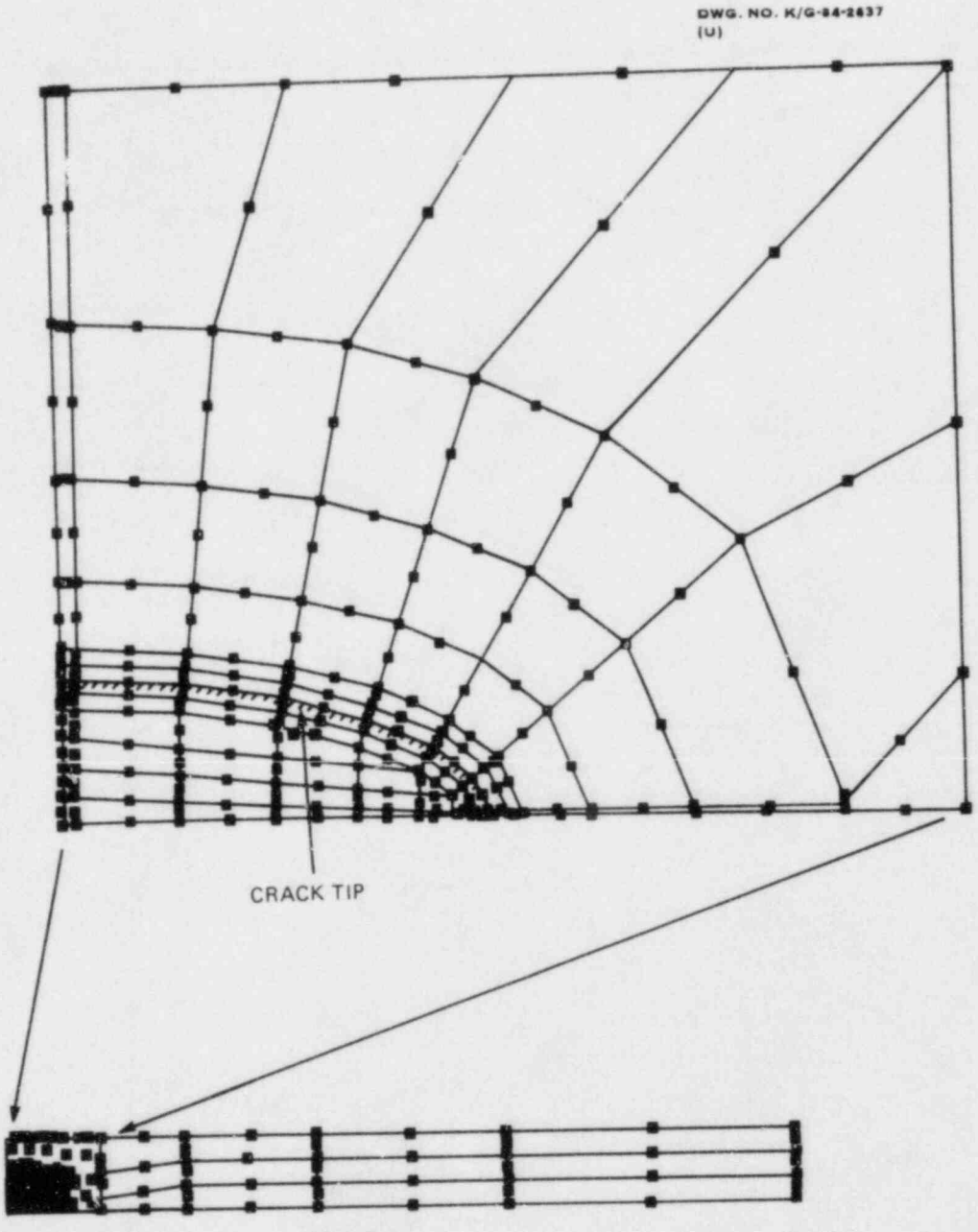

Fig. 3.1. Sample mesh in crack plane for a/w = 0.2, c/a = 2.5.

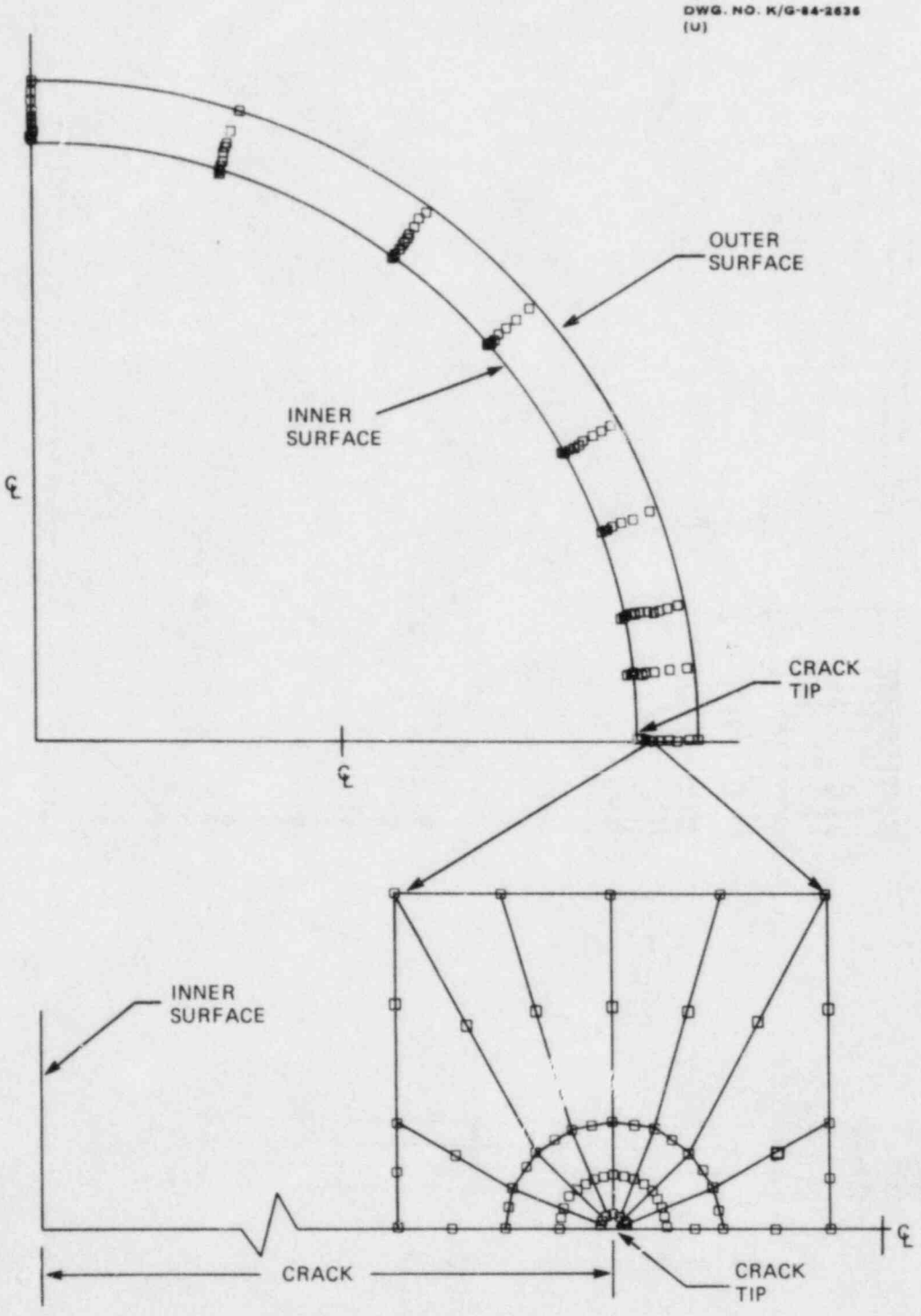

Fig. 3.2. Sample mesh viewed from axial direction.

3.4 90° vs 180° Model

To minimize demands on the computer, only a 90° segment of the cylinder was used in the calculation of the influence coefficients (Fig. 3.3). This corresponds to having flaws at 0° and 180° (two flaws opposite each other); however, as illustrated below, the error in using these same coefficients for a single flaw, which would require a 180° segment to be exact, is reasonably small for the flaws of interest.

The difference in K_I values associated with the 90° and 180° models increases with the length and depth of the flaw. Reference 10 states that the difference for a 2-D flaw with a/w = 0.8 is only 2%, but it appeared that this conclusion was based on an analysis that used an inappropriate model. Thus, a separate comparison analysis was performed for a 2-D inner-surface axial flaw in a typical PWR vessel. The 90° and 180° models are shown in Fig. 3.3. The cylinder dimensions were those indicated in this figure, and the thermal loading was that shown in Fig. 3.4. This loading is characteristic of a typical postulated severe thermal transient for a PWR.

Results of the 2-D comparison analysis (Table 3.1) show that for a/w = 0.8, the 90° model results in a 30% higher value of K_I. Because this value is rather large, a similar comparison was made for the 2-m flaw with a/w = 0.8. For this case, the K_I value for the 90° model was only 4% higher. Because the difference would be even less for shallower flaws of the same length, and because this study was not concerned with 3-D flaw lengths greater than 2 m, it was concluded that for the purposes at hand, the difference between the 90° and 180° models was negligible.

