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ABSTRACT

A number of sintered ceramic beryllium oxide balls were heated and then quenched in fast-flowing carbon dioxide gas to determine the thermal stress which would crack similar balls containing a small amount of uranium dioxide fuel in the core of a prospective pebble bed nuclear reactor. The stress to crack the average ball was determined using simplifying assumptions, and as the balls were quenched in groups this stress will be used to calculate the allowable heat output of fuel balls in a pebble bed reactor.

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BERYLLIUM OXIDES; CARBON DIOXIDE; CRACKS; FUEL ELEMENTS; HEAT TRANSFER; HIGH TEMPERATURE; PEBBLE BED REACTORS; POWER DENSITY; QUENCHING; SIMULATION; SOLID FUELS; SPHERICAL CONFIGURATION; THERMAL SHOCK; THERMAL STRESSES; THERMAL TESTING

CONTENTS

1. INTRODUCTION

A high temperature gas cooled pebble bed reactor had been proposed using BeO ball fuel elements. These would consist of a BeO matrix containing a dispersion of thorium and uranium oxide 3 to 4 per cent by weight.

The feasibility of the design depended on the power output which could be extracted from the balls without the thermal stress generated causing them to crack. The importance of thermal stress as a limiting factor in the power output of unclad ceramic fuel elements may be compared to that of the temperature limitations in clad fuel elements.

The most serious consequence of balls cracking was not their breaking apart, which was unlikely, but the setting free of fission products which would contaminate the coolant.

As the properties of ceramic bodies are generally influenced by the shape of the body and the fabrication process, it was desirable to subject the actual fuel balls to thermal stress and from the stress to cause cracking deduce the limiting power density rather than to deduce these data from conventional test specimens.

The small concentration of fuel oxide was not expected significantly to affect thermal stress resistance but nevertheless could be allowed for in applying the results to fuel balls.

The only practical method of generating the high thermal stresses in a ceramic ball out-of-pile was by quenching. Accordingly BeO balls 38 mm diameter, the size proposed for the reactor fuel were preheated to a chosen temperature in the range 630 to 790°C and then quenched in fast-flowing CO_2 gas effectively at 330°C. The test ball was nested among like balls to reproduce pebble bed conditions. This produced a temperature distribution at maximum stress reasonably closely approximating that in a ball fuel element generating nuclear heat uniformly throughout its volume.

Making the simplifying assumption that the heat transfer coefficient was uniform around the test ball, a hypothetical 'symmetrical' cracking stress (see part 4) was derived which could be used directly to calculate the allowable heat output of fuel balls in a pebble bed core. The ratio of the symmetrical ball cracking stress to the bend strength of the material (as measured with cylindrical test specimens 4 mm diameter at the same temperature) was assumed to remain constant regardless of whether the balls were fuelled or unfuelled and irrespective of temperature.

It is noteworthy that the temperatures quoted above compare with 1,000°C as the typical surface temperature for a fuel ball in the prospective nuclear reactor, the coolant gas being in the range 300°C – 900°C.

2. EXPERIMENTAL APPARATUS AND PROCEDURE

The ball arrangement for quenching in the test rig is shown in Figure 1 with the test ball centrally located. Dead weights housed above the ball assembly enabled loads of 0.6 kg and 6.1 kg to be applied to the test ball to simulate conditions at different depths in a pebble bed.

The rig developed at Lucas Heights for quenching the balls is shown diagrammatically in Figure 2.

The CO_2 gas preheater consisted of a bed of 6.4 mm diameter alumina pellets interspersed with electric heating elements. When heated to its maximum temperature this preheater enabled a gas temperature of approximately 330°C to be maintained for the 15 seconds duration of a quench.

The ball assembly was loaded into the rig and heated by electric elements within the walls of the test section to a pre-determined temperature an interval ΔT above the CO_2 temperature. A flap valve below the preheater prevented free convection between the preheater and the test section during the heating up period.

The reservoir was charged with CO_2 at 2 MPa and then with the quench valve closed (see Figure 2) the test section was pressurised to 0.55 MPa. Opening the quench valve allowed CO_2 to pass through the test section at approximately 0.5 kg per second, the flow being regulated by a 25 mm diameter orifice below the test section.

