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OCTOBER, 1978
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STRUCTURAL EVALUATION

OF

A DTHR BUNDLE DIVERTOR PARTICLE COLLECTOR

MASTER

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Westinghouse Electric Corporation
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1.0 INTRODUCTION

In the Demonstration Tokamak Hybrid Reactor (DTHR), the Bundle Divertor Particle Collector (BDPC) functions to remove charged particles from the plasma and dissipates the relatively severe heat flux associated with the charged particles[1]. The BDPC is arranged into two groups of V-shaped tube bundles. During DTHR operation, one group is placed in the plasma to collect charged particles which adhere to the surfaces of the V-shaped tube bundles. After a period of time, the group exposed to the plasma is moved to a bake chamber with the other group taking its place in the plasma. In the bake chamber, the absorbed particles are baked out by heating the V-shaped tube bundles to an elevated temperature and then removed by vacuum pumping. Thereafter, the process is repeated by cycling the groups of V-shaped tube bundles back and forth between the plasma and the bake chamber.

The BDPC V-shaped tube bundles consist of a number of thin-walled tubes brazed to each other in a side-by-side configuration. When the group of V-shaped tube bundles is placed in the plasma, only the vertex of each tube receives the intense incident heat flux. Along the inclined surfaces of the V-shaped tube bundles, the incident heat flux is greatly attenuated because of the shallow frontal angle. In order to protect the vertices of the thin-walled tubes, a thermal shield is provided which consists of a single thin-walled tube brazed to a thin backing plate and oriented perpendicular to the stack of V-shaped tubes. The function of the backing plate is to attenuate the temperature difference across the thermal shield tube by intercepting a small fraction of the intense incident heat flux, and thereby heating the backside of the tube by conduction, which otherwise would be heated only from the frontside by the incident heat flux. Coolant is provided to each of the V-shaped tube bundles by a common header. The thermal shield tube of each V-shaped tube bundle is cooled independently.

During DTHR operation, the BDPC serves an important function in removing charged particle impurities and attendant heat flux from the plasma. However, it is equally important that the BDPC be a highly reliable structure in relation to coolant leakage and subsequent contamination of the plasma. Owing to the severity of the surface particle heat flux, the potential for coolant leakage through the thin-walled tubes caused by high thermal loads exists, and as such, the BDPC is planned to be removed and replaced periodically over the life time of the DTHR.

2.0 PURPOSE

The purpose of this report is to present a structural evaluation of the current BDPC design under a peak heat flux in relation to criteria that protect against coolant leakage into the plasma over replacement schedules planned during DTHR operation. In addition, an assessment of the BDPC structural integrity at higher heat fluxes is presented. Further, recommendations for modifications in the current BDPC design that would improve design reliability to be considered in future design studies are described. Finally, experimental test programs directed to establishing materials data necessary in providing greater confidence in subsequent structural evaluations of BDPC designs in relation to coolant leakage over planned replacement schedules are identified.

2.1 SCOPE

The scope of the BDPC structural evaluation covers all V-shaped tube bundles and thermal shields, but was reduced by considering only the severely loaded thermal shield tube which is a worst case upper bound to the less severely loaded tubes in the V-shaped tube bundles. Other BDPC components including the headers and support structure not directly exposed to the heat flux are not considered to limit planned replacement schedules.

2.2 APPLICABILITY

The BDPC thermal shield tube structural evaluation is applicable to DTHR operation where the peak surface particle heat flux is 32 MW/M^2, while the assessment of a higher heat flux is based on 50 MW/M^2. The DTHR operation considered consists of 7 plasma on-off cycles for approximately 9.3 minutes followed by a 600° C temperature bake for two minutes. Each plasma on-off cycle is taken to be on for 70 seconds and off for 10 seconds. The plasma on-off cycles and bake period represent a combined block loading with a time duration of approximately 11.3 minutes. The planned replacement schedule for the BDPC is considered to be one year, or 8760 hours. In this arrangement, the BDPC thermal shield tube structural evaluation is applicable to 325,593 plasma on-off cycles combined with 1550 hours of baking at elevated temperature.

2.3 DESIGN

The structural evaluation of the BDPC thermal shield tube is based on a water cooled design with an inlet pressure of 3.45 MPa and temperature of 100° C. The thermal shield tubes are constructed from 0.8 O.D. x 0.051 cm wall Amzirc tubing. Amzirc is a heat treatable copper [2] alloyed 0.1% to 0.15% zirconium, which in a full thermally softened conditions, has a 0.1% off-set yield stress of 96.5 MPa and a thermal conductivity of 0.876 cal/sec-cm-°C. In contrast, pure OFHC copper [3] has a thermally softened yield stress and thermal conductivity of 27.6 MPa and 0.932 cal/sec-cm-°C. The thermally softened condition is of importance in the BDPC thermal shield tube because of the 1550 hours of baking at 600° C over the one year planned replacement schedule. The thermal shield backing plate is a 1 cm wide x 0.13 cm thick OFHC copper strip formed to mate the curvature of the 0.8 cm O.D. thermal shield tube. The spiral ribbon is a nominal 0.005 cm thick Inconel strip twisted to a pitch of 4 thermal shield tube diameters. The thermal shield tube is swaged periodically along its length to retain the spiral ribbon position. During operation in the plasma, the water outlet temperature is 158° C at a pressure of 1.47 MPa and a flow rate of 0.6 kgm/sec.

3.0 SUMMARY

A summary of the BDPC thermal shield tube structural evaluation for the current design under nominal surface particle heat flux, an assessment of structural integrity for the current design at a higher heat flux, and recommendations for future design studies and materials test data are as follows.

