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to Predict Safety Margin of
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SUMMARY

A thermal stress problem in beryllium at cryogenic temperature is analyzed for possible fracture and the safety factor is predicted. Round notched-bar tensile tests at -320°F and other temperatures up to 212°F are reported. Values of Energy Release Rate, G_c , are computed from the tests and used in the analysis.

OBJECTIVES

A component of a Westinghouse nuclear reactor involves a solid block of 98% pure, vacuum hot pressed beryllium, heated by neutron bombardment and cooled by the passage of cryogenic hydrogen gas through a pattern of holes drilled in the block. The resulting temperature distribution in the block creates biaxial and triaxial tensile stresses around the holes. Due to the presence of stress concentrations such as scratches and drill marks on the hole walls, and due to the very low ductility of beryllium in the temperature range expected (about -320°F), there is concern about the possibility of brittle fracture.

Previous analysis using computed temperature profiles and the theory of elasticity (Refs. 7, 5) has shown the expected maximum stress to be of the order of 6,000 psi under steady-state operation (see Fig. 1). Start-up conditions, however, may be more severe, and it was desired to find from appropriate tests on beryllium whether

- (a) adequate safety margin against brittle fracture is present under steady-state conditions,
- (b) start-up flow condition limitations could be specified.

A third objective was to find general information on notched properties of beryllium at cryogenic temperatures to aid in designing such features as threaded members.

It was decided that the following information and results were needed:

- (a) a plot of nominal stress at fracture versus elastic stress concentration factor, K_T , at cryogenic temperature
- (b) fracture toughness or "energy release rate", G_c , (Ref. 2) requirement for the actual part in steady-state condition
- (c) fracture toughness property at cryogenic temperature obtained from test specimens
- (d) fracture toughness as a function of temperature from room temperature down to -320°F
- (e) computation of the allowable size notch in the actual part

Manjoine (Ref. 11) defines fracture toughness as follows:

"In the Griffith-Irwin theory of fracture, the condition for rapid propagation of fracture is reached when the stored elastic strain energy released from a body as a result of the extension of a crack by a unit area is equal to the work absorbed in local plastic flow and cleavage to create the unit fracture area. This latter work is called fracture toughness, G_c . The fracture toughness is considered a materials property which must be determined experimentally just like the yield or ultimate strengths."

TEST EQUIPMENT AND PROCEDURE

The specimens were loaded in a hydraulic tensile machine at the Westinghouse Research Laboratories. The low temperature tests were run by enclosing the specimen in an insulating container cut out of a block of hardened foam. A thermocouple was attached to the part and liquid nitrogen was poured into the container. The specimen was shielded from rapid thermal shock as the liquid was added. Other tests were run in powdered dry ice, ice water, boiling water, and at room temperature.

An extensometer was attached to the notched specimens by means of a set of rods and collars. The rods extended down into the liquid and a Parker recording system, using resistance wire strain gage pick-ups, was used to measure the extension of the notch under load.

TEST SPECIMENS

The test specimens are described in Table 1. They were machined from hot-pressed QMV beryllium block. The material vendor's test results were as follows:

Chemical Analysis:

Beryllium Assay	98.8 %
Beryllium Oxide	1.29%
Iron	0.11%
Aluminum	0.04%
Carbon	0.02%
Magnesium	0.04%
Silicon	0.11%

Density: 1.86 gms/cc

Tensile Results (room temperature):

	<u>Ultimate</u>	<u>Yield</u>	<u>Elongation</u>
Longitudinal	45,400 psi	35,500 psi	1%
Transverse	55,800 psi	35,200 psi	4%

The specimens were machined with their axes in the longitudinal direction of the material. All final dimensions were ground, including the threads, and the test section and notches were polished to a surface finish of about 2 micro-inches, r.m.s.

The material was not annealed, nor was any other thermal treatment or surface treatment used.

TEST RESULTS

The test results are presented in Table 2 and Figs. 2, 3, and 4. Table 2 lists the net stress at the notched cross section at fracture and the test temperature as well as the elastic stress concentration factor, K_T (from Ref. 6) and the values of energy release rate (or fracture toughness), G_c , as calculated from the geometry of the specimen and the fracture stress by the method of Bueckner (Ref. 3).

