WISECRACK - A Fracture Mechanics Code for Lifetime Analysis of High Heat Flux Components in Fusion Reactors

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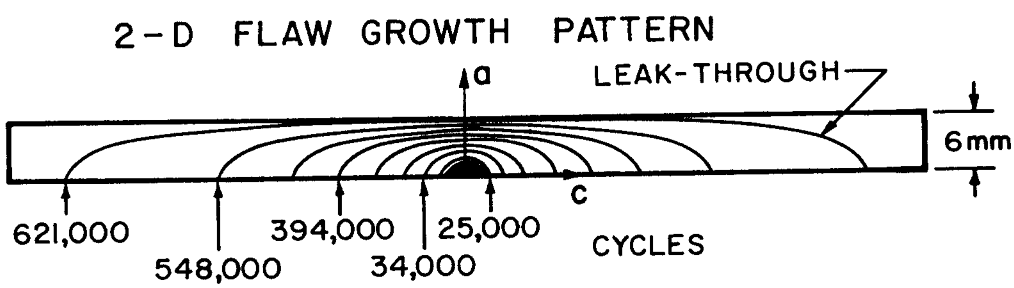
I. Introduction

The purpose of WISECRACK (Wisconsin semi-elliptical crack growth code) is to predict the lifetime of first walls, limiters, neutral beam dumps, divertor collector plates, or other high heat flux components used in fusion reactors. The component is modeled as a flat plate containing a small, pre-existent semi-elliptical surface flaw and is subjected to membrane loads, cyclic temperature gradients, irradiation creep and swelling, embrittlement, and wall erosion caused by sputtering or vaporization. The crack grows along both its major and minor axes due to the combined action of cyclic stresses (fatigue crack growth) and constant stresses at high temperatures (creep crack growth). Failure results when the crack either penetrates through the wall, therefore causing coolant to leak into the plasma chamber, or when the maximum stress intensity factor exceeds the material's fracture toughness and causes catastrophic fracture. Figure 1 illustrates a typical flaw growth pattern one might expect for a tokamak first wall component. In this example, WISECRACK predicted leak-through failure (leak-before-break) after 621,000 cycles of normal operation.[1]

Because of the unique environment in a fusion reactor, it was necessary to devise a special lifetime code that would include the effects of radiation damage and surface erosion. Table 1 highlights the important features of WISECRACK which make it an ideal choice for fusion applications.

Radiation damage and surface erosion have an impact also on the stresses and temperatures in these high heat flux components. For this reason, WISECRACK is designed to couple with the TSTRESS inelastic stress analysis code, written by R. Peterson[2]. TSTRESS in turn couples with a program written by G. Moses called WALL that solves the one-dimensional heat

Figure 1



Typical two-dimensional flaw growth pattern predicted by WISECRACK.

Table 1. Highlights of WISECRACK Code

Linear elastic fracture mechanics.

Semi-elliptical surface flaw in a flat plate.

Two-dimensional shape change growth model.

Time-dependent stress cycle (variable R-ratio).

Fatigue and creep crack growth rates linearly superimposed.

Leak-through and catastrophic fracture failure modes.

Bending stress intensity factor solutions.

Linearization over-the-crack of nonlinear stress gradients through the wall.

Fatigue crack growth model includes temperature effect, R-ratio effect, threshold ΔK, and embrittlement.

Short crack correction factor for $a_0 < 1$ mm.

Wall thinning and crack erosion included.

Neutron induced reduction in fracture toughness.

Fourth order Runge-Kutta numerical integration method with automatic step size selection.

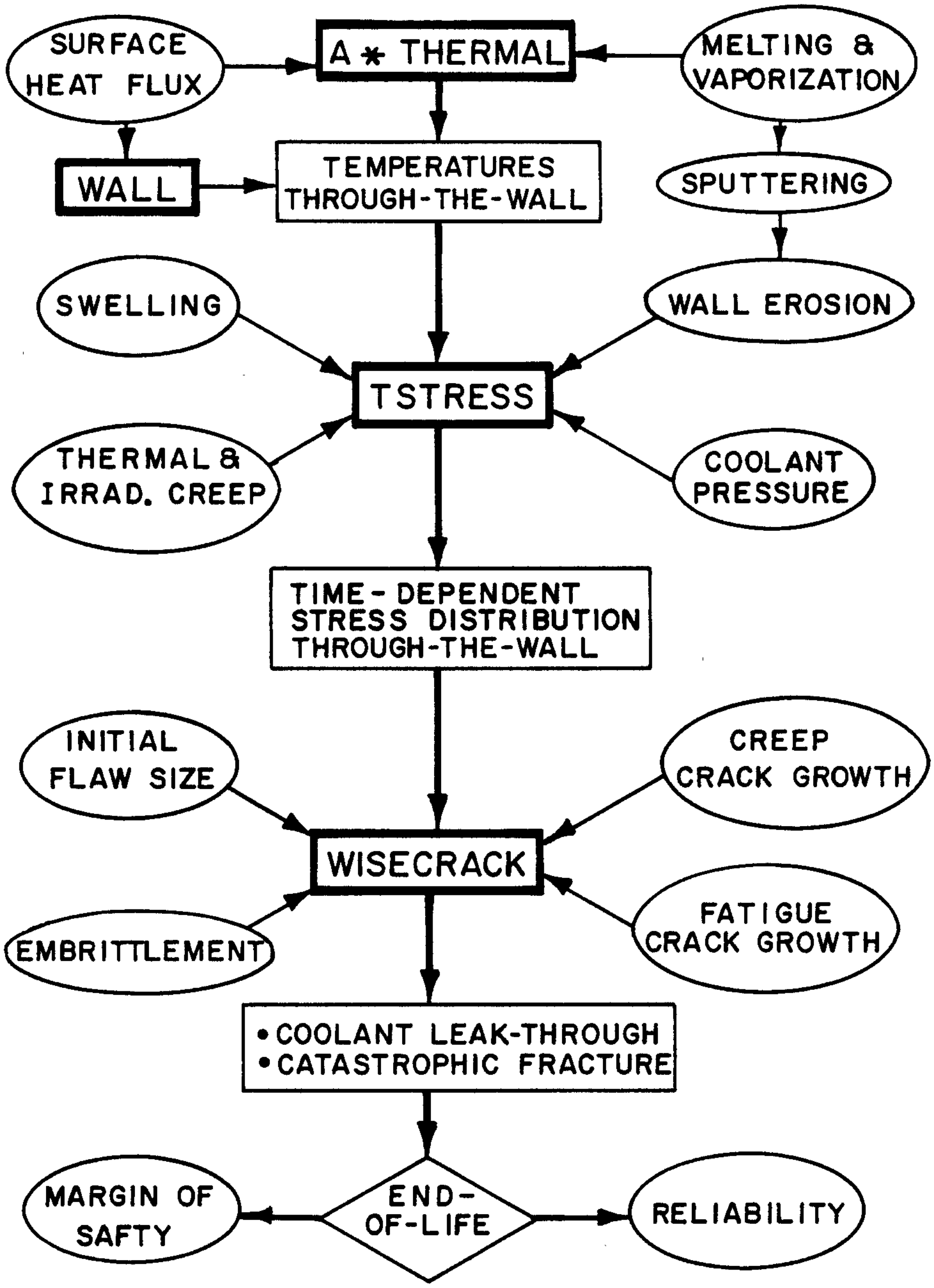
Two different models for fatigue crack growth rate.

Option for one-dimensional crack growth.

conduction equation for pulsed, arbitrary surface heat fluxes. Future versions of TSTRESS will also couple it to a temperature code written by A. Hassanein[3], called A*THERMAL, which includes the effects of melting and evaporation at the surface. If TSTRESS is not available, then any other existing inelastic (or elastic) stress analysis program may be used as well. However, the user must then write a short pre-processor program to correct the data output from the stress code into the appropriate format for input to WISECRACK. Instructions for doing this are described in section IV.B.

When all of these codes are linked together, as shown in Fig. 2, they form an integrated lifetime assessment package. With this integrated methodology, it is now possible to study the complex relationships between the structural response and crack propagation which, hitherto, have not been fully explored. The strongest feature of the two coupled codes, TSTRESS and WISECRACK, is their flexibility, which allows the user to study parametrically the effect of different radiation damage correlations on component lifetime without performing lengthy finite element computations. The reader is referred to the author's dissertation[4] for examples and discussion of the application of TSTRESS and WISECRACK to tokamak power reactor first wall component lifetime.

Figure 2



Methodology of lifetime analysis. WALL, A*THERMAL, TSTRESS, and WISECRACK are computer codes used in the Department of Nuclear Engineering.

II. Models for Crack Propagation

II.A. Flaw Characterization

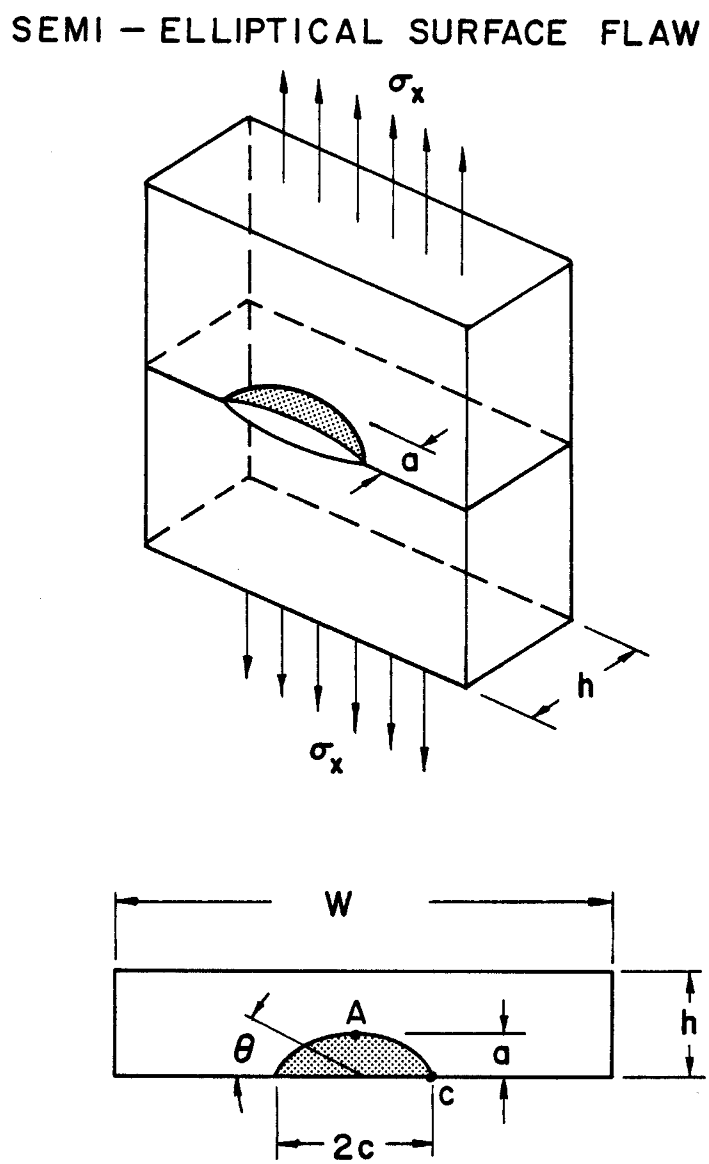
The initial, pre-existent defect used in WISECRACK is a semi-elliptical surface flaw, oriented perpendicular to the direction of maximum principal stress, as shown in Fig. 3. Although it is a three-dimensional defect, its dimensions are characterized only by a depth of "a" along its minor axis and a surface length of "2c" along its major axis. The flaw is allowed to grow independently along each axis, thus changing its aspect ratio, a/c (see Fig. 1).

The flat plate element shown in Fig. 4 represents an idealized model for a critical location from the global structure itself. This model is a useful approximation to the thin-walled, curved structures which are characteristic of high heat flux components. Flaw sizes are typically assumed to equal 25% of the wall thickness (1-10 mm), therefore giving flaw depths, a_0, in the range from 0.25 mm to 2.5 mm. It is traditionally assumed that the initial flaw shape is semi-circular ($a_0/c_0 = 1$).

II.B. Stress Intensity Factors

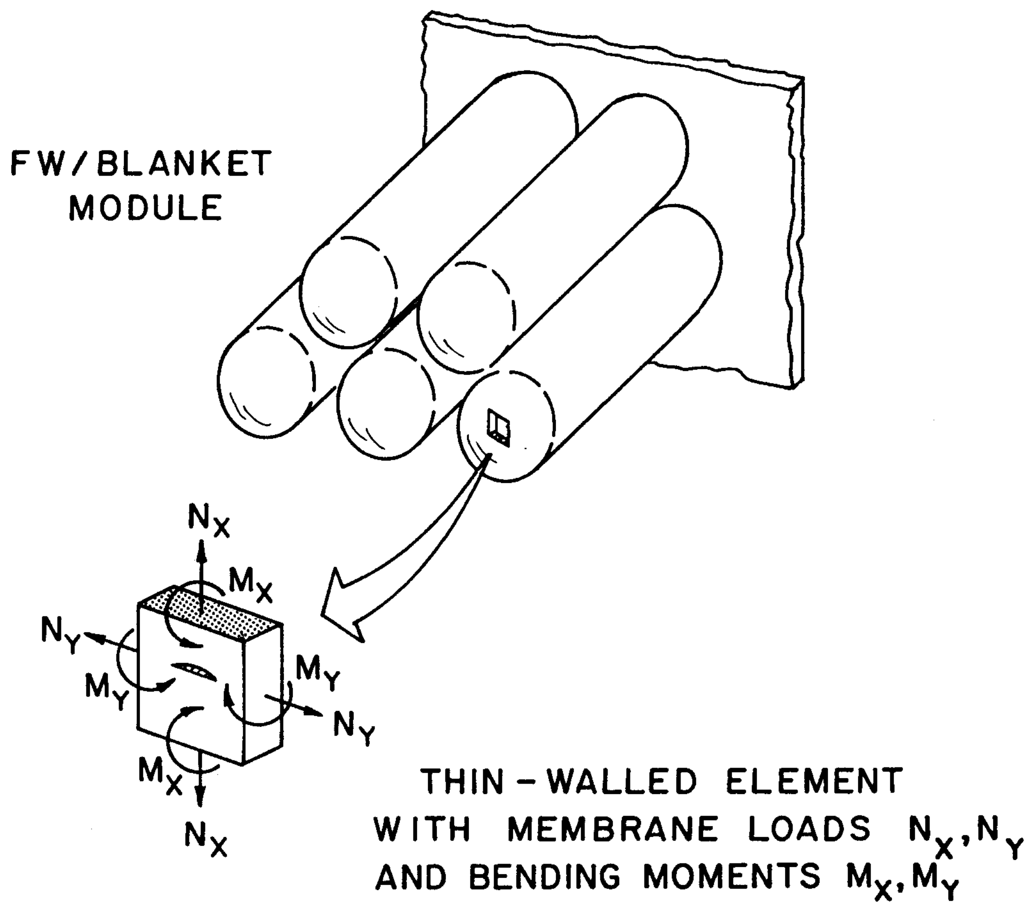
The driving force for fatigue crack growth is localized cyclic plasticity at the crack tip (or, in the case of a semi-elliptical surface flaw, plasticity around the entire crack from $\theta = 0$ to $\theta = 180°$). In linear elastic fracture mechanics the fundamental parameter that measures this concentration (or intensity) of stress and strain at the crack tip is defined as K_I, the stress intensity factor for type I crack opening mode (see Fig. 5). Type II and type III crack modes (K_{II} and K_{III}) are not considered in WISECRACK; hence, the subscript "I" in K_I will be dropped from future use in this report.

Figure 3



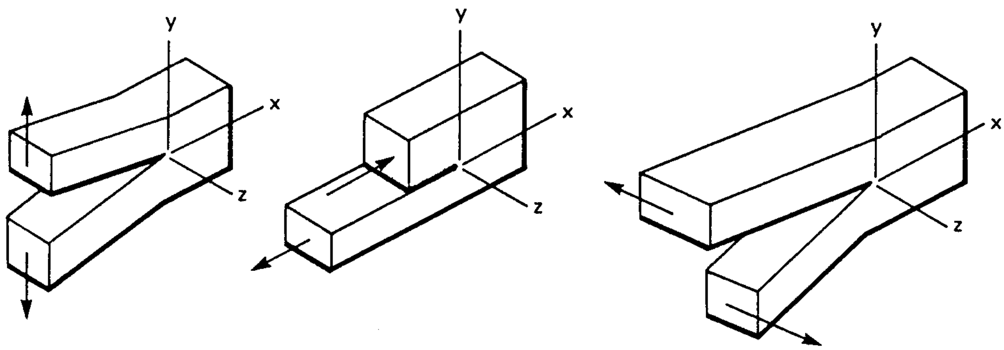
Model for a semi-elliptical surface flaw.

Figure 4



Relationship of a thin-walled plate element to the global structure. TSTRESS uses the membrane loads and bending moments to calculate the stresses distribution through the wall.

Figure 5



Mode I Mode II Mode III

Three different modes of crack displacement. Only the opening mode I is used.

In a typical high heat flux component there are two primary sources of stress: a membrane stress caused by coolant pressure and a bending stress caused by the linear temperature gradient through the wall. Within the limits of linear elastic fracture mechanics, the stress intensity factors from each of these sources of stress can simply be superimposed. Adopting the notation used in section XI of the ASME Boiler and Pressure Vessel Code[5] we can write the total stress intensity factor, K, as

$$K = (M_m M_m + M_b \sigma_b) \sqrt{\frac{\pi a}{Q}} \tag{1}$$

where: a = crack depth into plate

σ_m = membrane stress

σ_b = bending stress

Q = flaw shape factor

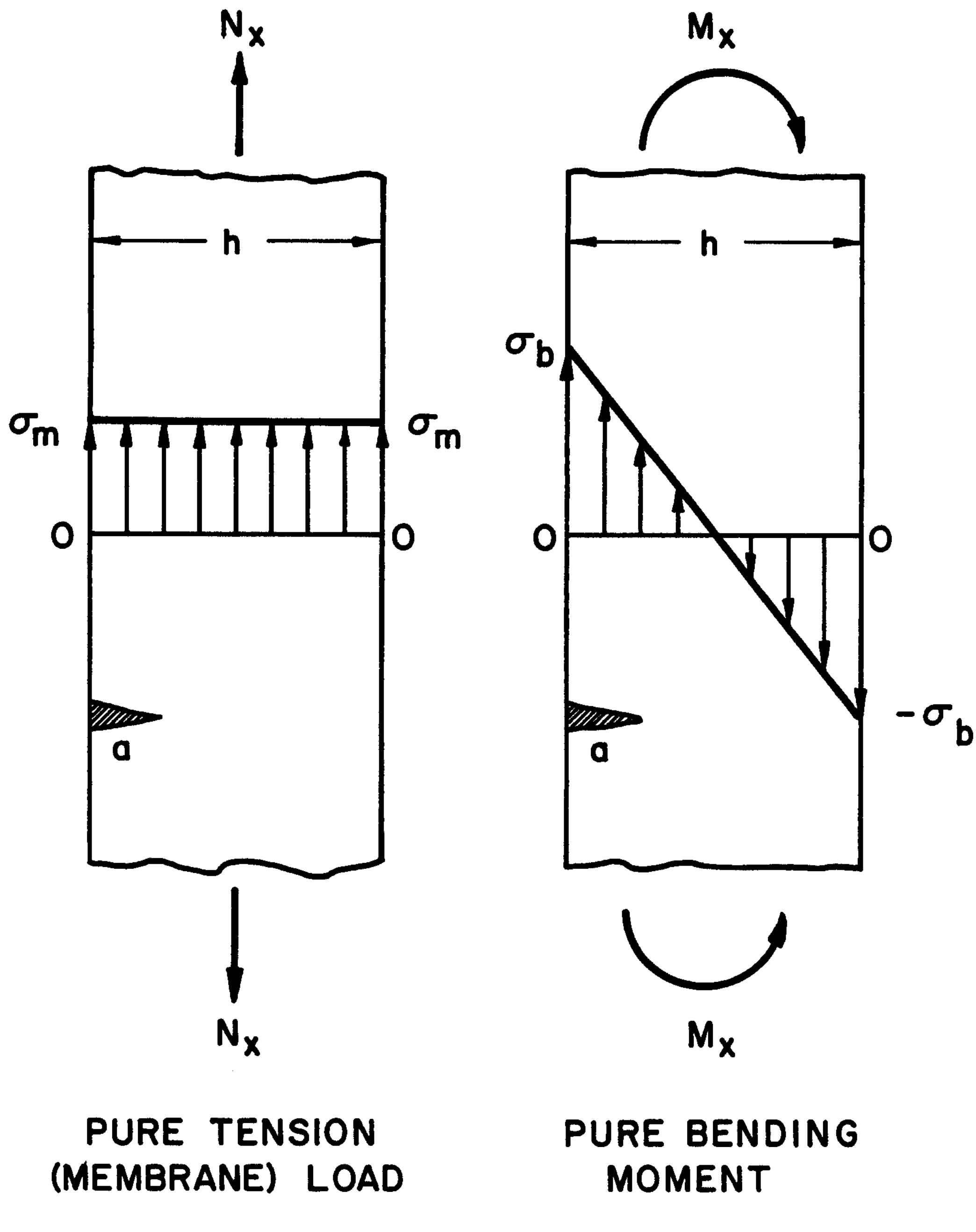
M_m = membrane correction factor

M_b = bending correction factor.

σ_m, σ_b, and a are defined in Fig. 6. The superposition of the two load types, tension and bending, is illustrated in Fig. 7. From this it can be seen that σ_m or σ_b can be either positive or negative numbers, depending on both the particular stress distribution through the wall and on which side of the plate the flaw is located. Note that the bending stress, σ_b, should always be measured on the same side that the crack is located (compare Fig. 7b and 7d).

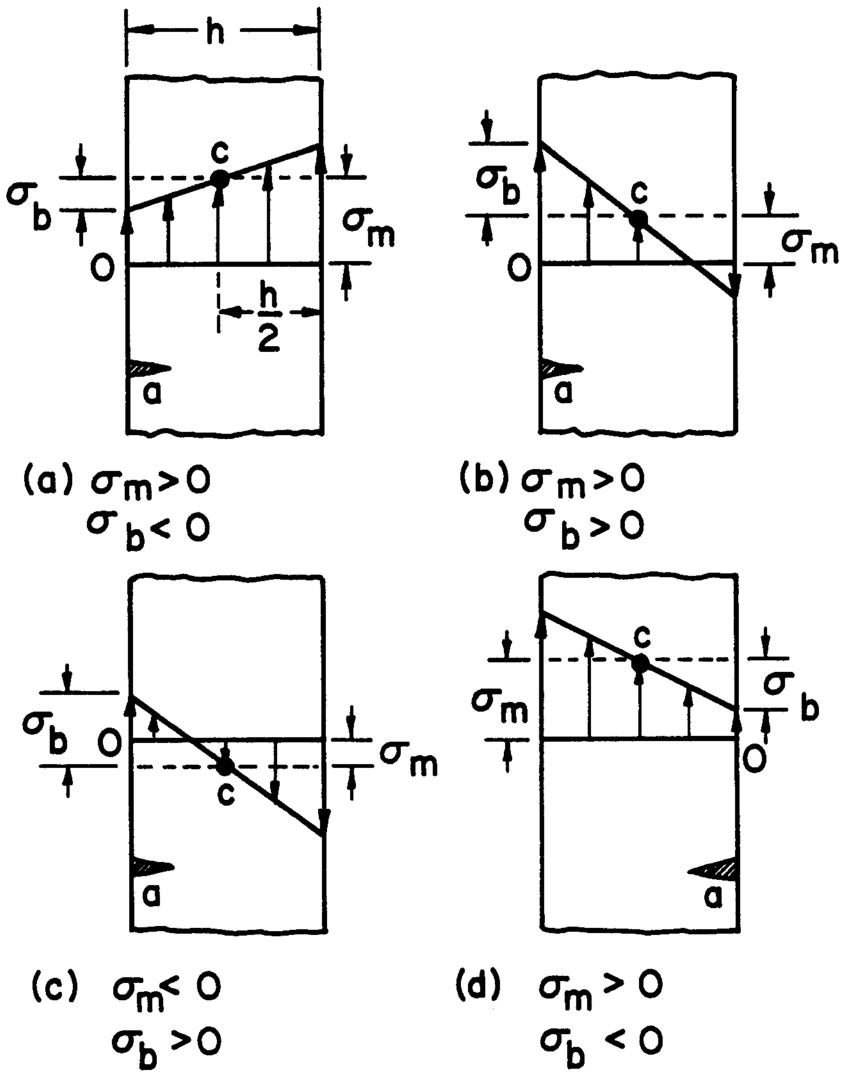
Growth patterns are different for pure tension or pure bending loadings, as illustrated in Fig. 8. Bending causes the flaw to elongate faster along the surface than it would under pure tension loads. After many cycles, when the crack reaches leak-through, the final aspect ratio is predicted by

Figure 6



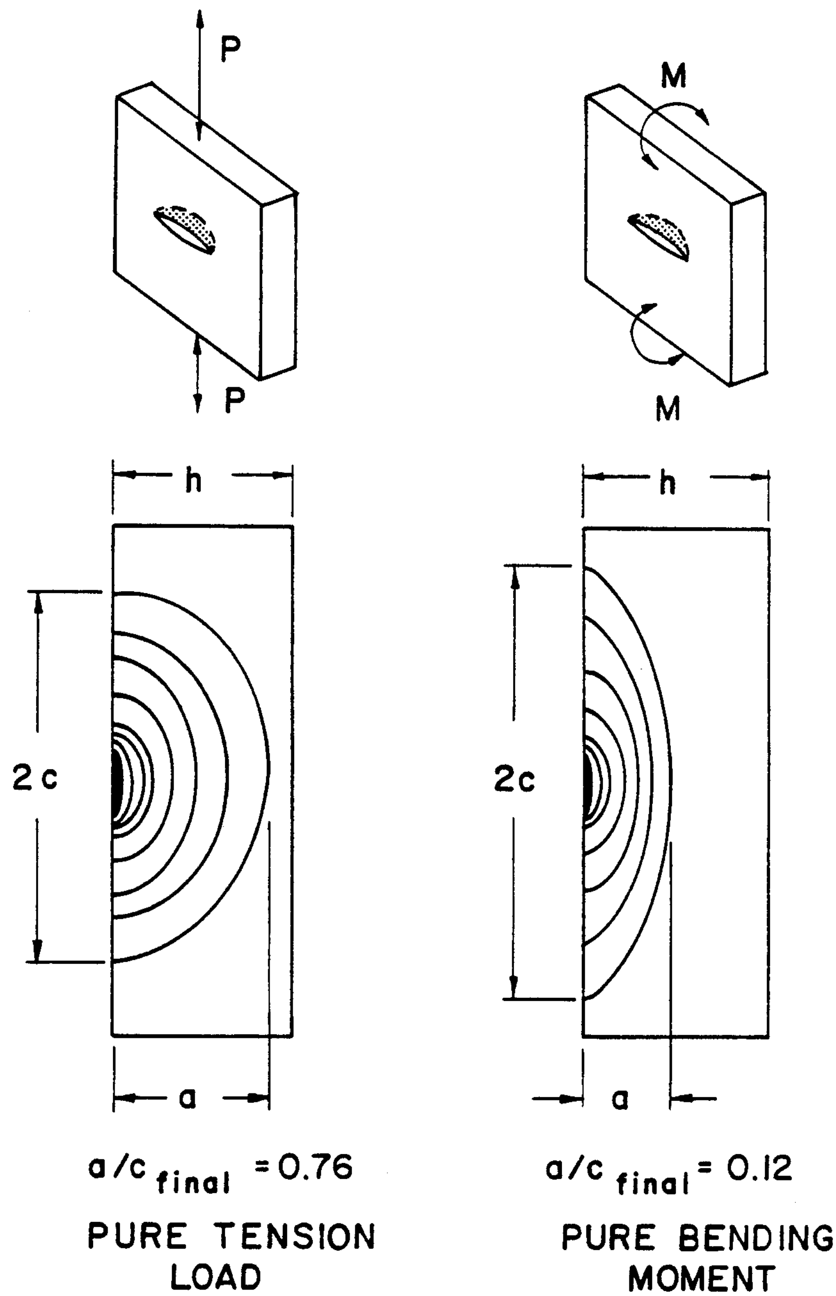
Definition of the membrane stress, σ_m, and the bending stress, σ_b.

Figure 7



Method for determining σ_m and σ_b. σ_m equals the stress at the midplane and σ_b equals the difference between the stress at the surface and σ_m. σ_b is always measured on the same side that the crack is located.