3.1 PEAK HEAT FLUX

The current BDPC thermal shield tube design under a nominal heat flux of 32 MW/M^2 was evaluated in relation to a structural criterion which protects against coolant leakage into the plasma over planned replacement schedules. Coolant leakage was quantified by assuming a surface crack at BOL of a depth equal to 25% of the BDPC thermal shield tube wall thickness, which prior to EOL slowly grows through the wall causing an opening by which coolant enters the plasma. In order to evaluate the current design, fatigue and creep-crack growth data for Amzirc at the elevated temperature-time history of the BDPC thermal shield tube are required, but not available. However, estimates of crack-growth based on available data suggest that coolant leakage is not expected for the BDPC thermal shield tube with a 32 MW/M^2 heat flux over the planned one year replacement schedule.

3.2 ASSESSMENT OF A HIGHER HEAT FLUX

The assessment of the current BDPC thermal shield tube design in relation to coolant leakage for a higher heat flux of 50 MW/M^2 is difficult to make with any accuracy at this time because of the lack of fatigue and creep-crack growth data. However, it can be said that the higher operating temperatures associated with a 50 MW/M^2 heat flux will likely enhance creep crack growth and creep-fatigue interactions, thereby requiring replacement of the BDPC thermal shield tube before the planned one year replacement schedule.

3.3 RECOMMENDATIONS FOR FUTURE DESIGN STUDIES

The current BDPC thermal shield tube design utilizes water as a coolant pressurized to 3.45 MPa and a spiral ribbon to promote a high film coefficient by inducing vortex flow. However, the high coolant pressure also enhances creep-crack growth in the Amzirc, and thereby reduces operating life at elevated temperature. In addition, the use of a spiral ribbon requires swaging to retain its position in the tube, but requires the use of Amzirc in an annealed condition to permit swaging. However, the use of cold work Amzirc is desirable because the resistance to creep-crack growth is retained longer, thereby promoting longer BDPC thermal shield tube replacement schedules. This is especially important for heat fluxes of 50 MW/M^2. In this arrangement, liquid sodium may be a better coolant selection for the BDPC thermal shield tube as a high film coefficient is obtained at low pressure without a spiral ribbon. As such, the use of liquid sodium, as the BDPC thermal shield tube coolant is recommended for future design studies.

3.4 RECOMMENDATIONS FOR MATERIALS DATA

In order to provide confidence in subsequent structural evaluations of the BDPC thermal shield tube at heat fluxes to 50 MW/M^2, fatigue and creep-crack growth data for cold worked Amzirc in a water or liquid sodium environment reflecting the thermal softening that occurs during operation and baking is required. Pre-cracked flat tensile specimens 2 cm wide x 0.05 cm thick are recommended. A semi-circular surface crack with a depth of 25% of the specimen thickness would be placed in the specimen normal to the loading direction. Hoop stress in the thermal shield tube would be simulated with a load controlled tensile force. Cyclic thermal stresses are simulated by displacement controlled motion of one end of the specimen.

4.0 DESCRIPTION

Descriptions of the overall BDPC design and specific details of the V-shaped tube bundle and thermal shield are given in the following.

4.1 BDPC

In the DTHR, the D-shaped plasma formed by the poloidal and toroidal fields is diverted through the BDPC by the divertor coils. The BDPC consists of two groups of V-shaped tube bundles stacked on top of each other which are periodically moved between the plasma and the bake chamber. Each group includes 14 V-shaped tube bundles, 7 per side to face the plasma from both directions. The V-shaped tube bundles in a group are approximately 300 cm wide x 200 cm high so as to intercept a projected plasma area of 6 m^2. An isometric view of the BDPC is illustrated in Figure 4.1-1.

4.2 V-SHAPED TUBE BUNDLE AND THERMAL SHIELD

Individual V-shaped tube bundles are fabricated from 0.95 O.D. x 0.08 cm wall tubes while the thermal shield tubes are 0.8 O.D. x 0.05 cm wall. Both tubes are constructed from Amzirc, a high thermal conductivity copper alloyed with zirconium, to provide a yield stress higher than that of pure OFHC copper. The V-shaped tubes are 35% cold worked and aged to provide the ductility necessary for forming the vertices without cracking. The thermal shield tube is 85% cold worked and aged to permit the spiral ribbon to be swaged in place. The thermal shield back plate is a 1 cm wide x 0.13 cm thick sheet formed to mate curvature of the 0.8 cm O.D. thermal shield tube. OFHC copper is used as the thermal shield material to provide an optimum brazing condition with the Amzirc tube. The coolant in both V-shaped tubes and the thermal shield tube is water at an inlet temperature of 100° C and pressurized to 0.072 MPa. The water flow rate in the V-shaped is adjusted to maintain the tube surface temperature below 300° C to provide optimum adherence of charged particles. For the thermal shield tube exposed to the intense incident heat flux, the water flow rate is selected to maintain reasonable metal temperatures with collection of charged particles of least importance. A spiral ribbon is provided in the thermal shield tube, is swaged in place to induce vortex flow and promote a high water to tube heat transfer coefficient necessary to dissipate the intense incident heat flux. An isometric view of the V-shaped tube bundle and thermal shield is presented in Figure 4.1-1.