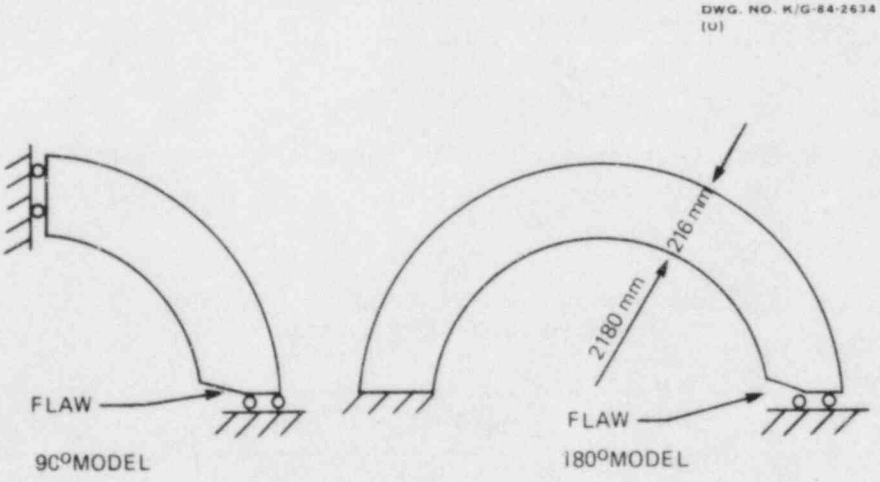

Fig. 3.3. 90° and 180° models used for determining difference in K_I values for single axial flaw and two opposite flaws.

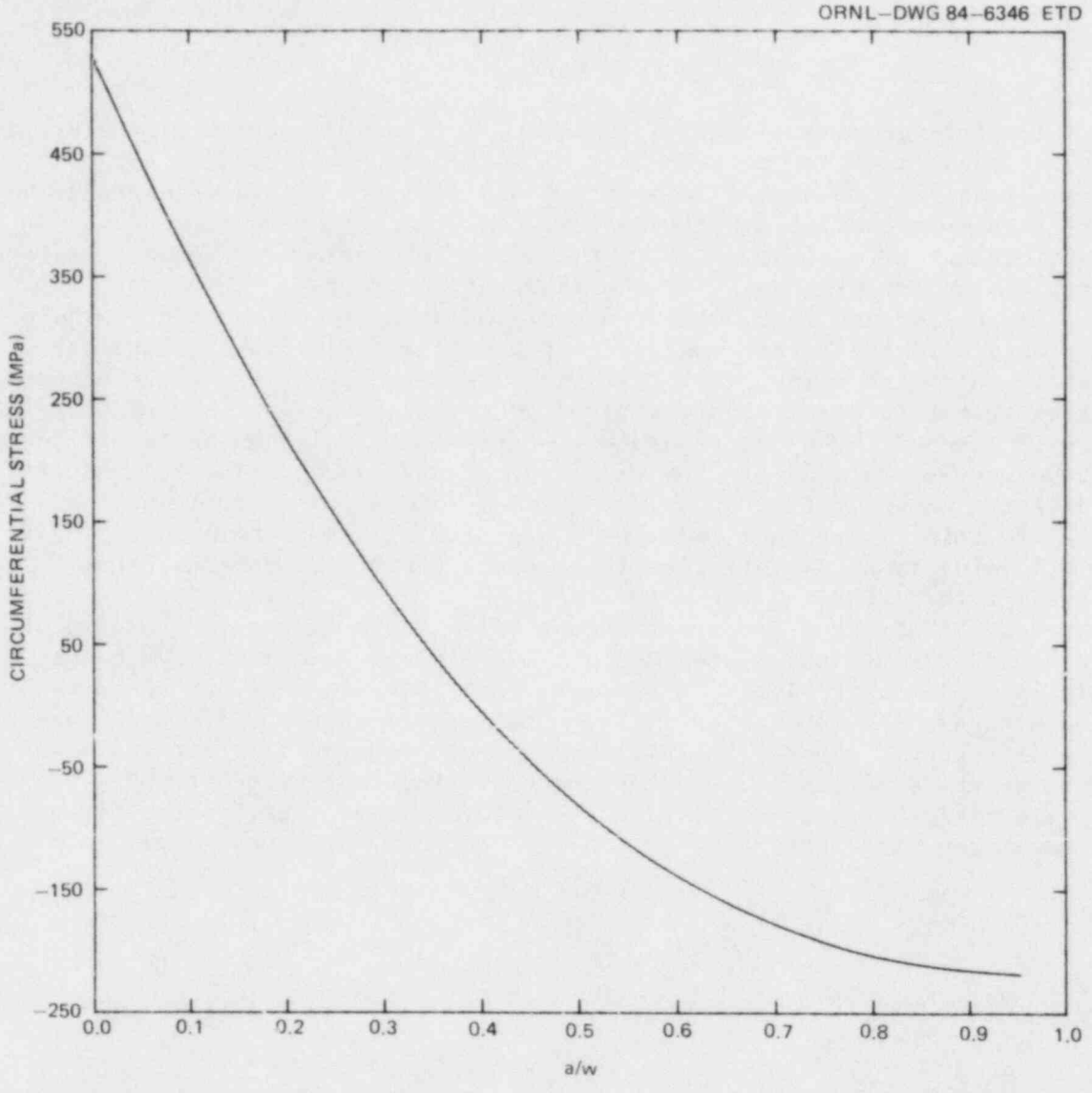

Fig. 3.4. Thermal stress profile in PWR used for comparison calculation of K_I in Table 3.1.

Table 3.1. Comparison of K values for 2-D flaws in 90° and 180° models

a/w	$\frac{K_I(90°) - K_I(180°)}{K_I(180°)} \times 10^2$ (%)
0.1	0.4
0.4	3.5
0.8	30.4

3.5 Length of Cylinder

With regard to cylinder length, a minimum incremental length of cylinder that could be added to the length of the flaw to negate end effects was estimated from Eq. (6) (Ref. 16):

$$\ell = \frac{2\pi}{\beta} , \tag{6}$$

where

$$\beta^4 = \frac{3(1 - \nu^2)}{R_i^2 \, w^2} ,$$

R_i = radius of cylinder,
w = wall thickness,
ν = Poisson's ratio.

For the cylinder radial dimensions given in Fig. 3.3, $\ell \approx 3300$ mm. A 3-D analysis, using the 2-m flaw and a typical transient, indicated that this added length was not sufficient to reduce end effects below ~5% at all points on the crack front, and that the required length to reduce end effects below 2% would be greater than the length of a typical PWR vessel between the lower head and the nozzle ring. It was decided that for the 2-m flaw, a cylinder length of 7010 mm would be appropriate. A similar analysis for the 6/1, inner-surface, semielliptical flaw with a maximum fractional depth of 0.2 indicated an appropriate length of 4670 mm. In both cases, the ends of the cylinder were free.

3.6 Adequacy of Third-Order Polynomial to Represent Stress Distribution

The adequacy of a third-order polynomial to represent the stress distribution was investigated by calculating K_I values by both the superposition and direct FE techniques. The first comparison was for the 2-m inner-surface flaw in a PWR with $a/w = 0.6$ and the loading indicated in Fig. 3.5. The results of this comparison analysis indicate a maximum difference of ~1% along the crack front (Fig. 3.6).

The second comparison was for the 1-m, axially oriented, outer-surface flaw in a pressurized-thermal-shock-experiment (PTSE) test vessel (a/w = 0.1 and 0.6). The applied load is shown in Fig. 3.7, and the results are given in Fig. 3.8. Again, good agreement was obtained.