Figure 8



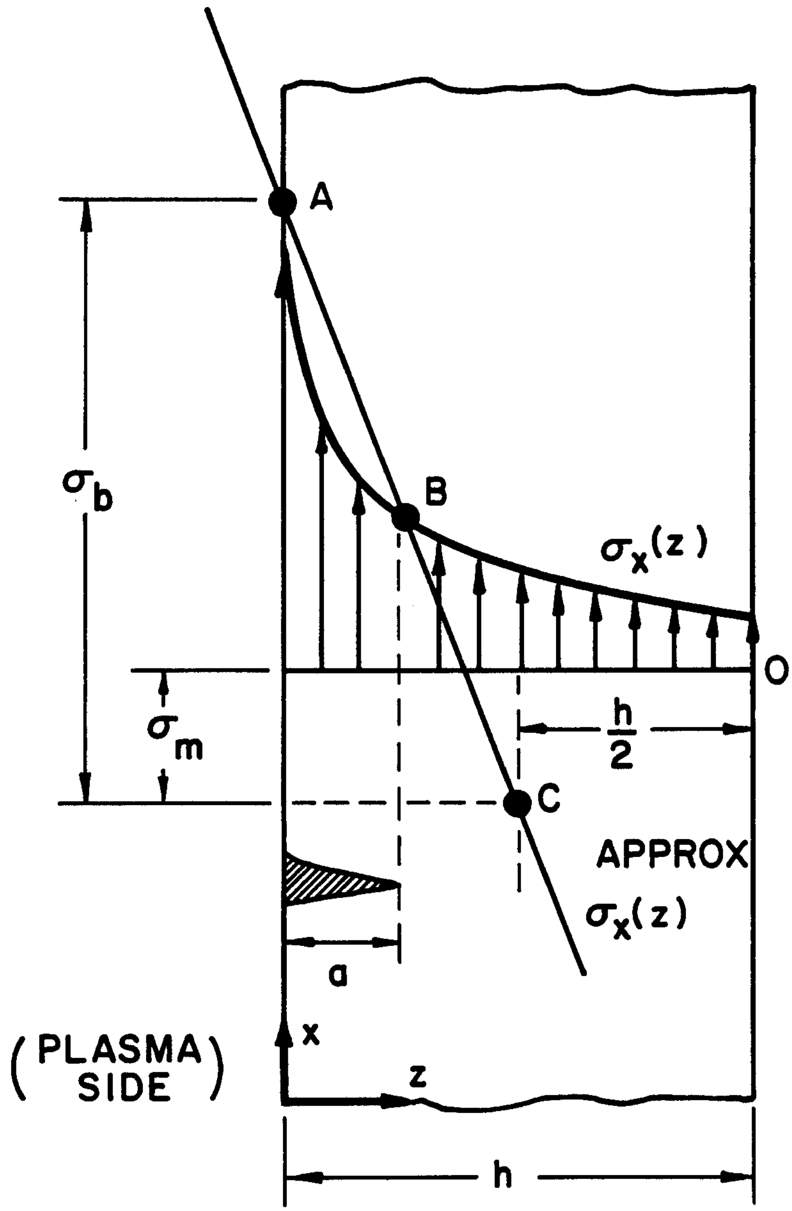
Crack growth patterns for either pure tension loads or pure bending moments.

WISECRACK to equal a/c = 0.76 for pure tension and a/c = 0.12 for pure bending loads.[4] Since most high heat flux components sustain a linear temperature gradient across the wall and, hence, a linear stress gradient (bending), we can reasonably expect all surface flaws to grow into long, thin crack shapes. It is, therefore, incorrect to assume that an initially semi-circular flaw (a/c = 1) will keep its same shape for its entire life, as has been the assumption in past first wall lifetime studies.

Over a period of many years while the reactor is running, inelastic deformation caused by irradiation creep and swelling will modify the initially linear stress distribution through the wall. However, the equations given by Newman and Raju[6] for the stress intensity factor can only be applied to a linear stress gradient. Therefore, WISECRACK uses a method recommended by the ASME Boiler and Pressure Vessel Code[5] to linearize these nonlinear stresses over the crack depth. Figure 9 illustrates the method. First, a straight line is drawn between points A and B, where point B is determined by the crack depth a. Line $\overline{AB}$ represents an equivalent linear stress distribution from which the two stresses, σ_m and σ_b, are easily calculated by using the drawings in Fig. 7.

This particular method of linearization derives from the assumption that only those stresses which act upon the face of the crack are important in determining the stress intensity factor. For moderately nonlinear gradients (long burn-time plasmas) the method gives very good results. However, it is not as accurate for the steep stress gradients that are produced from either ICF microexplosion or plasma disruption heat pulses. This remains an area of possible improvement in the code.

Figure 9



Technique for linearization over-the-crack of the nonlinear stress distribution, $\sigma_x(z)$, through the thickness.

Returning to Eq. (1), the flaw shape factor, Q, is equal to ϕ^2, where ϕ is the complete elliptic integral of the second kind

$$\phi = \int_0^{\pi/2} [1 - (\frac{c^2 - a^2}{c^2} \sin^2\theta)]^{1/2} \, d\theta \quad . \tag{2}$$

A convenient approximation is commonly used for ϕ^2, namely

$$Q = 1.0 + 1.464 \left(\frac{a}{c}\right)^{1.65} \tag{3}$$

for $a/c \leq 1.0$. In the limit as $c \to \infty$, the surface flaw becomes an edge crack, for which $Q = 1$.

The expressions used in WISECRACK for M_m and M_b are those developed by Newman and Raju.(6) They used a 3-D hybrid finite element method to compute accurate correction factors that depend on the crack depth (a), aspect ratio (a/c), plate width (w), angular location (θ), and load type (tension or bending) for the following ranges $0 < a/c \leq 1$, $0 \leq a/h \leq 1$, $c/w < 0.5$ and $0 \leq \theta \leq \pi$. The membrane correction factor, M_m, is given by

$$M_m = [M_1 + M_2\left(\frac{a}{h}\right)^2 + M_3\left(\frac{a}{h}\right)^4] \, f_\theta f_w g \tag{4}$$

where

$$M_1 = 1.13 - 0.09 \left(\frac{a}{c}\right) \tag{5}$$

$$M_2 = -0.54 + \frac{0.89}{0.2 + a/c} \tag{6}$$

$$M_3 = 0.5 - \frac{1}{0.65 + a/c} + 14\left(1 - \frac{a}{c}\right)^{24} \tag{7}$$

$$g = 1 + [0.1 + 0.35(\frac{a}{h})^2](1 - \sin\theta)^2 \qquad (8)$$

$$f_\theta = [(\frac{a}{c})^2 \cos^2\theta + \sin^2\theta]^{0.25} \qquad (9)$$

and

$$f_w = [\sec(\frac{\pi c}{2w}\sqrt{\frac{a}{h}})]^{0.5} \quad . \qquad (10)$$

The bending correction factor, M_b, is given by

$$M_b = H \cdot M_m \qquad (11)$$

where

$$H = H_1 + (H_2 - H_1)\sin^p\theta \qquad (12)$$

$$p = 0.2 + \frac{a}{c} + 0.6(\frac{a}{h}) \qquad (13)$$

$$H_1 = 1 - 0.34(\frac{a}{h}) - 0.11(\frac{a}{c})(\frac{a}{h}) \qquad (14)$$

$$H_2 = 1 + G_1(\frac{a}{h}) + G_2(\frac{a}{h})^2 \qquad (15)$$

$$G_1 = -1.22 - 0.12(\frac{a}{c}) \qquad (16)$$

and

$$G_2 = 0.55 - 1.05(\frac{a}{c})^{0.75} + 0.47(\frac{a}{c})^{1.5} \quad . \qquad (17)$$

Going back to Eq. (1), it can be rewritten in a more transparent form as

$$K = (\frac{M_m}{\sqrt{Q}}\sigma_m + \frac{M_b}{\sqrt{Q}}\sigma_b)\sqrt{\pi a} \qquad (18)$$

or as

$$K = (F_m \sigma_m + F_b \sigma_b)\sqrt{\pi a} \tag{19}$$

where we have defined the magnification factors F_m and F_b as

$$F_m = \frac{M_m}{\sqrt{Q}} \tag{20}$$

and

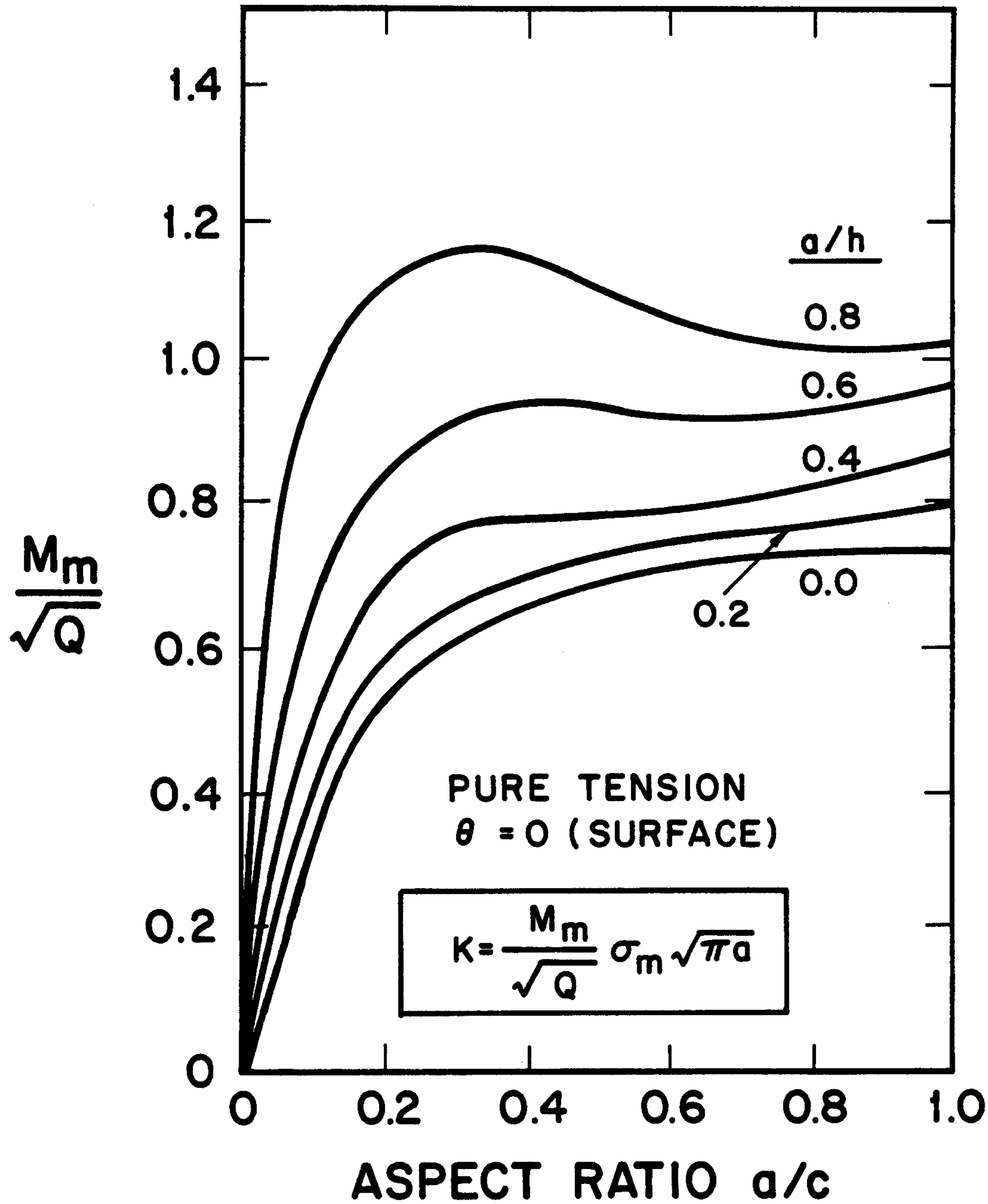
$$F_b = \frac{M_b}{\sqrt{Q}} \quad . \tag{21}$$

For comparison, the stress intensity factor for a through-thickness crack of length 2a subjected to a uniform tensile stress, σ, is given by[7]

$$K = \sigma\sqrt{\pi a} \quad . \tag{22}$$

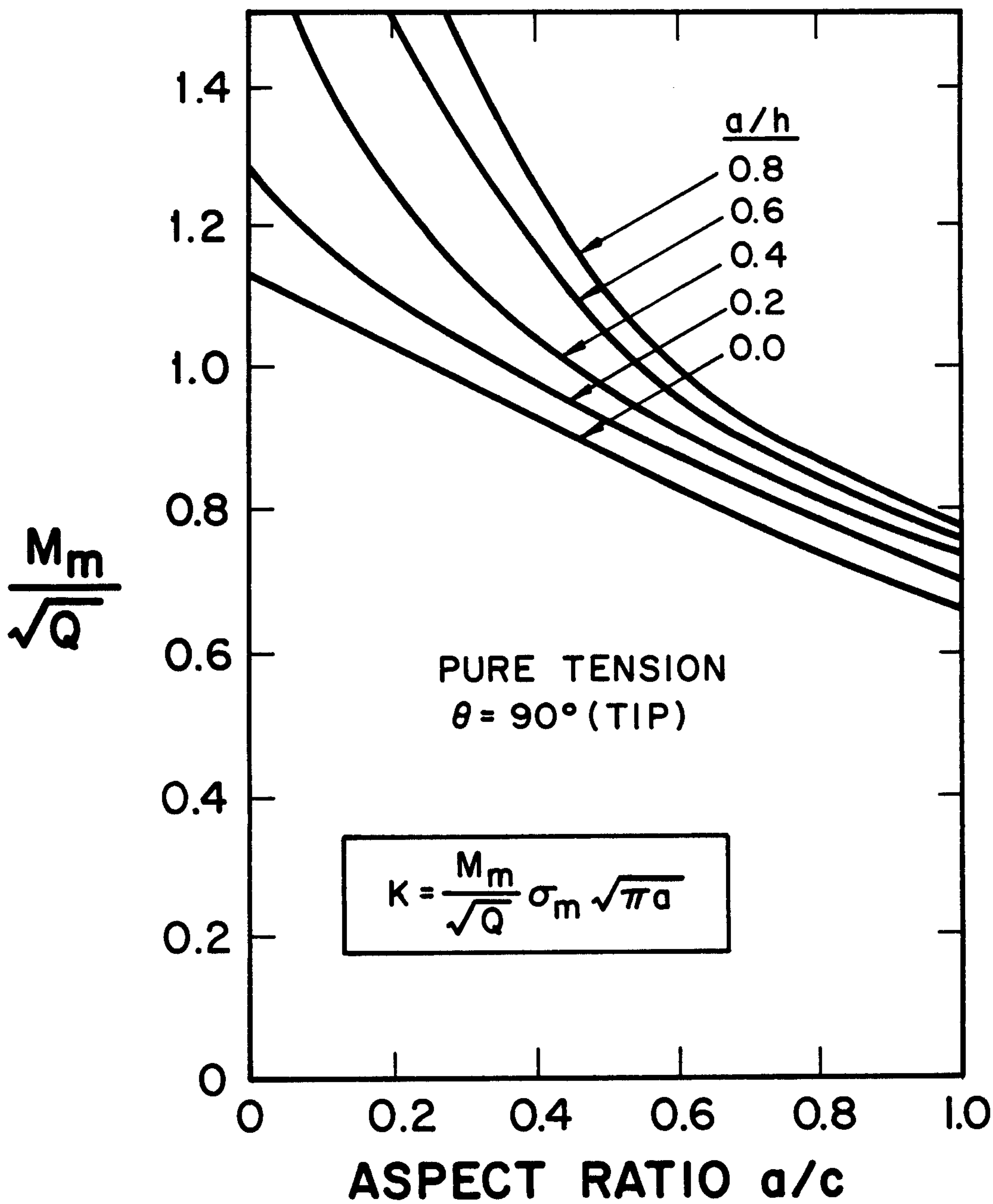
By comparing this to Eq. (19) we see that the magnification factors F_m and F_b are essentially a measure of the enhancement in stress intensity for a semi-elliptical surface flaw over that for a through-crack of the same surface length (width). The dependence of F_m and F_b upon the aspect ratio, a/c, and the dimensionless depth, a/h, is shown in Figs. 10, 11, 12, and 13. Note that a limiting value of $a/c = 0$ represents an edge crack and a value of $a/h = 0$ describes a surface flaw in a semi-infinite body (half-space). A general observation from these curves is that pure tension loads cause higher stress intensities than pure bending loads, for the same value of $\sigma_m = \sigma_b$. Also, when the stress field is predominantly bending, K is higher at the surface than at the tip of the crack, for $a/h \gtrsim 0.1$. This implies that fracture will usually originate at the surface in high heat flux components, rather than from within the wall.

Figure 10



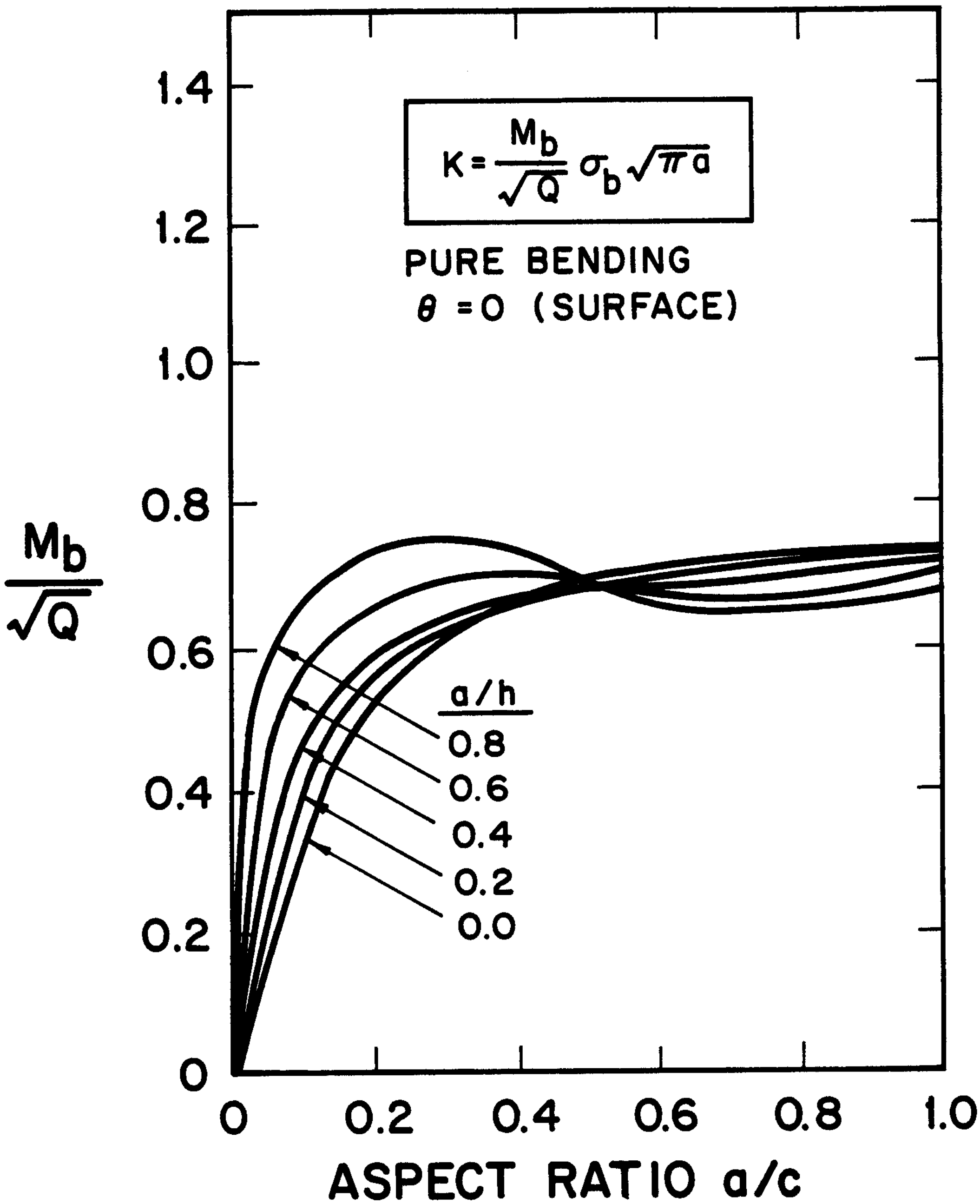
Variation of the magnification factor, F_m, with aspect ratio and crack depth for pure tension loads and $\theta = 0$. [6].

Figure 11



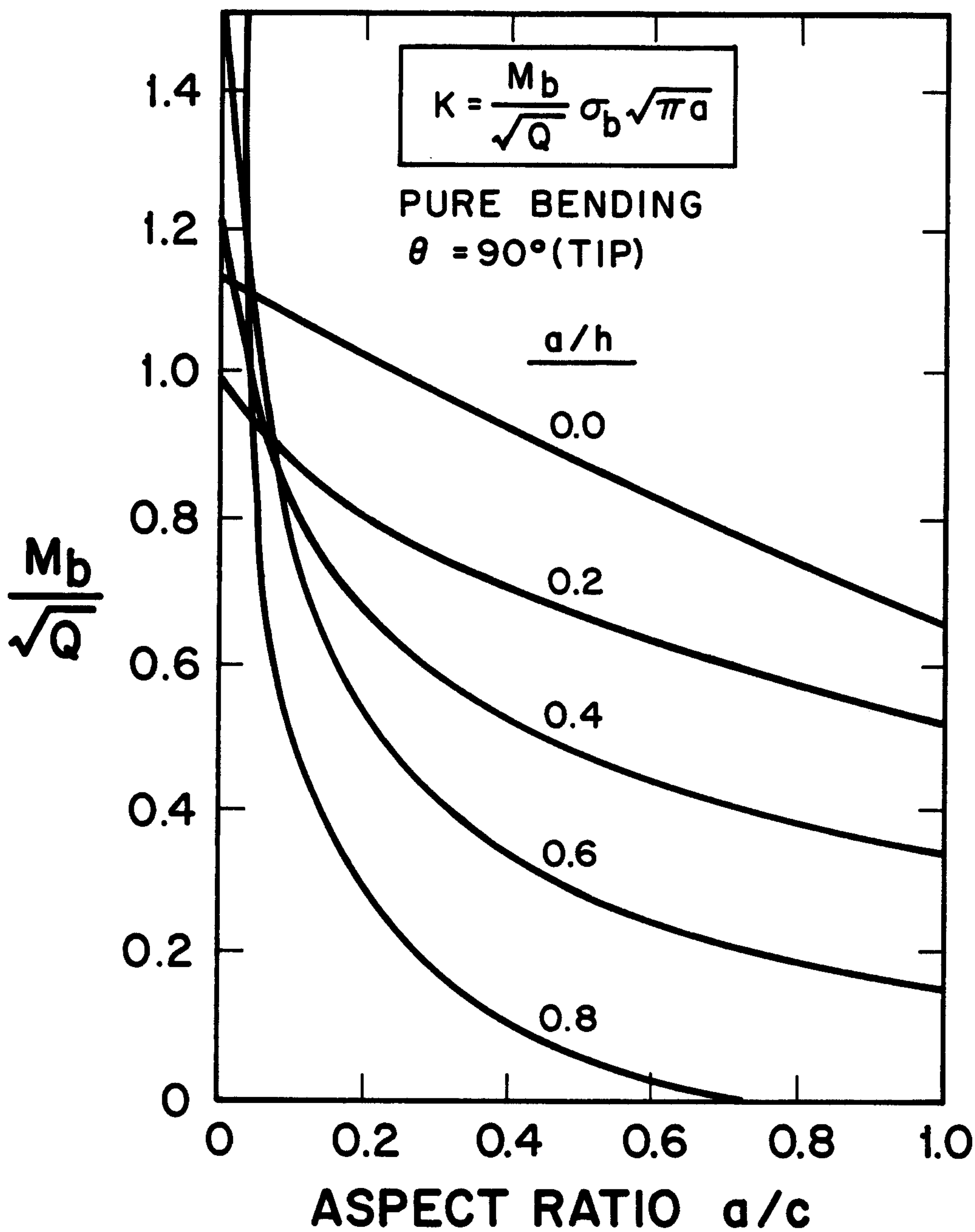
Variation of the magnification factor, F_m, with aspect ratio and crack depth for pure tension loads and $\theta = 90^o$. [6].

Figure 12



Variation of the magnification factor, F_b, with aspect ratio and crack depth for pure bending moments and $\theta = 0°$ [6].

Figure 13



Variation of the magnification factor, F_b, with aspect ratio and crack depth for pure bending moments and $\theta = 90^{\circ}$. [6].

II.C. Fatigue Crack Growth Rate

The rate of fatigue crack growth, da/dN, can be defined as the amount of crack extension caused by cyclic stresses within a single load cycle. It has been found to correlate very well with the cyclic stress intensity factor, ΔK, where

$$\Delta K = K_{max} - K_{min} \quad . \tag{23}$$

For most metals, the relationship between da/dN and ΔK exhibits three different regimes of behavior, as shown in Fig. 14.

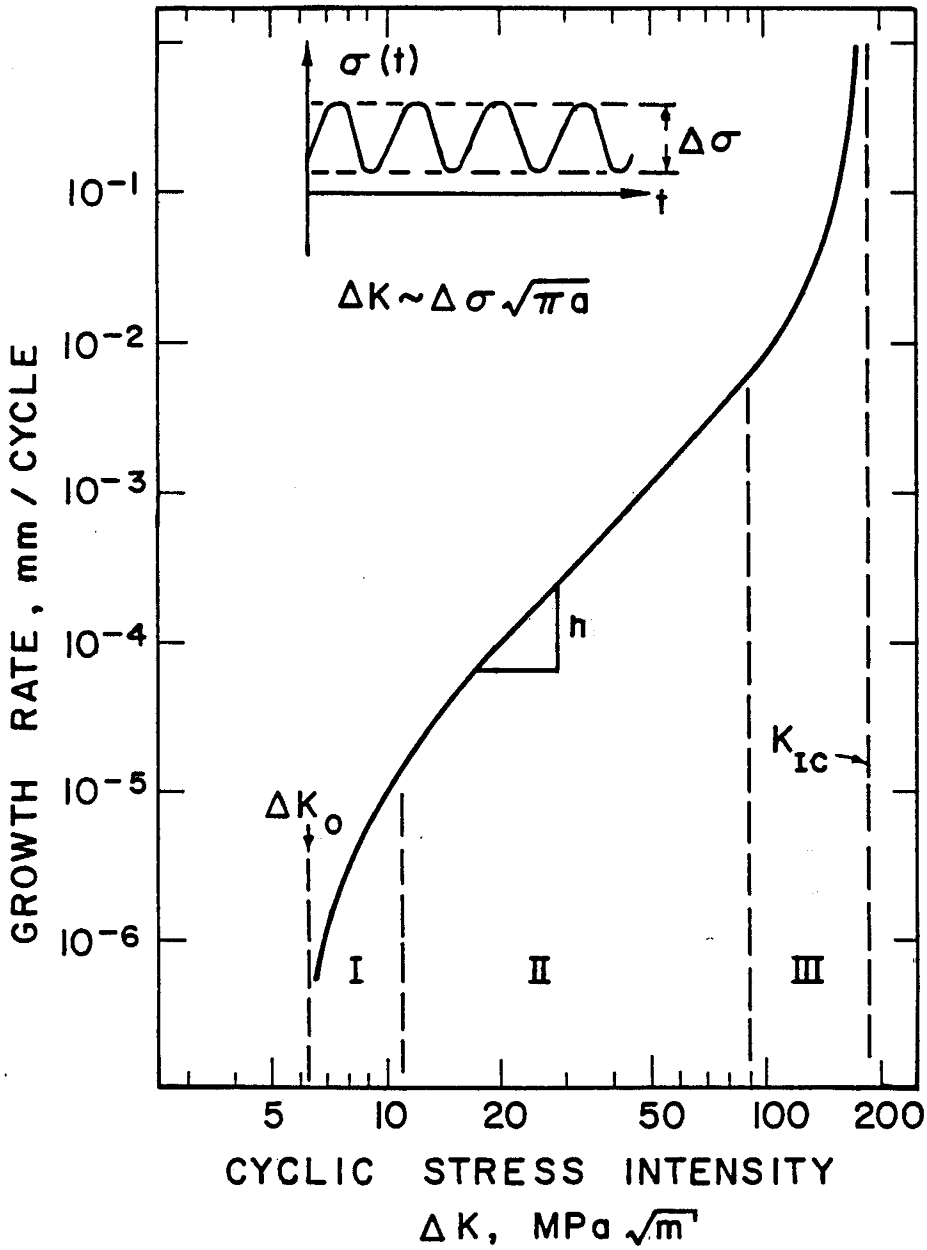
During stage I, the so-called threshold regime, da/dN becomes vanishingly small as ΔK approaches ΔK_0, the threshold stress intensity factor. In stage II, stable crack growth is observed over the range of ΔK from 10 MPa $\sqrt{m}$ to 100 MPa $\sqrt{m}$ for steels. Here, the data can be successfully fit to the traditional Paris equation

$$\frac{da}{dN} = B(\Delta K)^n \quad . \tag{24}$$

Finally, in stage III, unstable crack growth occurs when ΔK approaches K_{Ic}, the plane strain fracture toughness. Fast fracture occurs when $K_{max} \geq K_{Ic}$. ΔK_0 and K_{Ic} are traditionally considered to be basic materials properties. However, neutron irradiation is expected to degrade both of these properties, as will be discussed later on.