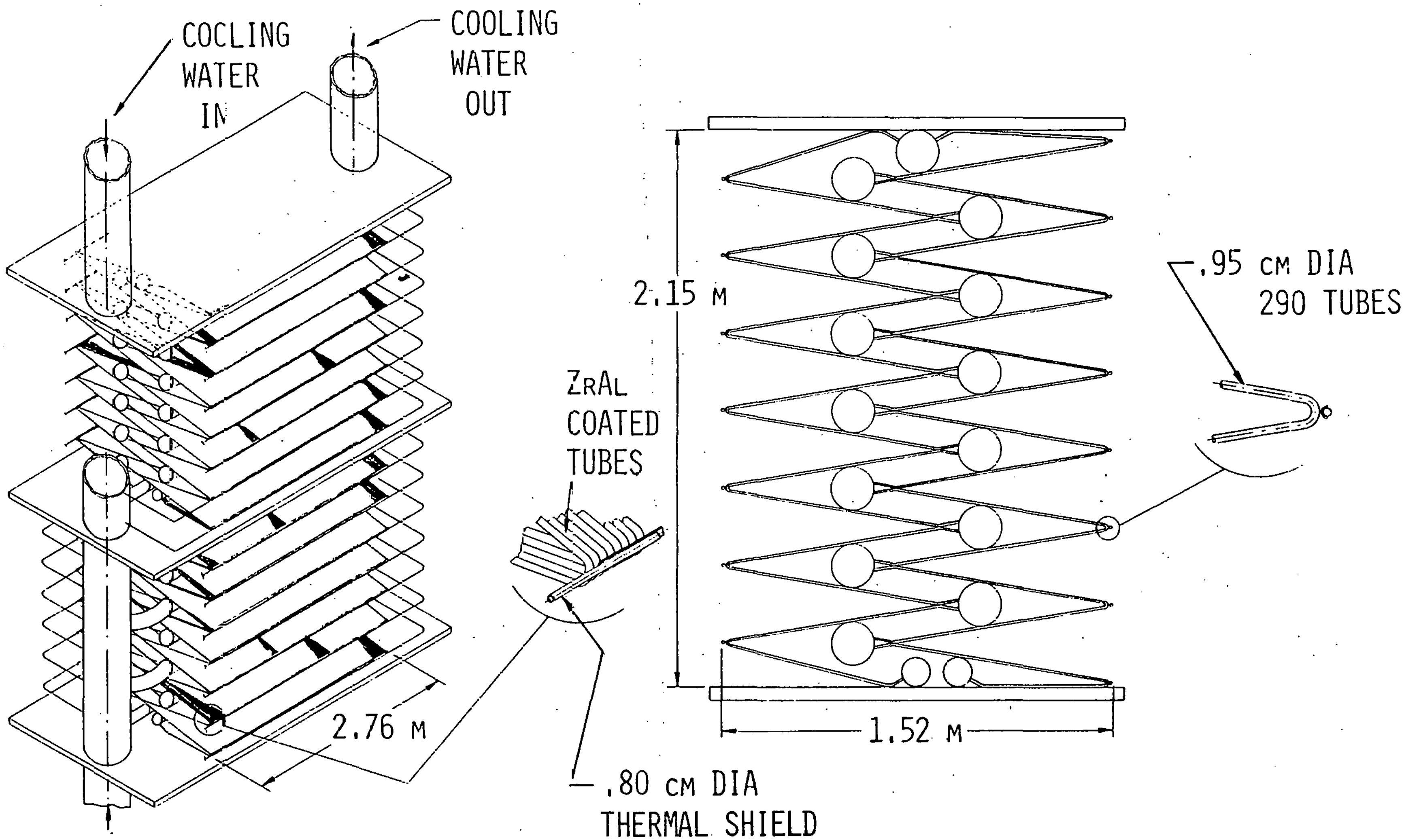

Figure 4.1-1. Isometric View of the V-Shaped Tube Bundle and Thermal Shield

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5.0 ANALYSIS

In order to perform a structural evaluation of the BDPC thermal shield tube, a loading and stress analysis is required.

5.1 LOADING

The loading analysis is directed to establishing a worst case duty cycle of mechanical, swelling, and thermal loads for the BDPC thermal shield tube.

5.1.1 MECHANICAL

The BDPC thermal shield tube mechanical loads include internal coolant pressure, deadweight, and seismic loads. Of these, only internal coolant pressure associated with operating the BDPC group in the plasma is considered significant. During the bake periods, the coolant pressure is reduced to zero. Owing to the water coolant flow pressure drop, the worst case internal pressure load (P) in the BDPC thermal shield tube occurs at the water inlet,

$$P = 3.45 \text{ MPa}$$

5.1.2 SWELLING

The BDPC thermal shield tube is exposed to the portion of the plasma as diverted by the divertor coils, but is shielded from the neutron irradiation source at the center of the plasma. Accordingly, swelling loads induced in the BDPC thermal shield tubes as constructed from Amzirc are not expected to be significant. However, irradiation induced creep and swelling data for Amzirc at fast fusion fluence levels expected for the BDPC thermal shield tube region are required to substantiate the assertion that neutron irradiation is insignificant.

5.1.3 THERMAL

The BDPC thermal shield tube thermal loads are the through-the-wall and across-the-tube temperature differences associated with the nominal heat flux of 32 MW/M^2. Of these thermal loads, only the through-the-wall temperature differences are of importance in the BDPC thermal shield tube. Owing to the presence of the backing plate, across-the-tube temperature differences are attenuated so as to reduce bending stresses in the thermal shield to be under the intense incident heat flux to negligible levels. Further, the through-the-wall temperature differences are worst case only at one end of the thermal shield tube, which by design corresponds to the inlet water coolant. This is so, as the orientation of the thermal shield tube imposes a peak heat flux of 32 MW/M^2 at the inlet coolant end with a rapidly decreasing incident heat flux along its length to the outlet coolant end.

In order to estimate the worst through-the-wall temperature difference in the BDPC thermal shield tube, a condition of 1-dimensional heat flow is assumed in the wall adjacent to the water coolant inlet. The assumption is conservative as a certain amount of circumferential heat flow occurs. The steady state heat flux (q/A) impinging on a thin plate of thickness (t) with a thermal conductivity (K) is related to its outside (T_o) and inside (T_I) temperatures by the relation:

$$q/A = K\,(T_o - T_I)/t$$

Thus, the BDPC thermal shield tube through-the-wall temperature difference (T_o-T_I) is given by:

$$T_o - T_I = \frac{t\,(q/A)}{K}$$

Numerically, for the worst heat flux location and an Amzirc tube with a 0.05 cm thick wall,

$$q/A = 32\ MW/M^2$$

$$q/A = 3200\ W/cm^2$$

$$K = 0.876 \text{ cal/sec - cm - °C}$$

$$K = 3.68 \text{ W/cm - °C}$$

$$t = 0.05 \text{ cm}$$

$$\therefore \quad T_o - T_I = \frac{0.05\ (3200)}{3.68}$$

$$T_o - T_I = 45° \text{ C}$$

Similarly, the peak BDPC thermal shield tube outside surface temperature (T_o) is related to the bulk water coolant temperature (T_B), film coefficient (h), and aforementioned thermal parameters by the relation.