After the quench run the test ball was removed and examined for cracks using fluorescent dye penetrant. For no observable cracking (0) a fresh ball was tested at an incrementally higher ΔT but if the ball had cracked (X) the next ball had a lower ΔT. The aim was to determine the average ΔT_{crit}, that is, the temperature difference just sufficient to crack the average ball, and this up-and-down method used fewer balls than, for example, batch tests at different ΔT levels (Jones 1966).

To change ΔT, adjustments were made to the temperature in the test section rather than the temperature of the CO_2 because the preheater response was slow. The increment by which ΔT was changed after each quench was the estimated standard deviation of the ΔT_{crit} distribution and this was taken to be 20°C. Balls were tested only once because of the possibility that repeated quenching would affect their strength; this precluded the possibility of observing the value of ΔT_{crit} for a given ball by successively quenching and increasing the ΔT interval until the ball cracked.

Test results with each loading are recorded in Tables 1 and 2.

A representative Biot number or non-dimensional surface heat transfer coefficient for the quench was necessary to calculate the thermal stress. It was obtained by quenching a specially prepared ball with a 1 mm diameter sheathed thermocouple at its centre and then deriving the Biot number from the recorded cooling curve. Figure 3 is the quench record used.

3. STATISTICAL ANALYSIS OF QUENCH TESTS

The procedure for calculating the mean (μ) and standard deviation (σ) of the ΔT_{crit} population from the test results is described by Dixon and Mood (1948) and the parameters calculated are in Table 3. The smaller total of balls either cracked (X) or not cracked (0) constitutes the effective sample and in both Tables 1 and 2 it was balls which had cracked.

The effect of ball-on-ball contact loads is seen by comparing the variances from Tables 1 and 2 and applying the Student 't' test. A difference in means as large or larger than that observed would be expected in more than 9 per cent of the means from further quench test runs should they be from a single population (Davies 1954). This difference is not considered significant, therefore contact loading does not affect the thermal stress resistance and the results in Tables 1 and 2 can be combined which is done in Table 3.

4. DERIVATION OF SYMMETRICAL CRACKING STRESS

This stress was calculated on the assumption that cooling was uniform around the quenched ball and hence the temperature and stress distributions were spherically symmetric.

The ball centre temperature history during the quench recorded in Figure 3 was corrected for thermocouple lag assuming a time constant of one second and is plotted in Figure 4. A Biot number (ah/k) was to be estimated for the quench on the assumption that h, k and T_g were constant. Equation 1 from Carslaw and Jaeger (1959) which is based on the usual heat transfer conditions for spherical geometry gives the theoretical temperature distribution in a quenched ball:

$$\tau = \frac{2\beta}{\gamma} \sum_{j=1}^{\infty} e^{-x_j^2 \theta} f(\beta, x_j) \sin(\gamma x_j) \tag{1}$$

where,

$$f(\beta, x_j) = \frac{x_j^2 + (\beta - 1)^2}{x_j^2 (x_j^2 + \beta(\beta - 1))} \sin x_j$$

$$x_j = j^{th} \text{ root of } x \cot x + \beta - 1 = 0 .$$

A preliminary calculation of β from equation 1 using data from Figure 4 showed that it varied but had an approximate value of 0.3 which, from formulae later in this section, gave the maximum stress in the ball as occurring 5 seconds after quenching began when the ball average temperature $\bar{T}$ was 600 °C.

Two further values of β were then calculated which are given in Table 4 and were the upper and lower limits at 5 seconds after the quench commenced. For the maximum Biot number the ball initial properties and the CO_2 temperature after one second were used and for the minimum value the ball properties and CO_2 temperature after 5 seconds were used.

The data was:

$T(0) = 630\,°C$ (from Figure 3)

$a = 19$ mm

$t = 5s$.

Ball centre temperature 5 seconds after quenching began:

$T_c(5) = 623\,°C$ (from Figure 4 corrected for lag).

Ball average temperature at this time approximately:

$\bar{T}(5) = 600\,°C$.