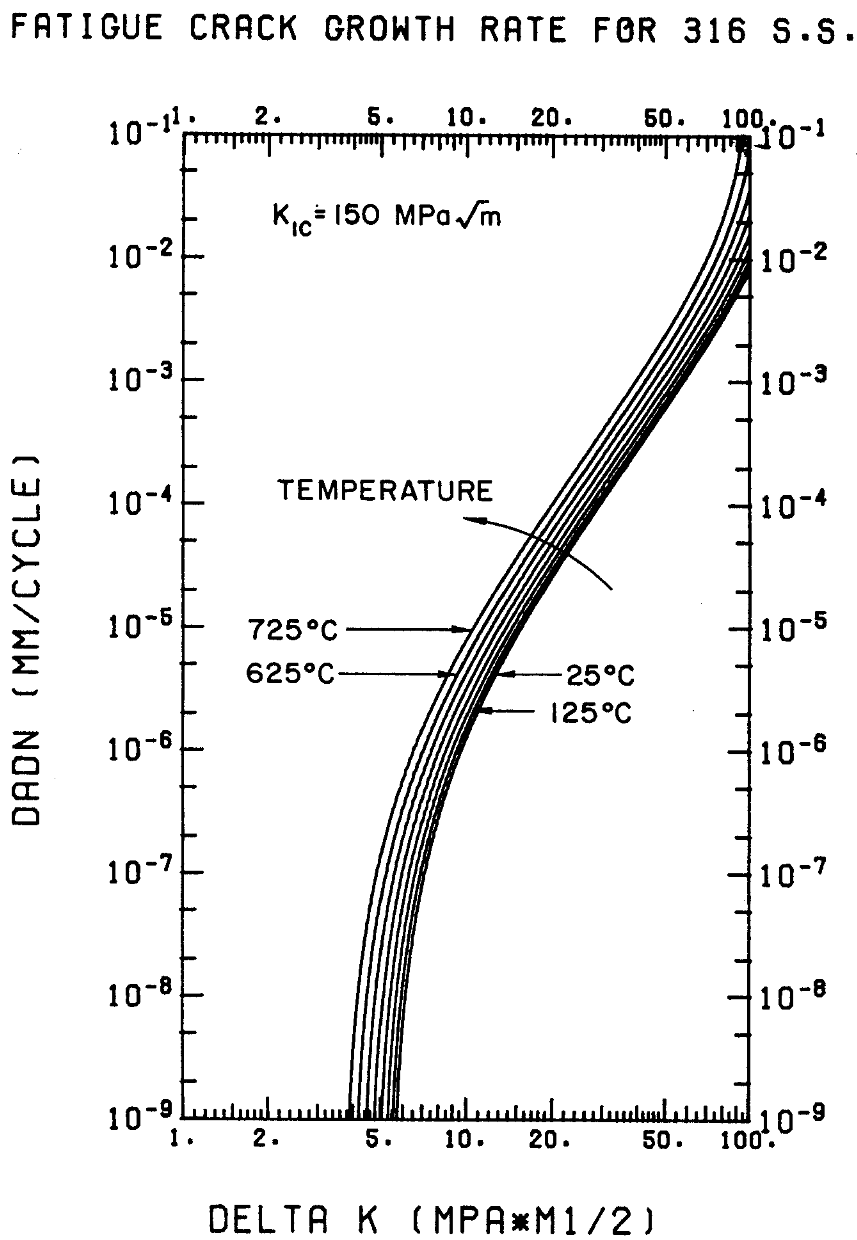
Fatigue crack growth rates are also influenced by temperature and mean stress level. It is observed that an increase in the temperature, T, will increase da/dN, as shown in Fig. 15. Sadanada and Shahinian[8] have

Figure 14



Schematic of three stages of fatigue crack growth behavior. Stage I is the threshold regime. Stage II is the linear, stable growth regime, and Stage III is the unstable, fast growth/fracture regime.

Figure 15



Effect of temperature on fatigue crack growth in 316 stainless steel.

successfully modeled this effect by correlating the data with $\Delta K/E(T)$ instead of ΔK, where $E(T)$ is Young's modulus of elasticity. WISECRACK uses this concept by replacing ΔK each place it appears in the da/dN equations with $f \cdot \Delta K$, where f is defined as

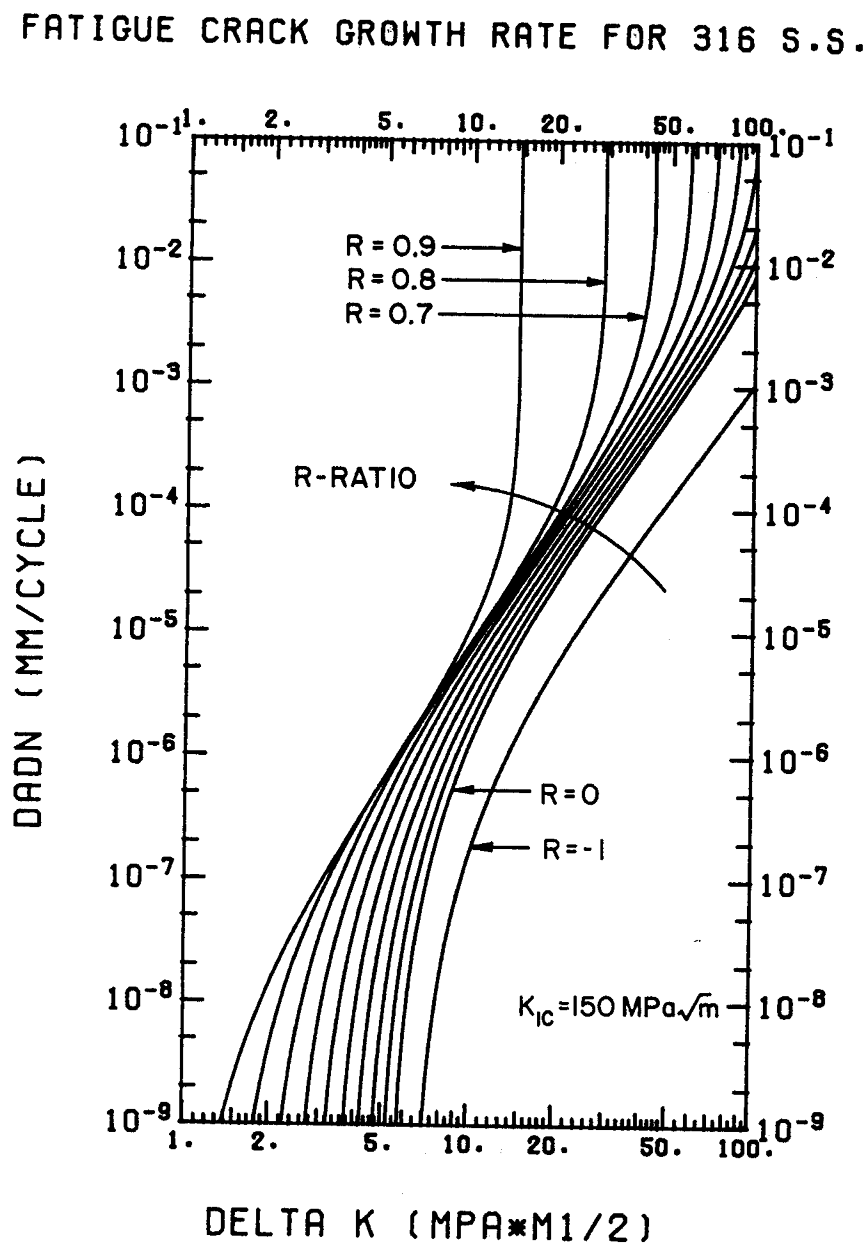
$$f = \frac{E(T_0)}{E(T)} \tag{25}$$

and T_0 is room temperature (25°C). Now, since the temperature is a function of both space and time, we must choose the appropriate value of T to compute f with. This is done by first selecting the temperature at the specific angular location along the crack front, θ (see Fig. 3). Secondly, the value of T must also coincide with the value at the particular moment in time when the crack opening is the greatest (e.g., at K_{max}). This model for temperature effect, which is based on a modulus correction, is accurate for inert environments (e.g., helium, liquid metals or vacuum). However, aggressive environments such as salt water, boiling water or even air will add an additional component to da/dN which has not been included in WISECRACK. Likewise, the current equations for 316 SS do not include any hydrogen embrittlement effects on da/dN.

In addition to the temperature effect, increasing the mean stress level $(\sigma_{max} + \sigma_{min})/2$ is also found to accelerate crack growth, as shown in Fig. 16. To model this effect, we can define a mean stress intensity factor, K_{mean}, which is directly proportional to the mean stress:

$$K_{mean} = \frac{1}{2}(K_{max} + K_{min}) \quad . \tag{26}$$

Figure 16



Effect of R-ratio on fatigue crack growth in 316 stainless steel.

This is related to the so-called R-ratio by

$$K_{mean} = \frac{1}{2} \Delta K \left[\frac{1 + R}{1 - R}\right] \tag{27}$$

where

$$R = \frac{K_{min}}{K_{max}} \quad . \tag{28}$$

From Eq. (27) we observe that for constant ΔK, increasing values of K_{mean} also correspond to larger values of R. Figure 16 shows that da/dN is most sensitive to the R-ratio during stage I and stage III crack growth, but changes little during stage II. The bulk of da/dN data is usually taken at R = 0.

In order to give the user some flexibility, WISECRACK allows a choice between two different equations for da/dN: the traditional Paris equation and the more accurate modified Forman equation. The Paris equation only models stage II accurately and is given by

$$\frac{da}{dN} = B(f\Delta K_{eff})^n \quad . \tag{29}$$

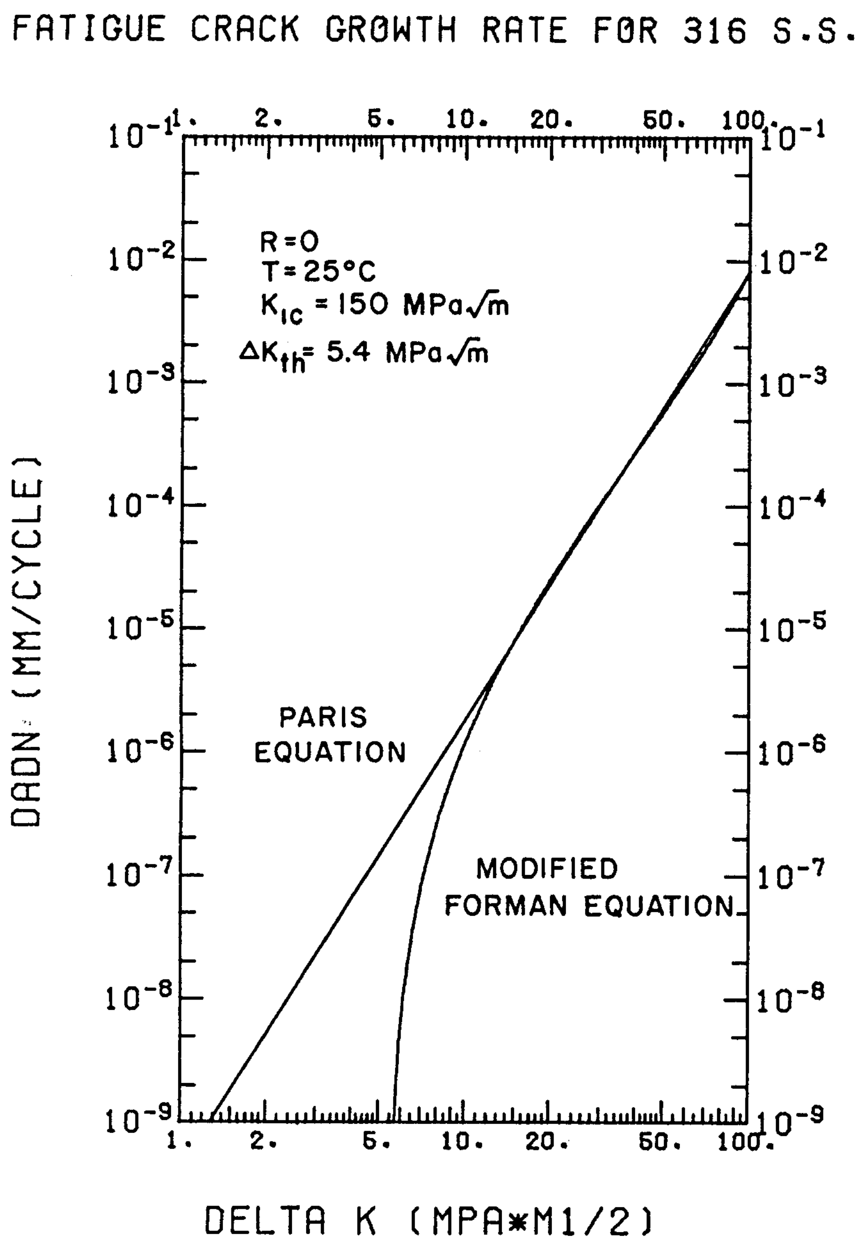
In order to correlate da/dN with the R-ratio (mean stress level), the Paris equation uses the Walker correction[9]:

$$\Delta K_{eff} = K_{max}(1 - R)^m \quad . \tag{30}$$

Note that the Paris equation is simply a straight line on the plot of ln(da/dN) vs. ln(ΔK), as shown in Fig. 17.

A much better correlation can be obtained by using the modified Forman equation, originally proposed by Speidel[10] as

Figure 17



Comparison of two different equations for fatigue crack growth.

$$\frac{da}{dN} = \frac{B\lambda^m[f\Delta K - \Delta K_o]^n}{K_{Ic} - \lambda f\Delta K} \qquad (31)$$

where

$$\lambda = \frac{1}{1 - R} \quad . \qquad (32)$$

Figure 17 shows how this equation correctly predicts the threshold for crack growth in stage I. Table 2 lists the constants used in WISECRACK for 316 SS.

Table 2. Fatigue Crack Growth Data for 316 SS

Paris Eq. (29)	Modified Forman Eq. (31)
$B = 3.94 \times 10^{-13}$ m/cycle	$B = 3.122 \times 10^{-9}$ m/cycle
$n = 3.66$	$n = 2.95$
$m = 0.5$	$m = 0.5$
	$K_{Ic} = 150$ MPa $\sqrt{m}$
	$\Delta K_o = \begin{cases} 5.4(1 - 0.9R) & R > 0 \\ 5.4(1 - 0.2R) & R < 0 \end{cases}$

II.D. Short Crack Correction

Most of the data for da/dN is obtained using "large" cracks. However, when "short" cracks are used, e.g., those with $a_0 \leq 0.5$ mm, then they are observed experimentally to grow faster than long cracks at the same ΔK and R-ratio (see Pearson[11], Kitagawa et al.[12], and El Haddad et al.[13]). Unfortunately, for the thin-walled high heat flux components in a fusion device, this is within the lower range of flaw sizes we are interested in.

Two possible effects may explain this behavior and both are related to the breakdown of continuum mechanics for these small flaws. First, Talug and Reifsnider[14] have shown that the crack tip stresses are enhanced, when compared to the classical solution, as the tip approaches the free surface. This would increase ΔK, and hence, da/dN. The second possibility for an enhanced ΔK is related to the reduced flaw resistance of the surface grains, as compared to interior grains, due to their lack of constraint by the surrounding grains.

El Haddad and co-workers[15] have developed a simple scheme for empirically correlating the increase in da/dN for small cracks. They recommend replacing the actual crack length, a, by an effective length, $a + \ell_0$, whenever this term appears in equations for ΔK. For example, Eq. (1) would then become

$$K = (M_m \sigma_m + M_b \sigma_b) \sqrt{\frac{\pi(a + \ell_0)}{Q}} \quad . \tag{33}$$

As $a \gg \ell_0$, we see the effect of the correction becomes negligible.

The reasoning behind using this short crack correction factor, ℓ_0, is related to the threshold for crack growth, ΔK_0. If we use the ΔK correction for a through-crack in a plate, we obtain

$$\Delta K = \Delta\sigma \sqrt{\pi(a + \ell_0)} \quad . \tag{34}$$

Now, at the threshold, we know that

$$\Delta K_0 = \Delta\sigma_0 \sqrt{\pi(a + \ell_0)} \tag{35}$$

where $\Delta\sigma_0$ is the cyclic stress range for non-propagating cracked specimens. Solving this equation for $\Delta\sigma_0$ gives

$$\Delta\sigma_o = \frac{\Delta K_o}{\sqrt{\pi(a + \ell_o)}} \quad . \tag{36}$$

According to a recent review article by Hudak[16], the use of Eq. (36) has enjoyed wide success in correlating stage I da/dN data for both long and short cracks.

Next, to determine ℓ_0, we must consider the limit as the actual crack depth, a, goes to zero:

$$\lim_{a \to o} [\Delta\sigma_o] = \frac{\Delta K_o}{\sqrt{\pi \ell_o}} \quad . \tag{37}$$

For smooth, uncracked fatigue specimens the left-hand side of Eq. (37) can now be interpreted as a definition of the so-called endurance limit $\Delta\sigma_e$, below which failure never occurs. Equating these two concepts then gives us a theoretical relationship between the endurance limit and the threshold stress intensity:

$$\Delta\sigma_e = \frac{\Delta K_o}{\sqrt{\pi \ell_o}} \quad . \tag{38}$$

Conversely, if both $\Delta\sigma_e$ and ΔK_0 are known, it then would allow us to calculate ℓ_0 as

$$\ell_o = \frac{1}{\pi} \left[\frac{\Delta K_o}{\Delta\sigma_e}\right]^2 \quad . \tag{39}$$

Using ΔK_0 = 5.4 MPa $\sqrt{m}$ and $\Delta\sigma_e$ = 380 MPa (55 ksi) for 316 SS, we find that ℓ_0 = 0.064 mm. Unfortunately, the effect of irradiation on ℓ_0 is unknown.

II.E. Irradiation Effects on Fatigue Crack Propagation

One of the most important uses of WISECRACK is to study the sensitivity of lifetime predictions to different correlations for radiation damage effects. This is accomplished in three ways. First, the long-term stress history which is supplied by TSTRESS includes the effects of irradiation creep and swelling, and wall thinning from erosion. Secondly, neutron induced embrittlement may eventually cause a substantial reduction in fracture toughness, K_{Ic} (according to a recent paper by Wolfer and Jones[17]). The consequence of this reduction is to enhance the probability of brittle fracture under peak loads.

The third and most important effect is the potentially damaging impact of neutron irradiation on fatigue crack growth rates. Existing data by James[18] indicate little effect for low doses (5-10 dpa). However, if severe embrittlement is experienced at higher fluences (50-100 dpa), da/dN may be seriously affected. The stage III regime of unstable crack growth (as defined in Fig. 14) represents an upper limit to ΔK, i.e. $\Delta K < K_{Ic}$ (at $R = 0$). Therefore, as K_{Ic} drops with increasing dpa, we would expect stage III to shift to lower values of ΔK. However, it is not obvious what effect this will have on the stage II regime of stable crack growth.

Because no data exists for da/dN on severely embrittled steels, WISECRACK gives the user a choice of three different models for da/dN, as shown in Fig. 18. The simplest model is the Paris equation (29), which automatically includes no irradiation effects on stage II. The second choice uses the modified Forman equation (31) without irradiation effects to stage II. This is accomplished, mathematically, by holding K_{Ic} in the denominator of Eq. (31) equal to its unirradiated value (e.g., 150 MPa $\sqrt{m}$) while allowing the actual K_{Ic} for the structure to drop with dpa. Figure 18 shows that the only difference between this approach and the Paris equation appears in stage I.

Finally, a third choice is to model irradiation effects to stage II with the modified Forman equation by allowing K_{Ic} to decrease in the denominator of Eq. (31), as shown in Figs. 18 and 19. The increase in da/dN for severely embrittled steels ($K_{Ic} \lesssim 50$ MPa $\sqrt{m}$) is quite large, up to an order of magnitude. Consequently, lifetimes are predicted to be significantly less.

Due to a lack of data, none of these three models includes any effects of irradiation on the threshold regime (stage I). It is expected, however, that since radiation hardening increases the yield strength, we may expect the threshold stress intensity factor, ΔK_0, to decrease with dpa. Experiments are needed to verify this assumption.

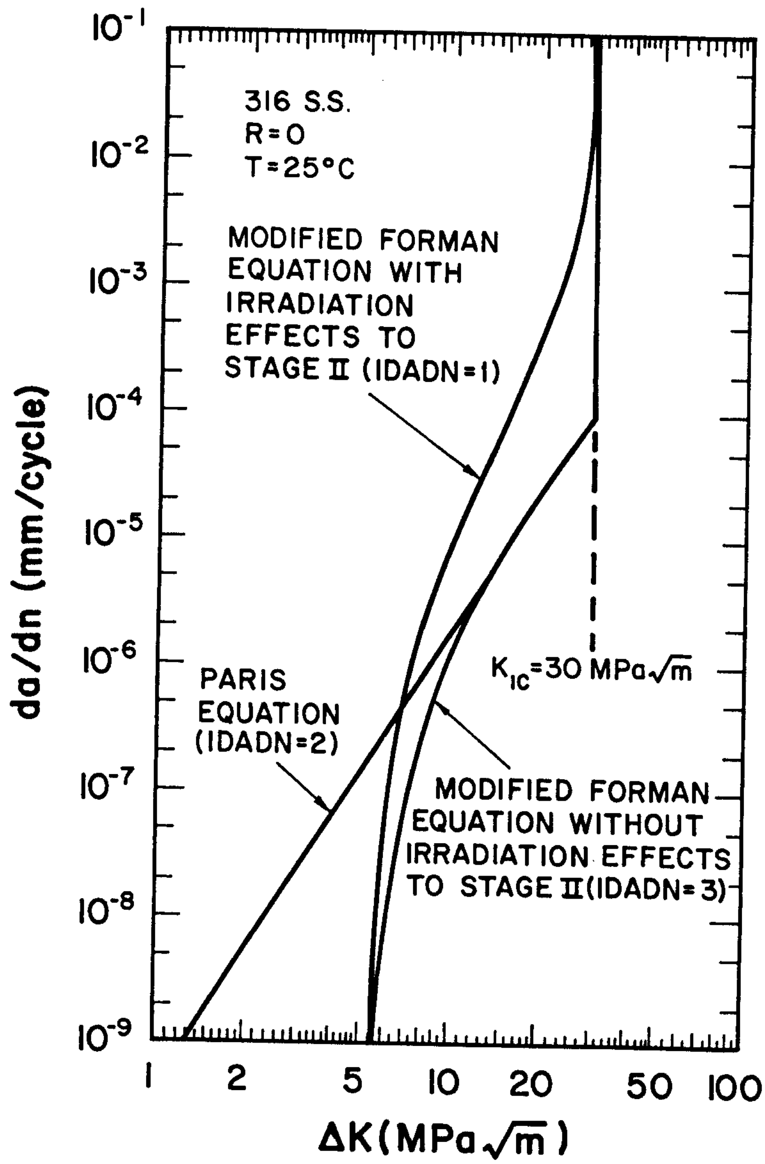
II.F. Creep Crack Growth Rate

Creep crack growth occurs in cracked specimens when held at an elevated temperature under a constant stress. While many different correlations exist (see the review article by Fu[19]), the creep crack growth rate, da/dt, appears to correlate well with the maximum stress intensity factor, K_{max}, for temperatures below 600°C in 316 SS. Because creep is a thermally activated process, an Arrhenius expression is assumed, giving

$$\frac{da}{dt} = D_o (K_{max})^P \, e^{-Q/RT} \quad . \tag{40}$$

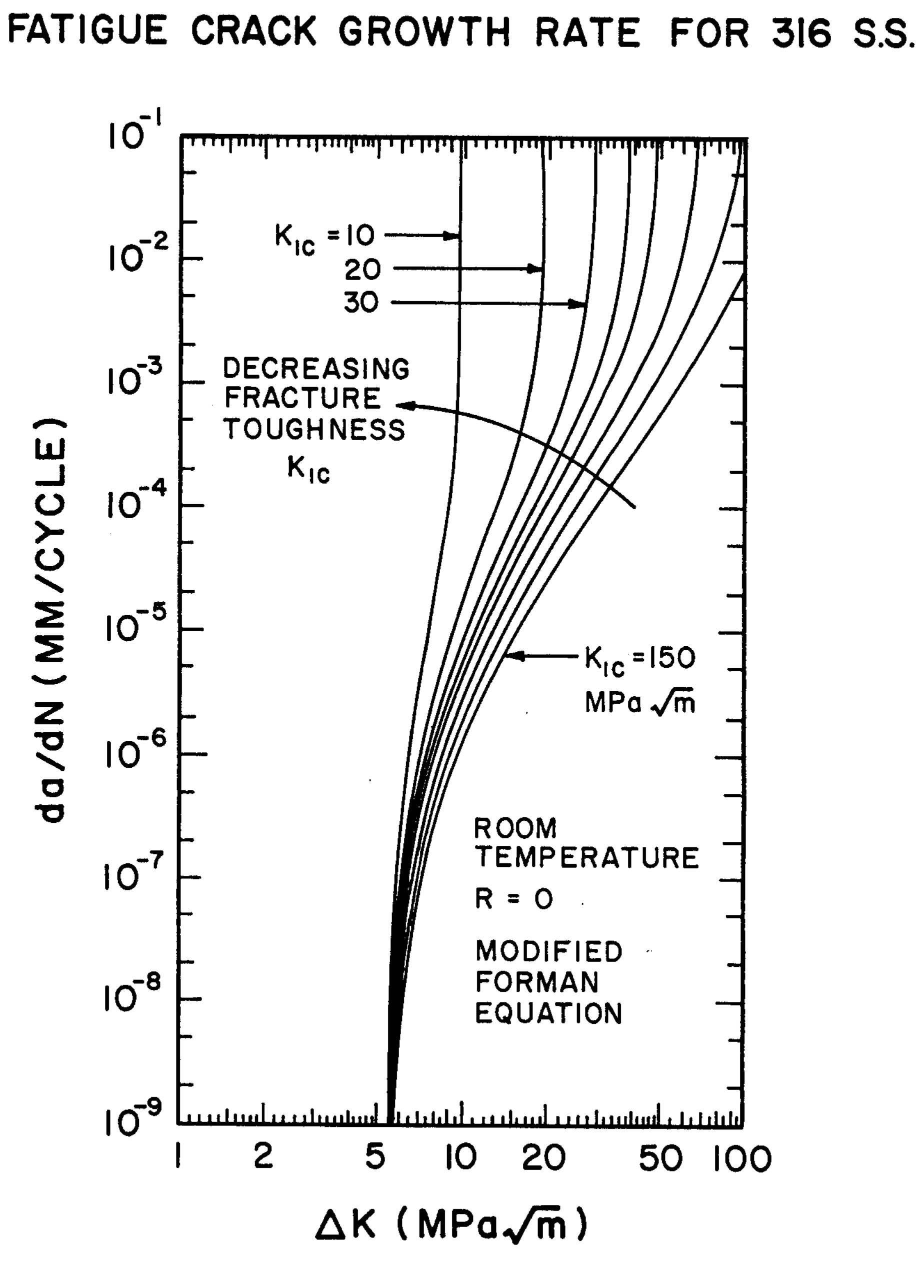
Most of the data for 316 SS are taken at 600-750°C and have provided consistent measurements of the activation energy, Q.

Figure 18



Three different model assumptions used in WISECRACK for the effects of neutron irradiation on fatigue crack growth in 316 stainless steel.

Figure 19



WISECRACK predictions of the effect of decreasing fracture toughness on fatigue crack growth rates in 316 stainless steel at room temperature and R = 0.

However, at these high temperatures the use of linear elastic fracture mechanics becomes somewhat questionable. This is due to large creep deformation at the crack tip which relaxes the $r^{-1/2}$ stress distribution and, hence, invalidates the stress intensity factor solutions. In this regime the data correlates best with the time-dependent J-integral, $\dot{J}$ or C^* (see Taira et al.[20]). Unfortunately, $\dot{J}$ or C^* is very difficult to calculate for the surface flaw, and no results seem to be available in the literature.

Therefore, the constants P and D_0 in Eq. (40) were fit by the authors to data taken by James[21] at 538°C, where K-factors are assumed to be valid. These constants are listed in Table 3. Note that Eq. (40) should be used with caution for temperatures above 650°C. This is especially true for inertial confinement reactors, where temperatures may exceed 1000°C.

Table 3. Creep Crack Growth Rate Data for 316 SS

$P = 15$

$D_0 = 1.39 \times 10^{-6}$ m/sec

$Q = 391,000$ J/mole

$R = 8.31$

K_{max} [MPa $\sqrt{m}$]

da/dt [m/sec]

II.G. Total Crack Growth Rate

The total crack growth rate, $(da/dN)_{total}$, is computed as a linear superposition of fatigue and creep rates, assuming no creep-fatigue interaction to exist. Since creep crack growth will be significant only when the plasma is burning for a time = t_{ON}, then we can write

$$\left(\frac{da}{dN}\right)_{total} = \underset{\text{(Fatigue)}}{\frac{da}{dN}} + t_{ON} \underset{\text{(Creep)}}{\frac{da}{dN}} \ . \tag{41}$$

Although creep-fatigue interactions have been observed in 316 SS[22], no models are currently available to predict these effects.

II.H. Wall Thinning and Crack Erosion

Both sputtering and vaporization of material from plasma disruptions are mechanisms that erode the surface of unprotected high heat flux components. Total erosion rates as large as 1-2 mm/yr have been calculated for INTOR conditions.[23] Because these rates are large, WISECRACK and TSTRESS both model the effects of surface erosion.

Surface erosion causes wall thinning, which affects the long-term stress history. As the wall thins down, the temperature difference across the wall decreases, thus lowering the cyclic thermal stress, $\Delta\sigma_{th}$. Since da/dN ~ $(\Delta\sigma_{th})^4$, even a small amount of erosion will extend the lifetime. However, too much erosion then causes the coolant pressure stress to increase, thereby enhancing the R-ratio (mean stress) and, hence, accelerating da/dN. Usually the first effect dominates over the second. TSTRESS computes this complicated stress history and passes it on to WISECRACK.

Now, if the crack is located on the plasma side of the wall, then surface erosion is assumed to reduce both of its dimensions, a and c, by an amount equal to Δa and Δc, respectively. For a given number of cycles, ΔN, we can write

$$\Delta a = e_r \, \Delta N \, t_{pulse} \quad (42)$$

and

$$\Delta c = c[1 - \sqrt{1 - (\frac{\Delta a}{a})^2}] \quad (43)$$

where: e_r = erosion rate

t_{pulse} = period of one pulse.