$$T_o = T_B + \left(\frac{t}{K} + \frac{1}{h} \right) (q/A)$$

Numerically, a typical film coefficient (h) for vortex flow using pressurized water [4] is 2.71 cal/sec - cm^2 - °C, or 11.35 W/cm^2 - °C. For the inlet water, the bulk temperature (T_B) is 100° C. Accordingly, the maximum BDPC thermal shield outside surface temperature (T_o) adjacent to the water inlet is:

$$T_o = 100 + \left[\frac{0.05}{3.68} + \frac{1}{11.35} \right] (3200)$$

$$T_o = 100 + 326$$

$$T_o \cong 426° \text{ C}$$

5.1.4 WORST CASE DUTY CYCLE

The worst case BDPC thermal shield tube duty cycle consists of a 0.072 MPa internal coolant pressure mechanical load sustained throughout plasma on-off cycling with a zero pressure condition maintained during the elevated temperature bake. Swelling loads associated with neutron irradiation are assumed to be negligible. Thermal loads corresponding to plasma-on conditions cause a through-the-wall temperature difference of 45° C with a peak outside wall surface temperature of 426° C. During plasma-off conditions, a zero through-the-wall temperature difference occurs with a peak outside surface temperature equal to the water inlet coolant temperature of 100° C. The plasma on-off cycles are repeated seven times for approximately 9.3 minutes followed by a 600° C temperature bake for two minutes. Each plasma on-off cycle is taken to be on for 70 seconds and off for 10 seconds. The seven plasma on-off cycles and the two-minute bake represent a block loading of a 11.3 minute duration which is repeated consecutively for a total of 46,513 times over the one year replacement schedule. The BDPC thermal shield tube worst case duty cycle is illustrated in Figure 5.1-1.

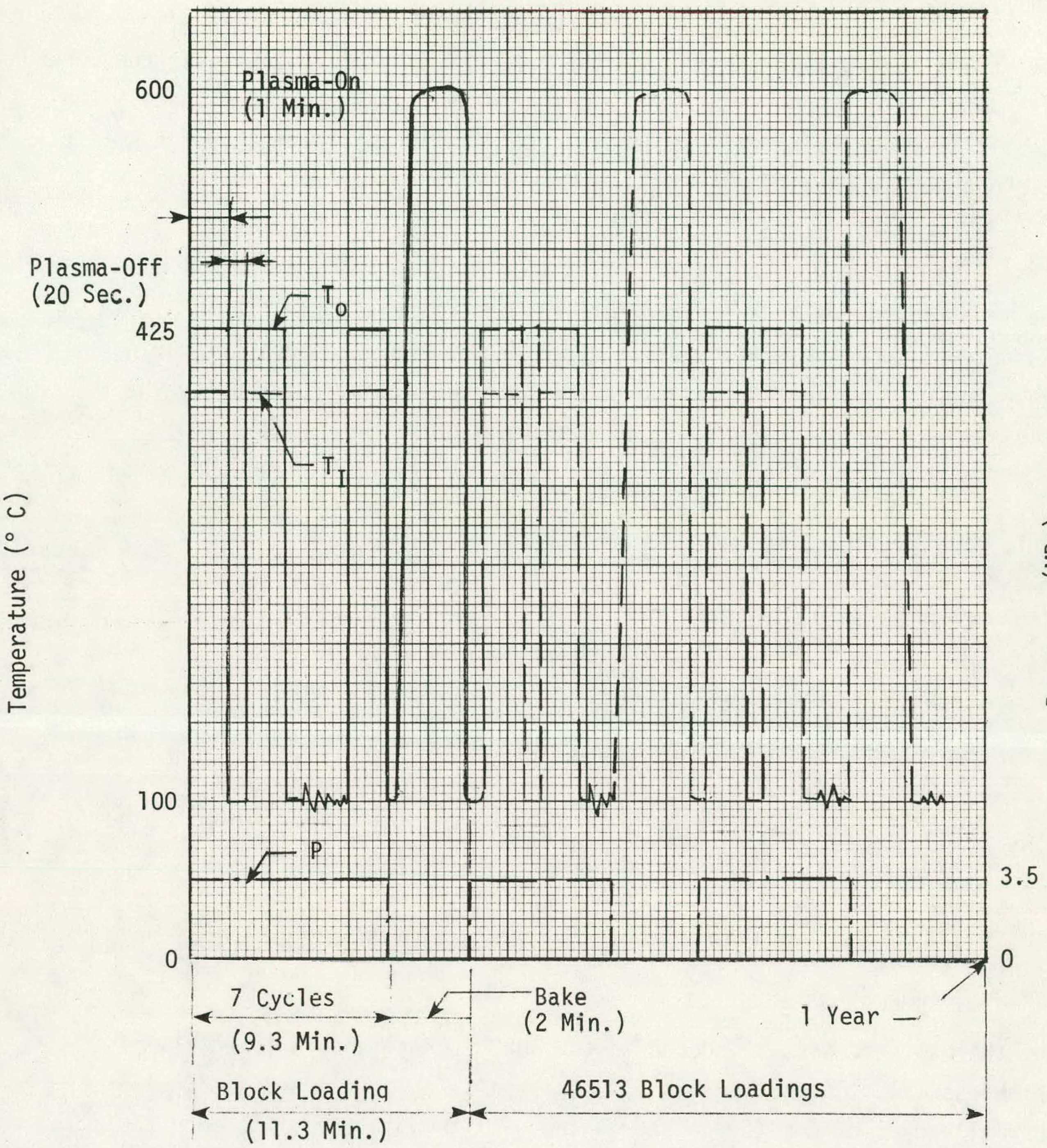

Figure 5.1-1. BDPC Thermal Shield Tube Worst Case Duty Cycle

5.2 STRESS

The stress analysis is directed to the BDPC thermal shield tube over the worst case duty cycles. The stresses are computed by linear elastic methods. The elastically calculated stresses and a justification of the method for Amzirc is presented as follows.