In equation 1:

$\tau = (T_c(5) - T_g)/(T(0) - T_g)$

$\theta = D.t/a^2$.

The following quench parameters were adopted:

$\beta = 0.25$

$T_g = 330\,°C$

and enabled ball centre temperatures to be calculated which are plotted in Figure 4.

There is good agreement between calculated points and the measured cooling curve when corrected for thermocouple lag assuming a time constant of one second.

The hoop stress on a uniformly cooled ball according to Timoshenko and Goodier (1951) is:

$$S = \frac{\alpha E}{1-\nu}(\bar{T} - T_a)$$

$$= \frac{\alpha E}{1-\nu}\Delta T(\bar{\tau} - \tau_1) \quad . \qquad (2)$$

The quantity $(\bar{\tau} - \tau_1)$ of course changes during a quench and for $\beta = 0.25$,

$(\bar{\tau} - \tau_1)_{max} = 0.04262$

at which time $\theta = 0.1325$

$\bar{\tau} = 0.9089$

$\tau_1 = 0.8663$.

Now still assuming that cooling was uniform around the quenched ball the maximum symmetrical stress reached in that quench which was just sufficient to crack the average ball is to be determined:

$\Delta T = 393.4\,°C$, being μ (ΔT_{crit}) in Table 3.

$\bar{T} = \Delta T . \bar{\tau} + T_g = 688\,°C$

$\frac{\alpha E}{1-\nu}(\bar{T}) = 5.07$ MPa K^{-1} , from Figure 5

$S_{crit} = \frac{\alpha E}{1-\nu}(\bar{T}) \cdot \Delta T \cdot (\bar{\tau} - \tau_1)_{max}$, from equation 2

$= 85.0$ MPa .

The ball surface temperature when maximum stress occurred was:

$T_a = \Delta T \cdot \tau_1 + T_g = 671\,°C$.

The average bend strength of beryllium oxide at this temperature, according to Rotsey (1964), is 193 MPa and the average thermal stress S_{crit} to crack a ball was 44 per cent of this, a relationship which will be assumed to hold at all temperatures and for fuelled as well as unfuelled BeO.

Because parameter $\alpha E/1-\nu$ was little changed over the range of T(0) used in the quench tests, the standard deviation of S_{crit} was taken as the same percentage of the mean as found for ΔT_{crit} namely 18.6 per cent with the sample size of 41.

5. CONCLUSION

The average symmetrical thermal hoop stress which is just sufficient to crack a beryllium oxide ball was found to be 44 per cent of the average bend strength of beryllium oxide, and the standard deviation was 18.6 per cent of the average for a sample size of 41.

Ball-to-ball contact loads of 0.6 kg and 6.1 kg, the probable range of loads experienced by a ball in a pebble bed, produced no significant difference in quench stress resistance and would not be expected to affect thermal stress performance in a reactor core.

The heat transfer coefficient of the quench was low giving a Biot number of approximately 0.25 and for this Biot number the theoretical temperature distribution in a quenched ball when maximum stress occurs is almost identical to the theoretical temperature distribution in a ball fuel element with the same heat output, assuming that both balls are uniformly cooled.

The spread of the quench test results and the relatively small number of specimens caused the statistical analysis to rely heavily on the assumption of a Gaussian distribution of the quench temperature intervals necessary to crack a ball.

For this reason the results are preliminary and any actual reactor development programme would require much more extensive test data.

6. NOTATION

a	ball radius (m)
c_p	specific heat of BeO (J kg^{-1} K^{-1})
$D = \frac{k}{\rho c_p}$	thermal diffusivity of BeO (m^2 s^{-1})