WISECRACK assumes that if the rate of crack erosion in the a-direction:

$$\frac{\Delta a}{\Delta N} = e_r t_{pulse} \quad (44)$$

is greater than the fatigue crack growth rate, da/dN, then the flaw will begin to shrink in size and eventually be obliterated. Although this seems plausible, no experimental data have been found to either confirm or refute this assumption.

There is a third synergistic effect caused by surface erosion that should be described. Wall thinning will indirectly change the stress intensity factor solutions by increasing the dimensionless depth ratio, a/h. This ratio is used in Eqs. (4), (8), (10), (13), (14), and (15) to compute the membrane and bending correction factors, M_m and M_b. Therefore, since $\frac{da}{dN} \sim (\Delta\sigma)^4$, small changes in a/h due to wall thinning may have a significant effect on da/dN through M_m and M_b.

II.I. Lifetime Prediction

Conceptually, the propagation of a surface flaw to failure is determined by integrating over time the rate of crack growth along a particular direction. For two-dimensional growth, this can be written as

$$a_f = a_o + \int_0^{N_f} \left(\frac{da}{dN}\right)_{total} dN \tag{45}$$

and

$$c_f = c_o + \int_0^{N_f} \left(\frac{dc}{dN}\right)_{total} dN \tag{46}$$

where: a_o = initial flaw depth

$2c_o$ = initial flaw surface length

a_f = flaw depth at failure

$2c_f$ = flaw length at failure

N = number of load cycles

N_f = cycles to failure.

In practice, however, WISECRACK solves these equations incrementally by choosing a small increment in cycles, ΔN, and then computing an approximate increment in growth as:

$$\Delta a \cong \left(\frac{da}{dN}\right)_{total} \Delta N \tag{47}$$

and

$$\Delta c \cong \left(\frac{dc}{dN}\right)_{total} \Delta N \quad . \tag{48}$$

The new crack size is obtained by adding these increments to the current dimensions:

$$a_{new} = a_{old} + \Delta a \tag{49}$$

$$c_{new} = c_{old} + \Delta c \tag{50}$$

and

$$N = N + \Delta N \quad . \tag{51}$$

Any degree of accuracy can be obtained with this method by choosing a sufficiently small step size ΔN. Chapter III describes the details of this numerical procedure.

The end-of-life is defined by one of two possible failure modes. One possible mode is when $a_f \geq h$ and coolant therefore leaks through the wall. Typically this mode is dominant when either the toughness is high ($K_{Ic} > 100$ MPa $\sqrt{m}$) or when the wall erosion rates are high ($e_r > 1$ mm/yr). The other failure mode is catastrophic fracture, which occurs when $K_{max} \geq K_{Ic}$. For embrittled steels, it is this second mode that controls the lifetime. Obviously, the leak-through failure mode is preferred over catastrophic fracture.

III. WISECRACK Code Description

III.A. Method of Solution

The approach taken in the WISECRACK code to compute the crack propagation involves a numerical solution of Eqs. (45) and (46), rewritten below as a coupled set of first order differential equations:

$$\left(\frac{da}{dN}\right)_{total} = f(a,c,h,N,T,\sigma,t_{ON},dpa) \quad (52)$$

and

$$\left(\frac{dc}{dN}\right)_{total} = g(a,c,h,N,T,\sigma,t_{ON},dpa) \quad . \quad (53)$$

The initial conditions are assumed to be:

$$a|_{N=0} = a_0 \quad (54)$$

and

$$c|_{N=0} = c_0 \quad . \quad (55)$$

WISECRACK employs a fourth-order Runge-Kutta multi-step algorithm to numerically obtain the solution to the equations listed above. The basic concept used by this method, as diagrammed in Fig. 20, is to compute four separate estimates (Δa_1, Δa_2, Δa_3, Δa_4) of the increment in crack size, Δa, and then average these four values to obtain a more accurate approximation to Δa:

$$\Delta a = \frac{1}{6}\left[\Delta a_1 + \frac{1}{2}\Delta a_2 + \frac{1}{2}\Delta a_3 + \Delta a_4\right] \quad . \quad (56)$$

It should be noted that the two governing equations for $(da/dN)_{total}$ and $(dc/dN)_{total}$ are coupled by a common dependence on the flaw shape factor, Q,

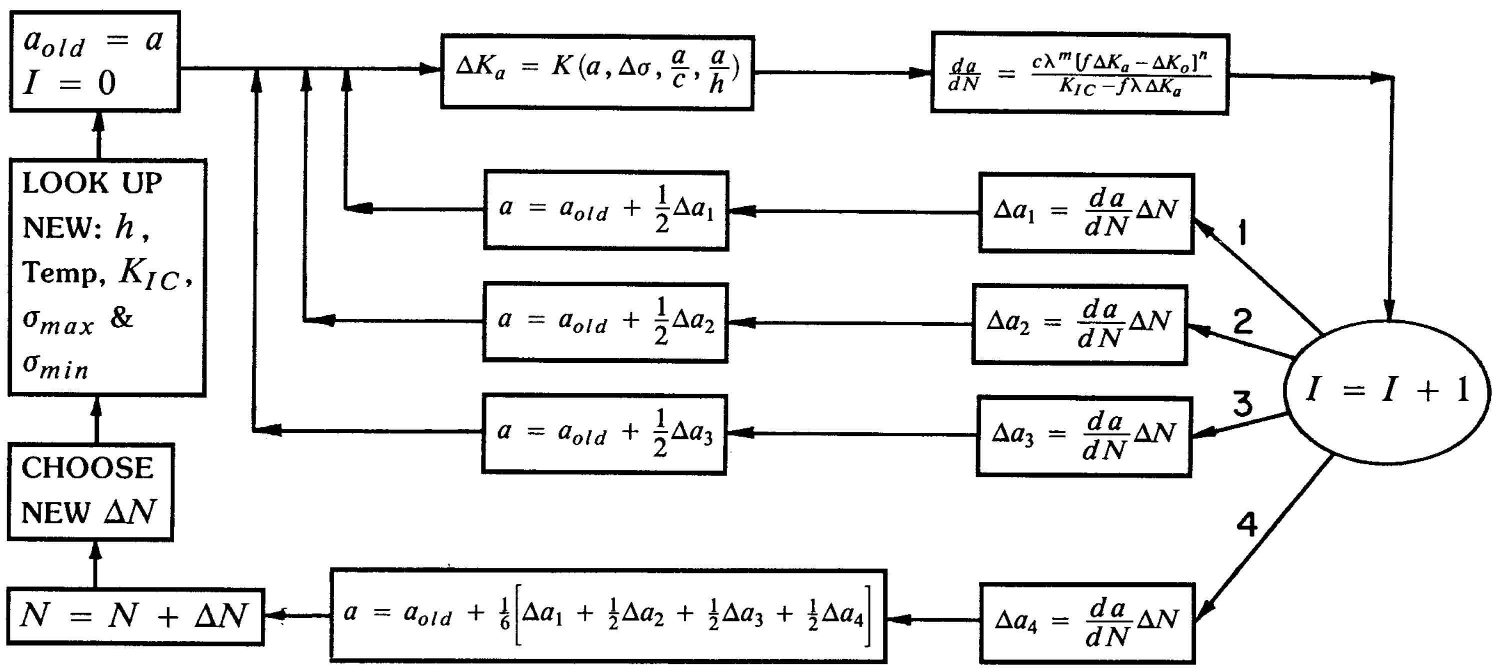


Figure 20

Method of solution used in WISECRACK.

the membrane correction factor, M_m, and on the bending correction factor, M_b, via the aspect ratio, a/c. The coupling with Q is not very significant, but the M_m and M_b coupling can be very strong in some cases.

III.B. Step Size Control

In order to minimize computing times, WISECRACK automatically calculates the increment in cycles, ΔN, at the beginning of each program iteration. The chosen value of ΔN must then satisfy four separate adjustable criteria which allow the largest possible ΔN, without sacrificing accuracy. ΔN is chosen to be the smaller of the following two numbers,

$$\Delta N = \text{minimum} \begin{pmatrix} \varepsilon \dfrac{a}{da/dN} \\ \\ \varepsilon \dfrac{c}{dc/dN} \end{pmatrix} . \tag{57}$$

These numbers are chosen so that $\Delta a \leq \varepsilon a$ and $\Delta c \leq \varepsilon c$, where ε is defined as the maximum allowed fractional change in crack size. The default value of ε is 1% (FRCHNG=0.01).

The first of four limiting criteria prevents ΔN from exceeding a specified maximum, therefore

$$\Delta N \leq \Delta N_{max} \quad . \tag{58}$$

The second rule prevents ΔN from growing faster than an allowed rate. If ΔN_{old} is the current value of ΔN, then

$$\Delta N \leq \Delta N_{old} \cdot \text{TGROW} \tag{59}$$

where TGROW typically equals 1.5.

The third criterion is related to the long-term stress history as computed by TSTRESS. These stresses are stored in an array at specific points in time: t_1, t_2, $t_3 \ldots t_n$. Since these stresses should not change significantly within the ΔN cycles, ΔN may not exceed the ratio

$$\Delta N \leq \frac{t_{n+1} - t_n}{t_{pulse}} \quad . \qquad (60)$$

This insures that the stress history will be followed accurately.

Finally, the fourth criterion simply prevents ΔN from taking on any fractional values, hence

$$\Delta N \geq 1 \quad . \qquad (61)$$

The user can control the accuracy and/or efficiency of the calculation by setting his/her own values for FRCHNG, NMAX and TGROW.

III.C. Description of Subroutines

Figure 21 shows the flow chart for WISECRACK. In the following, a brief description will be given of the major sections of WISECRACK.

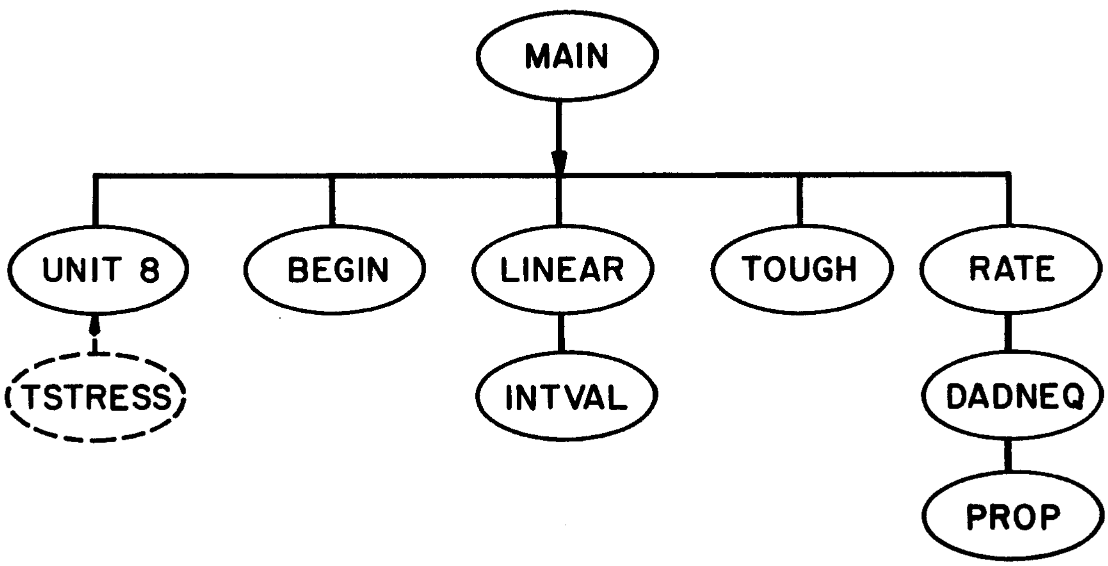
Namelist BEGIN

This is a namelist called "BEGIN" which includes all of the input variables that are read into the MAIN program (except any data read from unit 8).

MAIN Program

MAIN computes the increments in crack size by using the fourth-order Runge-Kutta method as illustrated in Fig. 20 to numerically integrate the crack growth rates over time. After each iteration, MAIN checks whether or

Figure 21



Flow chart of subroutines used in WISECRACK.

not leak-through or catastrophic fracture has occurred. When that happens, MAIN calls graphics routines which plot the results.

Subroutine LINEAR

LINEAR takes the actual nonlinear stress distribution through the wall and replaces it with an appropriate linear distribution. It then determines the linearized bending and membrane stresses. LINEAR also computes the plasma ON and OFF temperatures at different positions along the crack front and also the current value of the wall thickness, h. LINEAR computes the current values of $\sigma(z,t)$, $T(z,t)$, and $h(t)$ by interpolating between two time data points which are read from unit 8.

Subroutine INTVAL

INTVAL is a subroutine, called by both LINEAR and MAIN, which determines a pointer for the appropriate interval from among many data points to which a specific variable belongs. This information is used for the linear interpolations.

Subroutine TOUGH

TOUGH calculates the plane strain fracture toughness, K_{IC}, for 316 SS (or for any other metal) as a function of the current radiation damage level (dpa). For ferritic steels, K_{IC} would also depend on temperature because of the ductile to brittle transition (DBTT).

Subroutine RATE

RATE calculates, first, the stress intensity factors K_a^{ON} and K_a^{OFF} at the crack tip "A" and K_c^{ON} and K_c^{OFF} at the crack's intersection with the surface "C", for plasma-ON and plasma-OFF conditions, respectively. Then, it compares these four values and chooses the maximum and minimum stress intensities: K_a^{max}, K_a^{min}, K_c^{max}, and K_c^{min}. From these values the largest K is chosen, K_{max}.

Next, the two R-ratios are found, R_a and R_c. RATE then calls DADNEQ twice to obtain the total crack growth rates, da/dN and dc/dN. Finally, it reduces dc/dN by the factor $(0.9)^{3.66}$ to account for surface effects, as suggested by Newman and Raju.[6]

Subroutine DADNEQ

DADNEQ calculates $(da/dN)_{total}$ and $(dc/dN)_{total}$. Two different equations for fatigue crack growth rates are available to the user. If both K_{max} and K_{min} are negative numbers, then da/dN (or dc/dN) is set equal to zero. The creep and fatigue crack growth rates are then linearly superimposed, assuming no creep-fatigue interaction.

Subroutine PROP

PROP calculates the ratio, f, of elastic modulii at two different temperatures, $E(T_0)/E(T)$. T_0 is room temperature and T is the temperature at a specific location along the crack front corresponding to the appropriate plasma-ON or OFF conditions when the crack tip opening displacement is a maximum.

III.D. Units

WISECRACK uses the following conventions for units:

stress	MPa
time	seconds
length	meters
temperature	°K
neutron damage	dpa
K_I	MPa $\sqrt{m}$.

Unfortunately, the output from TSTRESS, which is stored on unit 8, is in the following units: cm, sec, ksi, °K, dpa. WISECRACK, therefore, converts the

TSTRESS units after it reads the data from unit 8. Also, TSTRESS solves the problem in units of "full power" time, e.g., full power years (FPY). However, WISECRACK operates on a "calendar year" basis for time. Therefore, WISECRACK converts the TSTRESS time units with the following formula:

$$t_{WISECRACK} = t_{TSTRESS} * \frac{t_{pulse}}{t_{ON}} \quad . \tag{62}$$

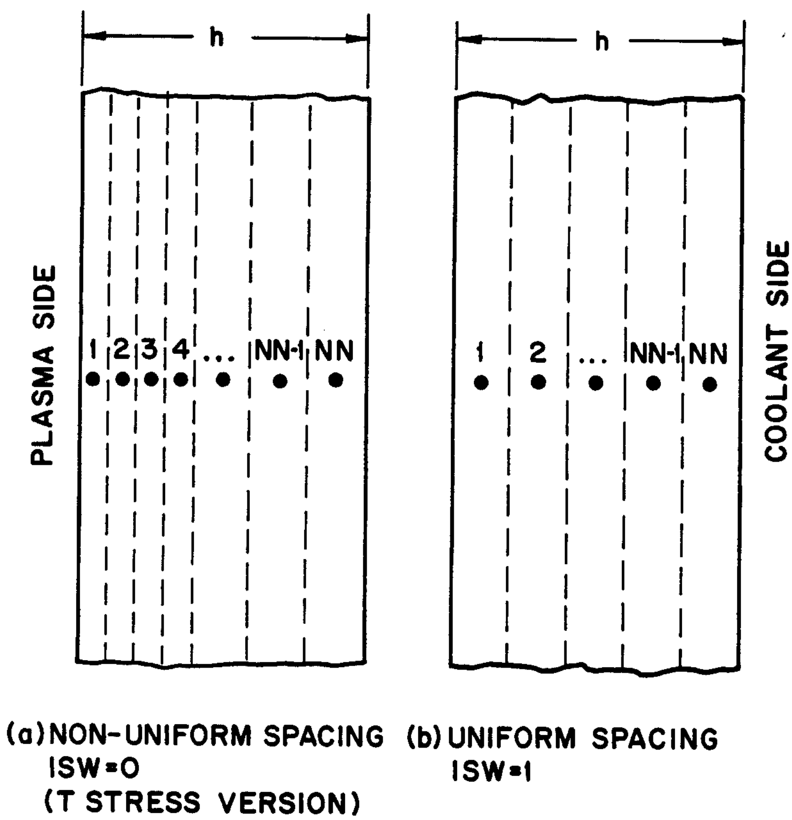
III.E. Spatial Zoning

The plate is divided into NN zones, and NN node points. When ISW=0, then the zoning data is as originally determined in TSTRESS and this information is passed to WISECRACK via unit 8. TSTRESS allows a variable zone spacing, as shown in Fig. 22(a). On the other hand, when ISW=1, then WISECRACK calculates its own uniformly-spaced mesh (e.g., constant zone size), as shown in Fig. 22(b).

III.F. Description of Variables

A	crack depth into plate
AEFF	effective crack depth ($a + \ell_0$)
AOLD	previous value of the crack depth, a
ASPECT	aspect ratio of the surface flaw (a/c)
BANNER=0	this indicates that KMAX occurred while the plasma was ON
BANNER=1	this indicates that KMAX occurred while the plasma was OFF
C	crack half-length along plate surface
COLD	previous value of the crack half-length c along the surface
C1,C2,C3,C4	intermediate values of the increment in crack half-length, c
DADN	effective value of the crack growth rate from fatigue and creep
DADNCG	crack growth rate due to fatigue loading only

Figure 22



Two different types of spatial meshes used in WISECRACK.

DADTOF	creep crack growth rate while plasma is OFF
DADTON	creep crack growth rate while plasma is ON
DELTAA	actual value of the increment in crack depth, for DELTAN cycles
DELTAC	actual value of the increment in crack half-length, c
DELTA1,2,3,4	intermediate values of the increment in crack depth
DELTAN	number of plasma cycles per program increment step size
DLTKEF	effective stress intensity factor range
DNMAX	maximum allowed cycle increment size
ERATE	wall surface erosion rate (m/sec)
FLUNCE	accumulated neutron damage (dpa)
FREQ	frequency of plasma ON/OFF cycles
KAOFF	stress intensity factor while plasma is OFF at the deepest point, "A"
KAON	stress intensity factor while plasma is ON at the deepest point
KCOFF	stress intensity factor while plasma is OFF at the surface, "C"
KCON	stress intensity factor while plasma is ON at the surface, "C"
KIC	plane strain fracture toughness
KMAX	maximum value of the stress intensity factor
KMIN	minimum value of the stress intensity factor
LA=0	maximum stress intensity factor at crack tip "A" occurs during plasma-ON conditions
LA=1	maximum stress intensity factor at "A" occurs during plasma-OFF conditions
LC=0	maximum stress intensity factor at surface "C" occurs during plasma-ON conditions

LC=1	maximum stress intensity factor at "C" occurs during plasma-OFF conditions
N	current number of plasma ON/OFF cycles
NOLD	previous value of number of plasma cycles
PHI=0	this indicates that KMAX occurs at the surface "C" of the crack
PHI=1	this indicates that KMAX occurs at the deepest point "A" of the crack
SBON	linearized bending stress while plasma is ON
SBOFF	linearized bending stress while plasma is OFF
SIGOFF(I)	total stress while plasma is OFF for i^{th} zone
SIGON(I)	total stress while plasma is ON for i^{th} zone
SMOFF	linearized membrane stress while plasma is OFF
SMON	linearized membrane stress while plasma is ON
STHMRL(I)	thermo-elastic stress component while plasma is ON for i^{th} zone
SXON	stress at crack tip "A" while plasma is ON
SXOFF	stress at crack tip "A" while plasma is OFF
SYON	stress at surface "C" while plasma is ON
SYOFF	stress at surface "C" while plasma is OFF
TEMPA	temperature at "A" while plasma is ON
TEMPC	temperature at "C" while plasma is ON
TAOFF	temperature at "A" while plasma is OFF
TCOFF	temperature at "C" while plasma is OFF
TIME	current time
Z(I)	node point locations along z-axis, z = 0 at plasma side

IV. Instructions for Using WISECRACK

IV.A. Problem Setup and Options

The setup for running a problem on WISECRACK is not difficult because most of the input variables have default values assigned to them. These twenty-one optional variables can be easily changed, thus giving the user a large degree of flexibility and control over the program.

The only required input variable that the user must specify each time a problem is solved is the initial crack depth, a_0 (ANOT). The initial aspect ratio, a_0/c_0 (ASPECT), is considered an optional input variable and has a default value of ASPECT=1 (a semi-circular surface flaw).

WISECRACK accepts data for stress, temperature, plate thickness, etc., in one of two different modes, depending on the value of ISW. When ISW=0 (its default value) the stress data is read from the TSTRESS output stored on unit 8. Otherwise, when ISW=1, the stress data must be supplied by the user directly through the input namelist BEGIN. A list of the required input variables is given in section IV.B.

WISECRACK always begins with the surface flaw located on the plasma side of the wall, computes the lifetime and then automatically starts over again with the flaw now on the coolant side.

The orientation of the plane in which the flaw lies should always be chosen perpendicular to the direction of maximum principal stress, either σ_x or σ_y. The optional variable JFLAG controls this choice (default = σ_x).

Section IV.C lists the optional input variables and gives their default values. The only option which should not be used at the present time is KFLAG. The inertial confinement version (KFLAG=2) does not work properly due to difficulties in the relationship between the stress behavior and stress intensity factors. Future versions will address this problem.

IV.B. Required Input Variables

NAME	TYPE	DESCRIPTION
ANOT	DP	Initial crack depth into plate (m)

If ISW=0, then this is the only required input to be contained in the namelist BEGIN. However, if ISW=1, then the following variables are also required:

HNOT	DP	Constant plate thickness (m)
ISW=1	I	Time-independent stress cycle flag
NN	I	Number of equally spaced zones through the thickness. Also equal to number of node points, see Fig. 22(b)
SON	DP	Array of size NN of stresses at i^{th} node point for plasma-ON (MPa)
SOFF	DP	Same as SON, except for plasma-OFF (MPa)
TEMPON	DP	Array, of size NN, of temperatures at i^{th} node point for plasma-ON (°K)
TEMPOF	DP	Same as TEMPON, except for plasma-OFF (°K)
TIMEON	DP	Time while plasma is ON (sec)
TIMEOF	DP	Time while plasma is OFF (sec)
TPUSLE	DP	Time for one complete ON/OFF cycle (sec)

Note: DP = double precision variable

I = integer

If WISECRACK is to be coupled to an inelastic stress analysis code other than TSTRESS, such as NASTRAN, ANSYS, or MARC, this would require writing a short pre-processor program to convert the data output from NASTRAN to the proper format for input to WISECRACK. This program would have to first read the NASTRAN data and then write it out onto unit 8 using the following format.

Pre-Processor Program

```
      DO 10 I=1, NTIMEX
      A(1)=FLAG
      A(2)=TIMEX(I)
      A(4)=TIMEON
      A(5)=NN
      A(6)=THICK(I)
      A(7)=FLUX
      A(8)=TPULSE
      A(9)=TIMEOF
      A(10)=ERATE
      A(11)=TCOOL
      WRITE(8) (A(J),J=1,NN)
      WRITE(8) (Z(I,J),J=1,NN)
      WRITE(8) (TEMPON(I,J),J=1,NN)
      WRITE(8) (SIGX(I,J),J=1,NN)
      WRITE(8) (SIGY(I,J),J=1,NN)
      WRITE(8) (STHMRL(I,J),J=1,NN)
10    CONTINUE
```

We have defined the following variables for this program:

FLAG	A number greater than zero except when used to signal the end of the data, in which case FLAG=-1.DO.
TIMEX	Array, of size NTIMEX, which stores the points in time when the stress data was saved.
NTIMEX	Number of entries in TIMEX.
THICK	Array, of size NTIMEX, which stores the current value of the wall thickness at a specific time, TIMEX(I).
TCOOL	Coolant temperature.
Z	Array, of size (NTIMEX * NN), which stores the node point coordinates in space and time.
TEMPON	Array of temperatures while plasma is ON.
SIGX	Stress in x-direction while plasma is ON.
SIGY	Stress in y-direction while plasma is ON.
STHMRL	Thermal stress for different node points and different points in time.

IV.C. Optional Input Variables

NAME	TYPE	DEFAULT VALUE	DESCRIPTION
ASPECT	DP	1.DO	Initial flaw aspect ratio
DEVICE	I	1	=1 graphics output sent to plotter =2 graphics output sent to line printer =3 no graphics output
DNMIN	DP	1.DO	Minimum cycle step size
FLAG	I	1	=1 crack on plasma side =2 crack on coolant side

FLUX	DP	0.D0	Neutron damage rate (dpa/sec)
FRCHNG	DP	1.D-2	Fractional change in crack dimensions per iteration
ICCG	I	1	=0 turn off creep crack growth law =1 turn on creep crack growth law
IDADN	I	1	=1 modified Forman equation for da/dN =2 Paris equation for da/dN =3 modified Forman equation without irradiation effects to stage II
IDIMEN	I	2	=1 one-dimensional flaw growth (aspect ratio remains constant) =2 two-dimensional flaw growth
IPRINT	I	0	=0 no special output =1 print out these variables after each call to LINEAR: SXON, SYON, SXOFF, SYOFF, SMON, SBON, SMOFF, SBOFF, TEMPA, TEMPC, SIGON(I), SIGOFF(I) (I=1,NN)
ISCATR	I	2	=1 upper bound to scatter in da/dN data: (nominal * 2) =2 nominal curve fit to da/dN =3 lower bound to scatter in da/dN data: (nominal ÷ 2)
ISW	I	0	=0 read in stress data from unit 8 =1 read data from namelist BEGIN
JFLAG	I	1	=0 use stress in x-direction =1 use stress in y-direction
KFLAG	I	1	=1 magnetic confinement version =2 inertial confinement version (not used)
KICMIN	DP	30.D0	Minimum allowed irradiated fracture toughness, K_{Ic} (MPa $\sqrt{m}$)
KICON	I	1	=0 K_{Ic} remains constant over time =1 K_{Ic} is a function of dpa
LZERO	DP	6.4D-5	Short crack correction factor, ℓ_0 (m)
MINPNT	I	40	Minimum number of points plotted on graphics output
NMAX	I	10,000,000	Maximum allowed number of ON/OFF cycles

TGROW	DP	1.5D0	Maximum allowed rate of change of ΔN
TMAX	DP	9.461D8	Maximum allowed time (sec)
W	DP	1.D4	Plate width (m)

IV.D. Sample Problem and Output

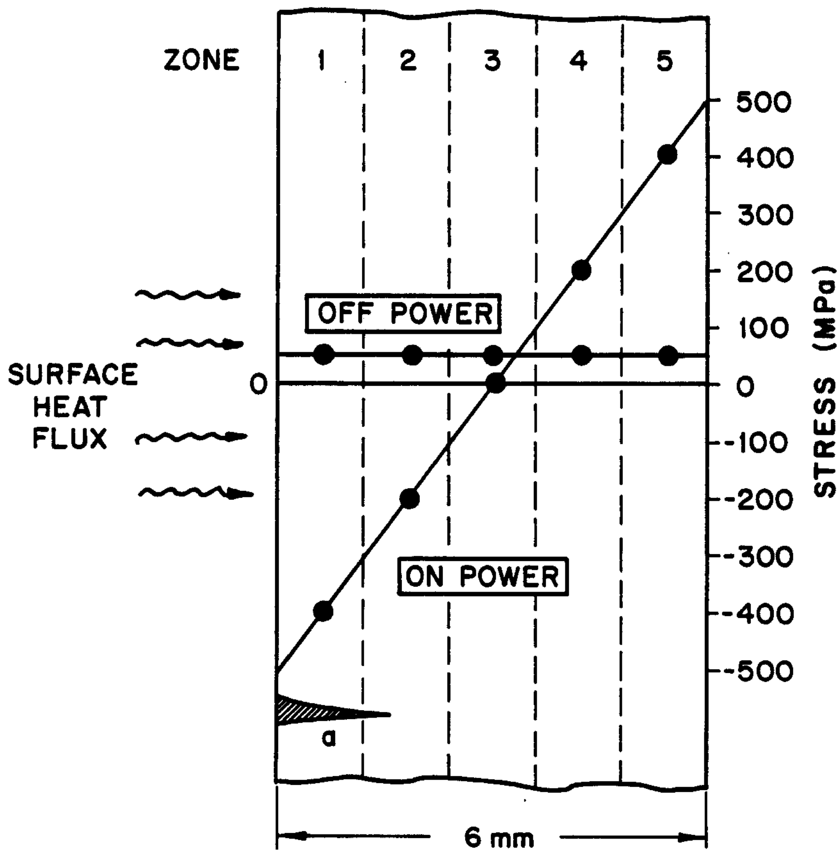
A simple example is presented in this section to illustrate the problem setup and the subsequent computer output. All of the required data was input through the namelist BEGIN, as listed below.