5.2.1 MECHANICAL

The mechanical stress (σ_p) induced in the BDPC thermal shield tube of radius (R) and wall thickness (t) under a sustained coolant pressure (P) during plasma on-off cycling is maximum in the hoop direction and given by the relation:

$$\sigma_p = \frac{PR}{t}$$

Numerically,

$$P = 3.45 \text{ MPa}$$

$$R = 0.4 \text{ cm}$$

$$t = 0.05 \text{ cm}$$

$$\therefore \sigma_p = \frac{3.45\ (0.4)}{0.05}$$

$$\sigma_p = 27.6 \text{ MPa}$$

5.2.2 THERMAL

The thermal stress (σ_T) induced in the BDPC Thermal shield tube wall of thickness (t), Young's modulus (E), Poisson's ratio (ν), and coefficient of thermal expansion (α) for a through-the-wall temperature difference (Δ T) in both hoop and meridional directions is given by the relation:

$$\sigma_T = \frac{E\ \alpha\ (\Delta T)}{2\ (1-\nu\ )}$$

Numerically, for Amzirc:

$$E = 12.9 \times 10^4 \text{ MPa}$$

$$\alpha = 17.64 \times 10^{-6}/°C$$

$$\nu = 0.3$$

$$\Delta T = 45° \text{ C}$$

$$\sigma_T = \frac{12.9 \times 10^4 \, (17.64 \times 10^{-6}) \, (45)}{2 \, (1-.3)}$$

$$\sigma_T = 73.1 \text{ MPa}$$

5.2.3 VALIDITY

The mechanical and thermal stresses developed in the BDPC thermal shield tube wall as derived by linear elastic methods are valid providing the equivalent stress (σ_{eq}) is less than the proportional elastic limit stress (σ_{pel}).

The equivalent stress (σ_{eq}) in terms of the meridional (σ_L) and hoop (σ_H) stresses is given by:

$$\sigma_{eq} = \frac{1}{\sqrt{2}} \sqrt{(\sigma_L - \sigma_H)^2 + \sigma_H^2 + \sigma_L^2}$$

At the inside surface of the BDPC thermal shield tube wall, the stress state is tensile, i.e.,

$$\sigma_H = \sigma_p + \sigma_T$$

$$\sigma_L = \frac{\sigma_p}{2} + \sigma_T$$

or, $$\sigma_{eq} = \frac{1}{\sqrt{2}} \sqrt{\left(\frac{\sigma_p}{2}\right)^2 + (\sigma_p + \sigma_T)^2 + \left(\frac{\sigma_p}{2} + \sigma_T\right)^2}$$

Numerically,

$$\sigma_p = 27.6 \text{ MPa}$$

$$\sigma_t = 73.1 \text{ MPa}$$

$$\therefore \quad \sigma_{eq} = \frac{1}{\sqrt{2}} \sqrt{13.4^2 + 99.1^2 + 85.6^2}$$

$$\sigma_q = 93.3 \text{ MPa}$$

The 0.1% off-set yield strength of Amzirc[1] in a full thermally softened condition associated with extended bake periods at 600° C is 96.5 MPa. The PEL is considered to be essentially the same as the 0.1% off-set yield for Amzirc. Accordingly, the validity of linear elastic methods in estimating the stresses in the BDPC thermal shield tube is marginal, but acceptable.

6.0 STRUCTURAL EVALUATION

The structural evaluation of the BDPC thermal shield tube including criteria to protect against coolant leakage based on a hypothetical surface crack at BOL, a LEFM analysis to estimate EOL crack depth as the controlled quantity, and a comparison of EOL crack depth with the coolant leakage criteria are presented as follows.

6.1 CRITERIA

The BDPC thermal shield tube structural criteria including background and scope, controlled quantity and criterion, and method of implementation are described as follows.

6.1.1 BACKGROUND AND SCOPE

The BDPC thermal shield tube structural criteria protect against coolant leakage and subsequent contamination of the plasma. Coolant leakage is characterized by a hypothetical surface crack at BOL of a depth which prior to EOL, slowly grows through the wall causing a coolant leakage into the plasma. The BDPC thermal shield tube structural criteria is similar to the criteria developed for the highly irradiated 20% CW-316-SS ORNL blanket module[5], except that coolant leakage by brittle fracture was neglected because of the high plane strain fracture toughness expected for unirradiated Amzirc. As such, the hypothetical surface crack at BOL is considered to cause EOL coolant leakage by combined fatigue and creep-crack growth alone. Criteria to protect against excessive deformation failure modes, such as perturbations of the spiral ribbon which lead to hot spots in the BDPC thermal shield tube and thereby promote coolant leakage by accelerated fatigue and creep crack growth, represent a greater degree of sophistication and are not justified for structural evaluations at this time.

6.1.2 CONTROLLED QUANTITY AND CRITERION

The specific BDPC thermal shield tube structural criteria is quantified by assuming a hypothetical semi-circular surface crack of a depth (a_o) and length (2Co) to be present in the tube wall at BOL. The BOL crack depth (a_o) is taken to be 25% of the wall thickness (t) or the mean grain size diameter of full thermally softed Amzirc ($a_o \cong 0.008$ cm.), whichever is greater. In order to protect against coolant leakage, the controlled quantity is selected as the change in crack depth (Δ a) with the criterion for acceptability being 10% of the initial crack depth (a_o). The change in crack depth (Δ a) corresponds to the difference between EOL crack depth (a_f) and BOL crack depth (a_o). In summary, the BDPC thermal shield tube structural criterion in protecting against coolant leakage is:

$$\Delta a = a_f - a_o \leq 0.10\, a_o$$

Where,

a_o = Depth of a semi-circular surface crack at BOL. Taken as 25% of the wall thickness or 0.008 cm, whichever is greater.