A number of the specimens failed at the threads before the notched section broke, and in these cases, the stress at the notch at the time of thread failure is shown with an asterisk *. This stress was also used in computing values of G_c for these points also. These values therefore are somewhat low but are nevertheless included in the table and Figs. 2 and 3. In the figures they are identified by flags as $\triangle$ and ∇ .

Figure 1 shows the stress condition in the actual reactor part as computed in Ref. 5. These stresses are used in the appendix to compute the required value of G_c to prevent fracture. This value is $0.027 \text{ in. lb./in.}^2$. Using Fig. 3, we have a G_c value for the material of $1.00 \text{ in. lb./in.}^2$ for low temperature (-320°F) and high stress concentration factor. The stress in the part would thus have to increase to

$$6,000 \sqrt{\frac{1.00}{.023}} = 36,600 \text{ psi}$$

before a crack would propagate in the part.

Figure 2 shows the net fracture stress (load/notched area) and energy release rate, G_c , as functions of elastic stress concentration factor, K_T , at the root of the notch. Both curves level out for K_T greater than 6.0. This shows that the effect of ductility is important even for this apparently quite brittle material. The failure curve for a theoretically completely brittle material is shown as "stress" $\times 1/K_T$ for comparison. At $K_T = 3.0$, the actual failure stress is twice that of the ideally brittle material. Stress problems in beryllium under these temperature and loading conditions

seem then to be divided into two categories: parts with smooth contours and good surface finish, for which the elastic stress concentration factor, K_T , can be reliably predicted (and for which K_T is less than 6.0); and parts with unavoidably rough surfaces or very sharp changes in section, for which the G_c value for $K_T \geq 6$ should be used in a suitable formula to show that a crack will not propagate even though provided with an initial very sharp notch. For the parts with predictable stress concentration factor, values of fracture strength can be taken from Fig. 2 as lying somewhere between the average test values and the $1/K_T$ curve depending on the reliability requirement of the application. Values of G_c for $K_T < 6$ are not really valid since the formula for computing G_c from fracture stress (Ref.3) assumes the specimen to be completely elastic prior to fracture, and it is seen from Fig. 2 that plastic flow does occur at the notch root in this range.

Figure 3 shows fracture stress and energy release rate results for a number of similar specimens with $K_T = 3.00$ tested at different temperatures from -320°F to 212°F . Smooth curves are obtained showing that the values for notched specimens increase quite regularly as the temperature is increased in this range. This is due to increasing ductility at the notch root.

Figure 4 shows an expanded plot of fracture stress vs. temperature. Results from Burnett (Ref. 8) are included to show that while notched strength increases with temperature, unnotched strength decreases. An estimated curve for $K_T \geq 6.0$ is drawn through a point representing average results from Fig. 2. Increasing temperature and ductility should give this curve an even steeper slope than for $K_T = 3.0$. The elongation curve for the unnotched specimens shows that a transition from ductile to brittle behavior occurs as the temperature is reduced from 1000°F . The fracture appearance transition temperature (FATT) is probably about 600°F and the nil ductility temperature (NDT) is near 0°F .

A number of specimens broke prematurely at the threaded section. This may have been due to a combination of factors. The first specimens tested had full height threads and thread root radii of .008 in. to .004 in. Later specimens were tested

with .014 in. smooth radii at the thread roots and .005 in. removed from the tips of the threads. New threaded adapters were also made up with fully machined threads. One of these later specimens also broke at the threads at approximately the same thread root area tensile stress, however. It is possible that some bending was introduced at the threads due to misalignment. Also, due to differences in thermal expansion coefficient between the collar and the specimen, there was about .001 in. difference in contraction at -320°F over the length of thread engagement. This would tend to load the threads at the end of the engagement length to a higher degree. A calculation of the required crack length (started by failure of one thread for instance) to cause propagation of the crack across the thread root area at the section is carried out in the Appendix, Item 2. This value is about .10 in., which is approximately the height of a thread. A similar calculation in Appendix, Item 1 shows that to cause fracture at the coolant hole in the actual part under steady-state conditions, an initial crack length on the order of .188 in. would be required.