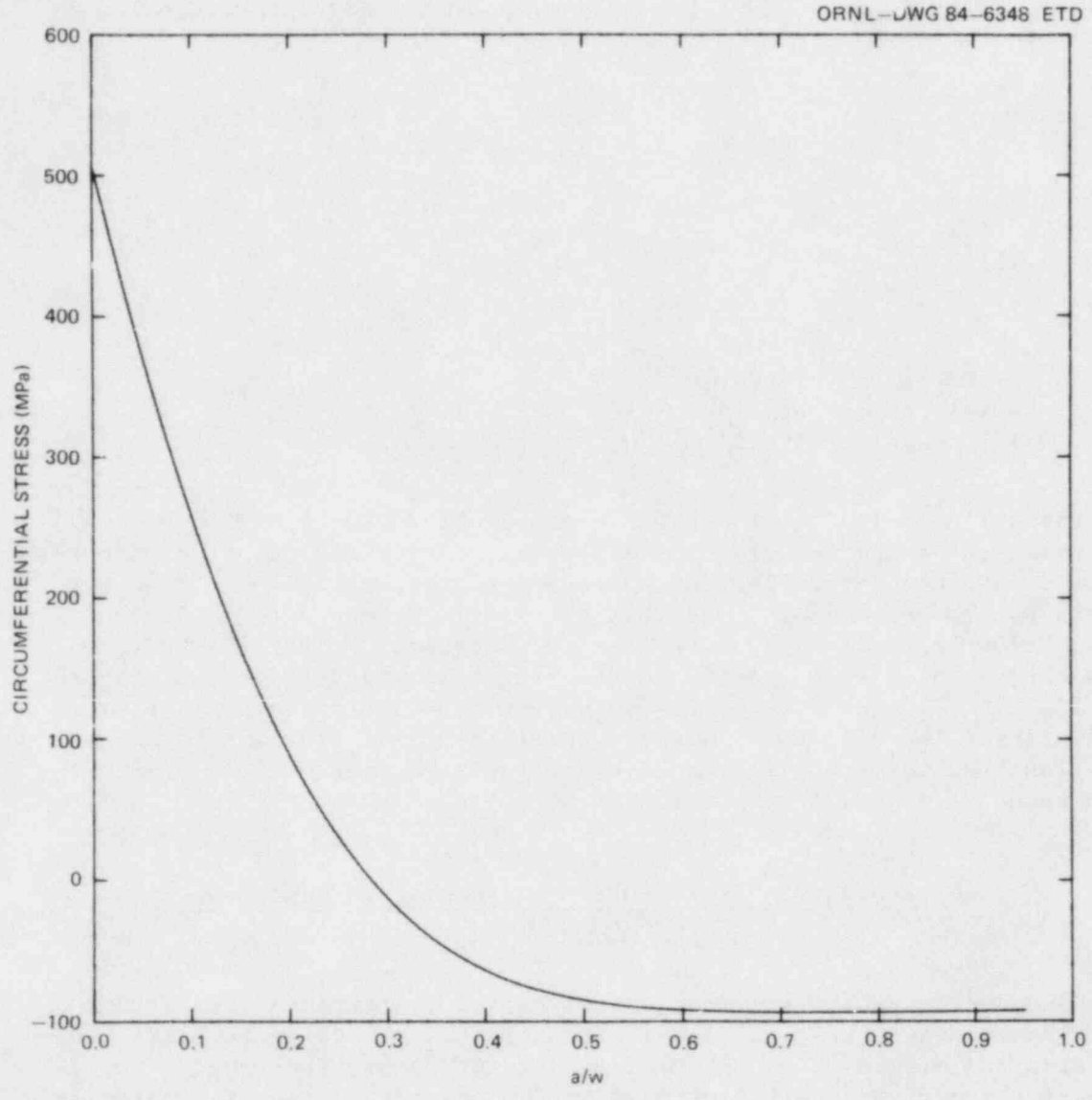

Fig. 3.5. Thermal stress profile in PWR used to calculate K_I given in Fig. 3.6.

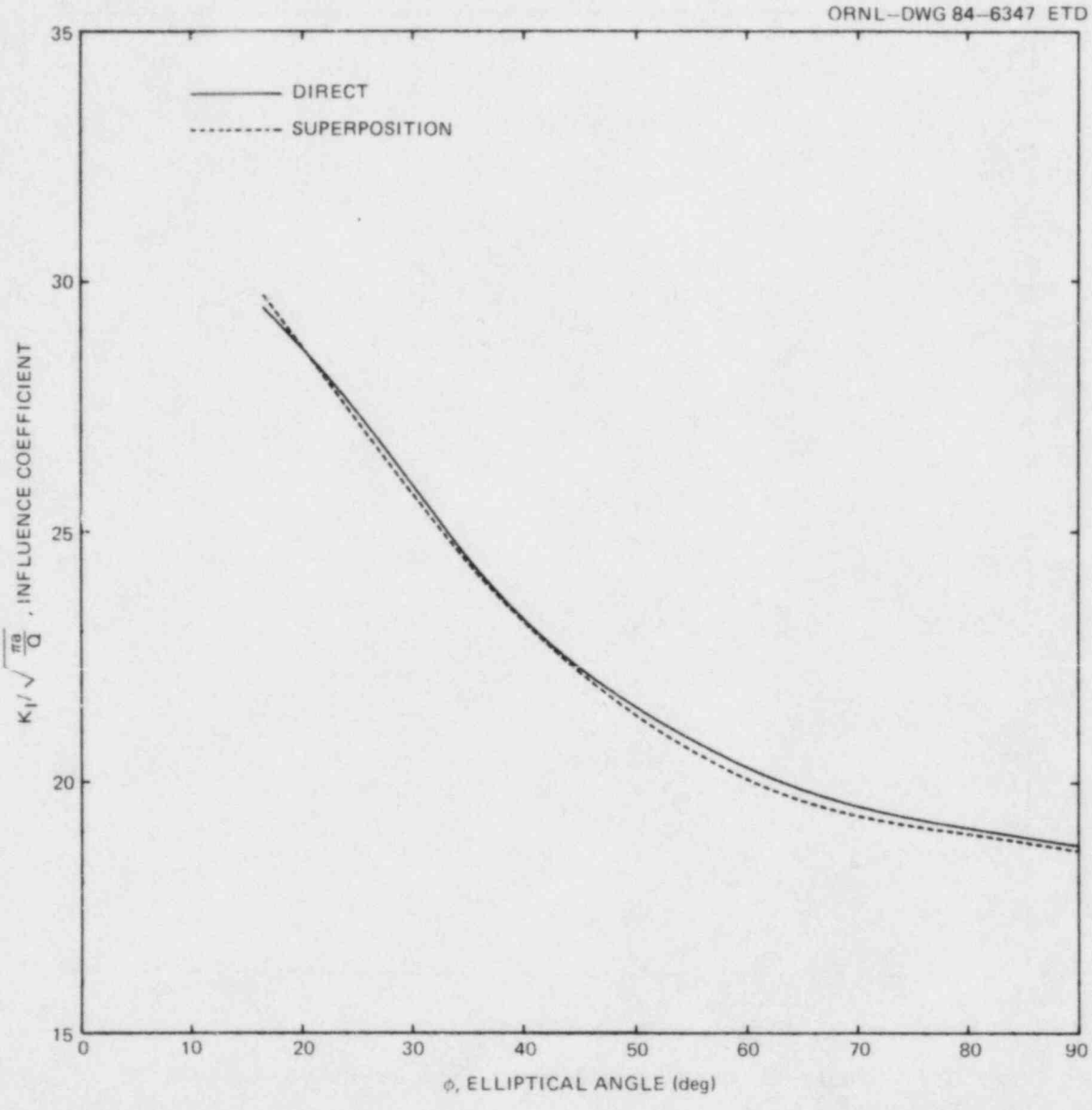

Fig. 3.6. Comparison of K_I values calculated by superposition and direct FE techniques for axially oriented, inner-surface 2-m flaw (a/w = 0.6) in PWR vessel during severe thermal transient.

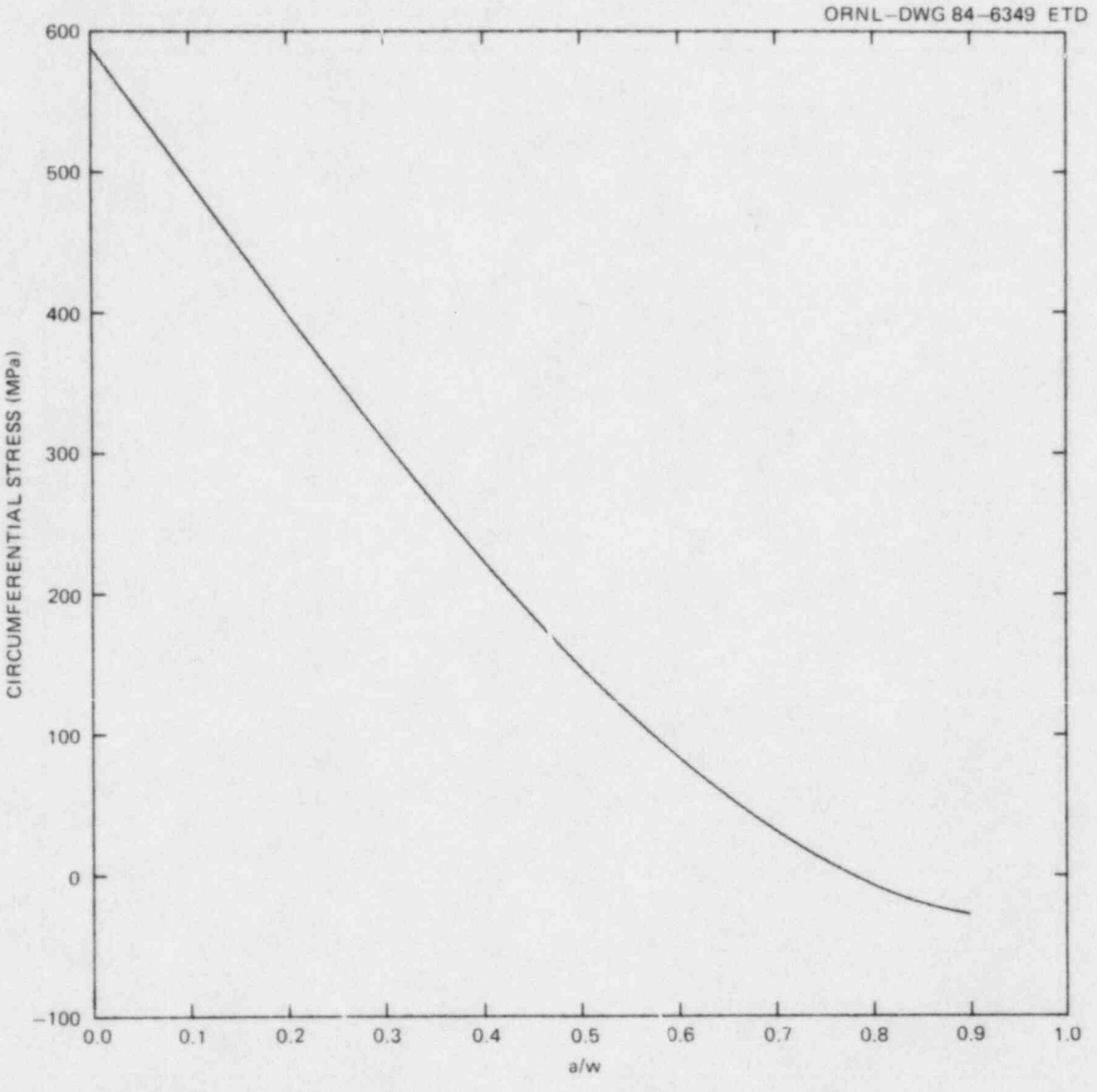

Fig. 3.7. Thermal stress profile in PTSE test vessel used to calculate K_I given in Fig. 3.8.