Δa = Increase in crack depth from BOL to EOL

6.1.3 METHOD OF IMPLEMENTATION

In order to implement the BDPC thermal shield tube criteria to protect against coolant leakage based on a hypothetical surface crack present at BOL, a method is required to estimate the EOL crack growth. The FBR Core Components Criteria[6] recommends Linear Elastic Fracture Mechanics (LEFM) methods for irradiated as well as unirradiated austenitic stainless steels. For the BDPC thermal shield tube constructed from Amzirc with a relatively low yield strength and applied elastically calculated equivalent stresses near yield values, the use of LEFM methods is a less defensible position than employing J-integral methods. However, it is not unreasonable that

LEFM methods provide a first approximation to estimates of fatigue and creep growth for elastically calculated equivalent stresses near the yield strength of Amzirc, and as such, were adopted for the BDPC thermal shield tube.

In the LEFM method, the crack growth is related to the elastic stress intensity factor (K). Fatigue-crack growth (da/dN) is dependent on the range of stress intensity factor (Δ K) between maximum (K_{max}) and minimum (K_{min}) values corresponding to plasma-on and off conditions, respectively. Creep-crack growth (da/dt) is dependent on the maximum stress intensity factor (K_{max}) associated with the hold-time during plasma-on conditions. With regard to creep-fatigue interaction on crack growth, no data is currently available for Amzirc to justify a linear damage summation. However, for the sake of completeness in the interim, a linear damage rule is assumed for the BDPC thermal shield tube constructed of Amzirc. Accordingly, the EOL crack depth (a_f) is expressed in terms of the BOL crack depth (A_o), and fatigue-creep crack growth materials data according to the relation:

$$a_f = a_o + \int_{a_o}^{a_f} \left(\frac{da}{dN}\right) dN + \int_{a_o}^{a_f} \left(\frac{da}{dt}\right) dt$$

Where,

a = Crack depth (cm)

$\frac{da}{dN}$ = Fatigue-crack growth (cm/cycle)

$$\frac{da}{dN} = C_f (\Delta K)^{n_f}$$

C_f, n_f = Fatigue constants

ΔK = Elastic stress intensity factor range (MPa $\sqrt{cm}$)

N = Number of fatigue cycles

$\frac{da}{dt}$ = Creep-crack growth (cm/hr)

$$\frac{da}{dt} = C_c \, (K_{max})^{n_c}$$

C_c, n_c = Creep constants

t = Time (hours)

6.2 CONTROLLED QUANTITY

In order to estimate the crack growth in the BDPC thermal shield tube from BOL to EOL, a LEFM analysis including the selection of a hypothetical BOL crack size, a representative K-Solution, and attendant maximum and minimum stress intensity factors, and an estimate of EOL crack depth based on available materials data is presented in the following.

6.2.1 LFFM ANALYSIS

6.2.1.1 HYPOTHETICAL CRACK SIZE

The BDPC thermal shield tube is assumed to have a semi-circular surface crack present at BOL with a crack depth (a_o) equal to the greater of 25% of the wall thickness or 0.008 cm. For the Amzirc tube with a wall thickness of 0.05 cm, the BOL crack depth (a_o) is governed by 25% of the wall thickness, i.e.,

$$a_o = 0.0125 \text{ cm}$$

6.2.1.2 K SOLUTION

The elastic stress intensity factor K-Solution selected for the BDPC thermal shield tube is taken from the approximate K-Solution developed for Mode I axial surface cracks in cylindrical shells such as LMFBR piping systems[7].

$$K = \left[M_K \sigma_t + M_b \sigma_b + 1.13\, P\right]\left[\frac{\sqrt{\pi a}}{\phi}\right]\left[f(\lambda)\right]$$

Where:

σ_t, σ_b = membrane and bending stresses linearized

M_K, M_b = surface crack magnification factors in tension and bending

P = internal pressure

a = crack depth

$2c$ = crack length

ϕ = elliptic integral of the second kind.

$$\phi = \int_0^{\pi/2}\left[1 - \left(\frac{c^2 - a^2}{c^2}\right)\sin^2\beta\right] d\beta \cong \sqrt{1 + 1.47\left(\frac{a}{c}\right)^{1.64}}$$

$f(\lambda)$ = curvature correction

$$f(\lambda) = 1 + \left[0.481\,\lambda + 0.386\left(e^{-1.25\,\lambda} - 1\right)\right]\left[\frac{a}{t}\right]$$

$$\lambda = \left[12\,(1 - \nu^2)\right]^{1/4} \frac{c}{\sqrt{Rt}}$$

R = cylinder radius

t = cylinder thickness

ν = Poisson's Ratio

Evaluating the eliptic integral (ϕ) for a semi-circular crack (a/c = 1.0),

$$\phi \cong \sqrt{1 + 1.47 \left(\frac{a}{c} \right)^{1.64}}$$

$$\phi = 1.572$$

For the BDPC thermal shield tube design, the shell curvature parameter (λ) is given by:

$$\lambda = \left[12 \left(1 - \nu^2\right)\right]^{1/4} \frac{C}{\sqrt{Rt}}$$

$$\lambda = \left[12 \left(1 - .297^2\right)\right]^{1/4} \left[\frac{0.0125}{\sqrt{0.40 \ (0.050)}}\right]$$

$$\lambda = 0.089$$

The curvature correction $\left(f(\lambda) \right)$

$$f(\lambda) = 1 + \left[0.481\lambda + .386 \left(e^{-1.25\lambda} - 1\right)\right] \left[\frac{a}{t} \right]$$

$$f(\lambda) = 1 + \left[0.481 \ (0.089) + .386 \left(e^{-.112} - 1\right)\right] [.25]$$

$$f(\lambda) = 1.0005$$

The surface crack mangification factors (Mk, Mb) for the crack depth to wall thickness ratio (a/t = 0.25) and crack depth to half length ratio (a/c = 1.0) are taken from Reference (8).