BEGIN File for Sample Problem

```
&BEGIN
  ANOT=1.D-3,
  HNOT=6.D-3,
  ISW=1,
  NN=5,
  SON=-400.D0,-200.D0,0.D0,200.D0,400,D0,
  SOFF=5*50.D0,
  TEMPON=700.D0,670.D0,640.D0,610.D0,580.D0,
  TEMPOF=5*573.D0,
  TIMEON=900.D0,
  TIMEOF=100.D0,
  TPULSE=1000.D0,
  FLUX=7.D-7,
  DEVICE=2,
&END
```

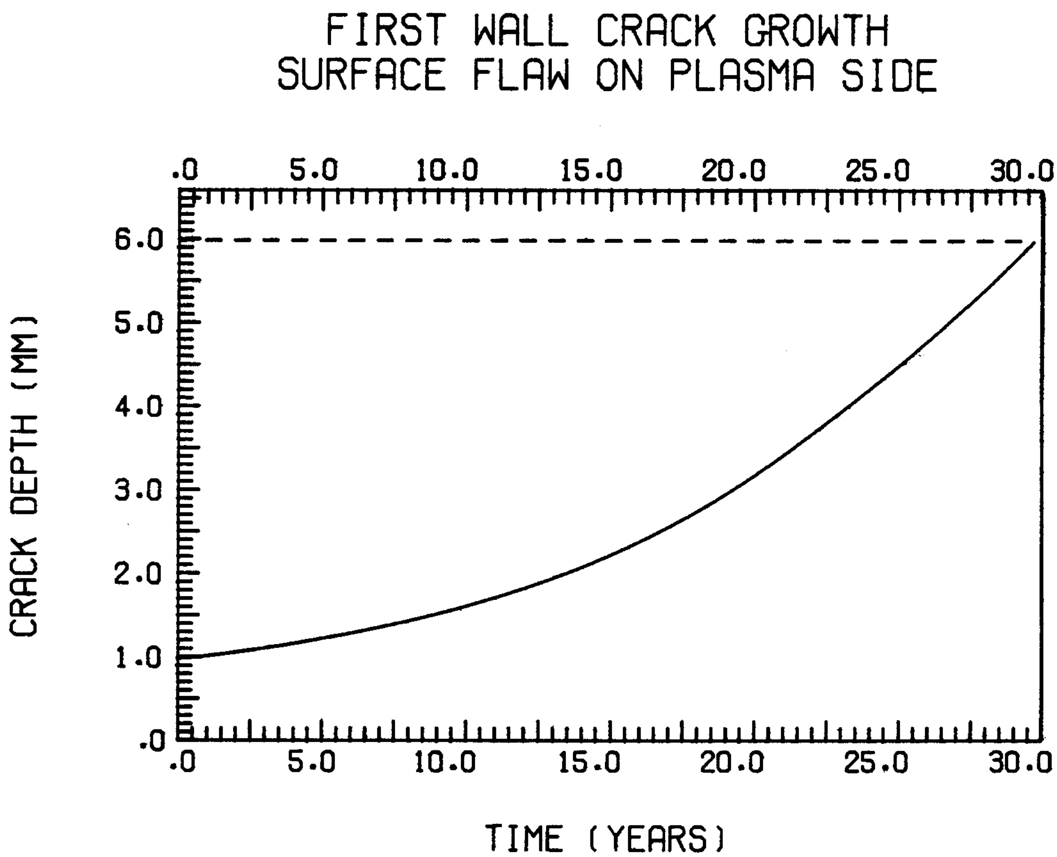
The first line of this file begins in column one. Figure 23 shows the ON/OFF stresses that are used in this example. Thirteen seconds of CPU time on the UNIVAC 1110 were required to solve this problem. Figure 24 shows the crack growth as a function of time for a flaw located on the plasma side. The code predicts leak-through failure after 30 years for this example. For a flaw located on the coolant side of the wall, WISECRACK predicted failure by catastrophic fracture after 0.5 years. Appendix A is a listing of the WISECRACK code and Appendix B contains the computer output for the sample problem.

Figure 23



Stresses used in sample problem.

Figure 24



WISECRACK output for the sample problem.

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APPENDIX A

WISECRACK Code Listing

===== BEGIN =====

```
&BEGIN
  ANOT=1.D-3,
  ASPECT=1.D0,
  DEVICE=2,
  ISCATR=2,
  IDIMEN=2,
  IDADN=1,
  KICMIN=30.D0,
  ICCG=0,
&END
```

```
      =====  BEGIN1  =====

 &BEGIN
    ANOT=1.D-3,
    ASPECT=1.D0,
    DEVICE=2,
    ISCATR=2,
    IDIMEN=2,
    IDADN=1,
    KICMIN=30.D0,
    ICCG=0,
 &END
```

```
     =====  BEGIN2  =====

&BEGIN
  ANOT=1.D-3,
  HNOT=6.D-3,
  ISW=1,
  NN=5,
  SON=-400.D0,-200.D0,0.D0,200.D0,400.D0,
  SOFF=5*50.D0,
  TEMPON=700.D0,670.D0,640.D0,610.D0,580.D0,
  TEMPOF=5*573.D0,
  TIMEON=900.D0,
  TIMEOF=100.D0,
  TPULSE=1000.D0,
  FLUX=7.D-7,
  DEVICE=2,
&END
```

```
      =====  PROP  =====

      SUBROUTINE PROP (F,R,T,KTH,M1)
      IMPLICIT REAL*8 (A-H, O-Z)
      REAL*8 M1,KTH0,NEXPON,KTH
      COMMON/NEXP/NEXPON
      KTH0=5.4D0
      NEXPON=3.66D0
      ALPHA1=9.07D-1
      ALPHA2=2.04D-1
      IF(R.GE.0.) KTH=KTH0*(1.D0-ALPHA1*R)
      IF(R.LT.0.) KTH=KTH0*(1.D0-ALPHA2*R)
      IF(R.LT.-1.) KTH=6.5D0
      IF(R.LE.0.) M1=1.D0
      IF(R.GE.0.) M1=1.D0-0.30611D0*R-1.227778D0*(R**2.D0)
      IF(R.LT.0.) M1=1.88D0
C
C   CHANGE TEMPERATURE FROM DEGREE K TO DEGREE F
C
      TF=(T-273.D0) * 9.D0/5.D0 + 32.D0
C
      A0=1.12476D1
      A1=-1.64275D-3
      A2=-1.330819D-6
      A3=3.567476D-10
C
C   RATIO = RATIO OF SHEAR MODULUS AT T TO SHEAR MODULUS AT ROOM TEMP
C
      RATIO=(A0+A1*TF+A2*TF**2+A3*TF**3)/1.1117D1
C
C   F = ENHANCEMENT FACTOR DUE TO TEMPERATURE EFFECT ON F.C.G
C
      F = 1.D0/RATIO
C
      RETURN
      END
```