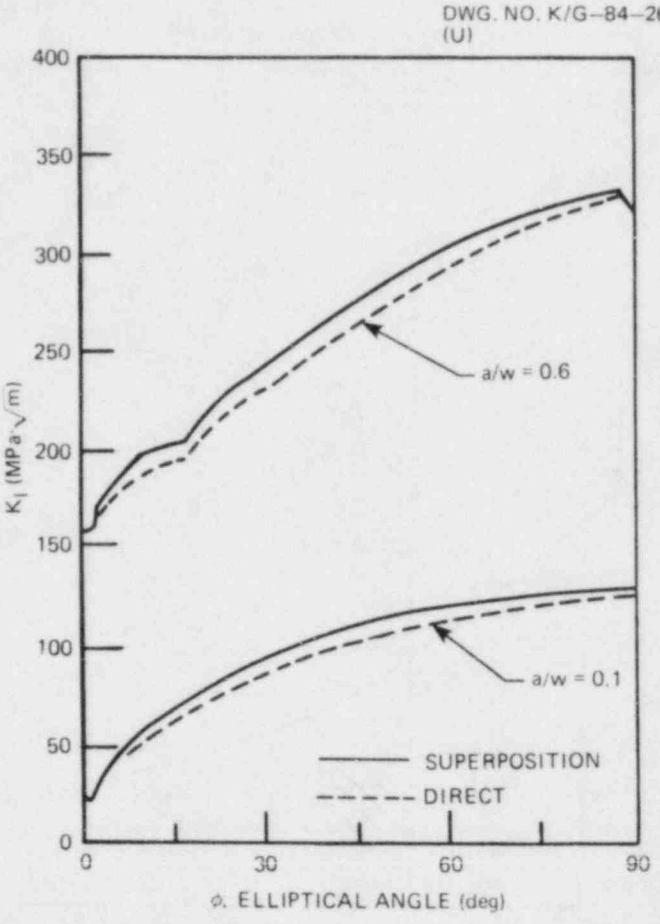

Fig. 3.8. Comparison of 3-D superposition with 3-D direct analysis for axially oriented, outer-surface 1-m flaw in PTSE test vessel.

3.7 Accommodation of Cladding

The presence of a thin layer of stainless steel cladding on the inner surface of PWR pressure vessels has a significant effect on the K_I values for inner-surface flaws because of very high thermal stresses generated in the cladding during a thermal transient. To accommodate the stress discontinuity associated with the cladding, influence coefficients were calculated for the cladding stresses alone; the corresponding K_I value can then be superimposed on the K_I value due to the stresses in the base material. As indicated in Fig. 3.9, this is accomplished by first calculating a K_I value for a continuous-function stress distribution that is obtained by a linear extrapolation into the cladding of the stress distribution in the base material. Then a K_I value is calculated for a stress distribution in the cladding that is obtained by subtracting the extrapolated distribution from the actual distribution in the cladding, which is also assumed to be linear. The total K_I value is simply the sum of the two. Because the stress distribution in the cladding is essentially linear, it is represented by a first-order polynomial.

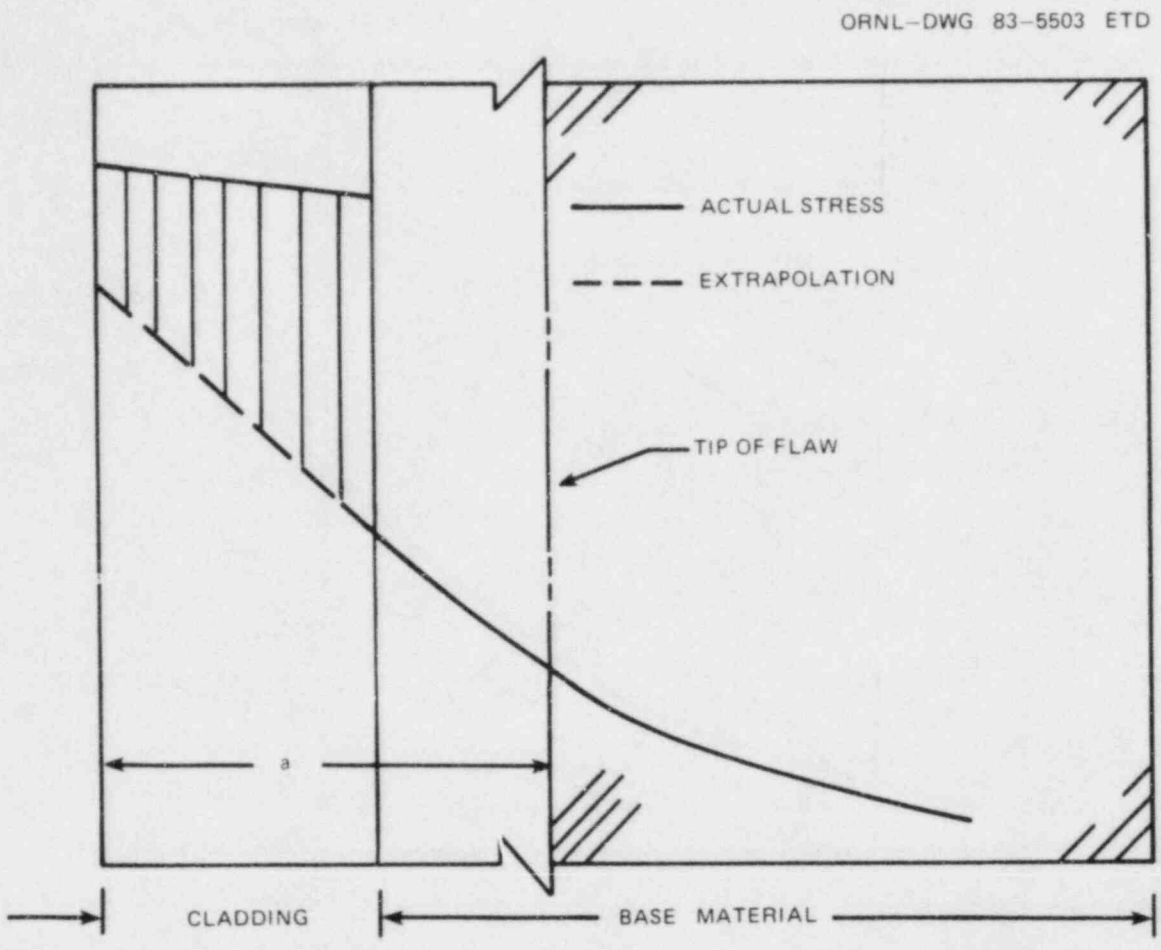

Fig. 3.9. Stress distributions used in superposition techniques for including effect of cladding on K_I.

4. COMPARISON WITH OTHER INVESTIGATORS

A comparison of some of the 3-D influence coefficients derived herein with similar coefficients obtained by other investigators[8-10] is shown in Figs. 4.1–4.3. (To compare the coefficients with those obtained from the closed-form solution for a buried elliptic flaw in an infinite medium with a uniform stress normal to the crack plane, the influence coefficients in Figs. 4.1–4.3 represent K_I values divided by $\sqrt{\pi a/Q}$, where Q is the square of the complete elliptic integral of the second kind.) As indicated in the figures, the coefficients being compared pertain to axially oriented, inner-surface flaws in a long cylinder with a/w = 0.2, 0.5, and 0.8; c/a = 2.5 and 3.0; and R_o/R_i = 1.10 (refer to Fig. 2.3).

The results of the comparison indicate good agreement, with our values being slightly higher and the biggest difference (7%) at the deepest point occurring for the cubic stress distribution. Furthermore, for a shallow flaw (a/w = 0.2, see Appendix B) the influence coefficients for a uniform stress and $\phi = \pi/2$ are ~1.10. This is consistent with estimates of the front-face correction factor that is applied to the buried-

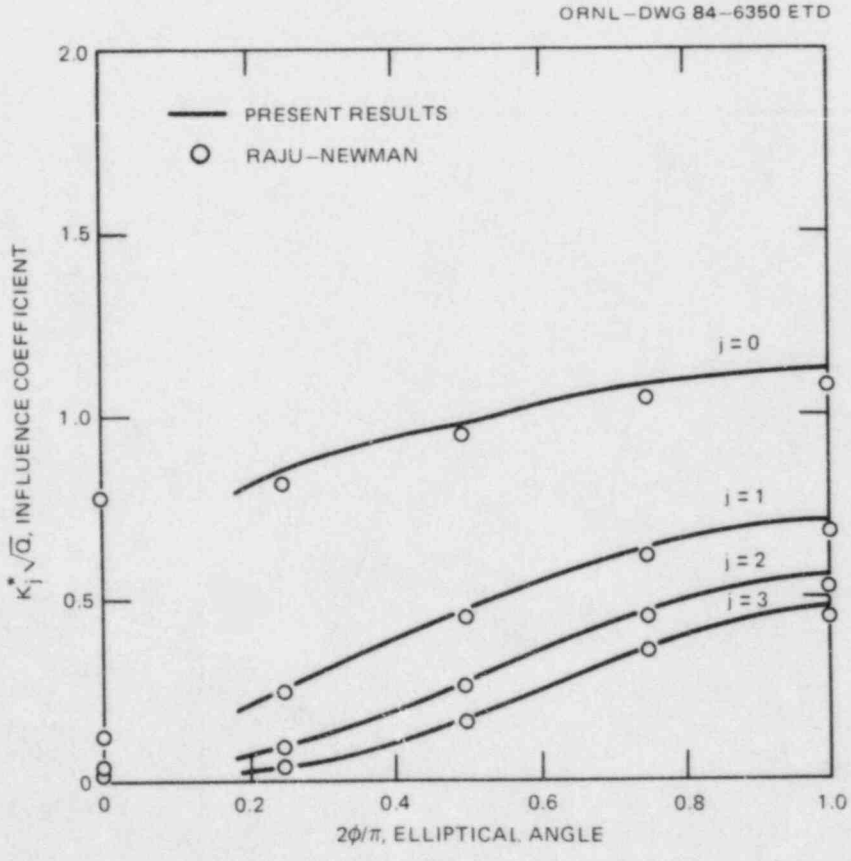

Fig. 4.1. Influence coefficients for longitudinal semielliptical crack on inner surface of cylinder: a/w = 0.2, c/a = 2.5, R_o/R_i = 1.1.