E	Young's modulus of BeO (Pa)
h	surface heat transfer coefficient ($W\ m^{-2}\ K^{-1}$)
k	thermal conductivity of BeO ($W\ m^{-1}\ K^{-1}$)
r	radius (m)
S	symmetrical hoop stress on ball (Pa)
t	time (s)
T	temperature (°C)
$\bar{T}$	average temperature of ball (°C)
$T(0)$	initial temperature of ball (°C)
$\Delta T \equiv T(0) - T_g$	quench temperature interval (°C)
α	thermal expansion coefficient of BeO (K^{-1})
$\beta \equiv ah/k$	Biot number
$\gamma \equiv r/a$	non-dimensional radius
$\theta \equiv D.t/a^2$	non-dimensional time
μ	mean value
ν	Poisson's ratio of BeO
ρ	density of BeO ($kg\ m^{-3}$)
σ	standard deviation
$\tau_0 \equiv (T_c - T_g)/\Delta T$	relative centre temperature of ball
$\bar{\tau} \equiv (\bar{T} - T_g)/\Delta T$	relative average temperature of ball
$\tau_1 \equiv (T_a - T_g)/\Delta T$	relative surface temperature of ball

Subscripts

a	ball surface
c	ball centre
f	fuelled BeO
g	quench gas
crit	critical value, sufficient to cause a ball to crack

7. ACKNOWLEDGEMENTS

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TABLE 1

0.6 kg LOAD ON BALL DURING QUENCH

T(0) °C	ΔT °C	Record of Sample of Forty–Three Tests	Number of Balls Cracked X	Number of Balls Not Cracked 0
790	460	X	1	
770	440	X X X X X 0 X X X X	9	1
750	420	0 X X 0 0 X O O X O 0 0 X 0 X 0	6	10
730	400	0 0 X 0 0 0 0 0	1	7
710	380	X 0 0	1	2
690	360	X X 0	2	1
670	340	0 0		2
		TOTALS	20	23

TABLE 2

6.1 kg LOAD ON BALL DURING QUENCH

T(0) °C	ΔT °C	Record of Sample of Forty–Six Tests	Number of Balls Cracked X	Number of Balls Not Cracked 0
770	440	X	1	
750	420	X 0 X X X X	5	1
730	400	X X 0 0 0 0 0 X X X 0	5	6
710	380	0 0 0 0 X 0 X 0	2	6
690	360	X X 0 X 0 X X 0	5	3
670	340	0 0 0 0 X X 0 0	2	6
650	320	0 X 0	1	2
630	300	0		1
		TOTALS	21	25

TABLE 3

ΔT_{crit} FOR DIFFERENT BALL LOADS

Ball Load kg	$\mu(\Delta T_{crit})$ °C	$\sigma(\Delta T_{crit})$ °C	Effective Sample Size
0.6 (Table 1)	375.7	84.7	21
6.1 (Table 2)	412.0	58.9	20
Combined (Tables 1 & 2)	393.4	73.4	41

TABLE 4

BIOT NUMBERS CALCULATED

U* or L	$T_g(t)$ (Figure 3) °C	τ	D(T) (Rotsey 1964) $\mu m^2 s^{-1}$	θ	β(equation 1)
U	347 ($t = 1s$)	0.975	8.45($T = T(0)$)	0.117	0.285
L	300 ($t = 5s$)	0.979	9.04($T = \bar{T}(5)$)	0.125	0.204