===== INTVAL =====

```
C     ******************************************************************
C     *                                                                *
C     *   'INTVAL' CALCULATES THE INTERVAL IN WHICH THE VALUE X BELONGS *
C     *   MEANING, Y(K) < X < Y(K+1)                                   *
C     *                                                                *
C     ******************************************************************
C
C
      SUBROUTINE INTVAL (X,Y,K,N)
C
C    X=ACTUAL VALUE INSIDE THE INTERVAL
C    Y(K)=ARRAY OF VALUES AT THE ENDPOINTS OF EACH INTERVAL (K=1,2,3...N)
C    K=INTERVAL COUNTER,E.G. K=1 MEANS THE FIRST INTERVAL,ETC.
C    N=TOTAL NUMBER OF POINTS IN THE Y-ARRAY
C
      IMPLICIT REAL*8 (A-H,O-Z)
      REAL*8 Y(100)
      K=1
C
C          TEST IF  X IS OUTSIDE (LESS THAN) THE RANGE OF DATA POINTS Y(K)
C
      IF (X.LT.Y(K)) GO TO 40
C
C         TEST IF X IS OUTSIDE (GREATER THAN) THE RANGE OF DATA POINTS Y(K)
C
   10 IF (K.EQ.N) GO TO 55
      K=K+1
      IF (X.GT.Y(K)) GO TO 10
      K=K-1
      RETURN
   40 PRINT 50,X,Y(K),K
   50 FORMAT ('0','ERROR: THE VALUE OF X IS LESS THAN THE SMALLEST VALUE
     * OF THE Y-ARRAY',5X,'X=',D11.4,5X,'Y(K)=',D11.4,5X,'K=',I6)
      RETURN
   55 PRINT 60,X,Y(K),K
   60 FORMAT ('0','ERROR: THE VALUE OF X IS GREATER THAN THE LARGEST  VA
     *LUE OF THE Y-ARRAY',5X,'X=',D11.4,5X,'Y(K)=',D11.4,5X,'K=',I6)
      RETURN
      END
C
```

```
===== TOUGH =====
C
C     **********************************************************************
C     *                                                                    *
C     *   'TOUGH' CALCULATES THE PLANE STRAIN FRACTURE TOUGHNESS,KIC,      *
C     *   AS A FUNCTION OF TEMPERATURE AND NEUTRON FLUENCE                 *
C     *                                                                    *
C     **********************************************************************
C
C
      SUBROUTINE TOUGH
      IMPLICIT REAL*8 (A-H,O-Z)
      REAL*8 KIC,KICMIN,KICNOT
      COMMON/TOUGHZ/KIC,FLUNCE,KICON,KICMIN,KICNOT
      KIC=115.D0*DEXP(-2.5D-1*FLUNCE)+3.5D1*DEXP(-1.34D-2*FLUNCE)
      IF (KICON.EQ.0) KIC = 150.D0
      IF (KIC.LT.KICMIN) KIC=KICMIN
      KICNOT=150.D0
      RETURN
      END
```

```
      =====  DADNEQ  =====
C
C     ******************************************************************
C     *                                                                *
C     *   'DADNEQ' CALCULATES THE EFFECTIVE CRACK GROWTH RATE AT ANY   *
C     *   LOCATION ALONG THE CRACK FRONT.  IT INCLUDES BOTH FATIGUE AND *
C     *   CREEP CRACK GROWTH PHENOMENA.                                *
C     *                                                                *
C     ******************************************************************
C
      SUBROUTINE DADNEQ (KMAX,KMIN,DXDN,KON,KOFF,TIMEON,TIMEOF,R,T)
      IMPLICIT
     +    REAL*8 (A-H,O-Z)
      REAL*8
     +    KIC,               KICMIN,          KICNOT,          KMAX,
     +    KMIN,              KOFF,            KON,             KTH,
     +    LAMBDA,            M1,              M2,              N,
     +    NEXPON
      INTEGER
     +    FLAG
      COMMON /TOUGHZ/
     +    KIC,               FLUNCE,          KICON,           KICMIN,
     +    KICNOT
      COMMON /NEXP/
     +    NEXPON
      COMMON /DATAS/
     +    ISCATR,            IDADN
      COMMON /LINEAZ/
     +    FLAG,              KFLAO
      COMMON /CCG/
     +    ICCG
C
C           STRESS INTENSITY IS IN UNITS OF MPA * SQUARE ROOT (METERS)
C
C           FATIGUE CRACK GROWTH RATE (DADNCG) FOR 316 STAINLESS STEEL
C
      DADTON=0.D0
      DADTOF=0.D0
C
C           MODIFIED FORMAN EQUATION FOR DA/DN
C
      N=2.591D0
      IF (ISCATR.EQ.1) C=3.122D-9*2.D0
      IF (ISCATR.EQ.2) C=3.122D-9
      IF (ISCATR.EQ.3) C=3.122D-9/2.D0
      DNOT=1.38889D-6
      P=15.D0
      Q=391450.D0
      RCONST=8.31D0
C
C           Q = ACTIVATION ENERGY FOR CREEP CRACK GROWTH (J/MOLE)
C
      IF (ICCG.EQ.0) DNOT=0.D0
      IF (IDADN.EQ.2) GO TO 40
      CALL PROP (F,R,T,KTH,M1)
      LAMBDA=1.D0/(1.D0-R)
      DELTAK=KMAX-KMIN
      IF (DELTAK*F.LT.KTH) GO TO 30
      IF (KMAX.LT.0.D0.AND.KMIN.LT.0.D0) GO TO 30
```

```
      =====  DADNEQ  =====

      IF (IDADN.EQ.1) X=KIC
      IF (IDADN.EQ.3) X=KICNOT
      DENOM=X-LAMBDA*DELTAK*F
      IF (DENOM.LE.0.D0) GO TO 10
      DADNCG=C*(LAMBDA**M1)*((DELTAK*F-KTH)**N)/DENOM
      GO TO 50
   10 DADNCG=1.D20
      PRINT 20
   20 FORMAT ('0','DENOMINATOR OF THE MODIFIED FORMAN EQ FOR DA/DN HAS
     + GONE TO ZERO',/)
      GO TO 50
   30 DADNCG=0.D0
      GO TO 50
C
C             PARIS EQUATION FOR DA/DN
C
   40 CALL PROP (F,R,T,KTH,M1)
      CP=3.94D-13
      M2=0.5D0
      DKEFF=KMAX*(1.D0-R)**M2
      IF (DKEFF.LT.0.D0) DKEFF=0.D0
      DADNCG=CP*(DKEFF*F)**NEXPON
C
   50 CONTINUE
C
C             DADTON=CREEP CRACK GROWTH RATE WHILE PLASMA IS ON
C
      DUMMY=DNOT*DEXP(-1.D0*Q/(RCONST*T))
      IF (KON.LT.0.D0) GO TO 60
      DADTON=DUMMY*(KON**P)
C
C             DADTOF=CREEP CRACK GROWTH RATE WHILE PLASMA IS OFF
C
   60 IF (KOFF.LT.0.D0) GO TO 70
      DADTOF=DUMMY*(KOFF**P)
C
C             DXDN=EFFECTIVE CRACK GROWTH RATE, A LINEAR SUPERPOSITION OF
C             FATIGUE
C             AND CREEP CRACK GROWTH.  NO CREEP-FATIGUE INTERACTION IS ASSUMED.
C
   70 DXDN=DADNCG+DADTON*TIMEON+DADTOF*TIMEOF
      RETURN
      END
```

```
      =====  LINEAR  =====

C     ************************************************************************
C     *                                                                      *
C     *    'LINEAR' CALCULATES THE LINEARIZED MEMBRANE AND BENDING STRESSES*
C     *    FROM A NON-LINEAR STRESS DISTRIBUTION USING THE LINEAR-ENVELOPE-*
C     *    OVER-THE-CRACK METHOD.                                            *
C     *                                                                      *
C     ************************************************************************
C
      SUBROUTINE LINEAR
      IMPLICIT
     +    REAL*8 (A-H,O-Z)
      REAL*8
     +    BIG(50,100,4), SIGOFF(50),    SIGON(50),     TEMP(50),
     +    THICK(100),    TIMEX(100),    Z(50),     TEMPOF(50)
      INTEGER
     +    FLAG
      COMMON /THREE/
     +    SMON,          SMOFF,         SBON,          SBOFF
      COMMON /LINEAZ/
     +    FLAG,          KFLAG
      COMMON /ONE/
     +    A,             H
      COMMON /MAINZ/
     +    NN,            NP
      COMMON /STRESZ/
     +    TIME,          Z,             SIGON,         SIGOFF
      COMMON /TEN/
     +    TIMEX,         NTIMEX,        THICK
      COMMON /BIG/
     +    BIG
      COMMON /TEM/
     +    TEMP
      COMMON /TBLOCK/
     +    TEMPA,         TEMPC,     TAOFF,     TCOFF
      COMMON /IP/
     +    IPRINT
      COMMON/NEWBLK/TEMPOF
C
      M=1
      MM=2
      MMM=3
      MMMM=4
C             FIND THE INTERVAL WITHIN THE ARRAY 'TIMEX' IN WHICH THE CURRENT
C             TIME B
C
      CALL INTVAL (TIME,TIMEX,K,NTIMEX)
C
      II=K+1
C
      FRACT=(TIME-TIMEX(K))/(TIMEX(II)-TIMEX(K))
C
C             CALCULATE THE PLATE THICKNESS BY INTERPOLATING BETWEEN THE TWO
C             POINTS IN THE ARRAY THICK(I,J)
C
      H=(THICK(II)-THICK(K))*FRACT+THICK(K)
C
C             CALCULATE THE STRESSES AT THE BEGINNING OF THE PULSE (SIGOFF) BY
```

```
      =====  LINEAR  =====

C              LINEARILY INTERPOLATING BETWEEN THE TWO POINTS IN THE ARRAY
C              SIGMA(I,J)
C
      DO 30 I=1,NN
C
        SIGTH=(BIG(I,II,MM)-BIG(I,K,MM))*FRACT+BIG(I,K,MM)
        STRESS=(BIG(I,II,MMM)-BIG(I,K,MMM))*FRACT+BIG(I,K,MMM)
C
C              CALCULATE THE STRESSES WHILE THE PLASMA IS ON (AT THE PEAK OF THE
C              TEMP
C              BY ADDING THE ELASTIC THERMAL STRESSES TO THE STRESSES AT THE
C              BEGINNING OF THE
C              PULSE, I.E. WHEN THE PLASMA IS OFF.
C
C              NOTE:  PLASMA-OFF CONDITIONS REFER ALSO TO THE BEGINNING OF A
C              PULSE.
C
C              NOTE:  PLASMA-ON CONDITIONS REFER ALSO THE THE PART OF THE PULSE
C              WHERE
C              THE TEMPERATURE GRADIENTS ARE THE LARGEST.
C
      IF (KFLAG.EQ.2) GO TO 10
C
C              COMPUTE THE STRESSES FOR A TOKAMAK REACTOR
C
      SIGON(I)=STRESS
      SIGOFF(I)=SIGON(I)-SIGTH
      GO TO 20
C
C              COMPUTE THE STRESSES FOR AN INERTIAL CONFINEMENT REACTOR
C
   10   SIGOFF(I)=STRESS
      SIGON(I)=SIGOFF(I)+SIGTH
C
   20   CONTINUE
C
C              CALCULATE THE NODE POINT Z-COORDINATES BY INTERPOLATING BETWEEN
C              THE TWO
C              POINTS IN THE ARRAY ZARY(I,J)
C
      Z(I)=(BIG(I,II,MMMM)-BIG(I,K,MMMM))*FRACT+BIG(I,K,MMMM)
C
C              INTERPOLATE THE TEMPERATURE BETWEEN THE TWO POINTS IN TIME
C              AT A GIVEN NODE POINT
C
      TEMP(I)=(BIG(I,II,M)-BIG(I,K,M))*FRACT+BIG(I,K,M)
C
   30 CONTINUE
C
C              IF FLAG=1 THEN THE CRACK IS LOCATED ON THE PLASMA SIDE OF THE
C              PLATE.
C              IF FLAG=2 THEN THE CRACK IS LOCATED ON THE COOLANT SIDE OF THE
C              PLATE.
C
C              CALCULATE THE TWO NODE POINTS,I AND I+1, WHICH ARE ON
C              EITHER SIDE OF  THE CRACK TIP.
C
```

```
      =====  LINEAR  =====

      IF (FLAG.EQ.1) X=A
      IF (FLAG.EQ.2) X=H-A
      IF (X.LT.Z(1)) I=1
      IF (X.GE.Z(1).AND.X.LE.Z(NN)) CALL INTVAL (X,Z,I,NN)
      IF (X.GT.Z(NN)) I=NN-1
      II=I+1
C
C             LINEARLY INTERPOLATE THE STRESSES BETWEEN LOCATIONS Z(I) AND
C             Z(I+1)
C
      SXON=(SIGON(II)-SIGON(I))*(X-Z(I))/(Z(II)-Z(I))+SIGON(I)
      SXOFF=(SIGOFF(II)-SIGOFF(I))*(X-Z(I))/(Z(II)-Z(I))+SIGOFF(I)
C
C             FIND THE TEMPERATURES AT THE POINT "A"
C
      TEMPA=(TEMP(II)-TEMP(I))*(X-Z(I))/(Z(II)-Z(I))+TEMP(I)
      TAOFF=(TEMPOF(II)-TEMPOF(I))*(X-Z(I))/(Z(II)-Z(I))+TEMPOF(I)
      IF (FLAG.EQ.1) GO TO 40
      X=H
      I=NN-1
      GO TO 50
   40 X=0.D0
      I=1
   50 CONTINUE
      II=I+1
      SYON=(SIGON(II)-SIGON(I))*(X-Z(I))/(Z(II)-Z(I))+SIGON(I)
      SYOFF=(SIGOFF(II)-SIGOFF(I))*(X-Z(I))/(Z(II)-Z(I))+SIGOFF(I)
C
C             FIND THE TEMPERATURES AT THE POINT "C"
C
      TEMPC=(TEMP(II)-TEMP(I))*(X-Z(I))/(Z(II)-Z(I))+TEMP(I)
      TCOFF=(TEMPOF(II)-TEMPOF(I))*(X-Z(I))/(Z(II)-Z(I))+TEMPOF(I)
C
C             CALCULATE SMON, THE EQUIVALENT MEMBRANE STRESS FOR PLASMA-ON
C             CONDITIONS
C
      SMON=(SXON-SYON)*H/(2.*A)+SYON
C
C             CALCULATE SMOFF,THE EQUIVALENT MEMBRANE STRESS FOR PLASMA-OFF
C             PERIOD
C
      SMOFF=(SXOFF-SYOFF)*H/(2.*A)+SYOFF
C
C             CALCULATE SBON, THE EQUIVALENT BENDING  STRESS FOR PLASMA-ON
C             CONDITIONS
C
      SBON=SYON-SMON
C
C             CALCULATE SBOFF,THE EQUIVALENT BENDING  STRESS FOR PLASMA-OFF
C             PERIOD
C
      SBOFF=SYOFF-SMOFF
C
      IF (IPRINT.EQ.0) RETURN
      PRINT 60, SXON,SYON,SXOFF,SYOFF,SMON,SBON,SMOFF,SBOFF
   60 FORMAT ('0',8(F12.4,3X))
      PRINT , TEMPA,TEMPC
```

```
      ===== LINEAR =====

      DO 80 I=1,NN
        PRINT 70, I,SIGON(I),SIGOFF(I)
70      FORMAT (' ',I3,2X,2(F12.4))
80    CONTINUE
      RETURN
      END
```

```
     =====  MAIN  =====

C
C                   ************************************
C                   ************************************
C                   ************************************
C                   **********                **********
C                   **********    WISECRACK   **********
C                   **********                **********
C                   ************************************
C                   ************************************
C                   ************************************
C
C     *********************************************************************
C     *                                                                   *
C     *   'WISECRACK' CALCULATES THE LIFETIME OF A FLAT PLATE SUBJECTED   *
C     *   TO CYCLIC LOADS BY CONSIDERING THE INCREMENTAL GROWTH OF A      *
C     *   PRE-EXISTANT SEMI-ELLIPTICAL SURFACE FLAW.  THE CYCLIC STRESS,  *
C     *   TEMPERATURE AND NEUTRON IRRADIATION HISTORY ARE INPUTS TO THE   *
C     *   PROGRAM AND ARE, IN GENERAL, TIME-DEPENDENT FUNCTIONS.  CRACK   *
C     *   SHAPE CHANGES ARE CALCULATED ALONG THE MAJOR AND MINOR AXIS.    *
C     *   NON-LINEAR STRESS DISTRIBUTIONS ARE LINEARIZED INTO MEMBRANE    *
C     *   AND BENDING COMPONENTS USING THE LINEAR-ENVELOPE-OVER-THE-CRACK *
C     *   METHOD.  STRESS INTENSITY FACTORS ARE COMPUTED FROM NEWMAN'S    *
C     *   EQUATION AND USED TO FIND BOTH THE FATIGUE CRACK GROWTH RATES   *
C     *   AND THE CREEP CRACK GROWTH RATES.  THE RATES ARE LINEARLY       *
C     *   SUPERIMPOSED TO GET AN EFFECTIVE GROWTH RATE, ASSUMING NO       *
C     *   CREEP-FATIGUE INTERACTION.  A FOURTH-ORDER RUNGE-KUTTA NUMERICAL*
C     *   ROUTINE IS USED TO COMPUTE THE INCREMENTAL CHANGES IN CRACK     *
C     *   SIZE.  AUTOMATIC SELECTION OF THE CYCLE STEP SIZE IS USED TO    *
C     *   MINIMIZE COMPUTING TIME.  FAILURE OF THE PLATE IS DETERMINED    *
C     *   WHEN EITHER THE CRACK PENETRATES THROUGH THE THICKNESS, CALLED  *
C     *   LEAK-THROUGH OR THE MAXIMUM STRESS INTENSITY FACTOR EXCEEDS THE *
C     *   FRACTURE TOUGHNESS (BRITTLE FRACTURE).                          *
C     *                                                                   *
C     *********************************************************************
C
C   A=CRACK DEPTH INTO PLATE
C
C   ANOT=INITIAL DEPTH OF THE CRACK
C
C   AOLD=PREVIOUS VALUE OF THE CRACK DEPTH, A
C
C   ASPECT=ASPECT RATIO OF THE SURFACE FLAW (A/C)
C
C   BANNER=0   THIS INDICATES THAT KMAX OCCURRED WHILE THE PLASMA WAS ON
C
C   BANNER=1   THIS INDICATES THAT KMAX OCCURRED WHILE THE PLASMA WAS OFF
C
C   C=CRACK HALF-LENGTH ALONG PLATE SURFACE
C
C   COLD=PREVIOUS VALUE OF THE CRACK HALF-LENGTH C ALONG THE SURFACE
C
C   C1,C2,C3,C4=INTERMEDIATE VALUES OF THE INCREMENT IN CRACK HALF-LENGTH, C
C
C   DADN=EFFECTIVE VALUE OF THE CRACK GROWTH RATE FROM FATIGUE AND CREEP
C
C   DADNCG=CRACK GROWTH RATE PER CYCLE DUE TO FATIGUE LOADING ONLY
C
```

```
    =====  MAIN  =====

C   DADTOF=CREEP CRACK GROWTH RATE WHILE PLASMA IS OFF
C
C   DADTON=CREEP CRACK GROWTH RATE WHILE PLASMA IS ON
C
C   DELTAA=ACTUAL VALUE OF THE INCREMENT IN CRACK DEPTH, FOR DELTAN CYCLES
C
C   DELTAC=ACTUAL VALUE OF THE INCREMENT IN CRACK HALF-LENGTH, C
C
C   DELTA1,2,3,4=INTERMEDIATE VALUES OF THE INCREMENT IN CRACK DEPTH
C
C   DELTAN=NUMBER OF PLASMA CYCLES PER PROGRAM INCREMENT STEP SIZE
C
C   DEVICE=1  MEANS PLOT IS DONE AT MACC.
C   DEVICE=2  MEANS PLOT IS DONE ON THE LINE PRINTER.
C   DEVICE=3  MEANS NO PLOT IS DONE.
C
C   DLTKEF=EFFECTIVE STRESS INTENSITY FACTOR RANGE
C
C   DNMAX=MAXIMUM ALLOWED CYCLE INCREMENT SIZE  (CYCLES)
C
C   DNMIN=MINIMUM ALLOWED CYCLE INCREMENT SIZE
C
C   ERATE = WALL EROSION RATE IN MM/SEC
C
C   FLAG=1  WHEN THE FLAW IS LOCATED ON THE PLASMA SIDE OF THE FIRST WALL
C
C   FLAG=2  WHEN THE FLAW IS LOCATED ON THE COOLANT SIDE OF THE FIRST WALL
C
C   FLUNCE=ACCUMULATED NEUTRON DAMAGE (DPA)
C
C   FLUX=NEUTRON DAMAGE RATE (DPA/SEC)
C
C   FRCHNG = MAXIMUM ALLOWED FRACTIONAL CHANGE IN THE CRACK SIZE
C   INCREMENT (DELTAA OR DELTAC) PER PROGRAM INCREMENT OF DELTAN CYCLES
C
C   FREQ=FREQUENCY OF PLASMA ON-OFF CYCLES  (HZ)
C
C   H=PLATE THICKNESS
C
C   IDADN=1 USE THE MODIFIED FORMAN EQUATION FOR DA/DN
C   IDADN=2 USE THE PARIS EQUATION FOR DA/DN
C   IDADN=3 USE MODIFIED FORMAN EQUATION, BUT WITHOUT IRRADIATION EFFECTS
C
C   IDIMEN=1  MEANS THIS IS A ONE DIMENSIONAL FLAW GROWTH CALCULATION
C   IDIMEN=2  MEANS THIS IS A TWO DIMENSIONAL FLAW GROWTH CALCULATION
C
C   ISCATR=1  USE THE UPPER BOUND ON THE DA/DN DATA SET.
C   ISCATR=2  USE THE NOMINAL CURVE FOR THE DA/DN DATA.
C   ISCATR=3  USE THE LOWER BOUND ON THE DA/DN DATA SET.
C
C   ISW=0  READ IN DATA FROM FILE 8.
C   ISW=1  READ IN DATA FROM THE NAMELIST.
C
C    ICCG=0 TURN OFF CREEP CRACK GROWTH.
C    ICCG=1 TURN ON CREEP CRACK GROWTH.
C
C   JFLAG=1   THIS MEANS THAT THE STRESSES IN THE X-DIRECTION WILL BE USED
```

```
     =====  MAIN  =====
C
C   JFLAG=2   THIS MEANS THAT THE STRESSES IN THE Y-DIRECTION WILL BE USED
C
C   KFLAG=1  TOKAMAK VERSION OF WISECRACK
C
C   KFLAG=2  INERTIAL CONFINEMENT VERSION OF WISECRACK
C
C   KAOFF=STRESS INTENSITY FACTOR WHILE PLASMA IS OFF AT THE DEEPEST POINT: 'A'
C
C   KAON=STRESS INTENSITY FACTOR WHILE PLASMA IS ON AT THE DEEPEST POINT: 'A'
C
C   KCOFF=STRESS INTENSITY FACTOR WHILE PLASMA IS OFF AT THE SURFACE: 'C'
C
C   KCON=STRESS INTENSITY FACTOR WHILE PLASMA IS ON AT THE SURFACE: 'C'
C
C   KIC=PLANE STRAIN FRACTURE TOUGHNESS
C
C   KICMIN=MINIMUM FRACTURE TOUGHNESS (MPA(M))
C
C   KICON = 0   MEANS THAT KIC REMAINS A CONSTANT
C
C   KICON = 1   MEANS THAT KIC IS A FUNCTION OF FLUENCE (DPA)
C
C   KICNOT = UNIRRADIATED FRACTURE TOUGHNESS KIC
C
C   KMAX=MAXIMUM VALUE OF THE STRESS INTENSITY FACTOR
C
C   KMIN=MINIMUM VALUE OF THE STRESS INTENSITY FACTOR
C
C   LZERO=ADDITIONAL AMOUNT OF CRACK LENGTH TO BE ADDED TO CORRECT
C   FOR SMALL CRACK SIZES.
C
C   MINPNT = MINIMUM NUMBER OF POINTS TO BE PLOTTED ON GRAPHICS OUTPUT
C
C   N=CURRENT NUMBER OF PLASMA ON-OFF CYCLES
C
C   NOLD=PREVIOUS VALUE OF NUMBER OF PLASMA CYCLES
C
C   NN=TOTAL NUMBER OF NODE POINTS THROUGH PLATE THICKNESS
C
C   PHI=0  THIS INDICATES THAT KMAX OCCURS AT THE SURFACE 'C' OF THE CRACK
C
C   PHI=1  THIS INDICATES THAT KMAX OCCURS AT THE DEEPEST POINT 'A' OF THE CRACK
C
C   SBON=LINEARIZED BENDING STRESS WHILE PLASMA IS ON
C
C   SBOFF=LINEARIZED BENDING STRESS WHILE PLASMA IS OFF
C
C   SIGOFF(I)=TOTAL STRESS WHILE PLASMA IS OFF
C
C   SIGON(I)=TOTAL STRESS WHILE PLASMA IS ON
C
C   SMOFF=LINEARIZED MEMBRANE STRESS WHILE PLASMA IS OFF
C
C   SMON=LINEARIZED MEMBRANE STRESS WHILE PLASMA IS ON
C
C   STHMRL(I)=THERMO-ELASTIC STRESS COMPONENT WHILE PLASMA IS ON  (MPA)
```

```
     =====  MAIN  =====
C
C   TPULSE=TIME FOR ONE COMPLETE PLASMA ON-OFF CYCLE  (SEC)
C
C   TEMPOF(I)=TEMPERATURE WHILE PLASMA IS OFF (DEGREES K)
C
C   TEMPON(I)=TEMPERATURE WHILE PLASMA IS ON  (DEGREES K)
C
C   TIME =CURRENT TIME  (SEC)
C
C   TIMEOF=TIME WHILE THE PLASMA IS OFF DURING ONE PLASMA ON-OFF CYCLE
C
C   TIMEON=TIME WHILE THE PLASMA IS ON DURING ONE PLASMA ON-OFF CYCLE
C
C   TGROW=MULTIPLIER FACTOR TO KEEP DELTAN FROM GROWING TOO FAST
C
C   W=PLATE WIDTH
C
C   Z(I)=NODE POINT LOCATIONS ALONG Z-AXIS (M) ... Z=0 AT THE PLASMA SIDE
C
C     *********************************************************************
C     *                                                                   *
C     *   'MAIN' CALCULATES THE SUCCESSIVE INCREMENTS IN CRACK SIZE BY    *
C     *   INTEGRATING THE CONTRIBUTIONS TO CRACK GROWTH FROM BOTH FATIGUE *
C     *   CRACK GROWTH AND FROM CREEP CRACK GROWTH, USING A FOURTH-ORDER  *
C     *   RUNGE-KUTTA NUMERICAL ROUTINE.  FAILURE IS THEN DETERMINED TO   *
C     *   OCCUR WHEN THE CRACK EITHER PENETRATES THROUGH THE PLATE'S      *
C     *   THICKNESS OR WHEN BRITTLE FRACTURE HAPPENS.                     *
C     *                                                                   *
C     *********************************************************************
C
      IMPLICIT
     +    REAL*8 (A-H,O-Z)
      REAL*8
     +    BIG(50,100,4), HNOT,          KIC,            KICMIN,
     +    KICNOT,        KMAX,          KMIN,           LZERO,
     +    N,             NOLD,          PARA(11),       SOFF(50),
     +    SON(50),       TARRAY(800),   TEMP(50),       TEMPOF(50),
     +    TEMPON(50),    THICK(100),    TIMEX(100),     XLIMIT(2),
     +    XSCALE(10),    Y1(800),       Y2(800),        Y3(800),
     +    Y4(800),       Y5(800),       YLIMIT(2),      YSCALE(10),
     +    Z(50)
      INTEGER
     +    BANNER,        DEVICE,        FLAG,           PHI
      DATA/E/'A'/
      DATA/F/'C'/
      COMMON /MAINZ/
     +    NN,            NP
      COMMON /STRESZ/
     +    TIME,          Z,             SIGON,          SIGOFF
      COMMON /SLOPZ/
     +    ASPECT,        KMAX,          KMIN,           BANNER,
     +    DADN,          TIMEON,        TIMEOF,         R
      COMMON /TOUGHZ/
     +    KIC,           FLUNCE,        KICON,          KICMIN,
     +    KICNOT
      COMMON /LINEAZ/
     +    FLAG,          KFLAG
```

```
      =====  MAIN  =====

      COMMON /ONE/
     +    A,              H
      COMMON /TWO/
     +    B,              C
      COMMON /THREE/
     +    SMON,           SMOFF,          SBON,           SBOFF
      COMMON /FOUR/
     +    W
      COMMON /FIVE/
     +    AOVERT,         AOVERC
      COMMON /X/
     +    DCDN,           PHI
      COMMON /TEN/
     +    TIMEX,          NTIMEX,         THICK
      COMMON /BIG/
     +    BIG
      COMMON /TEM/
     +    TEMP
      COMMON /DATAS/
     +    ISCATR,         IDADN
      COMMON /IP/
     +    IPRINT
      COMMON /CCG/
     +    ICCG
      COMMON /LSTAR/
     +    LZERO
      COMMON /NEWBLK/
     +    TEMPOF
      COMMON /CYCLE/
     +    N
      NAMELIST /BEGIN/
     +    ANOT,           ASPECT,         DEVICE,         DNMIN,
     +    FLAG,           FLUX,           FRCHNG,         HNOT,
     +    ICCG,           IDADN,          IDIMEN,         IPRINT,
     +    ISCATR,         ISW,            JFLAG,          KFLAG,
     +    KICMIN,         KICON,          LZERO,          MINPNT,
     +    NMAX,           NN,             SOFF,           SON,
     +    TEMPOF,         TEMPON,         TGROW,          TIMEOF,
     +    TIMEON,         TMAX,           TPULSE,         W
C
C  SET THE DEFAULT VALUES
C
      M=1
      MM=2
      MMM=3
      MMMM=4
      ISCATR=2
      IDIMEN=2
      IDADN=1
      IPRINT=0
      ISW=0
      ERATE=0.D0
      ICCG=1
      FLAG=1
      TMAX=9.46808D8
      KFLAG=1
      KICON=1
```

```
      =====  MAIN  =====

      LZERO=6.4D-5
      NMAX=10000000
      FRCHNG=1.D-2
      FLUX=0.D0
      MINPNT=40.D0
      ASPECT=1.D0
      W=1.D4
      JFLAG=1
      DEVICE=1
      KICMIN=30.D0
      TGROW=1.5D0
      DNMIN=1.D0
C
C               READ IN INPUT DATA FROM NAMELIST BEGIN
C
      READ (5,BEGIN)
C
      ASPOLD=ASPECT
      IF (ISW.EQ.1) GO TO 80
C               READ IN DATA THAT IS STORED ON UNIT 8.
C
      NSAVE=0
   10 NSAVE=NSAVE+1
      IF (NSAVE.GT.100) PRINT 20
   20 FORMAT ('0','****** ERROR ******   NSAVE IS GREATER THAN 100  ****
     +  **')
      READ (8) (PARA(J),J=1,11)
      IF (PARA(1).LT.0) GO TO 30
      NN=PARA(5)
      TIMEX(NSAVE)=PARA(2)
      THICK(NSAVE)=PARA(6)
      TIMEON=PARA(4)
      TIMEOF=PARA(9)
      FLUX=PARA(7)
      TPULSE=PARA(8)
      ERATE=PARA(10)
      TCOOL=PARA(11)
      READ (8) (BIG(J,NSAVE,MMMM),J=1,NN)
C
C               BIG(I,J,1) IS THE SAME AS THE ARRAY TEMPON(I,J)
C
C               BIG(I,J,2) IS THE SAME AS THE ARRAY STHMRL(I,J)
C
C               BIG(I,J,3) IS THE SAME AS THE ARRAY SIGMA(I,J)
C
C               BIG(I,J,4) IS THE SAME AS THE ARRAY ZARY(I,J)
C
      IF (KFLAG.EQ.1) READ (8) (BIG(J,NSAVE,M),J=1,NN)
      IF (KFLAG.EQ.2) READ (8) (TEMPOF(J),J=1,NN)
      IF (JFLAG.EQ.1) READ (8) (BIG(J,NSAVE,MMM),J=1,NN)
      IF (JFLAG.EQ.1) READ (8) (DUM,J=1,NN)
      IF (JFLAG.EQ.2) READ (8) (DUM,J=1,NN)
      IF (JFLAG.EQ.2) READ (8) (BIG(J,NSAVE,MMM),J=1,NN)
      READ (8) (BIG(J,NSAVE,MM),J=1,NN)
      GO TO 10
   30 CONTINUE
      NTIMEX=NSAVE-1
```

```
      =====  MAIN  =====
C
C              CONVERT UNITS OF TWISTR OUTPUT TO UNITS FOR USE IN WISECRACK:
C
C              CHANGE KSI TO MPA,  AND CM TO METERS.
C
      ERATE=ERATE/100.D0
      DO 50 I=1,NN
        DO 40 J=1,NTIMEX
          BIG(I,J,MM)=BIG(I,J,MM)*6.8948D0
          BIG(I,J,MMM)=BIG(I,J,MMM)*6.8948D0
          BIG(I,J,MMMM)=BIG(I,J,MMMM)*1.D-2
   40   CONTINUE
   50 CONTINUE
      DO 60 J=1,NTIMEX
        THICK(J)=THICK(J)*1.D-2
C
C              CONVERT 'TWISTR' TIME TO 'WISECRACK' TIME
C
        TIMEX(J)=TIMEX(J)*TPULSE/TIMEON
C
        IF (FLAG.EQ.1) PRINT , J,TIMEX(J),BIG(1,J,MMM),THICK(J)
   60 CONTINUE
C
C              FOR TOKAMAKS; SET TEMPERATURES FOR PLASMA OFF CONDITIONS
C              EQUAL TO THE COOLANT TEMPERATURE, TCOOL.
C
      IF (KFLAG.EQ.2) GO TO 80
      DO 70 I=1,NN
   70 TEMPOF(I)=TCOOL
C
   80 IF (ISW.EQ.0) GO TO 100
C
      I=1
      J=2
      H=HNOT
C
C              TIME-INDEPENDENT STRESSES, READ FROM NAMELIST 'BEGIN'.
C
      DO 90 K=1,NN
        BIG(K,I,MMMM)=H*(K-1+0.5D0)/NN
        BIG(K,I,MMM)=SON(K)
        BIG(K,I,MM)=SON(K)-SOFF(K)
        BIG(K,I,M)=TEMPON(K)
        BIG(K,J,M)=BIG(K,I,M)
        BIG(K,J,MM)=BIG(K,I,MM)
        BIG(K,J,MMM)=BIG(K,I,MMM)
        BIG(K,J,MMMM)=BIG(K,I,MMMM)
   90 CONTINUE
      TIMEX(1)=0.D0
      TIMEX(2)=TMAX
      NTIMEX=2
      THICK(1)=H
      THICK(2)=H
C
C              CALCULATE THE INITIAL VALUES
C
  100 N=0
```

```
      ===== MAIN =====

      H=THICK(1)
      XLIMIT(1)=0.D0
      XLIMIT(2)=TMAX
      YLIMIT(2)=1.1D3*H
      YLIMIT(1)=0.D0
      ISAVE=0
      ASPECT=ASPOLD
      TIME=0.D0
      DNMAX=TIMEX(NTIMEX)/(MINPNT*TPULSE)
      DELTAN=DNMAX
      FLUNCE=0.D0
      FREQ=1.D0/TPULSE
C
      C=ANOT/ASPECT
      A=ANOT
C
      DO 110 I=1,NN
  110 Z(I)=BIG(I,1,MMMM)
C
C               PRINT OUT ALL THE INITIAL DATA
C
      PRINT 120, NN
  120 FORMAT ('1','NUMBER OF NODES = ',I3)
      PRINT 130, FRCHNG
  130 FORMAT ('0','FRACTIONAL CHANGE IN CRACK SIZE =',F9.3)
      PRINT 140, ANOT
  140 FORMAT ('0','INITIAL FLAW DEPTH = ',F8.4,' METERS')
      PRINT 150, ASPECT
  150 FORMAT ('0','INITIAL ASPECT RATIO  A/C = ',F8.4)
      PRINT 160, H,W
  160 FORMAT ('0','PLATE THICKNESS =',E10.4,' METERS',10X,'PLATE WIDTH =
     +    ',E10.4,' METERS')
      PRINT 170, TPULSE,TIMEON,TIMEOF
  170 FORMAT ('0','TPULSE =',E10.4,'SEC',6X,'TIMEON =',E10.4,' SECONDS',
     +5X,'TIMEOF=',E10.4,' SECONDS')
      IF (FLAG.EQ.1) PRINT 180
  180 FORMAT ('0','SURFACE FLAW IS LOCATED ON THE PLASMA SIDE')
      IF (FLAG.EQ.2) PRINT 190
  190 FORMAT ('0','SURFACE FLAW IS LOCATED ON THE COOLANT SIDE')
      PRINT 200, FLUX
  200 FORMAT ('0','NEUTRON DAMAGE RATE =',E12.4,'DPA/SEC')
      PRINT 210, ERATE
  210 FORMAT ('0','WALL EROSION RATE =',E12.4,2X,'METERS/SEC')
      PRINT 220, FREQ
  220 FORMAT ('0','PLASMA ON-OFF FREQUENCY =',E10.4)
      PRINT 230, DNMAX
  230 FORMAT ('0','MAXIMUM INCREMENT IN CYCLES (DNMAX) =',F10.2)
      PRINT 240, DNMIN
  240 FORMAT ('0','MINIMUM INCREMENT IN CYCLES (DNMIN)=',F10.4)
      PRINT 250, KICMIN
  250 FORMAT ('0','MINIMUM FRACTURE TOUGHNESS=',F10.4,' MPA(M)')
C
      IF (IDIMEN.EQ.1) PRINT 260
  260 FORMAT ('0','ONE-DIMENSIONAL FLAW GROWTH')
      IF (IDIMEN.EQ.2) PRINT 270
  270 FORMAT ('0','TWO-DIMENSIONAL FLAW GROWTH')
      IF (ISCATR.EQ.1) PRINT 280
```

```
  280 FORMAT ('0','UPPER BOUND ON DA/DN DATA SET')
      IF (ISCATR.EQ.2) PRINT 290
  290 FORMAT ('0','NOMINAL CURVE FOR DA/DN DATA SET')
      IF (ISCATR.EQ.3) PRINT 300
  300 FORMAT ('0','LOWER BOUND ON DA/DN DATA SET')
      IF (IDADN.EQ.1) PRINT 310
  310 FORMAT ('0','MODIFIED FORMAN EQUATION FOR DA/DN')
      IF (IDADN.EQ.2) PRINT 320
  320 FORMAT ('0','PARIS EQUATION FOR DA/DN')
      IF (IDADN.EQ.3) PRINT 330
  330 FORMAT ('0','MODIFIED FORMAN EQUATION FOR DA/DN,
     +WITHOUT IRRADIATION EFFECTS')
      IF (ICCG.EQ.0) PRINT 340
  340 FORMAT ('0','CREEP CRACK GROWTH LAW IS TURNED OFF')
      IF (ICCG.EQ.1) PRINT 350
  350 FORMAT ('0','CREEP CRACK GROWTH LAW IS TURNED ON')
C
      PRINT 360, NTIMEX
  360 FORMAT ('0','NUMBER OF STRESS POINTS READ FROM FILE 8.
     +      NTIMEX=',I6)
      IF (ISW.EQ.1) PRINT 370
  370 FORMAT ('0','TIME-INDEPENDENT STRESS INPUT FROM NAMELIST')
      PRINT 380
  380 FORMAT ('0','NODE',4X,'Z(I)',7X,'TEMPON',7X,'TEMPOFF',7X,'STRESS O
     +N',7X,'STRESS OFF')
      PRINT 390
  390 FORMAT (' ',8X,'(METERS)',3X,'(DEG K)',6X,'(DEG K)',9X,'(MPA)',11X
     +,'(MPA)'/' ')
      DO 410 I=1,NN
        SANDY=BIG(I,M,MMM)-BIG(I,M,MM)
        PRINT 400, I,Z(I),BIG(I,M,M),TEMPOF(I),BIG(I,M,MMM),SANDY
  400   FORMAT (' ',I2,6X,E7.3,3X,E7.3,6X,E7.3,7X,E9.3,7X,E9.3)
  410 CONTINUE
C
      CALL LINEAR
      CALL TOUGH
      CALL RATE
      KICNOT=KIC
C
      PRINT 420
  420 FORMAT ('1')
      PRINT 430
  430 FORMAT ('0',1X,'TIME',5X,'CYCLES',3X,'FLUENCE',5X,'A',9X,'H',3X,'
     + A/T',4X,'A/C',2X,'R-RATIO',4X,'KMAX',6X,'KMIN',7X,'KIC',7X,'DA/DN
     +',7X,'DC/DN',7X,'KMAX',/2X'(YEARS)',11X,'(DPA)',4X,'(METERS)',1X,'
     +(METERS)',25X,'(MPA(M))',2X,'(MPA(M))',3X,'(MPA(M))',2X,'(M/CYCLE)
     +',3X,'(M/CYCLE)',4X,'AT'/)
      S=A/H
      TYEARS=TIME/3.1536D7
      IF (PHI.EQ.0) PRINT 440, TYEARS,N,FLUNCE,A,H,S,ASPECT,R,KMAX,KMIN,
     +KIC,DADN,DCDN
  440 FORMAT (' ',5(E8.3,1X),F5.3,1X,2(F7.3,1X),3(F9.3,2X),2(E10.5,2X),
     +'SURFACE')
      IF (PHI.EQ.1) PRINT 450, TYEARS,N,FLUNCE,A,H,S,ASPECT,R,KMAX,KMIN,
     +KIC,DADN,DCDN
  450 FORMAT (' ',5(E8.3,1X),F5.3,1X,2(F7.3,1X),3(F9.3,2X),2(E10.5,2X)
     +,'TIP "A"')
```

```
      =====  MAIN  =====

C
C               CHECK IF EITHER CRACK GROWTH RATE IS ZERO OR NEGATIVE
C
      IF (DADN.LE.0) PRINT 460
  460 FORMAT (' ','DA/DN = 0')
      IF (DCDN.LE.0) PRINT 470
  470 FORMAT (' ','DC/DN = 0')
C
C               SAVE THE OLD (PREVIOUS) VALUES OF A,C & N.
C
  480 AOLD=A
      COLD=C
      NOLD=N
      HOLD=H
C
C               SAVE VARIOUS DATA POINTS FOR GRAPHICS OUTPUT LATER ON
C
      IF (ISAVE.GT.800) GO TO 490
      ISAVE=ISAVE+1
      TARRAY(ISAVE)=TYEARS
      Y1(ISAVE)=A*1.D3
      Y2(ISAVE)=H*1.D3
      Y3(ISAVE)=KMAX
      Y4(ISAVE)=KIC
      Y5(ISAVE)=KMIN
      GO TO 510
  490 PRINT 500, ISAVE
  500 FORMAT ('0','ISAVE IS GREAT THAN 800... ISAVE=',I7)
  510 CONTINUE
C
C               HAS THE MAXIMUM TIME BEEN EXCEEDED?
C
      IF (TIME.GT.TMAX) GO TO 650
C
C               HAS THE MAXIMUM NUMBER OF CYCLES BEEN EXCEEDED?
C
      IF (N.GT.NMAX) GO TO 670
C
C               TEST IF THE CRACK HAS GROWN THROUGH TO THE OPPOSITE
C               SIDE OF THE PLATE (LEAK THROUGH).
C
      IF (A.GE.H) GO TO 530
C
      CALL LINEAR
      CALL TOUGH
      CALL RATE
C
C               TEST IF THE MAXIMUM STRESS INTENSITY FACTOR,KMAX, HAS EXCEEDED
C               PLANE STRAIN FRACTURE TOUGHNESS,KIC,I.E. 'BRITTLE FRACTURE'
C
      IF (KMAX.GE.KIC) GO TO 550
C
C               CHECK IF EITHER CRACK GROWTH RATE IS ZERO OR NEGATIVE
C
      IF (DADN.LE.0) PRINT 460
      IF (DCDN.LE.0) PRINT 470
C
```

```
      =====  MAIN  =====

C           CALCULATE THE NUMBER OF CYCLES DELTAN NEEDED TO GIVE A
C           SPECIFIED INCREMENT IN CRACK SIZE.
C           DELTAN IS CHOSEN AS THE SMALLER OF THE TWO PREDICTED CYCLE
C           STEP SIZES IN THE 'A' AND THE 'C' DIRECTION
C
      IF (DADN.LE.0.D0) DA=DNMAX
      IF (DADN.GT.0.D0) DA=FRCHNG*A/DADN
      IF (DCDN.LE.0.D0) DC=DNMAX
      IF (DCDN.GT.0.D0) DC=FRCHNG*C/DCDN
      DNOLD=DELTAN
      IF (DA.LE.DC) DELTAN=DA
      IF (DA.GT.DC) DELTAN=DC
      IF (IDIMEN.EQ.1) DELTAN=DA
C
C           CHECK IF THE STRESSES VARY FASTER THAN THE CYCLE STEP SIZE
C           (DELTAN).
C           IF SO, THEN LIMIT THE SIZE OF DELTAN SO THAT THE STRESS HISTOR
C           CAN
C           BE ACCURATELY FOLLOWED IN TIME.
C
      CALL INTVAL (TIME,TIMEX,KK,NTIMEX)
      TIMDIF=TIMEX(KK+1)-TIMEX(KK)
      DTIME=DELTAN*TPULSE
      IF (DTIME.GT.TIMDIF) DELTAN=TIMDIF/TPULSE
C
C           IS DELTAN TOO LARGE?
C
      IF (DELTAN.GT.DNMAX) DELTAN=DNMAX
C
C           PREVENT DELTAN FROM GROWING TOO FAST.
C
      DNNEXT=TGROW*DNOLD
      IF (DELTAN.GT.DNNEXT) DELTAN=DNNEXT
C
C           IS DELTAN TOO SMALL?
C
      IF (DELTAN.LT.DNMIN) DELTAN=DNMIN
C
      DELTA1=DADN*DELTAN
      C1=DCDN*DELTAN
      N=NOLD+0.5*DELTAN
      TIME=N*TPULSE
      TYEARS=TIME/3.1536D7
C
C           TEST IF THE TIME HAS EXCEEDED THE MAXIMUM ALLOWED TIME
C
      IF (TIME.GT.TIMEX(NTIMEX)) GO TO 610
C
      FLUNCE=FLUX*TIME
      A=AOLD+0.5*DELTA1
      C=COLD+0.5*C1
      IF (IDIMEN.EQ.1) C=A/ASPOLD
      ASPECT=A/C
      IF (A.GE.H) GO TO 530
      CALL LINEAR
      CALL TOUGH
      CALL RATE
```

```
      DELTA2=DADN*DELTAN
      A=AOLD+0.5*DELTA2
      C2=DCDN*DELTAN
      C=COLD+0.5*C2
      IF (IDIMEN.EQ.1) C=A/ASPOLD
      ASPECT=A/C
      IF (A.GE.H) GO TO 530
      IF (KMAX.GE.KIC) GO TO 550
      CALL LINEAR
      CALL TOUGH
      CALL RATE
      DELTA3=DADN*DELTAN
      C3=DCDN*DELTAN
C
C             INCREMENT THE TOTAL NUMBER OF CYCLES,N, BY THE AMOUNT= DELTAN
C
      N=NOLD+DELTAN
C
C             CALCULATE THE NEW  VALUE OF TIME AND FLUENCE
C
      TIME=N*TPULSE
      TYEARS=TIME/3.1536D7
      DTD=DELTAN*TPULSE
C
C             TEST IF THE TIME HAS EXCEEDED THE MAXIMUM ALLOWED TIME
C
      IF (TIME.GT.TIMEX(NTIMEX)) GO TO 610
C
      FLUNCE=FLUX*TIME
      A=AOLD+DELTA3
      C=COLD+C3
      IF (IDIMEN.EQ.1) C=A/ASPOLD
      ASPECT=A/C
      IF (A.GE.H) GO TO 530
      IF (KMAX.GE.KIC) GO TO 550
C
C             CORRECT FOR 1-D FLAW GROWTH
C
      IF (IDIMEN.EQ.1) C=A/ASPOLD
C
      CALL LINEAR
      CALL TOUGH
      CALL RATE
      HNEW=H
      DELTA4=DADN*DELTAN
      C4=DCDN*DELTAN
      DELTAA=(DELTA1+2.D0*DELTA2+2.D0*DELTA3+DELTA4)/6.0D0
      DELTAC=(C1+2.D0*C2+2.D0*C3+C4)/6.0D0
      RATIOA=DELTAA/AOLD
      RATIOC=DELTAC/COLD
C
C             INCREMENT THE PREVIOUS CRACK DEPTH,AOLD, BY THE AMOUNT=DELTAA
C
      A=AOLD+DELTAA
C
C             INCREMENT THE PREVIOUS CRACK LENGTH,COLD, BY THE AMOUNT=DELTAC
C
```

```
      C=COLD+DELTAC
C
C              CORRECT FOR 1-D FLAW GROWTH
C
      IF (IDIMEN.EQ.1) C=A/ASPOLD
C
C              ADJUST THE CRACK DIMENSIONS BECAUSE OF CHANGES IN THE
C              PLATE'S THICKNESS DUE TO EROSION
C
      DELTA=HOLD-HNEW
      IF (FLAG.EQ.2) GO TO 520
      AOLD1=A
      A=A-DELTA
C
C              HAS THE CRACK ON THE PLASMA SIDE BEEN COMPLETELY ERODED AWAY?
C
      IF (A.LE.0.D0) GO TO 630
C
      C=C*DSQRT(1.D0-(DELTA/AOLD1)**2.D0)
      IF (IDIMEN.EQ.1) A=A/ASPOLD
  520 CONTINUE
C
C              UPDATE THE NEW ASPECT RATIO, A/C.
C
      ASPECT=A/C
      S=A/H
      IF (PHI.EQ.0) PRINT 440, TYEARS,N,FLUNCE,A,H,S,ASPECT,R,KMAX,KMIN,
     +KIC,DADN,DCDN
      IF (PHI.EQ.1) PRINT 450, TYEARS,N,FLUNCE,A,H,S,ASPECT,R,KMAX,KMIN,
     +KIC,DADN,DCDN
C
C              THE CRACK SIZE HAS BEEN UPDATED, NOW GO BACK AND REPEAT THE WHOLE
C              CYCLE
C
      GO TO 480
C
C              PRINT OUT MESSAGES FOR EACH TYPE OF FAILURE MODES.
C
  530 PRINT 540
  540 FORMAT ('0','*****************************************'/'
     +        LEAK-THROUGH'/'***************************************')
      IF (KMAX.GE.KIC) GO TO 550
      PRINT 430
      S=A/H
      IF (PHI.EQ.0) PRINT 440, TYEARS,N,FLUNCE,A,H,S,ASPECT,R,KMAX,KMIN,
     +KIC,DADN,DCDN
      IF (PHI.EQ.1) PRINT 450, TYEARS,N,FLUNCE,A,H,S,ASPECT,R,KMAX,KMIN,
     +KIC,DADN,DCDN
      IF (FLAG.EQ.1) GO TO 690
      IF (FLAG.EQ.2) GO TO 700
  550 PRINT 560
  560 FORMAT ('0','***********************************************')
      IF (BANNER.EQ.1) GO TO 580
      PRINT 570
  570 FORMAT (' ',5X,'BRITTLE FRACTURE OCCURRED DURING PLASMA-ON'/'*****
     +*******************************************')
      GO TO 600
```

```
  580 PRINT 590
  590 FORMAT (' ',5X,'BRITTLE FRACTURE OCCURRED DURING PLASMA-OFF'/'****
     +*********************************************')
  600 PRINT 430
      S=A/H
      IF (PHI.EQ.0) PRINT 440, TYEARS,N,FLUNCE,A,H,S,ASPECT,R,KMAX,KMIN,
     +KIC,DADN,DCDN
      IF (PHI.EQ.1) PRINT 450, TYEARS,N,FLUNCE,A,H,S,ASPECT,R,KMAX,KMIN,
     +KIC,DADN,DCDN
      IF (FLAG.EQ.1) GO TO 690
      IF (FLAG.EQ.2) GO TO 700
C
C              PRINT OUT MORE MESSAGES.
C
  610 PRINT 620, TIME
  620 FORMAT ('0','TIME HAS EXCEEDED THE MAXIMUM ALLOWED TIME
     +     TIME =',D12.5,2X,'SECONDS')
      GO TO 600
  630 PRINT 640
  640 FORMAT ('0',8('**********')/11X,'CRACK ON PLASMA SIDE HAS BEEN OBL
     +ITERATED BY WALL EROSION'/8('**********'))
      GO TO 600
C
  650 PRINT 660, TIME,TMAX
  660 FORMAT ('0','STOP...TIME',2X,D10.4,2X,'HAS EXCEEDED THE MAXIMUM AL
     +LOWED TIME OF',2X,D10.4,2X,'SECONDS')
      GO TO 600
C
  670 PRINT 680, N,NMAX
  680 FORMAT ('0','STOP...CYCLES',2X,I8,'HAS EXCEEDED THE MAXIMUM ALLOWE
     +D CYCLES',2X,I10)
      GO TO 600
C
  690 FLAG=2
C
C              PLOT GRAPHICS OUTPUT
C
      IF (DEVICE.EQ.2) CALL DEVSET (12)
      IF (DEVICE.EQ.3) GO TO 100
      TT=TARRAY(ISAVE)
      IF (TT.LE.5.D0) XLIMIT(2)=5.D0
      IF (TT.LE.10.D0.AND.TT.GT.5.D0) XLIMIT(2)=10.D0
      IF (TT.LE.15.D0.AND.TT.GT.10.D0) XLIMIT(2)=15.D0
      IF (TT.LE.20.D0.AND.TT.GT.15.D0) XLIMIT(2)=20.D0
      IF (TT.LE.25.D0.AND.TT.GT.20.D0) XLIMIT(2)=25.D0
      IF (TT.GT.25.D0) XLIMIT(2)=30.D0
      CALL GRAPH (XLIMIT,'DOUBLE',YLIMIT,'DOUBLE',2,'NONE','BLANK','TIME
     + (YEARS)$$','CRACK DEPTH (MM)$/$WALL THICKNESS (MM)$$','FRAME','FI
     +RST WALL CRACK GROWTH$/$SURFACE FLAW ON PLASMA SIDE$$','FULL','TRB
     +IND')
      CALL GRAPHM (TARRAY,'SCAL1',Y1,'SCAL1',ISAVE,'NONE','SOLID')
      CALL GRAPHM (TARRAY,'SCAL1',Y2,'SCAL1',ISAVE,'NONE',1)
      YLIMIT(2)=1.1D0*KICNOT
      YLIMIT(1)=-2.D1
      CALL GRAPH (XLIMIT,'DOUBLE',YLIMIT,'DOUBLE',2,'NONE','BLANK','TIME
     + (YEARS)$$',' STRESS INTENSITY FACTORS$/$FRACTURE TOUGHNESS (MPA-M
     +**1/2)$$','FRAME','FIRST WALL CRACK GROWTH$/$SURFACE FLAW ON PLASM
```

```
     +A SIDE$$´,´FULL´,´TRBIND´)
      CALL QGRAPH (´SCAL1´,XSCALE,YSCALE)
      CALL AXLIN (XSCALE,YSCALE,0.,0,0,´NONE´,0,0)
      CALL GRAPHM (TARRAY,´SCAL1´,Y3,´SCAL1´,ISAVE,´NONE´,´SOLID´)
      CALL GRAPHM (TARRAY,´SCAL1´,Y4,´SCAL1´,ISAVE,´NONE´,1)
      CALL GRAPHM (TARRAY,´SCAL1´,Y5,´SCAL1´,ISAVE,´NONE´,´SOLID´)
C
      GO TO 100
C
C              PLOT SECOND SET OF GRAPHICS OUTPUT
C
  700 CONTINUE
C
      IF (DEVICE.EQ.2) CALL DEVSET (12)
      IF (DEVICE.EQ.3) STOP
      TT=TARRAY(ISAVE)
      IF (TT.LE.5.D0) XLIMIT(2)=5.D0
      IF (TT.LE.10.D0.AND.TT.GT.5.D0) XLIMIT(2)=10.D0
      IF (TT.LE.15.D0.AND.TT.GT.10.D0) XLIMIT(2)=15.D0
      IF (TT.LE.20.D0.AND.TT.GT.15.D0) XLIMIT(2)=20.D0
      IF (TT.LE.25.D0.AND.TT.GT.20.D0) XLIMIT(2)=25.D0
      IF (TT.GT.25.D0) XLIMIT(2)=30.D0
      CALL GRAPH (XLIMIT,´DOUBLE´,YLIMIT,´DOUBLE´,2,´NONE´,´BLANK´,´TIME
     + (YEARS)$$´,´CRACK DEPTH (MM)$/$WALL THICKNESS (MM)$$´,´FRAME´,´FI
     +RST WALL CRACK GROWTH$/$SURFACE FLAW ON COOLANT SIDE$$´,´FULL´,´TR
     +BIND´)
      CALL GRAPHM (TARRAY,´SCAL1´,Y1,´SCAL1´,ISAVE,´NONE´,´SOLID´)
      CALL GRAPHM (TARRAY,´SCAL1´,Y2,´SCAL1´,ISAVE,´NONE´,1)
      YLIMIT(2)=1.1D0*KICNOT
      YLIMIT(1)=-2.D1
      CALL GRAPH (XLIMIT,´DOUBLE´,YLIMIT,´DOUBLE´,2,´NONE´,´BLANK´,´TIME
     + (YEARS)$$´,´ STRESS INTENSITY FACTORS$/$FRACTURE TOUGHNESS (MPA-M
     +**1/2)$$´,´FRAME´,´FIRST WALL CRACK GROWTH$/$SURFACE FLAW ON COOLA
     +NT SIDE$$´,´FULL´,´TRBIND´)
      CALL QGRAPH (´SCAL1´,XSCALE,YSCALE)
      CALL AXLIN (XSCALE,YSCALE,0.,0,0,´NONE´,0,0)
      CALL GRAPHM (TARRAY,´SCAL1´,Y3,´SCAL1´,ISAVE,´NONE´,´SOLID´)
      CALL GRAPHM (TARRAY,´SCAL1´,Y4,´SCAL1´,ISAVE,´NONE´,1)
      CALL GRAPHM (TARRAY,´SCAL1´,Y5,´SCAL1´,ISAVE,´NONE´,´SOLID´)
      STOP
      END
```