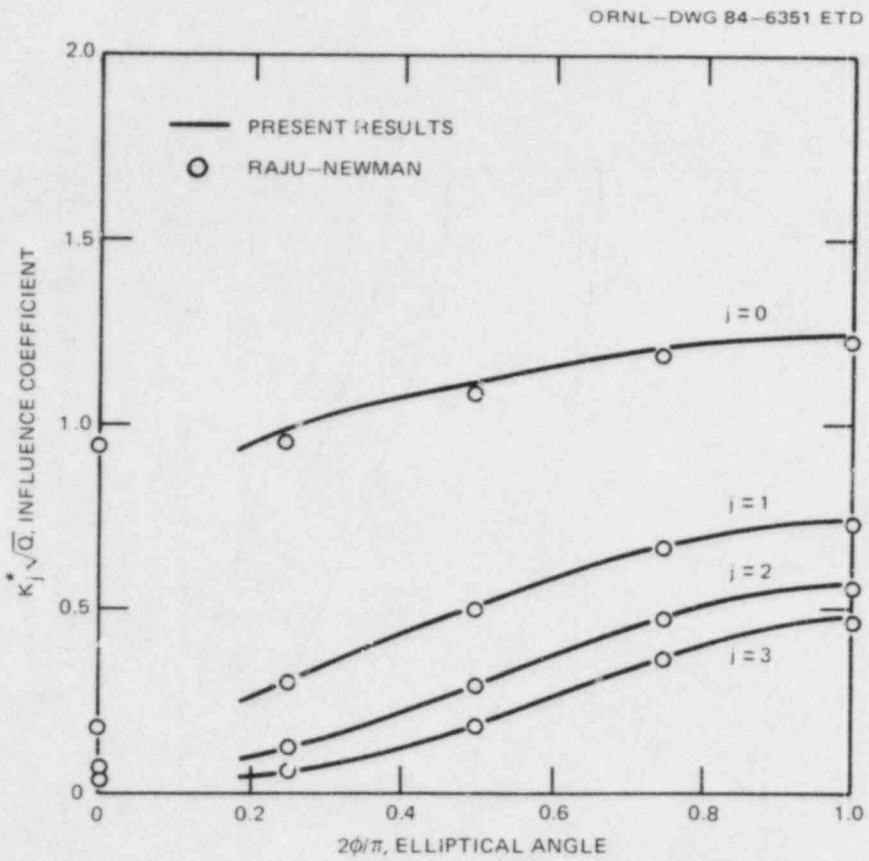

Fig. 4.2. Influence coefficients for longitudinal semielliptical crack on inner surface of cylinder: a/w = 0.5, c/a = 2.5, R_o/R_i = 1.1.

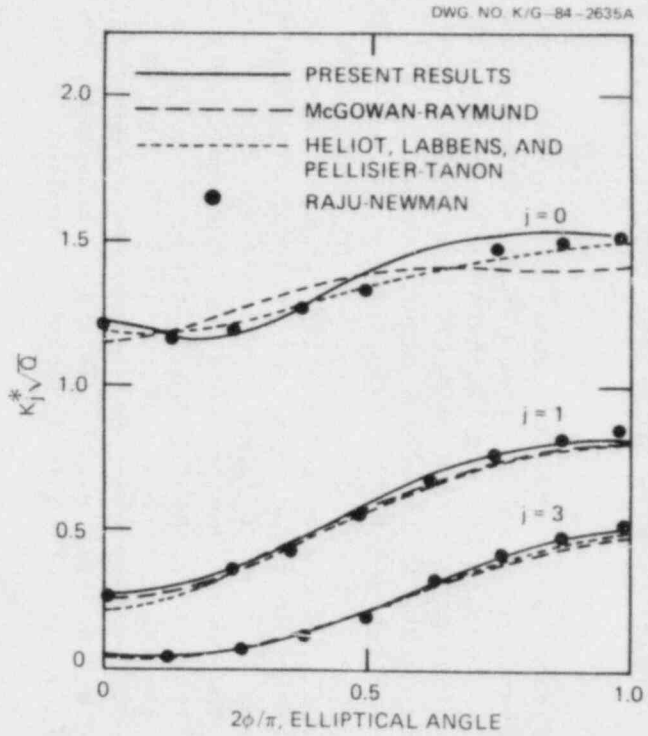

Fig. 4.3. Influence coefficients for longitudinal semielliptical crack on inner surface of cylinder: a/w = 0.8, c/a = 3, R_o/R_i = 1.1.

ellipse K_I value to obtain the K_I value for a semielliptical surface flaw in a semi-infinite medium.[17] For deeper flaws, the finiteness of the wall becomes apparent; that is, the coefficients become larger than those for the semi-infinite medium.

5. INFLUENCE COEFFICIENTS FOR SPECIFIC APPLICATIONS

5.1 Pressurized-Water Reactor

Flaws in a PWR pressure vessel are most likely to be located in the welds that join the segments of the vessel. For most of the vessels in operation today, radiation embrittlement is greater in the welds than in the base material because of higher concentrations of copper in the welds. Thus, although a flaw may extend in length as the result of an overcooling accident (OCA), the length of the flaw tends to be limited to the length of the weld. For many of the plate-type vessels, which have both axial and circumferential welds in the belt-line region, the length of the axial welds is ~2 m, which is equal to the height of a shell course. Recent calculations[18] indicate that the stress-intensity factor for a deep axial flaw of this length is substantially less than for an infinitely long (2-D) flaw, which has been used extensively in the evaluation of vessel integrity during OCAs. Thus, replacement of the 2-D axial flaw with the 2-m axial flaw in crack-growth models could represent a benefit in terms of projected vessel lifetime. For this reason, influence coefficients for 2-m semielliptical, axial flaws were calculated and are included in Appendix A.

Another finite-length flaw of interest, particularly for initial flaws, is a semielliptical flaw with a surface-length-to-depth ratio of 6/1. There is no particular technical justification for using this specific initial flaw in the analysis of OCAs except that, presumably, initial flaws are much more likely to be short than long. With this in mind, and also because other investigators have included the 6/1 flaw in their studies, coefficients for a 6/1 flaw were calculated and are given in Appendix B.

5.2 Pressurized-Thermal-Shock-Experiment Test Vessel

An experimental program[19] is under way at Oak Ridge National Laboratory (ORNL) to examine the response of surface-cracked test vessels to time-dependent combined pressure and thermal loadings similar to those calculated for PWR postulated OCAs. The PTSE facility (Fig. 5.1) at ORNL subjects a heated thick-walled cylindrical test vessel with a long axial flaw on the outer surface to a sudden flow of chilled liquid on the outside surface and to a prescribed pressure transient on the inner surface. Data from these experiments will be used to help validate methods of fracture analysis that are useful in predicting crack behavior for certain accident scenarios.

Influence coefficients were calculated for the flaw in Fig. 5.1, assuming that the flaw was semielliptical in shape and that it would grow in depth but not length. Coefficients were obtained for several crack depths and several positions on the crack front. These values are presented in Appendix C.

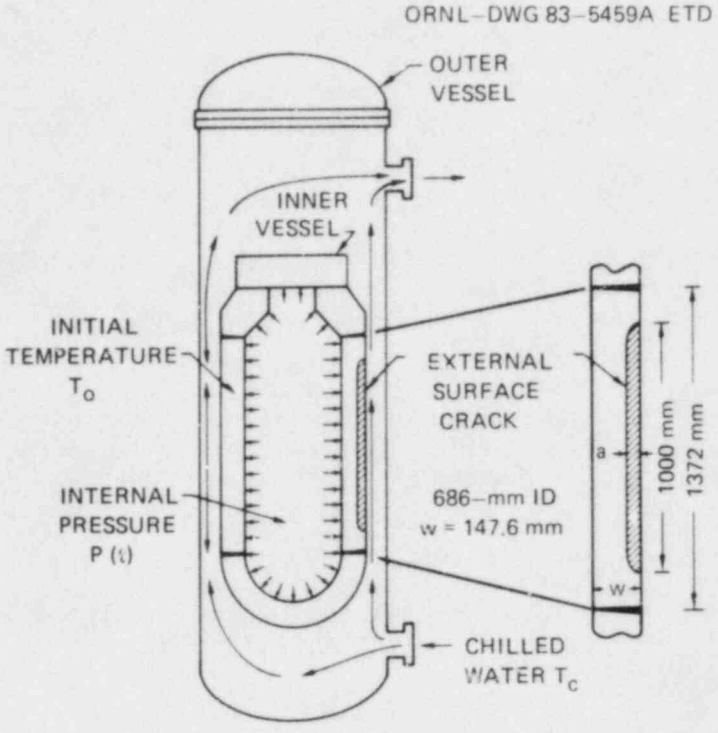

Fig. 5.1. PTSE test vessel with longitudinal outer-surface crack.