At the start of testing it was desired to compute G_c in two different ways, once from the fracture stress and once from the load-deflection measurements at the notched section. This second procedure is outlined in the Appendix, Item 2. Unfortunately, the procedure of using a remotely positioned extensometer was not sufficiently accurate to measure the extension at the notch. Only five of the extensometer readings were good enough to compute the deflection constant K (in./lb.). These constants are listed in Table 2. To obtain G_c from load-deflection measurements, it is required to obtain a smooth curve of deflection constant vs notched area for a range of specimen sizes. The slope of this curve is used in the calculation. The values of K obtained have far too much scatter to provide an accurate slope.

CONCLUSIONS

1. The stress in the beryllium reactor component has a safety factor of 6.0 for steady-state operation. An initial crack of .188 in., or about the size of the cooling hole diameter itself, would be required to cause fracture at steady state. A cooling hole model should be tested to determine the resulting temperature and stress profiles at startup. From these results the safety factor at startup can be computed.
2. Enough ductility is present in hot pressed beryllium at -320°F to allow the use of stress concentration factors less than the theoretical value (K_T) for smooth members free of bad surface cracks.
3. The value of Energy Release Rate, G_c , is about $1.0 \text{ in.-lb./in.}^2$ for sharply notched ($K_T \geq 6$) specimens of hot pressed beryllium at -320°F .
4. Fracture stresses of moderately notched specimens ($K_T \approx 3.0$) increase about 30% as the temperature is increased from -320°F to room temperature. At the same time, unnotched specimens, while still stronger than the notched specimens, will lose strength by about 10%.
5. Great care must be used in designing threaded beryllium fasteners for use at cryogenic temperatures. Thread root area tensile stresses in the order of 10,000 psi are sufficient to cause fracture under some conditions.

APPENDIX - DATA REDUCTION

APPENDIX ITEM 1

Problem: Compute the required fracture toughness, G_c , in the beryllium reflector to prevent cracking at the coolant holes.

Assumptions:

1. no plastic flow before fracture

The actual part has a stress condition at the hole which is biaxial tension.

As soon as we go to any depth, a tensile stress occurs in the third axis (see Fig. 1).

In order to use an available equation for " G_c ", we can consider our stress system as being analogous to a flat plate under tension in two directions (the plate is assumed to be in a state of plane strain).

We have the following formula from Winne and Wundt (Ref. 2) (Fig. 5):

$$\sigma^2 = \frac{G_c E}{\pi(1 - \mu^2)R_1} F(\lambda)^2$$

FIGURE 5 - $F(\lambda)$ AS A FUNCTION OF RELATIVE CRACK LENGTH

$$\lambda = \frac{L}{R_1}$$

For our case there is a 125 micro-inch surface finish requirement; therefore, we can take the initial crack length equal to

$$L = .000125 \text{ in.}$$

The hole is .188 diameter,

$$R_1 = .094 \text{ in.}$$

$$\lambda = \frac{.000125}{.094000} = .00133$$

$$F(\lambda) = 2.8 \text{ (from p 12 of Winne and Wundt, Fig. 5)}$$

From the IBM and hand calculations of Sept. 14, 1962,

$$\sigma = \underline{6000 \text{ psi}}$$

$$\begin{aligned} G_{c \text{ min req'd}} &= \frac{\sigma^2 \pi (1 - \mu^2) R_1}{E F(\lambda)^2} \\ &= \frac{6000^2 (\pi) (1 - .09) (.094)}{44 \times 10^6 \times 2.8^2} \\ &= \underline{\underline{.0272 \text{ lbs.-in./in.}^2}} \end{aligned}$$

The average value of G_c for sharp notches is $G_c = 1.0 \text{ in.-lb./in.}^2$ (from Fig. 2). Using this value, we can compute the depth of the crack which would be required to cause fracture:

$$F_\lambda \sim \sqrt{\frac{1}{G}}$$

$$F_{\lambda_{\text{req'd}}} = 2.8 \sqrt{\frac{.027}{1.00}}$$

$$\approx .50$$

$$\lambda = 2.0 \text{ (from p 12 of Winne and Wundt)}$$

$$L_{\text{req'd}} = 2.0 (R_1)$$

$$= 2.0 (.094)$$

$$= \underline{\underline{.188}}$$

APPENDIX ITEM 2

Problem: Compute the "fracture toughness" or "energy release rate," G_c , of the notched beryllium specimens tested.