===== RATE =====

```
C     ************************************************************************
C     *                                                                      *
C     *   'RATE' CALCULATES THE STRESS INTENSITY FACTORS AND ASSOCIATED      *
C     *   CRACK GROWTH RATES FOR THE TWO DIFFERENT DIRECTIONS OF GROWTH,     *
C     *   E.G. THE MAJOR & MINOR AXIS OF THE SEMI-ELLIPSE.                   *
C     *                                                                      *
C     ************************************************************************
C
      SUBROUTINE RATE
      IMPLICIT
     +    REAL*8 (A-H,O-Z)
      INTEGER
     +    BANNER,         PHI
      REAL*8
     +    J,              KAMAX,          KAMIN,          KAOFF,
     +    KAON,           KCMAX,          KCMIN,          KCOFF,
     +    KCON,           KIC,            KICMIN,         KICNOT,
     +    KMAX,           KMIN,           LZERO,          M1,
     +    M2,             M3,             NEXPON,    N
      COMMON /SLOPZ/
     +    ASPECT,         KMAX,           KMIN,           BANNER,
     +    DADN,           TIMEON,         TIMEOF,         R
      COMMON /TOUGHZ/
     +    KIC,            FLUNCE,         KICON,          KICMIN,
     +    KICNOT
      COMMON /ONE/
     +    A,              T
      COMMON /THREE/
     +    SMON,           SMOFF,          SBON,           SBOFF
      COMMON /FOUR/
     +    W
      COMMON /X/
     +    DCDN,           PHI
      COMMON /NEXP/
     +    NEXPON
      COMMON /TBLOCK/
     +    TEMPA,          TEMPC,          TAOFF,          TCOFF
      COMMON /LSTAR/
     +    LZERO
      COMMON/CYCLE/N
      AOT=A/T
C
C             C=CRACK HALF-LENGTH ALONG THE SURFACE
C
      C=A/ASPECT
      Q=1.0+1.464*(ASPECT**1.65)
C
C             FW=CORRECTION FACTOR FOR FINITE WIDTH OF PLATE
C
C             FW=(COS(3.1416*C*DSQRT(AOT)/(2*W)))**-0.5
      FW=1.D0
      M1=1.13-0.09*ASPECT
      M2=-0.54+0.89/(0.2+ASPECT)
      M3=0.5-1.0/(0.65+ASPECT)+14.*(1.0-ASPECT)**24.
      H1=1.0-0.34*AOT-0.11*ASPECT*AOT
      G1=-1.22-0.12*ASPECT
      G2=0.55-1.05*(ASPECT**0.75)+0.47*(ASPECT**1.5)
```

```
      =====  RATE  =====

      H2=1.0+G1*AOT+G2*(AOT**2)
C
C              USE SHORT CRACK CORRECTION FACTOR LZERO
C
      AEFF=A+LZERO
      J=DSQRT(3.1416*(AEFF)/Q)
      DUM=M1+M2*(AOT**2.)+M3*(AOT**4.)
C
C              F=MAGNIFICATION FACTOR FOR PURE TENSION STRESSES
C
      F=FW*DUM
C
C              F*H=MAGNIFICATION FACTOR FOR PURE BENDING STRESSES
C
      H=H2
C
C              CALCULATE STRESS INTENSITY FACTOR AT DEEPEST POINT 'A' WITH
C              PLASMA ON
C
      KAON=(SMON+H*SBON)*J*F
C
C              CALCULATE STRESS INTENSITY FACTOR AT DEEPEST POINT 'A' WITH
C              PLASMA OFF
C
      KAOFF=(SMOFF+H*SBOFF)*J*F
      G=1+0.1+0.35*(AOT**2.)
      FPHI=DSQRT(ASPECT)
      H=H1
      F=DUM*FPHI*G*FW
C
C              CALCULATE STRESS INTENSITY FACTOR AT SURFACE 'C' WITH PLASMA ON
C
      KCON=(SMON+H*SBON)*J*F
C              CALCULATE STRESS INTENSITY FACTOR AT SURFACE 'C' WITH PLASMA OFF
C
      KCOFF=(SMOFF+H*SBOFF)*J*F
C
C              DETERMINE IF THE MAXIMUM STRESS INTENSITY FACTOR AT THE DEEPEST
C              POINT
C              'A' OCCURS DURING PLASMA-ON (LA=0) OR PLASMA-OFF (LA=1) CONDITIONS
C
C              CHOOSE THE APPROPIATE TEMPERATURES TO GO WITH THE MAXIMEM STRESS
C              INTENSITY FACTORS AT THAT LOCATION
C
      IF (KAON.GT.KAOFF) GO TO 10
      KAMAX=KAOFF
      KAMIN=KAON
      LA=1
      TA=TAOFF
      GO TO 20
   10 KAMAX=KAON
      KAMIN=KAOFF
      LA=0
      TA=TEMPA
C
C              DETERMINE IF THE MAXIMUM STRESS INTENSITY FACTOR AT THE SURFACE
C              'C'
```

```
      =====  RATE  =====
C             OCCURS DURING PLASMA-ON (LC=0) OR PLASMA-OFF (LC=1) CONDITIONS.
C
   20 IF (KCON.GT.KCOFF) GO TO 30
      KCMAX=KCOFF
      KCMIN=KCON
      LC=1
      TC=TCOFF
      GO TO 40
   30 KCMAX=KCON
      KCMIN=KCOFF
      LC=0
      TC=TEMPC
C
C             DETERMINE IF THE MAXIMUM STRESS INTENSITY FACTOR OCCURS AT  THE
C             SURFACE
C             OR AT THE DEEPEST POINT OF THE CRACK.
C             BANNER=0 MEANS THAT KMAX HAPPENED WHILE THE PLASMA WAS ON
C             BANNER=1 MEANS THAT KMAX HAPPENED WHILE THE PLASMA WAS OFF
C             PHI=0 MEANS THAT KMAX IS LOCATED AT THE SURFACE OF THE CRACK 'C'
C             PHI=1 MEANS THAT KMAX IS LOCATED AT THE DEEPEST POINT OF THE
C             CRACK 'A'
C
   40 CONTINUE
C
      IF (KAMAX.EQ.0.D0) RA=-1.D10
      IF (KAMAX.NE.0.D0) RA=KAMIN/KAMAX
      IF (KCMAX.EQ.0.D0) RC=-1.D10
      IF (KCMAX.NE.0.D0) RC=KCMIN/KCMAX
C
      IF (KAMAX.GE.KCMAX) GO TO 50
      KMAX=KCMAX
      KMIN=KCMIN
      R=RC
      BANNER=LC
      PHI=0
      GO TO 60
   50 KMAX=KAMAX
      KMIN=KAMIN
      R=RA
      BANNER=LA
      PHI=1
C
C             CALCULATE THE EFFECTIVE CRACK GROWTH RATES AT 'A' AND 'C'
C
   60 CALL DADNEQ (KAMAX,KAMIN,DADN,KAON,KAOFF,TIMEON,TIMEOF,RA,TA)
      CALL DADNEQ (KCMAX,KCMIN,DCDN,KCON,KCOFF,TIMEON,TIMEOF,RC,TC)
C
C             REDUCE THE CRACK GROWTH RATE AT THE SURFACE BY (0.9**NEXPON), AS
C             SUGGESSTED
C             BY JIM NEWMAN,DECEMBER,1979.
C
      DCDN=DCDN*(0.9**NEXPON)
C
      RETURN
      END
C
```

APPENDIX B

Computer Output for Sample Problem

NUMBER OF NODES = 5

FRACTIONAL CHANGE IN CRACK SIZE = .010

INITIAL FLAW DEPTH = .0010 METERS

INITIAL ASPECT RATIO A/C = 1.0000

PLATE THICKNESS = .6000-02 METERS PLATE WIDTH = .1000+05 METERS

TPULSE = .1000+04SEC TIMEON = .9000+03 SECONDS TIMEOF= .1000+03 SECONDS

SURFACE FLAW IS LOCATED ON THE PLASMA SIDE

NEUTRON DAMAGE RATE = .7000-06DPA/SEC

WALL EROSION RATE = .0000 METERS/SEC

PLASMA ON-OFF FREQUENCY = .1000-02

MAXIMUM INCREMENT IN CYCLES (DNMAX) = 23670.20

MINIMUM INCREMENT IN CYCLES (DNMIN)= 1.0000

MINIMUM FRACTURE TOUGHNESS= 30.0000 MPA(M)

TWO-DIMENSIONAL FLAW GROWTH

NOMINAL CURVE FOR DA/DN DATA SET

MODIFIED FORMAN EQUATION FOR DA/DN

CREEP CRACK GROWTH LAW IS TURNED ON

NUMBER OF STRESS POINTS READ FROM FILE 8. NTIMEX= 2

TIME-INDEPENDENT STRESS INPUT FROM NAMELIST

NODE	Z(I) (METERS)	TEMPON (DEG K)	TEMPOFF (DEG K)	STRESS ON (MPA)	STRESS OFF (MPA)
1	.600-03	.700+03	.573+03	-.400+03	.500+02
2	.180-02	.670+03	.573+03	-.200+03	.500+02
3	.300-02	.640+03	.573+03	.000	.500+02
4	.420-02	.610+03	.573+03	.200+03	.500+02
5	.540-02	.580+03	.573+03	.400+03	.500+02

TIME (YEARS)	CYCLES	FLUENCE (DPA)	A (METERS)	H (METERS)	A/T	A/C	R-RATIO	KMAX (MPA(M))	KMIN (MPA(M))	KIC (MPA(M))	DA/DN (M/CYCLE)	DC/DN (M/CYCLE)	KMAX AT
.000	.000	.000	.100-02	.600-02	.167	1.000	-9.250	2.137	-19.764	150.000	.24124-09	.32349-09	SURFACE
.751+00	.237+05	.166+02	.102-02	.600-02	.170	.994	-9.236	2.159	-19.941	30.000	.13375-08	.17914-08	SURFACE
.932+00	.294+05	.206+02	.103-02	.600-02	.171	.991	-9.231	2.167	-20.005	30.000	.13585-08	.18144-08	SURFACE
.111+01	.351+05	.246+02	.103-02	.600-02	.172	.989	-9.226	2.176	-20.074	30.000	.13809-08	.18392-08	SURFACE
.129+01	.408+05	.286+02	.104-02	.600-02	.174	.986	-9.221	2.185	-20.143	30.000	.14036-08	.18644-08	SURFACE
.147+01	.465+05	.325+02	.105-02	.600-02	.175	.984	-9.215	2.193	-20.213	30.000	.14265-08	.18901-08	SURFACE
.165+01	.521+05	.365+02	.106-02	.600-02	.176	.982	-9.209	2.202	-20.283	30.000	.14497-08	.19162-08	SURFACE
.183+01	.578+05	.404+02	.107-02	.600-02	.178	.980	-9.204	2.211	-20.354	30.000	.14732-08	.19428-08	SURFACE
.201+01	.634+05	.444+02	.108-02	.600-02	.179	.977	-9.198	2.221	-20.425	30.000	.14968-08	.19698-08	SURFACE
.219+01	.689+05	.483+02	.108-02	.600-02	.181	.975	-9.192	2.230	-20.496	30.000	.15208-08	.19973-08	SURFACE
.236+01	.745+05	.522+02	.109-02	.600-02	.182	.973	-9.186	2.239	-20.568	30.000	.15450-08	.20252-08	SURFACE
.254+01	.801+05	.560+02	.110-02	.600-02	.184	.971	-9.180	2.248	-20.641	30.000	.15695-08	.20536-08	SURFACE
.271+01	.856+05	.599+02	.111-02	.600-02	.185	.969	-9.174	2.258	-20.714	30.000	.15942-08	.20825-08	SURFACE
.289+01	.911+05	.638+02	.112-02	.600-02	.186	.967	-9.168	2.267	-20.787	30.000	.16192-08	.21119-08	SURFACE
.306+01	.966+05	.676+02	.113-02	.600-02	.188	.965	-9.162	2.277	-20.861	30.000	.16445-08	.21417-08	SURFACE
.323+01	.102+06	.714+02	.114-02	.600-02	.189	.963	-9.155	2.287	-20.935	30.000	.16700-08	.21721-08	SURFACE
.341+01	.107+06	.752+02	.115-02	.600-02	.191	.961	-9.149	2.296	-21.010	30.000	.16958-08	.22030-08	SURFACE
.358+01	.113+06	.790+02	.116-02	.600-02	.193	.959	-9.142	2.306	-21.085	30.000	.17219-08	.22344-08	SURFACE
.375+01	.118+06	.828+02	.116-02	.600-02	.194	.957	-9.136	2.316	-21.160	30.000	.17483-08	.22663-08	SURFACE
.392+01	.124+06	.865+02	.117-02	.600-02	.196	.955	-9.129	2.326	-21.236	30.000	.17749-08	.22988-08	SURFACE
.409+01	.129+06	.903+02	.118-02	.600-02	.197	.954	-9.123	2.336	-21.313	30.000	.18018-08	.23318-08	SURFACE
.426+01	.134+06	.940+02	.119-02	.600-02	.199	.952	-9.116	2.346	-21.389	30.000	.18290-08	.23653-08	SURFACE
.443+01	.140+06	.977+02	.120-02	.600-02	.200	.950	-9.109	2.357	-21.467	30.000	.18565-08	.23994-08	SURFACE
.459+01	.145+06	.101+03	.121-02	.600-02	.202	.948	-9.102	2.367	-21.544	30.000	.18842-08	.24341-08	SURFACE
.476+01	.150+06	.105+03	.122-02	.600-02	.204	.946	-9.095	2.377	-21.623	30.000	.19123-08	.24693-08	SURFACE
.493+01	.155+06	.109+03	.123-02	.600-02	.205	.945	-9.088	2.388	-21.701	30.000	.19406-08	.25051-08	SURFACE
.509+01	.161+06	.112+03	.124-02	.600-02	.207	.943	-9.081	2.398	-21.780	30.000	.19693-08	.25415-08	SURFACE
.526+01	.166+06	.116+03	.125-02	.600-02	.209	.941	-9.074	2.409	-21.860	30.000	.19982-08	.25785-08	SURFACE
.542+01	.171+06	.120+03	.126-02	.600-02	.211	.940	-9.066	2.420	-21.939	30.000	.20274-08	.26162-08	SURFACE
.558+01	.176+06	.123+03	.127-02	.600-02	.212	.938	-9.059	2.431	-22.020	30.000	.20570-08	.26544-08	SURFACE
.574+01	.181+06	.127+03	.128-02	.600-02	.214	.936	-9.051	2.442	-22.100	30.000	.20868-08	.26933-08	SURFACE
.591+01	.186+06	.130+03	.130-02	.600-02	.216	.935	-9.044	2.453	-22.181	30.000	.21169-08	.27328-08	SURFACE
.607+01	.191+06	.134+03	.131-02	.600-02	.218	.933	-9.036	2.464	-22.263	30.000	.21473-08	.27729-08	SURFACE
.623+01	.196+06	.137+03	.132-02	.600-02	.220	.932	-9.029	2.475	-22.345	30.000	.21780-08	.28137-08	SURFACE
.639+01	.201+06	.141+03	.133-02	.600-02	.221	.930	-9.021	2.486	-22.427	30.000	.22091-08	.28552-08	SURFACE
.654+01	.206+06	.144+03	.134-02	.600-02	.223	.929	-9.013	2.497	-22.510	30.000	.22404-08	.28973-08	SURFACE
.670+01	.211+06	.148+03	.135-02	.600-02	.225	.927	-9.005	2.509	-22.593	30.000	.22720-08	.29401-08	SURFACE
.686+01	.216+06	.151+03	.136-02	.600-02	.227	.925	-8.997	2.520	-22.676	30.000	.23040-08	.29837-08	SURFACE
.702+01	.221+06	.155+03	.137-02	.600-02	.229	.924	-8.989	2.532	-22.760	30.000	.23362-08	.30279-08	SURFACE
.717+01	.226+06	.158+03	.138-02	.600-02	.231	.922	-8.981	2.544	-22.844	30.000	.23688-08	.30728-08	SURFACE
.733+01	.231+06	.162+03	.140-02	.600-02	.233	.921	-8.973	2.555	-22.929	30.000	.24017-08	.31185-08	SURFACE
.748+01	.236+06	.165+03	.141-02	.600-02	.235	.919	-8.965	2.567	-23.014	30.000	.24349-08	.31649-08	SURFACE
.763+01	.241+06	.169+03	.142-02	.600-02	.237	.918	-8.956	2.579	-23.099	30.000	.24684-08	.32121-08	SURFACE
.779+01	.246+06	.172+03	.143-02	.600-02	.239	.916	-8.948	2.591	-23.185	30.000	.25022-08	.32600-08	SURFACE
.794+01	.250+06	.175+03	.144-02	.600-02	.241	.915	-8.939	2.603	-23.271	30.000	.25364-08	.33087-08	SURFACE
.809+01	.255+06	.179+03	.146-02	.600-02	.243	.913	-8.931	2.615	-23.358	30.000	.25708-08	.33582-08	SURFACE
.824+01	.260+06	.182+03	.147-02	.600-02	.245	.912	-8.922	2.628	-23.445	30.000	.26056-08	.34085-08	SURFACE
.839+01	.265+06	.185+03	.148-02	.600-02	.247	.910	-8.914	2.640	-23.532	30.000	.26407-08	.34596-08	SURFACE
.854+01	.269+06	.189+03	.149-02	.600-02	.249	.909	-8.905	2.653	-23.620	30.000	.26761-08	.35116-08	SURFACE
.869+01	.274+06	.192+03	.151-02	.600-02	.251	.907	-8.896	2.665	-23.708	30.000	.27119-08	.35643-08	SURFACE
.884+01	.279+06	.195+03	.152-02	.600-02	.253	.906	-8.887	2.678	-23.797	30.000	.27479-08	.36179-08	SURFACE
.898+01	.283+06	.198+03	.153-02	.600-02	.255	.905	-8.878	2.690	-23.886	30.000	.27843-08	.36724-08	SURFACE

.913+01	.288+06	.202+03	.154-02	.600-02	.257	.903	-8.869	2.703	-23.975	30.000	.28210-08	.37278-08	SURFACE
.927+01	.292+06	.205+03	.156-02	.600-02	.260	.902	-8.860	2.716	-24.065	30.000	.28581-08	.37840-08	SURFACE
.942+01	.297+06	.208+03	.157-02	.600-02	.262	.900	-8.851	2.729	-24.155	30.000	.28954-08	.38412-08	SURFACE
.956+01	.302+06	.211+03	.158-02	.600-02	.264	.899	-8.841	2.742	-24.245	30.000	.29331-08	.38992-08	SURFACE
.971+01	.306+06	.214+03	.160-02	.608-02	.266	.897	-8.832	2.755	-24.336	30.000	.29711-08	.39582-08	SURFACE
.985+01	.311+06	.217+03	.161-02	.600-02	.268	.896	-8.823	2.769	-24.427	30.000	.30095-08	.40182-08	SURFACE
.999+01	.315+06	.221+03	.162-02	.600-02	.271	.894	-8.813	2.782	-24.518	30.000	.30481-08	.40791-08	SURFACE
.101+02	.320+06	.224+03	.164-02	.600-02	.273	.893	-8.804	2.795	-24.610	30.000	.30871-08	.41410-08	SURFACE
.103+02	.324+06	.227+03	.165-02	.600-02	.275	.891	-8.794	2.809	-24.703	30.000	.31264-08	.42039-08	SURFACE
.104+02	.328+06	.230+03	.167-02	.600-02	.278	.890	-8.784	2.823	-24.795	30.000	.31660-08	.42678-08	SURFACE
.106+02	.333+06	.233+03	.168-02	.600-02	.280	.888	-8.775	2.836	-24.888	30.000	.32060-08	.43328-08	SURFACE
.107+02	.337+06	.236+03	.169-02	.600-02	.282	.887	-8.765	2.850	-24.982	30.000	.32462-08	.43987-08	SURFACE
.108+02	.341+06	.239+03	.171-02	.600-02	.285	.885	-8.755	2.864	-25.076	30.000	.32868-08	.44658-08	SURFACE
.110+02	.346+06	.242+03	.172-02	.600-02	.287	.884	-8.745	2.878	-25.170	30.000	.33277-08	.45339-08	SURFACE
.111+02	.350+06	.245+03	.174-02	.600-02	.289	.882	-8.735	2.892	-25.264	30.000	.33690-08	.46031-08	SURFACE
.112+02	.354+06	.248+03	.175-02	.600-02	.292	.881	-8.725	2.906	-25.359	30.000	.34105-08	.46735-08	SURFACE
.114+02	.359+06	.251+03	.177-02	.600-02	.294	.879	-8.715	2.921	-25.454	30.000	.34524-08	.47449-08	SURFACE
.115+02	.363+06	.254+03	.178-02	.600-02	.297	.878	-8.705	2.935	-25.550	30.000	.34945-08	.48176-08	SURFACE
.116+02	.367+06	.257+03	.180-02	.600-02	.299	.876	-8.694	2.950	-25.646	30.000	.35370-08	.48913-08	SURFACE
.118+02	.371+06	.260+03	.181-02	.600-02	.302	.875	-8.684	2.964	-25.743	30.000	.35798-08	.49663-08	SURFACE
.119+02	.375+06	.263+03	.182-02	.600-02	.304	.873	-8.674	2.979	-25.839	30.000	.36230-08	.50425-08	SURFACE
.120+02	.380+06	.266+03	.184-02	.600-02	.307	.872	-8.663	2.994	-25.937	30.000	.36664-08	.51199-08	SURFACE
.122+02	.384+06	.269+03	.186-02	.600-02	.309	.870	-8.653	3.009	-26.034	30.000	.37101-08	.51986-08	SURFACE
.123+02	.388+06	.271+03	.187-02	.600-02	.312	.868	-8.642	3.024	-26.132	30.000	.37542-08	.52785-08	SURFACE
.124+02	.392+06	.274+03	.189-02	.600-02	.314	.867	-8.631	3.039	-26.230	30.000	.37985-08	.53598-08	SURFACE
.126+02	.396+06	.277+03	.190-02	.600-02	.317	.865	-8.621	3.054	-26.329	30.000	.38432-08	.54423-08	SURFACE
.127+02	.400+06	.280+03	.192-02	.600-02	.320	.864	-8.610	3.069	-26.428	30.000	.38881-08	.55262-08	SURFACE
.128+02	.404+06	.283+03	.193-02	.600-02	.322	.862	-8.599	3.085	-26.528	30.000	.39334-08	.56114-08	SURFACE
.129+02	.408+06	.286+03	.195-02	.600-02	.325	.860	-8.588	3.100	-26.628	30.000	.39789-08	.56980-08	SURFACE
.131+02	.412+06	.288+03	.196-02	.600-02	.327	.859	-8.577	3.116	-26.728	30.000	.40247-08	.57861-08	SURFACE
.132+02	.416+06	.291+03	.198-02	.600-02	.330	.857	-8.566	3.132	-26.828	30.000	.40708-08	.58755-08	SURFACE
.133+02	.420+06	.294+03	.200-02	.600-02	.333	.856	-8.555	3.148	-26.930	30.000	.41172-08	.59664-08	SURFACE
.134+02	.424+06	.297+03	.201-02	.600-02	.335	.854	-8.544	3.164	-27.031	30.000	.41639-08	.60588-08	SURFACE
.136+02	.428+06	.299+03	.203-02	.600-02	.338	.852	-8.533	3.180	-27.133	30.000	.42108-08	.61527-08	SURFACE
.137+02	.431+06	.302+03	.205-02	.600-02	.341	.851	-8.522	3.196	-27.235	30.000	.42580-08	.62481-08	SURFACE
.138+02	.435+06	.305+03	.206-02	.600-02	.344	.849	-8.511	3.212	-27.338	30.000	.43055-08	.63450-08	SURFACE
.139+02	.439+06	.307+03	.208-02	.600-02	.346	.847	-8.499	3.229	-27.441	30.000	.43533-08	.64435-08	SURFACE
.140+02	.443+06	.310+03	.210-02	.600-02	.349	.845	-8.488	3.245	-27.544	30.000	.44013-08	.65437-08	SURFACE
.142+02	.447+06	.313+03	.211-02	.600-02	.352	.844	-8.477	3.262	-27.648	30.000	.44495-08	.66454-08	SURFACE
.143+02	.451+06	.315+03	.213-02	.600-02	.355	.842	-8.465	3.278	-27.752	30.000	.44980-08	.67489-08	SURFACE
.144+02	.454+06	.318+03	.215-02	.600-02	.358	.840	-8.454	3.295	-27.857	30.000	.45468-08	.68540-08	SURFACE
.145+02	.458+06	.321+03	.216-02	.600-02	.360	.838	-8.442	3.312	-27.962	30.000	.45957-08	.69608-08	SURFACE
.146+02	.462+06	.323+03	.218-02	.600-02	.363	.837	-8.430	3.329	-28.067	30.000	.46449-08	.70694-08	SURFACE
.148+02	.465+06	.326+03	.220-02	.600-02	.366	.835	-8.419	3.346	-28.173	30.000	.46944-08	.71797-08	SURFACE
.149+02	.469+06	.328+03	.221-02	.600-02	.369	.833	-8.407	3.364	-28.279	30.000	.47440-08	.72919-08	SURFACE
.150+02	.473+06	.331+03	.223-02	.600-02	.372	.831	-8.395	3.381	-28.386	30.000	.47939-08	.74058-08	SURFACE
.151+02	.476+06	.333+03	.225-02	.600-02	.375	.829	-8.383	3.399	-28.493	30.000	.48440-08	.75217-08	SURFACE
.152+02	.480+06	.336+03	.227-02	.600-02	.378	.827	-8.372	3.416	-28.600	30.000	.48942-08	.76394-08	SURFACE
.153+02	.484+06	.338+03	.228-02	.600-02	.381	.826	-8.360	3.434	-28.708	30.000	.49447-08	.77591-08	SURFACE
.154+02	.487+06	.341+03	.230-02	.600-02	.384	.824	-8.348	3.452	-28.817	30.000	.49954-08	.78807-08	SURFACE
.156+02	.491+06	.343+03	.232-02	.600-02	.387	.822	-8.336	3.470	-28.925	30.000	.50462-08	.80043-08	SURFACE
.157+02	.494+06	.346+03	.234-02	.600-02	.390	.820	-8.324	3.488	-29.035	30.000	.50972-08	.81300-08	SURFACE
.158+02	.498+06	.348+03	.236-02	.600-02	.393	.818	-8.312	3.506	-29.144	30.000	.51483-08	.82577-08	SURFACE
.159+02	.501+06	.351+03	.237-02	.600-02	.396	.816	-8.300	3.525	-29.254	30.000	.51996-08	.83875-08	SURFACE
.160+02	.505+06	.353+03	.239-02	.600-02	.399	.814	-8.288	3.543	-29.365	30.000	.52511-08	.85194-08	SURFACE
.161+02	.508+06	.356+03	.241-02	.600-02	.402	.812	-8.275	3.562	-29.476	30.000	.53026-08	.86535-08	SURFACE
.162+02	.512+06	.358+03	.243-02	.600-02	.405	.810	-8.263	3.581	-29.587	30.000	.53543-08	.87898-08	SURFACE