$$Mk = 1.03$$

$$Mb = 0.70$$

Accordingly, the K-Solution for the BDPC thermal shield tube is reduced to the following.

$$K = \left[1.03 \ \sigma_t + 0.70 \ \sigma_b + 1.13P\right] \sqrt{\frac{\pi(0.0125)}{1.572}} \ [1.0018]$$

$$K = 0.127 \ \left[1.03 \ \sigma_t + 0.70 \ \sigma_b + 1.13P\right]$$

6.2.1.3 MAXIMUM AND MINIMUM STRESS INTENSITY FACTORS

In the BDPC thermal shield tube, the maximum elastic stress intensity factor (K_{max}) occurs during plasma-on conditions, while the minimum value (K_{min}) corresponds to plasma-off conditions.

For plasma-on conditions, the linearized elastically calculated membrane (σ_t) and bending (σ_b) stresses for an internal coolant pressure (P) are worst case tensile at the inside surface of the BDPC thermal shield tube.

$$\sigma_t = 27.6 \text{ MPa}$$

$$\sigma_b = 73.1 \text{ MPa}$$

$$P = 3.45 \text{ MPa}$$

Accordingly, the maximum stress intensity factor (K_{max}),

$$K_{max} = 0.127 \left[1.03 \ (27.6) + 0.7 \ (73.1) + 1.13 \ (3.45)\right]$$

$$K_{max} = 10.6 \text{ MPa} \sqrt{\text{cm}}$$

Similarly, for plasma-off conditions,

$$\sigma_t = 27.6 \text{ MPa}$$

$$\sigma_b = 0 \text{ MPa}$$

$$P = 3.45 \text{ MPa}$$

Thus, the minimum stress intensity factor (K_{min}),

$$K_{min} = 0.127 \left[1.03\ (27.6) + 0 + 1.13\ (3.45) \right]$$

$$K_{min} = 4.10\ \text{MPa} \sqrt{\text{cm}}$$

6.2.2 MATERIALS DATA AND ESTIMATE OF EOL CRACK DEPTH

Currently, fatigue and creep-crack growth data for Amzirc is not available at the specific plasma-on operating temperature of 426° C in the presence of periodic baking at a temperature of 600° C. Accordingly, accurate estimates of EOL crack depth are not possible at present. On the other hand, some related materials data is available which, if extrapolated to BDPC thermal shield tube temperatures, can be used in the interim to establish the potential for design acceptability until specific materials data becomes available.

6.2.2.1 FATIGUE-CRACK GROWTH

Fatigue-crack growth data within Westinghouse is available for annealed OFHC copper in an air, dry argon, dry hydrogen and hydrogen saturated water at 24° and 82° C shows no effect of environment or temperature on either crack growth rate (da/dN) or the threshold stress intensity factor range (ΔK threshold). In the open literature, the threshold value reported[9] for copper is 13.2 MPa$\sqrt{\text{cm}}$. However, the Westinghouse data indicates that the threshold value for annealed OFHC copper is higher than 13.2 MPa$\sqrt{\text{cm}}$. The threshold stress intensity factor range is of special interest in high cycle — low stress applications such as the BDPC thermal shield tube because no crack growth occurs for applied stress intensity factor ranges less than the threshold value.

Owing to the similarities between OFHC copper and Amzirc, and the fact that an environmental or temperature effect was not observed over test conditions for annealed OFHC copper, it is not unreasonable that the fatigue threshold for Amzirc at 426° C would be similar to that for annealed OFHC copper at 82° C. For the purposes of the BDPC thermal shield tube structural evaluation, the fatigue-crack growth rate (da/dN) for Amzirc at 426° C is taken to be zero for an applied stress intensity factor range (Δ K) less than the threshold (Δ K) threshold), i.e.,

$$\frac{da}{dN} = 0, \text{ for } \Delta K < \Delta \text{ Threshold}$$

Where,

$$\Delta K \text{ Threshold} = 13.2 \text{ MPa} \sqrt{\text{cm}}$$

6.2.2.2 CREEP-CRACK GROWTH

In ductile materials, such as Amzirc and OFHC copper, crack tip blunting occurs at elevated temperature so that conventional stress rupture properties provide an indication of creep-crack growth (da/dt) at instability. Available stress rupture data[2] for 85% cold worked Amzirc aged during the stress-rupture test at 400° C show rupture times of 100 and 300 hours at stress levels of 241.4 and 220.7 MPa, respectively. The stress rupture data is representtative of the BDPC thermal shield tube at a maximum operating temperature of 426° C, but does not reflect the accelerated aging at the bake temperature of 600° C. Stress rupture data [2] for hard drawn OFHC copper at 450 and 650° C show a rapid decrease in rupture times with increasing temperature. The effect of the elevated temperature bake on 85% cold worked Amzirc based on the decrease in rupture time observed for hard drawn OFHC copper is illustrated in Figure 6.2-1.