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Appendix A

INFLUENCE COEFFICIENTS FOR THE 2-m FLAW IN A PWR

Influence coefficients are included for the 2-m flaw [an axially oriented, 1.83-m-long semielliptical inner-surface flaw in a cylinder with R_i = 2184.4 mm, w = 215.9 mm, and ℓ = 7010 mm; the cladding thickness is 5.4 mm (Table A.1)]. The coefficients are presented in terms of G_j, where $G_j = K_j^* \sqrt{Q}$, and Q is the square of the complete elliptic integral of the second kind. Figures A.1 and A.2 are graphs of the influence coefficients at the deepest point on the crack front vs a/w for the unclad cylinder and for the cladding area.

Table A.1. Influence coefficients for the 2-m flaw in a PWR

a/w	2φ/π	Unclad cylinder				Cladding	
		G_0	G_1	G_2	G_3	G_0	G_1
0.200	0.184	0.641	0.112	0.031	0.010	0.172	0.087
	0.263	0.753	0.197	0.062	0.014	0.161	0.082
	0.421	0.935	0.356	0.167	0.080	0.131	0.066
	0.579	1.082	0.516	0.306	0.195	0.120	0.061
	0.737	1.188	0.646	0.441	0.327	0.119	0.060
	0.895	1.249	0.723	0.530	0.423	0.123	0.062
	1.000	1.283	0.752	0.573	0.485	0.129	0.065
0.250	0.184	0.656	0.119	0.032	0.009	0.144	0.073
	0.263	0.778	0.208	0.069	0.022	0.134	0.067
	0.421	0.974	0.369	0.175	0.088	0.112	0.057
	0.579	1.131	0.531	0.315	0.203	0.107	0.054
	0.737	1.245	0.663	0.451	0.335	0.108	0.054
	0.895	1.313	0.742	0.540	0.431	0.112	0.056
	1.000	1.345	0.770	0.580	0.485	0.117	0.058
0.300	0.184	0.681	0.129	0.035	0.011	0.126	0.063
	0.263	0.813	0.221	0.077	0.029	0.116	0.059
	0.421	1.020	0.385	0.184	0.095	0.101	0.051
	0.579	1.186	0.548	0.325	0.210	0.099	0.049
	0.737	1.309	0.683	0.462	0.343	0.101	0.050
	0.895	1.384	0.765	0.552	0.440	0.105	0.052
	1.000	1.414	0.793	0.590	0.489	0.109	0.054
0.400	0.184	0.752	0.157	0.047	0.018	0.104	0.052
	0.263	0.899	0.251	0.093	0.040	0.097	0.049
	0.421	1.124	0.420	0.204	0.109	0.088	0.044
	0.579	1.309	0.589	0.347	0.226	0.089	0.044
	0.737	1.449	0.729	0.486	0.359	0.093	0.046
	0.895	1.535	0.815	0.578	0.457	0.096	0.048
	1.000	1.560	0.842	0.613	0.501	0.099	0.049
0.500	0.184	0.855	0.194	0.064	0.028	0.093	0.047
	0.263	1.016	0.291	0.113	0.052	0.088	0.044
	0.421	1.255	0.464	0.227	0.123	0.083	0.041
	0.597	1.454	0.638	0.372	0.242	0.085	0.042
	0.737	1.605	0.781	0.513	0.377	0.089	0.044
	0.895	1.698	0.870	0.607	0.475	0.092	0.046
	1.000	1.717	0.896	0.640	0.516	0.094	0.047
0.600	0.184	0.983	0.238	0.085	0.040	0.089	0.044
	0.263	1.155	0.337	0.136	0.065	0.085	0.042
	0.421	1.400	0.513	0.251	0.139	0.080	0.040
	0.579	1.603	0.687	0.398	0.258	0.083	0.041
	0.737	1.753	0.831	0.538	0.393	0.086	0.043
	0.895	1.842	0.919	0.632	0.491	0.088	0.044
	1.000	1.857	0.944	0.664	0.530	0.089	0.044

Table A.1 (continued)

a/w	2φ/π	Unclad cylinder				Cladding	
		G_0	G_1	G_2	G_3	G_0	G_1
0.700	0.184	1.135	0.288	0.109	0.053	0.087	0.044
	0.263	1.311	0.387	0.160	0.079	0.084	0.042
	0.421	1.552	0.562	0.276	0.153	0.080	0.040
	0.579	1.746	0.734	0.422	0.273	0.081	0.041
	0.737	1.880	0.875	0.562	0.408	0.083	0.041
	0.895	1.955	0.961	0.655	0.507	0.083	0.041
	1.000	1.968	0.986	0.688	0.546	0.083	0.041
0.800	0.184	1.290	0.336	0.131	0.066	0.086	0.043
	0.263	1.463	0.435	0.182	0.092	0.082	0.041
	0.421	1.675		0.295	0.164	0.078	0.039
	0.579	1.837	0.706	0.438	0.283	0.078	0.039
	0.737	1.954	0.908	0.582	0.422	0.076	0.038
	0.895	2.014	0.998	0.682	0.527	0.074	0.037
	1.000	2.049	1.034	0.722	0.573	0.075	0.038
0.900	0.184	1.449	0.383	0.152	0.077	0.086	0.043
	0.263	1.612	0.480	0.203	0.102	0.082	0.041
	0.421	1.789	0.639	0.312	0.174	0.077	0.038
	0.579	1.920	0.802	0.459	0.296	0.073	0.036
	0.737	2.021	0.959	0.619	0.449	0.066	0.033
	0.895	2.091	1.084	0.751	0.582	0.061	0.031
	1.000	2.169	1.149	0.814	0.648	0.061	0.031

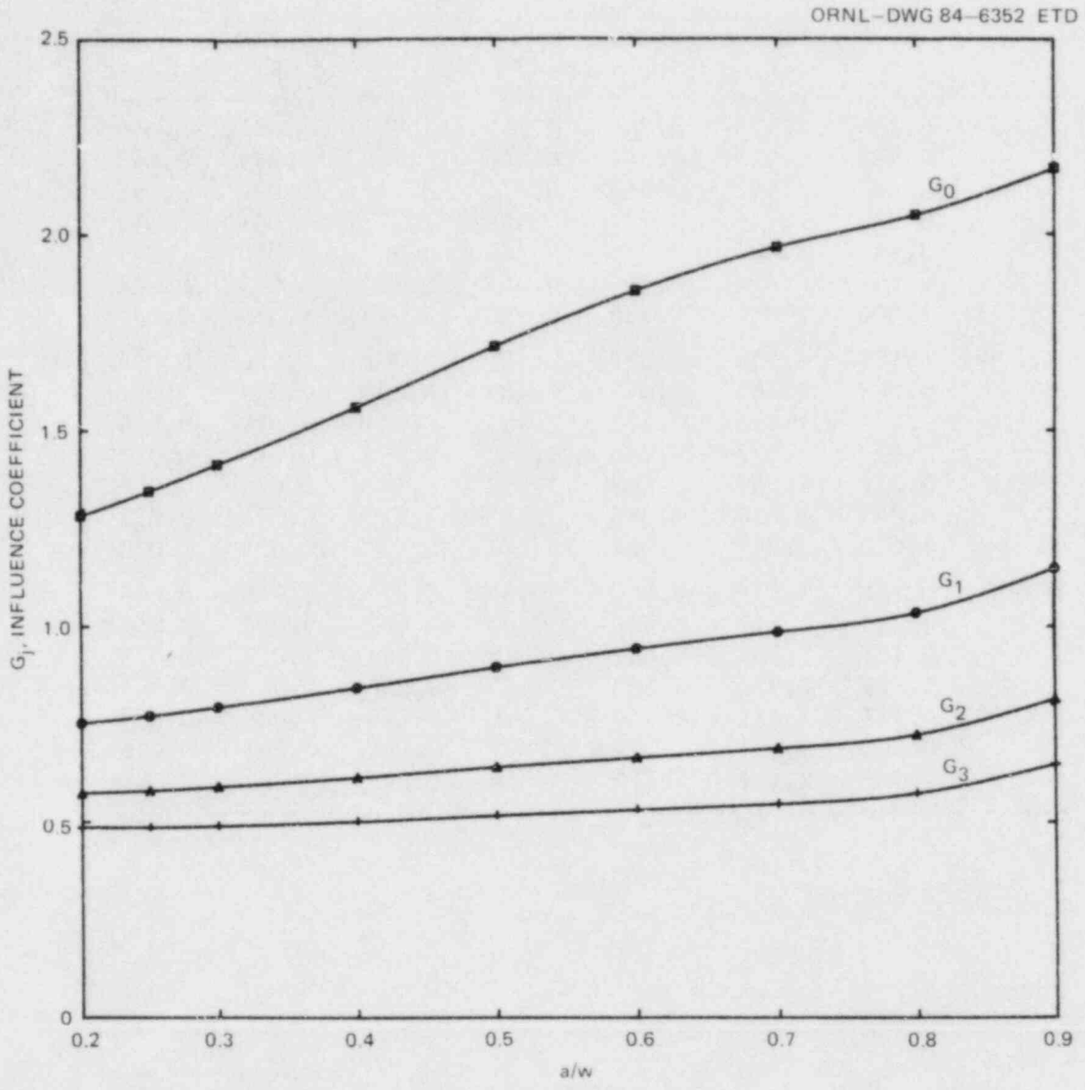

Fig. A.1. Influence coefficients for 2-m flaw at $\phi = 90°$.