Assumptions:

1. Nil ductility

Lubahn (Ref. 3) quotes Bueckner on the relationship for G based on numerical analysis of the specimen geometry and measured nominal stress at fracture

$$G = \frac{\pi(1 - \mu^2)D\sigma_m^2}{4E} \left(\frac{D}{d}\right)^4$$

where:

D = diameter of unnotched area

d = diameter of notched area

m = function of d/D (determined numerically)

σ = stress at unnotched section

d/D	m
.1	.21
.2	.30
.3	.37
.4	.42
.5	.46
.6	.47
.7	.46
.8	.435
.9	.39

From test No. 4,

$D = .505$ in. $K_T = 6.0$

$d = .357$ in.

load at failure = 2700 lbs.

$$\begin{aligned}
 \therefore \sigma &= \frac{2700}{\pi/4(.505)^2} \\
 &= \underline{13,500 \text{ psi}} \\
 \frac{d}{D} &= .707 \\
 m &= .458
 \end{aligned}$$

Then

$$\begin{aligned}
 G_c &= \frac{\pi(1 - .3^2)(.505)(13,500)^2(.458)^2}{4 \times 44.0 \times 10^6} \left(\frac{.505}{.357} \right)^4 \\
 &= \frac{\pi(.91)(.505)(182 \times 10^6)(.21)}{44.0 \times 10^6} \\
 &= \underline{\underline{1.25 \text{ in.-lb./in.}^2}}
 \end{aligned}$$

We can compute another value of G_c by using the load-deflection curves of a number of different size specimens

$$G = \frac{\pi^2 d^4 S_n^2}{32} \left(\frac{dK}{dA} \right)$$

where:

S_n = nominal stress at notch area

A = notch area

$K = \Delta \sigma / P$

P = load applied

$\Delta \sigma$ = extra deflection due to notch

$$\alpha = \Delta \sigma + \frac{P \chi_o}{A_o E}$$

where:

A_o = unnotched area

l = gage length

α = total elongation

For run No. 6

$$\alpha = \Delta\sigma + \frac{705(.50)}{.10 \times 44 \times 10^6}$$

$$\alpha = .00022 \text{ in.}$$

$$\Delta\sigma = .00022 - .00008$$

$$= \underline{\underline{.00014 \text{ in.}}}$$

$$K_{\#6} = \frac{.00014}{705}$$

$$= \underline{\underline{.199 \times 10^{-6} \text{ in./lb.}}}$$

A number of specimens broke at the threaded section. Due to eccentricity, there is a moment at the threaded section which causes the thread to fail. This thread failure starts a crack into the root area of the section. It is desired to estimate the length of this initial crack which is sufficient to allow propagation across the section under the nominal tensile stress. The load at failure for two different specimens, one at room temperature and one at 140°R, was about

$$P_{\text{room}} = 4280 \text{ lbs.}$$

$$P_{140^{\circ}\text{R}} = 3560 \text{ lbs.}$$

From Winne and Wundt (Ref. 2), we have the following equation:

$$\sigma^2 = \frac{GE}{\pi(1 - \mu^2)C}$$

The area at the root of the threads is

$$\begin{aligned} A &= \pi/4(.6145)^2 \\ &= \underline{.295 \text{ in.}^2} \end{aligned}$$

$$\begin{aligned} \sigma &= \frac{3560}{.295} \\ &= \underline{12,100 \text{ psi}} \end{aligned}$$

In order to propagate the crack,

$$C_{\text{req'd}} = \frac{GE}{\pi(1 - \mu^2)\sigma^2}$$

Using the average computed value of G from Fig. 2 for $K_T > 6.0$

$$\begin{aligned} C_{\text{req'd}} &= \frac{1.25(44 \times 10^6)}{\pi(1 - .30^2)(12,100)^2} \\ &= \underline{.107 \text{ in.}} \end{aligned}$$