A review of the estimated stress rupture data in relation to creep-crack growth (da/dt) for 85% CW-Amzirc at 600° C for the BDPC thermal shield tube is as follows. Over a one year replacement schedule, a total of 325,591 plasma-on cycles with 70 second durations correspond to 6330 hours of operation at 426° C. At a water coolant pressure of 3.45 MPa, the hoop stress in the BDPC thermal shield tube is 27.6 MPa with a time to rupture of 100,000 hours. Accordingly, the creep damage is approximately 6% and stress rupture is not expected for the BDPC thermal shield tube. Alternately, unstable creek-crack growth (da/dt)

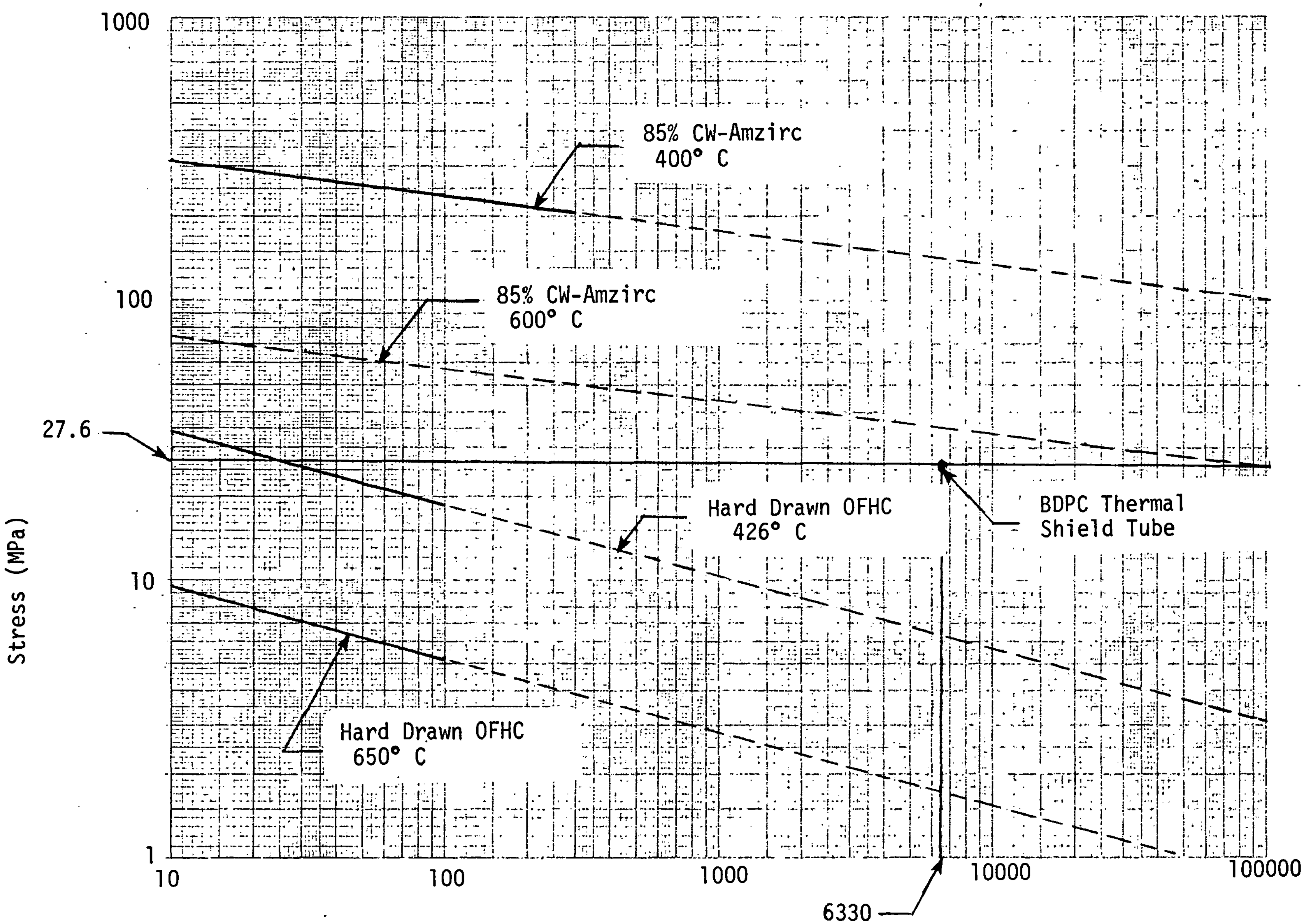

Figure 6.2-1. Estimated Amzirc Stress Rupture Data

for Amzirc at BDPC thermal shield tube temperatures over planned replacement schedules is not expected. For the purposes of the BDPC thermal shield tube structural evaluation, the creep-crack growth (da/dt) is taken to be zero.

$$\frac{da}{dt} = 0$$

6.2.2.2 ESTIMATE OF EOL CRACK DEPTH

The growth of the hypothetical crack of depth (a_o) present at BOL in the BDPC thermal shield tube to a crack depth (a_f) at EOL is given by the expression:

$$a_f = a_o + \int_{a_o}^{a_f} \left(\frac{da}{dN}\right) + \int_{a_o}^{a_f} \left(\frac{da}{dt}\right) dt$$

Based on the LEFM analysis, the applied stress intensity factor range (ΔK),

$$\Delta K = K_{max} - K_{min}$$

$$\Delta K = 10.6 - 4.1$$

$$\Delta K = 6.5 \text{ MPa} \sqrt{\text{cm}}$$

Now, ΔK threshold = 13.2 MPa$\sqrt{\text{cm}}$. As $\Delta K \leq \Delta K$ threshold, no fatigue crack growth occurs, i.e.,

$$\frac{da}{dN} = 0$$

Further, the creep crack growth is negligible based on estimated stress rupture data, i.e.,

$$\frac{da}{dt} = 0$$

Thus, the EOL crack depth (a_f) is estimated as approximately equal to the BOL crack depth (a_o), i.e.,

$$a_f \cong a_o$$

6.2.3 COMPARISON OF CONTROLLED QUANTITY WITH CRITERION

The BDPC thermal shield tube structural criterion in protecting against coolant leakage into the plasma requires that the increase in crack depth (Δa) from BOL to EOL to be less than 10% of the BOL crack depth, i.e.,

$$\Delta a \leq 0.10 \, a_o$$

As the EOL and BOL crack depth were found to be approximately equal to each other, the change in crack depth ($\Delta a = a_f - a_o \cong 0$). For the criterion ($0.10 \, a_o = 0.00125$ cm, coolant leakage caused by crack growth is not expected in the BDPC thermal shield tube over planned replacement schedule.

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