.163+02	.515+06	.360+03	.245-02	.600-02	.408	.808	-8.251	3.599	-29.699	30.000	.54061-08	.89283-08	SURFACE
.164+02	.518+06	.363+03	.247-02	.600-02	.411	.806	-8.239	3.618	-29.811	30.000	.54580-08	.90691-08	SURFACE
.165+02	.522+06	.365+03	.248-02	.600-02	.414	.804	-8.226	3.638	-29.924	30.000	.55100-08	.92122-08	SURFACE
.166+02	.525+06	.368+03	.250-02	.600-02	.417	.802	-8.214	3.657	-30.037	30.000	.55621-08	.93577-08	SURFACE
.168+02	.528+06	.370+03	.252-02	.600-02	.420	.800	-8.202	3.676	-30.150	30.000	.56143-08	.95055-08	SURFACE
.169+02	.532+06	.372+03	.254-02	.600-02	.423	.798	-8.189	3.696	-30.264	30.000	.56665-08	.96558-08	SURFACE
.170+02	.535+06	.375+03	.256-02	.600-02	.426	.795	-8.177	3.715	-30.379	30.000	.57188-08	.98085-08	SURFACE
.171+02	.538+06	.377+03	.258-02	.600-02	.430	.793	-8.165	3.735	-30.494	30.000	.57711-08	.99637-08	SURFACE
.172+02	.542+06	.379+03	.260-02	.600-02	.433	.791	-8.152	3.755	-30.609	30.000	.58234-08	.10121-07	SURFACE
.173+02	.545+06	.381+03	.262-02	.600-02	.436	.789	-8.140	3.775	-30.725	30.000	.58757-08	.10282-07	SURFACE
.174+02	.548+06	.384+03	.263-02	.600-02	.439	.787	-8.127	3.795	-30.841	30.000	.59281-08	.10445-07	SURFACE
.175+02	.551+06	.386+03	.265-02	.600-02	.442	.785	-8.115	3.815	-30.958	30.000	.59804-08	.10610-07	SURFACE
.176+02	.554+06	.388+03	.267-02	.600-02	.445	.782	-8.102	3.835	-31.075	30.000	.60327-08	.10779-07	SURFACE
.177+02	.558+06	.390+03	.269-02	.600-02	.449	.780	-8.090	3.856	-31.193	30.000	.60849-08	.10950-07	SURFACE
.178+02	.561+06	.393+03	.271-02	.600-02	.452	.778	-8.077	3.876	-31.311	30.000	.61371-08	.11124-07	SURFACE
.179+02	.564+06	.395+03	.273-02	.600-02	.455	.776	-8.065	3.897	-31.429	30.000	.61893-08	.11301-07	SURFACE
.180+02	.567+06	.397+03	.275-02	.600-02	.458	.773	-8.052	3.918	-31.548	30.000	.62413-08	.11480-07	SURFACE
.181+02	.570+06	.399+03	.277-02	.600-02	.462	.771	-8.039	3.939	-31.668	30.000	.62932-08	.11663-07	SURFACE
.182+02	.573+06	.401+03	.279-02	.600-02	.465	.769	-8.027	3.960	-31.788	30.000	.63450-08	.11848-07	SURFACE
.183+02	.576+06	.403+03	.281-02	.600-02	.468	.766	-8.014	3.981	-31.908	30.000	.63967-08	.12037-07	SURFACE
.184+02	.579+06	.405+03	.283-02	.600-02	.471	.764	-8.002	4.003	-32.029	30.000	.64483-08	.12228-07	SURFACE
.185+02	.582+06	.408+03	.285-02	.600-02	.475	.762	-7.989	4.024	-32.150	30.000	.64996-08	.12423-07	SURFACE
.186+02	.585+06	.410+03	.287-02	.600-02	.478	.759	-7.976	4.046	-32.272	30.000	.65508-08	.12621-07	SURFACE
.187+02	.588+06	.412+03	.289-02	.600-02	.481	.757	-7.964	4.068	-32.394	30.000	.66018-08	.12822-07	SURFACE
.187+02	.591+06	.414+03	.291-02	.600-02	.484	.754	-7.951	4.090	-32.517	30.000	.66526-08	.13026-07	SURFACE
.188+02	.594+06	.416+03	.293-02	.600-02	.488	.752	-7.939	4.112	-32.640	30.000	.67031-08	.13233-07	SURFACE
.189+02	.597+06	.418+03	.295-02	.600-02	.491	.749	-7.926	4.134	-32.764	30.000	.67534-08	.13444-07	SURFACE
.190+02	.600+06	.420+03	.297-02	.600-02	.494	.747	-7.913	4.156	-32.888	30.000	.68034-08	.13658-07	SURFACE
.191+02	.603+06	.422+03	.299-02	.600-02	.498	.744	-7.901	4.178	-33.012	30.000	.68531-08	.13876-07	SURFACE
.192+02	.606+06	.424+03	.301-02	.600-02	.501	.742	-7.888	4.201	-33.137	30.000	.69026-08	.14097-07	SURFACE
.193+02	.609+06	.426+03	.303-02	.600-02	.504	.739	-7.876	4.223	-33.263	30.000	.69517-08	.14322-07	SURFACE
.194+02	.612+06	.428+03	.305-02	.600-02	.508	.737	-7.863	4.246	-33.389	30.000	.70004-08	.14550-07	SURFACE
.195+02	.614+06	.430+03	.307-02	.600-02	.511	.734	-7.851	4.269	-33.515	30.000	.70488-08	.14782-07	SURFACE
.196+02	.617+06	.432+03	.309-02	.600-02	.514	.732	-7.838	4.292	-33.642	30.000	.70968-08	.15017-07	SURFACE
.197+02	.620+06	.434+03	.311-02	.600-02	.518	.729	-7.825	4.315	-33.769	30.000	.71445-08	.15256-07	SURFACE
.198+02	.623+06	.436+03	.313-02	.600-02	.521	.726	-7.813	4.339	-33.897	30.000	.71917-08	.15499-07	SURFACE
.198+02	.626+06	.438+03	.315-02	.600-02	.524	.724	-7.800	4.362	-34.025	30.000	.72384-08	.15746-07	SURFACE
.199+02	.628+06	.440+03	.317-02	.600-02	.528	.721	-7.788	4.385	-34.154	30.000	.72847-08	.15996-07	SURFACE
.200+02	.631+06	.442+03	.319-02	.600-02	.531	.718	-7.776	4.409	-34.283	30.000	.73305-08	.16251-07	SURFACE
.201+02	.634+06	.444+03	.321-02	.600-02	.534	.716	-7.763	4.433	-34.412	30.000	.73759-08	.16509-07	SURFACE
.202+02	.637+06	.446+03	.323-02	.600-02	.538	.713	-7.751	4.457	-34.542	30.000	.74207-08	.16771-07	SURFACE
.203+02	.639+06	.448+03	.325-02	.600-02	.541	.710	-7.738	4.481	-34.672	30.000	.74649-08	.17037-07	SURFACE
.204+02	.642+06	.449+03	.327-02	.600-02	.544	.708	-7.726	4.505	-34.803	30.000	.75087-08	.17308-07	SURFACE
.204+02	.645+06	.451+03	.329-02	.600-02	.548	.705	-7.714	4.529	-34.934	30.000	.75518-08	.17582-07	SURFACE
.205+02	.647+06	.453+03	.331-02	.600-02	.551	.702	-7.701	4.553	-35.066	30.000	.75943-08	.17861-07	SURFACE
.206+02	.650+06	.455+03	.333-02	.600-02	.554	.699	-7.689	4.578	-35.198	30.000	.76363-08	.18144-07	SURFACE
.207+02	.653+06	.457+03	.335-02	.600-02	.558	.696	-7.677	4.602	-35.330	30.000	.76776-08	.18431-07	SURFACE
.208+02	.655+06	.459+03	.337-02	.600-02	.561	.694	-7.665	4.627	-35.463	30.000	.77182-08	.18722-07	SURFACE
.209+02	.658+06	.460+03	.339-02	.600-02	.564	.691	-7.652	4.652	-35.596	30.000	.77582-08	.19018-07	SURFACE
.209+02	.660+06	.462+03	.341-02	.600-02	.568	.688	-7.640	4.677	-35.730	30.000	.77975-08	.19318-07	SURFACE
.210+02	.663+06	.464+03	.343-02	.600-02	.571	.685	-7.628	4.701	-35.864	30.000	.78361-08	.19623-07	SURFACE
.211+02	.665+06	.466+03	.345-02	.600-02	.574	.682	-7.616	4.727	-35.999	30.000	.78739-08	.19932-07	SURFACE
.212+02	.668+06	.468+03	.347-02	.600-02	.578	.679	-7.604	4.752	-36.133	30.000	.79111-08	.20245-07	SURFACE
.213+02	.670+06	.469+03	.349-02	.600-02	.581	.676	-7.592	4.777	-36.268	30.000	.79474-08	.20563-07	SURFACE
.213+02	.673+06	.471+03	.351-02	.600-02	.584	.674	-7.580	4.802	-36.404	30.000	.79830-08	.20886-07	SURFACE
.214+02	.675+06	.473+03	.353-02	.600-02	.588	.671	-2.461	4.829	-11.885	30.000	.80178-08	.21213-07	TIP "A"
.215+02	.678+06	.475+03	.355-02	.600-02	.591	.668	-2.424	4.860	-11.782	30.000	.80519-08	.21545-07	TIP "A"

.255+02	.803+06	.562+03	.462-02	.600-02	.770	.486	-.736	7.068	-5.202	30.000	.93138-08	.49886-07	TIP "A"
.255+02	.805+06	.563+03	.464-02	.600-02	.773	.483	-.713	7.114	-5.075	30.000	.93538-08	.50575-07	TIP "A"
.256+02	.807+06	.565+03	.466-02	.600-02	.776	.480	-.691	7.160	-4.948	30.000	.93914-08	.51273-07	TIP "A"
.256+02	.809+06	.566+03	.467-02	.600-02	.779	.478	-.669	7.207	-4.821	30.000	.94267-08	.51980-07	TIP "A"
.257+02	.811+06	.567+03	.469-02	.600-02	.782	.475	-.647	7.254	-4.692	30.000	.94598-08	.52696-07	TIP "A"
.258+02	.812+06	.569+03	.471-02	.600-02	.785	.472	-.625	7.301	-4.563	30.000	.94905-08	.53421-07	TIP "A"
.258+02	.814+06	.570+03	.473-02	.600-02	.788	.469	-.603	7.348	-4.434	30.000	.95192-08	.54155-07	TIP "A"
.259+02	.816+06	.571+03	.474-02	.600-02	.791	.466	-.582	7.396	-4.305	30.000	.95456-08	.54897-07	TIP "A"
.259+02	.818+06	.573+03	.476-02	.600-02	.794	.463	-.561	7.444	-4.175	30.000	.95700-08	.55648-07	TIP "A"
.260+02	.820+06	.574+03	.478-02	.600-02	.797	.460	-.540	7.492	-4.045	30.000	.95924-08	.56408-07	TIP "A"
.261+02	.822+06	.575+03	.480-02	.600-02	.800	.457	-.519	7.540	-3.914	30.000	.96129-08	.57176-07	TIP "A"
.261+02	.824+06	.576+03	.482-02	.600-02	.803	.454	-.499	7.589	-3.784	30.000	.96314-08	.57953-07	TIP "A"
.262+02	.825+06	.578+03	.483-02	.600-02	.806	.451	-.478	7.638	-3.654	30.000	.96482-08	.58738-07	TIP "A"
.262+02	.827+06	.579+03	.485-02	.600-02	.808	.448	-.458	7.687	-3.523	30.000	.96633-08	.59532-07	TIP "A"
.263+02	.829+06	.580+03	.487-02	.600-02	.811	.446	-.439	7.737	-3.393	30.000	.96767-08	.60334-07	TIP "A"
.263+02	.831+06	.582+03	.489-02	.600-02	.814	.443	-.419	7.787	-3.263	30.000	.96885-08	.61145-07	TIP "A"
.264+02	.833+06	.583+03	.490-02	.600-02	.817	.440	-.400	7.837	-3.133	30.000	.96989-08	.61964-07	TIP "A"
.265+02	.834+06	.584+03	.492-02	.600-02	.820	.437	-.381	7.887	-3.003	30.000	.97079-08	.62791-07	TIP "A"
.265+02	.836+06	.585+03	.494-02	.600-02	.823	.434	-.362	7.938	-2.874	30.000	.97157-08	.63626-07	TIP "A"
.266+02	.838+06	.587+03	.496-02	.600-02	.826	.431	-.344	7.989	-2.745	30.000	.97222-08	.64470-07	TIP "A"
.266+02	.840+06	.588+03	.497-02	.600-02	.829	.429	-.325	8.040	-2.617	30.000	.97276-08	.65322-07	TIP "A"
.267+02	.842+06	.589+03	.499-02	.600-02	.832	.426	-.308	8.092	-2.489	30.000	.97320-08	.66182-07	TIP "A"
.267+02	.843+06	.590+03	.501-02	.600-02	.835	.423	-.290	8.143	-2.361	30.000	.97355-08	.67050-07	TIP "A"
.268+02	.845+06	.592+03	.502-02	.600-02	.837	.420	-.273	8.195	-2.234	30.000	.97381-08	.67926-07	TIP "A"
.269+02	.847+06	.593+03	.504-02	.600-02	.840	.417	-.256	8.248	-2.108	30.000	.97400-08	.68810-07	TIP "A"
.269+02	.849+06	.594+03	.506-02	.600-02	.843	.415	-.239	8.300	-1.982	30.000	.97413-08	.69702-07	TIP "A"
.270+02	.850+06	.595+03	.508-02	.600-02	.846	.412	-.222	8.353	-1.857	30.000	.97420-08	.70603-07	TIP "A"
.270+02	.852+06	.596+03	.509-02	.600-02	.849	.409	-.206	8.406	-1.732	30.000	.97423-08	.71511-07	TIP "A"
.271+02	.854+06	.598+03	.511-02	.600-02	.852	.406	-.190	8.460	-1.608	30.000	.97421-08	.72428-07	TIP "A"
.271+02	.856+06	.599+03	.513-02	.600-02	.854	.404	-.174	8.514	-1.485	30.000	.97418-08	.73353-07	TIP "A"
.272+02	.857+06	.600+03	.514-02	.600-02	.857	.401	-.159	8.568	-1.362	30.000	.97412-08	.74286-07	TIP "A"
.272+02	.859+06	.601+03	.516-02	.600-02	.860	.398	-.144	8.622	-1.240	30.000	.97405-08	.75227-07	TIP "A"
.273+02	.861+06	.603+03	.518-02	.600-02	.863	.396	-.129	8.677	-1.119	30.000	.97397-08	.76177-07	TIP "A"
.273+02	.862+06	.604+03	.519-02	.600-02	.866	.393	-.114	8.731	-.998	30.000	.97391-08	.77134-07	TIP "A"
.274+02	.864+06	.605+03	.521-02	.600-02	.868	.390	-.100	8.787	-.878	30.000	.97385-08	.78100-07	TIP "A"
.275+02	.866+06	.606+03	.523-02	.600-02	.871	.388	-.086	8.842	-.759	30.000	.97381-08	.79075-07	TIP "A"
.275+02	.868+06	.607+03	.524-02	.600-02	.874	.385	-.072	8.898	-.641	30.000	.97380-08	.80058-07	TIP "A"
.276+02	.869+06	.608+03	.526-02	.600-02	.877	.382	-.058	8.954	-.523	30.000	.97383-08	.81049-07	TIP "A"
.276+02	.871+06	.610+03	.528-02	.600-02	.880	.380	-.045	9.010	-.406	30.000	.97389-08	.82049-07	TIP "A"
.277+02	.873+06	.611+03	.529-02	.600-02	.882	.377	-.032	9.067	-.290	30.000	.97400-08	.83058-07	TIP "A"
.277+02	.874+06	.612+03	.531-02	.600-02	.885	.375	-.019	9.123	-.175	30.000	.97416-08	.84076-07	TIP "A"
.278+02	.876+06	.613+03	.533-02	.600-02	.888	.372	-.007	9.180	-.060	30.000	.97438-08	.85102-07	TIP "A"
.278+02	.878+06	.614+03	.534-02	.600-02	.891	.369	.006	9.238	.054	30.000	.98109-08	.86137-07	TIP "A"
.279+02	.879+06	.616+03	.536-02	.600-02	.893	.367	.018	9.296	.172	30.000	.99416-08	.87193-07	TIP "A"
.279+02	.881+06	.617+03	.538-02	.600-02	.896	.364	.031	9.354	.292	30.000	.10065-07	.88269-07	TIP "A"
.280+02	.883+06	.618+03	.539-02	.600-02	.899	.362	.044	9.412	.416	30.000	.10181-07	.89363-07	TIP "A"
.280+02	.884+06	.619+03	.541-02	.600-02	.902	.359	.057	9.471	.542	30.000	.10289-07	.90477-07	TIP "A"
.281+02	.886+06	.620+03	.543-02	.600-02	.905	.357	.070	9.530	.670	30.000	.10388-07	.91609-07	TIP "A"
.282+02	.888+06	.621+03	.544-02	.600-02	.907	.354	.084	9.590	.801	30.000	.10480-07	.92760-07	TIP "A"
.282+02	.889+06	.623+03	.546-02	.600-02	.910	.352	.097	9.650	.933	30.000	.10564-07	.93927-07	TIP "A"
.283+02	.891+06	.624+03	.548-02	.600-02	.913	.350	.110	9.710	1.067	30.000	.10640-07	.95112-07	TIP "A"
.283+02	.893+06	.625+03	.550-02	.600-02	.916	.347	.123	9.771	1.202	30.000	.10708-07	.96314-07	TIP "A"
.284+02	.894+06	.626+03	.552-02	.600-02	.919	.345	.136	9.831	1.339	30.000	.10769-07	.97531-07	TIP "A"
.284+02	.896+06	.627+03	.553-02	.600-02	.922	.343	.149	9.893	1.475	30.000	.10822-07	.98764-07	TIP "A"
.285+02	.898+06	.628+03	.555-02	.600-02	.925	.340	.162	9.954	1.613	30.000	.10868-07	.10001-06	TIP "A"
.285+02	.899+06	.629+03	.557-02	.600-02	.928	.338	.175	10.016	1.751	30.000	.10908-07	.10128-06	TIP "A"
.286+02	.901+06	.631+03	.559-02	.600-02	.931	.336	.187	10.078	1.888	30.000	.10942-07	.10255-06	TIP "A"

.286+02	.903+06	.632+03	.560-02	.600-02	.934	.333	.200	10.140	2.026	30.000	.10970-07	.10384-06	TIP "A"
.287+02	.904+06	.633+03	.562-02	.600-02	.937	.331	.212	10.203	2.163	30.000	.10992-07	.10515-06	TIP "A"
.287+02	.906+06	.634+03	.564-02	.600-02	.940	.329	.224	10.266	2.299	30.000	.11010-07	.10646-06	TIP "A"
.288+02	.907+06	.635+03	.566-02	.600-02	.943	.327	.236	10.330	2.435	30.000	.11023-07	.10779-06	TIP "A"
.288+02	.909+06	.636+03	.567-02	.600-02	.946	.324	.247	10.393	2.570	30.000	.11032-07	.10914-06	TIP "A"
.289+02	.911+06	.637+03	.569-02	.600-02	.949	.322	.259	10.457	2.704	30.000	.11038-07	.11049-06	TIP "A"
.289+02	.912+06	.639+03	.571-02	.600-02	.952	.320	.270	10.522	2.837	30.000	.11042-07	.11186-06	TIP "A"
.290+02	.914+06	.640+03	.573-02	.600-02	.955	.318	.280	10.586	2.969	30.000	.11043-07	.11324-06	TIP "A"
.290+02	.915+06	.641+03	.575-02	.600-02	.958	.316	.291	10.651	3.099	30.000	.11042-07	.11463-06	TIP "A"
.291+02	.917+06	.642+03	.576-02	.600-02	.960	.313	.301	10.716	3.228	30.000	.11039-07	.11603-06	TIP "A"
.291+02	.919+06	.643+03	.578-02	.600-02	.963	.311	.311	10.782	3.356	30.000	.11036-07	.11744-06	TIP "A"
.292+02	.920+06	.644+03	.580-02	.600-02	.966	.309	.321	10.848	3.482	30.000	.11033-07	.11887-06	TIP "A"
.292+02	.922+06	.645+03	.582-02	.600-02	.969	.307	.330	10.914	3.607	30.000	.11029-07	.12031-06	TIP "A"
.293+02	.923+06	.646+03	.583-02	.600-02	.972	.305	.340	10.981	3.730	30.000	.11026-07	.12176-06	TIP "A"
.293+02	.925+06	.647+03	.585-02	.600-02	.975	.303	.349	11.048	3.852	30.000	.11023-07	.12323-06	TIP "A"
.294+02	.926+06	.648+03	.587-02	.600-02	.978	.300	.357	11.115	3.972	30.000	.11021-07	.12471-06	TIP "A"
.294+02	.928+06	.650+03	.588-02	.600-02	.981	.298	.366	11.183	4.091	30.000	.11020-07	.12620-06	TIP "A"
.295+02	.930+06	.651+03	.590-02	.600-02	.984	.296	.374	11.251	4.209	30.000	.11021-07	.12771-06	TIP "A"
.295+02	.931+06	.652+03	.592-02	.600-02	.986	.294	.382	11.319	4.325	30.000	.11024-07	.12923-06	TIP "A"
.296+02	.933+06	.653+03	.594-02	.600-02	.989	.292	.390	11.388	4.440	30.000	.11028-07	.13077-06	TIP "A"
.296+02	.934+06	.654+03	.595-02	.600-02	.992	.290	.397	11.457	4.553	30.000	.11035-07	.13232-06	TIP "A"
.297+02	.936+06	.655+03	.597-02	.600-02	.995	.288	.405	11.526	4.665	30.000	.11044-07	.13389-06	TIP "A"
.297+02	.937+06	.656+03	.599-02	.600-02	.998	.286	.412	11.596	4.777	30.000	.11055-07	.13547-06	TIP "A"

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LEAK-THROUGH

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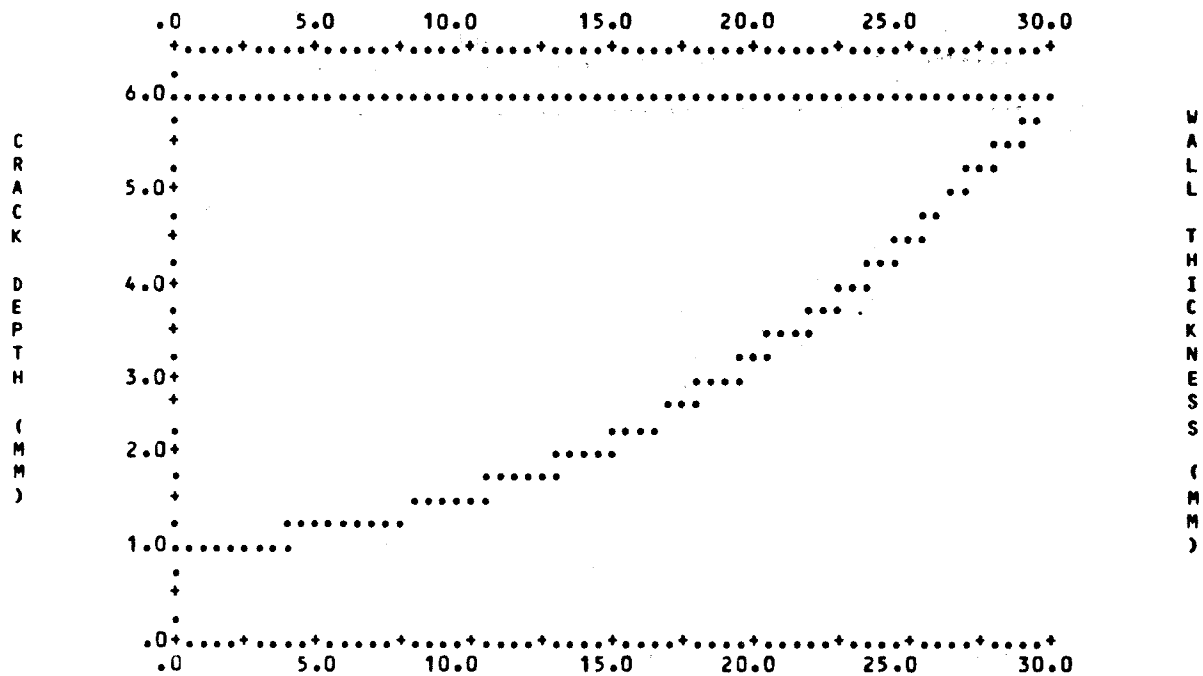
TIME (YEARS)	CYCLES	FLUENCE (DPA)	A (METERS)	H (METERS)	A/T	A/C	R-RATIO	KMAX (MPA(M))	KMIN (MPA(M))	KIC (MPA(M))	DA/DN (M/CYCLE)	DC/DN (M/CYCLE)	KMAX AT
.298+02	.939+06	.657+03	.600-02	.600-02	1.001	.284	.415	11.631	4.831	30.000	.11064-07	.13627-06	TIP "A"

FIRST WALL CRACK GROWTH

SURFACE FLAW ON PLASMA SIDE



TIME (YEARS)

NUMBER OF NODES = 5