TABLE 1 - DIMENSIONS OF SPECIMENS

Quan.	A	A/A _o	ITEM	D	d	r	L	TYPE	K _T
1	.05		1		.252/.251	4.0	3/4	C	1.0
1	.10	.5	2	.505/.504	.357/.356	.0025/.0035	3/4	A	6.0
1	.10	.25	3	.714/.713	.357/.356	.0025/.0035	3/4	A	6.5
1	.20	.5	4	.714/.713	.505/.504	.0025/.0035	3/4	A* 1"-8	7.0
2	.20	.5	5	.714/.713	.505/.504	.021/.019	3/4	A* 1"-8	3.0
3	.10	.25	6	.714/.713	.357/.356	.021/.019	3/4	A	2.7
1	.10	.25	7	.714/.713	.357/.356	.051/.049	3/4	A	1.87
1	.05	.125	8	.714/.713	.252/.251	.201/.199	3/4	A	1.13
1	.20	.333	9	.874/.875	.505/.504	.0025/.0035	3/4	A* 1"-8	7.6
1	.30	.5	10	.874/.875	.618/.619	.0025/.0035	3/4	A* 1"-8	7.8
	.20	.5	13	.505/.504	.357/.356	.0025/.0035	3/4	A	6.0
	.20	.5	14	.714/.713	.505/.504	.0025/.0035	3/4	A	7.0
	.20	.5	15	.714/.713	.505/.504	.021/.019	3/4	A	3.0
	.10	.5	16	.505/.504	.357/.356	.0025/.0035	3/4	A	6.0
	.20	.5	17	.714/.713	.505/.504	.0025/.0035	3/4	A	7.0
	.10	--	18		.357/.356	4.0		C	1.0

TABLE 2 - TEST RESULTS

Test No.	Notch Areg (in.) ²	Item No.	Failed at	Load (lbs.)	Temp. °F	Thread Rad.(in.)	Thread Root Area Stress(psi)	K in./lb. x 10 ⁶	Fracture Stress	G _c in.-lbs. in. ²	K _T
1	.20	14	threads	3,570	-320	.004	11,500*	.029	17,900*	.78*	7.0
2	.20	15	threads	3,510	-320	.004	11,300*	----	17,600*	.75*	3.0
3	.20	15	threads	4,280	68	.004	13,800*	.014	21,400*	1.12*	3.0
4	.10	16	notch	2,690	-320	.004	8,680	----	26,900	1.25	6.0
5	.20	18	threads	3,200	-320	.004	10,300*	----	16,000*	----	1.0
6	.05	2	notch	705	-320	.004	4,640	.114	14,100	.24	5.1
7	.05	1	-----	2,040	-320	.014	6,590	----	40,800	----	1.0
8	.10	3	notch	2,040	-320	.004	6,590	----	20,400	1.02	6.5
9	.10	7	threads	2,520	-320	.004	8,130*	.052	25,200*	1.56*	1.87
10	.05	8	-----	2,340	-320	.004	7,550	----	46,700	3.98	1.13
11	.20	4	notch	3,900	-320	.014	6,930	.102	19,500	.93	7.0
12	.20	5	notch	5,900	-320	.014	10,500	----	29,500	2.12	3.0
13	.20	5	notch	6,880	-110	.014	12,200	----	34,400	2.88	3.0
14	.10	6	notch	3,470	32	.004	11,200	----	34,700	2.96	2.7
15	.10	6	notch	4,410	212	.004	14,200	----	44,100	4.80	2.7
16	.10	6	notch	3,830	68	.004	12,350	----	28,300	3.62	2.7
17	.10	2	notch	1,500	-320	.014	4,840	----	15,000	.39	6.0
18	.30	10	threads	7,040	-320	.014	12,500*	----	23,400*	1.63*	7.8
19	.20	9	notch	3,270	-320	.004	5,800	----	16,450	.83	7.6

*Specimen broke at threads. Value computed for maximum load obtained.

FIGURE 1 - TRI-AXIAL STRESS CONDITION EXISTING IN BERYLLIUM BLOCK IN NUCLEAR REACTOR COMPONENT AT STEADY STATE OPERATING CONDITIONS (FROM REF. 5)

FIGURE 2 - FRACTURE STRESS AND ENERGY RELEASE RATE AS FUNCTIONS OF ELASTIC STRESS CONCENTRATION FACTOR, K_T , AT -320°F

FIGURE 3 - FRACTURE STRESS AND ENERGY RELEASE RATE AS FUNCTIONS OF TEMPERATURE

FIGURE 4 - FRACTURE STRESS FOR ROUND NOTCHED AND UN-NOTCHED HOT PRESSED BERYLLIUM SPECIMENS AS A FUNCTION OF TEMPERATURE

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