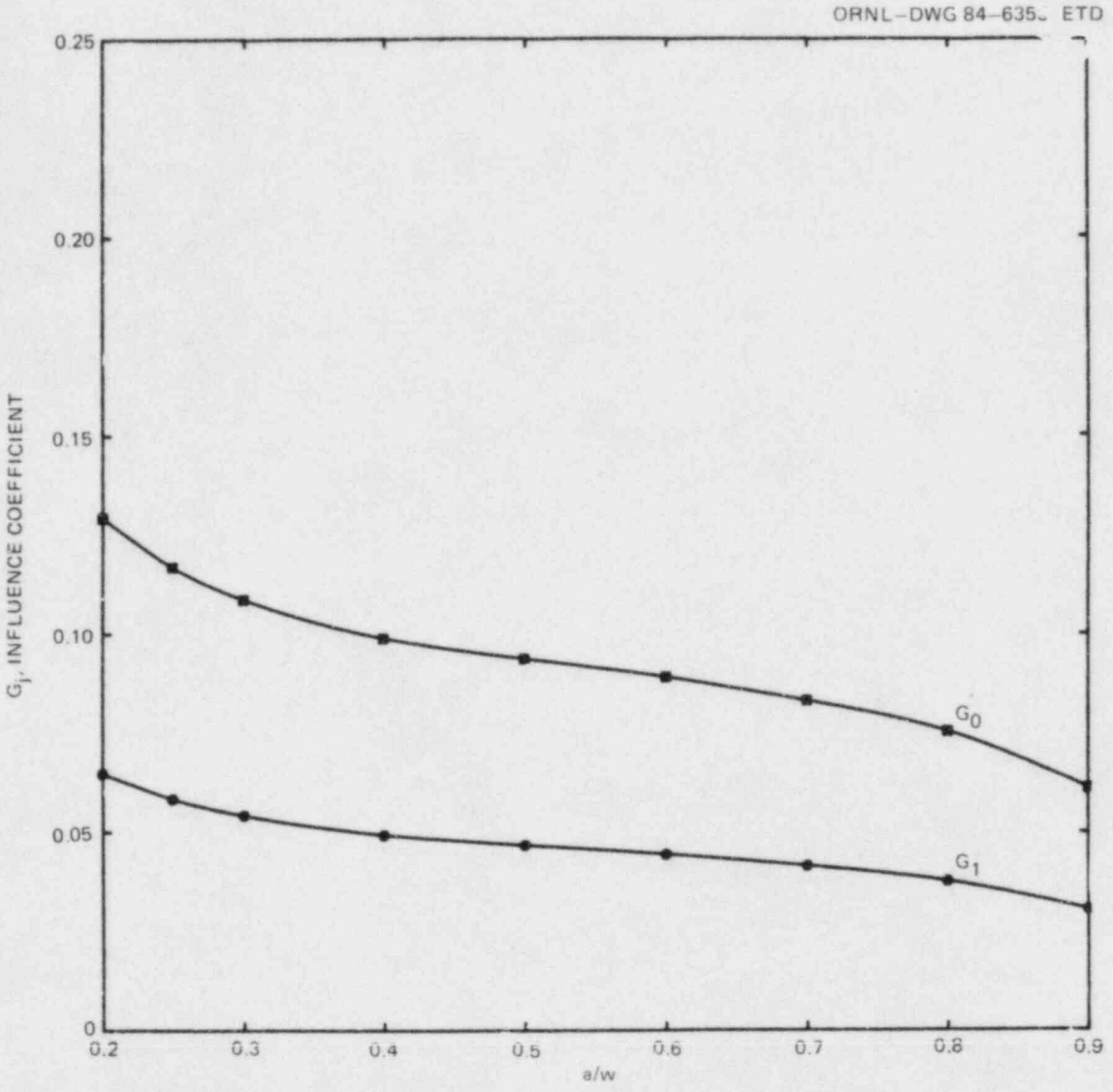

Fig. A.2. Cladding influence coefficients for 2-m flaw at $\phi = 90°$.

Appendix B

INFLUENCE COEFFICIENTS FOR THE 6/1 FLAW IN A PWR

Influence coefficients are included for the 6/1 flaw [an axially oriented, inner-surface flaw in a cylinder with a surface length-to-depth ratio of 6 and with R_i = 2184.4 mm, w = 215.9 mm, and ℓ = 4670 mm; the cladding thickness is 5.4 mm (Table B.1)]. The coefficients are presented in terms of G_j where $G_j = K_j^* \sqrt{Q}$, and Q is the square of the complete elliptic integral of the second kind. Figure B.1 is a graph of the influence coefficients at the deepest point on the crack front vs a/w for the unclad cylinder.

Table B.1. Influence coefficients for the 6/1 flaw in a PWR

a/w	$2\phi/\pi$	Unclad cylinder				Cladding	
		G_0	G_1	G_2	G_3	G_0	G_1
0.050	1.000	1.180	0.779	0.611	0.515	[a]	[a]
0.075	0.184	0.776	0.173	0.051	0.019	[a]	[a]
	0.263	0.874	0.253	0.096	0.042	[a]	[a]
	0.421	0.977	0.398	0.201	0.111	[a]	[a]
	0.579	1.040	0.538	0.336	0.227	[a]	[a]
	0.737	1.087	0.651	0.466	0.359	[a]	[a]
	0.895	1.116	0.717	0.551	0.455	[a]	[a]
	1.000	1.126	0.737	0.579	0.489	[a]	[a]
0.100	0.184	0.752	0.173	0.053	0.020	[a]	[a]
	0.263	0.843	0.250	0.097	0.043	0.242	0.131
	0.421	0.938	0.390	0.199	0.111	0.192	0.105
	0.579	1.008	0.525	0.330	0.224	0.159	0.086
	0.737	1.066	0.635	0.456	0.352	0.153	0.081
	0.895	1.102	0.701	0.538	0.445	0.159	0.083
	1.000	1.114	0.721	0.565	0.478	0.163	0.085
0.150	0.184	0.746	0.177	0.056	0.022	0.180	0.093
	0.263	0.830	0.252	0.099	0.045	0.171	0.089
	0.421	0.923	0.387	0.199	0.111	0.127	0.066
	0.579	1.003	0.519	0.326	0.222	0.112	0.058
	0.737	1.070	0.627	0.448	0.347	0.113	0.058
	0.895	1.110	0.691	0.528	0.437	0.117	0.060
	1.000	1.122	0.710	0.555	0.469	0.120	0.061
0.200	0.184	0.751	0.182	0.059	0.024	0.147	0.075
	0.263	0.834	0.256	0.101	0.046	0.134	0.069
	0.421	0.928	0.388	0.199	0.112	0.100	0.051
	0.579	1.013	0.518	0.325	0.221	0.092	0.047
	0.737	1.081	0.624	0.445	0.344	0.094	0.047
	0.895	1.120	0.687	0.524	0.433	0.095	0.048
	1.000	1.132	0.706	0.550	0.465	0.097	0.049

[a] Not available at the time of this writing.

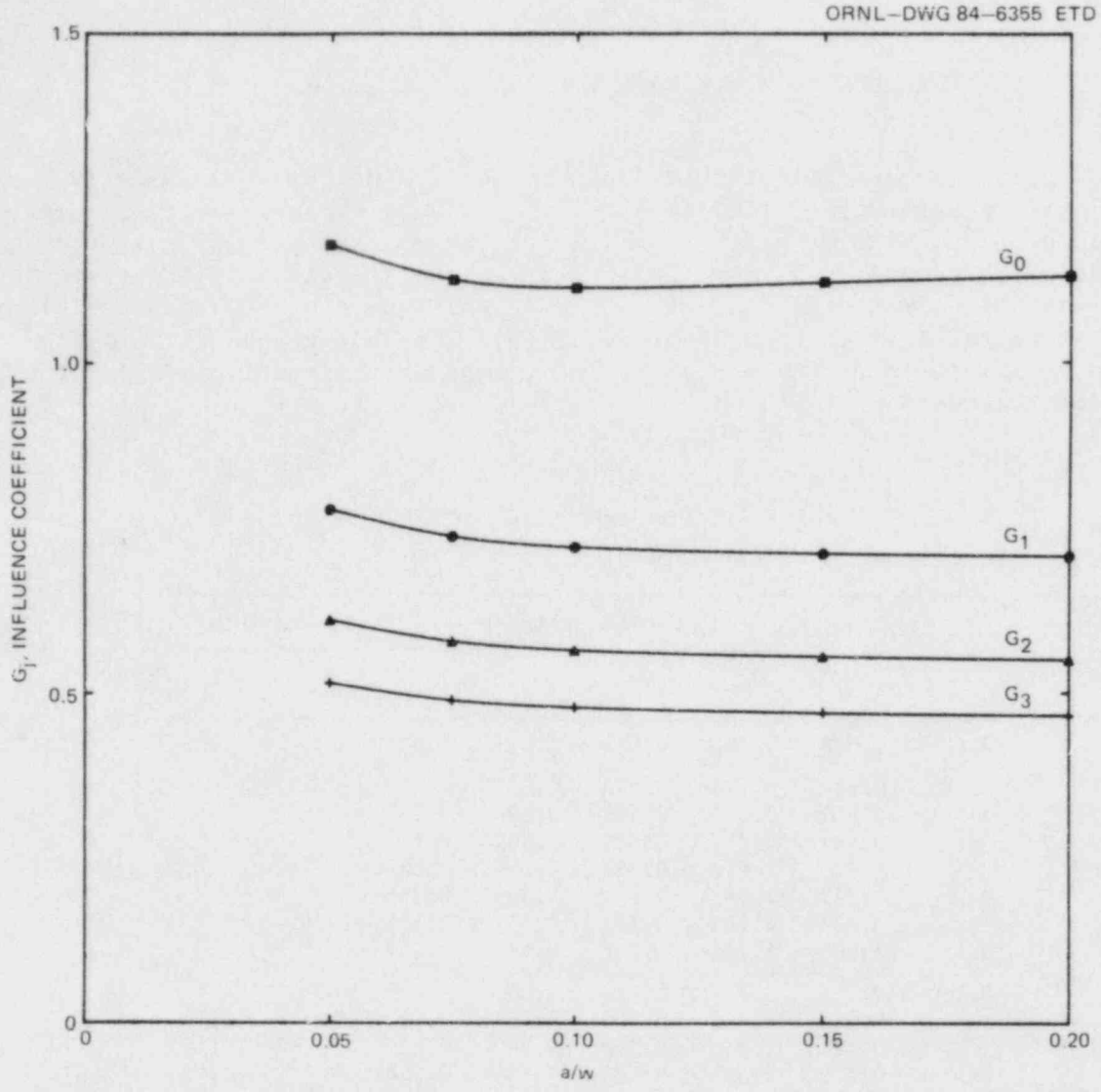

Fig. B.1. Influence coefficients for 6/1 flaw at $\phi = 90°$.

Appendix C

INFLUENCE COEFFICIENTS FOR THE 1-m FLAW IN A PTSE VESSEL

Influence coefficients are included for the 1-m flaw [an axially oriented, 1.0-m-long, semielliptical, outer-surface flaw in a cylinder with R_i = 342.9 mm and w = 152.4 mm (Table C.1)]. The coefficients are presented in terms of G_j where $G_j = K_j^* \sqrt{Q}$, and Q is the square of the complete elliptic integral of the second kind. Figure C.1 is a graph of the influence coefficients at the deepest point on the crack front vs a/w.

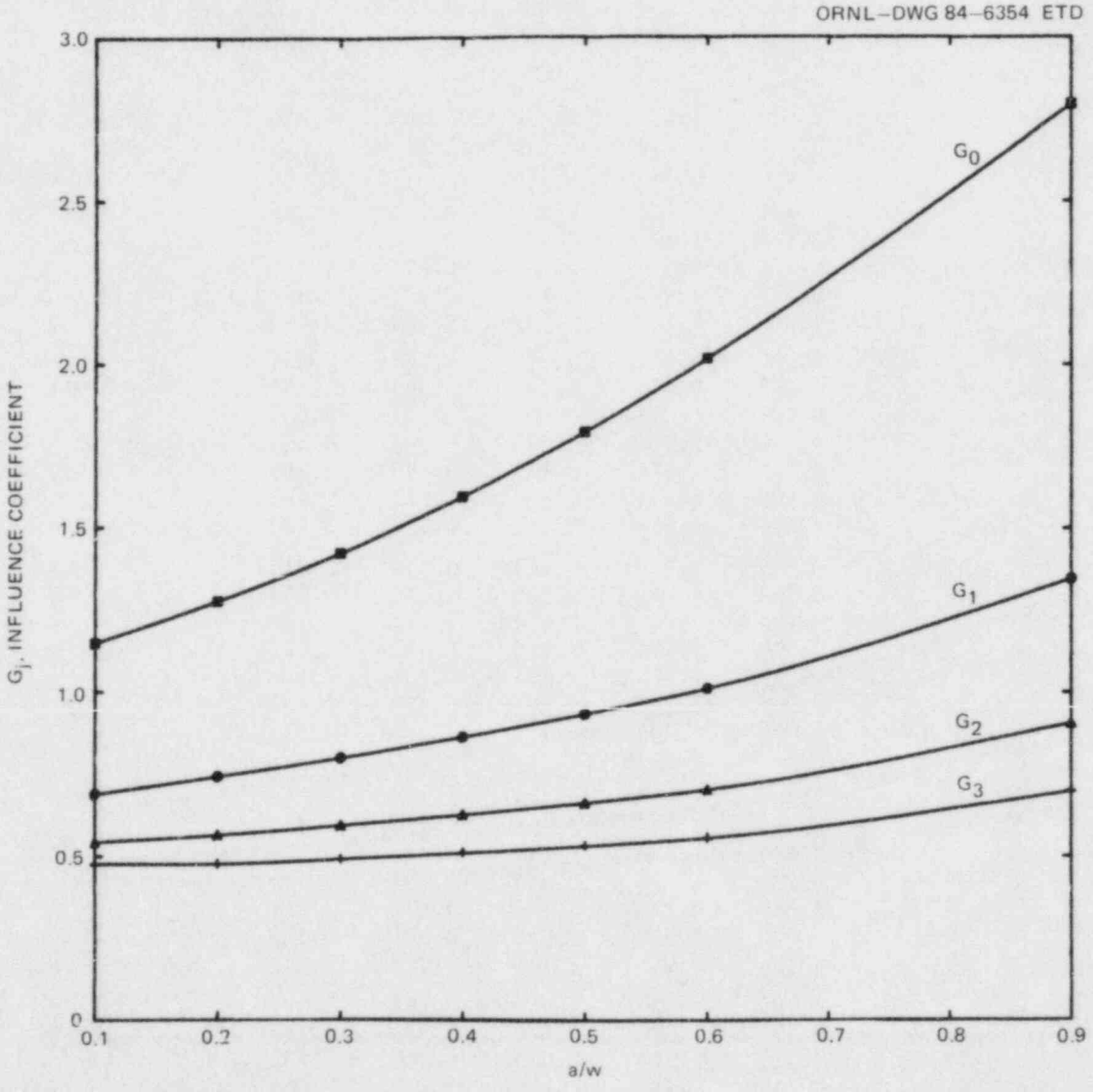

Fig. C.1. Influence coefficients for 1-m outer-surface flaw at deepest point (ϕ = 90°).

Table C.1. Influence coefficients for the 1-m flaw in a PTSE test vessel

a/w	$2\phi/\pi$	G_0	G_1	G_2	G_3
0.100	0.105	0.457	0.052	0.000	0.000
	0.263	0.695	0.175	0.042	0.000
	0.421	0.873	0.325	0.144	0.054
	0.579	0.994	0.471	0.275	0.167
	0.737	1.077	0.589	0.402	0.293
	0.895	1.124	0.660	0.485	0.385
	1.000	1.148	0.688	0.543	0.476
0.200	0.105	0.505	0.065	0.009	0.000
	0.263	0.744	0.192	0.060	0.015
	0.421	0.935	0.349	0.163	0.080
	0.579	1.082	0.506	0.301	0.193
	0.737	1.189	0.636	0.435	0.324
	0.895	1.253	0.716	0.524	0.421
	1.000	1.276	0.742	0.564	0.475
0.300	0.105	0.555	0.080	0.017	0.000
	0.263	0.795	0.210	0.071	0.025
	0.421	1.005	0.374	0.178	0.092
	0.579	1.182	0.542	0.322	0.209
	0.737	1.318	0.684	0.463	0.345
	0.895	1.402	0.772	0.557	0.444
	1.000	1.422	0.799	0.593	0.490
0.400	0.105	0.619	0.099	0.025	0.008
	0.263	0.860	0.233	0.083	0.033
	0.421	1.093	0.405	0.195	0.104
	0.579	1.302	0.585	0.345	0.225
	0.737	1.471	0.739	0.493	0.365
	0.895	1.578	0.836	0.592	0.468
	1.000	1.596	0.862	0.627	0.510
0.500	0.105	0.701	0.123	0.036	0.015
	0.263	0.945	0.263	0.098	0.042
	0.421	1.202	0.444	0.215	0.116
	0.579	1.445	0.635	0.372	0.242
	0.737	1.646	0.801	0.526	0.386
	0.895	1.777	0.907	0.630	0.492
	1.000	1.794	0.933	0.664	0.532
0.600	0.105	0.809	0.155	0.051	0.023
	0.263	1.056	0.300	0.116	0.053
	0.421	1.339	0.491	0.240	0.131
	0.579	1.617	0.694	0.402	0.262
	0.737	1.850	0.872	0.563	0.410
	0.895	2.001	0.985	0.671	0.519
	1.000	2.019	1.012	0.704	0.557
0.900	0.105	1.291	0.300	0.115	0.058
	0.263	1.534	0.459	0.192	0.096
	0.421	1.886	0.678	0.335	0.188
	0.579	2.242	0.917	0.520	0.335
	0.737	2.534	1.134	0.709	0.505
	0.895	2.727	1.290	0.851	0.641
	1.000	2.795	1.346	0.906	0.698

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In the fracture-mechanics analysis of reactor pressure vessels, stress-intensity-factor influence coefficients are used in conjunction with superposition techniques to reduce the cost of calculating stress-intensity factors. The present study uses a finite-element code, together with a virtual crack extension technique, to obtain influence coefficients for semielliptical surface flaws in a cylinder, and particular emphasis was placed on mesh convergence (less than 1% error was sought in the results from any one mesh construction parameter). Comparison of the coefficients with those obtained by other investigators shows good agreement. Furthermore, stress-intensity factors obtained by superposition for a severe thermal-transient loading condition agree within 1% of the values calculated by a direct finite-element method.

Influence coefficients were calculated for three specific axially oriented semielliptical surface flaws. The first was a 2-m-long inner-surface flaw in a nuclear reactor pressure vessel with depth-to-wall-thickness ratios between 0.2 and 0.9. The second was an inner-surface flaw in the reactor vessel with a surface-length-to-depth ratio of 6 and with depth-to-wall-thickness ratios between 0.05 and 0.2. The third was a 1-m-long flaw on the outer surface of a test vessel with depth-to-wall-thickness ratios between 0.1 and 0.9. For the reactor vessel, separate coefficients were calculated for the cladding on the inner surface and for the base-material region. This allows for an accurate accounting of the effect of thermal stresses in the cladding on the stress-intensity factor for surface flaws that extend through the cladding into the base material.

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