*U – Upper bound of Biot number

L – Lower bound of Biot number

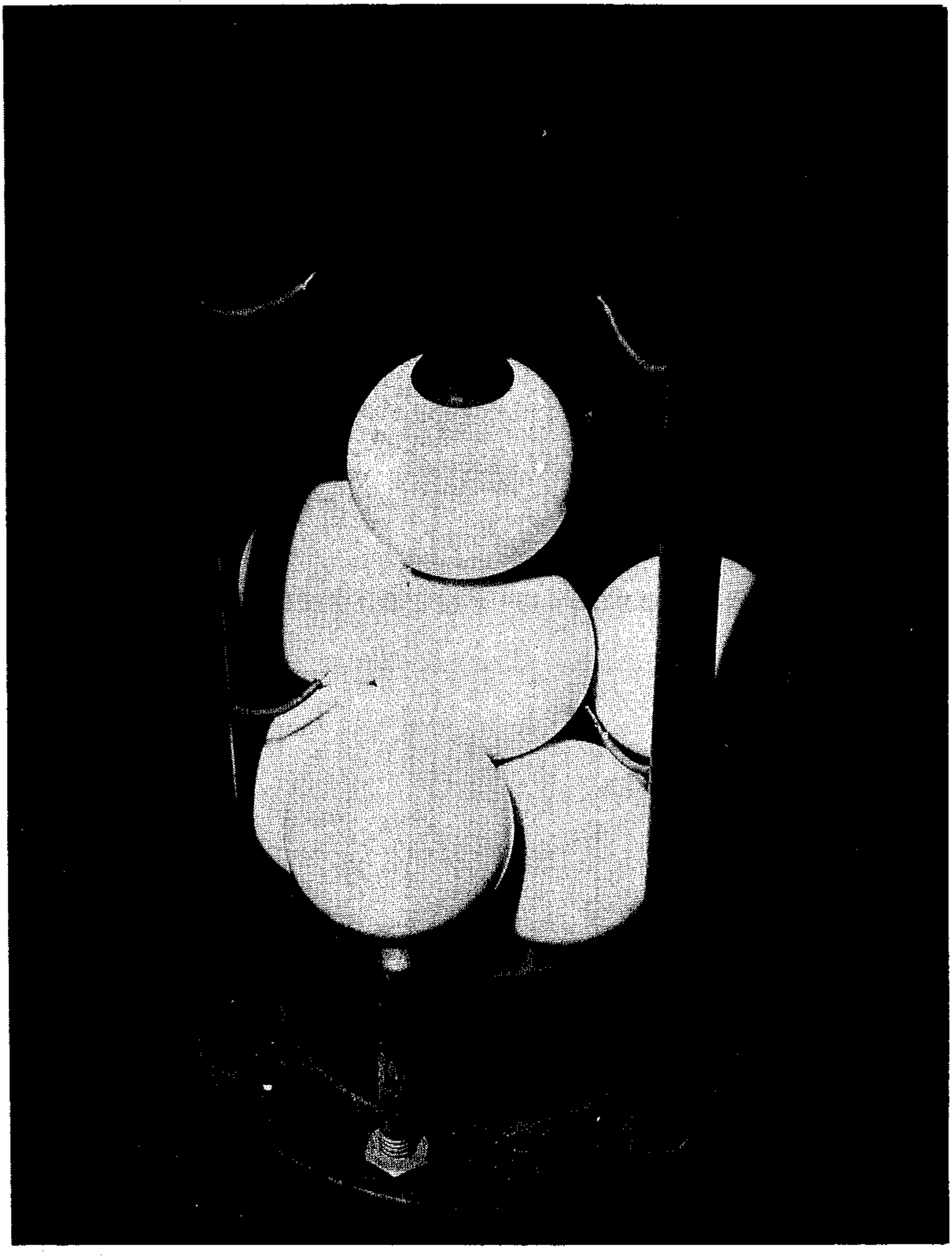

FIGURE 1. QUENCH BALL ARRAY

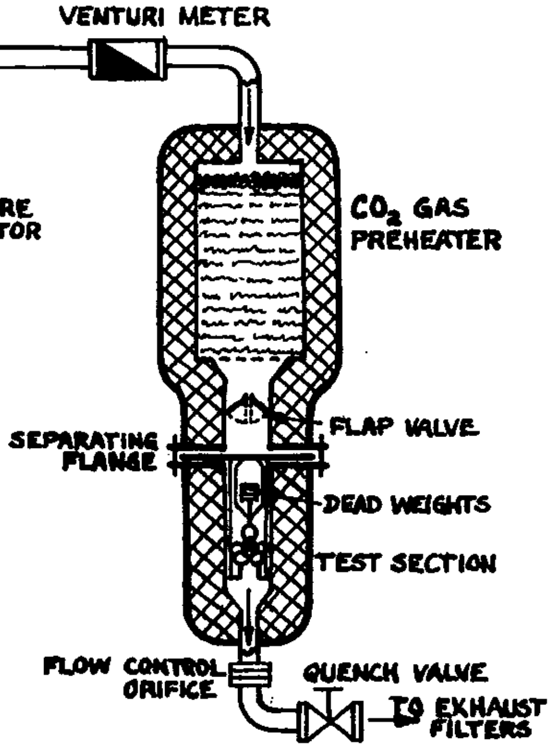

FIGURE 2. LAYOUT OF BALL QUENCHING RIG

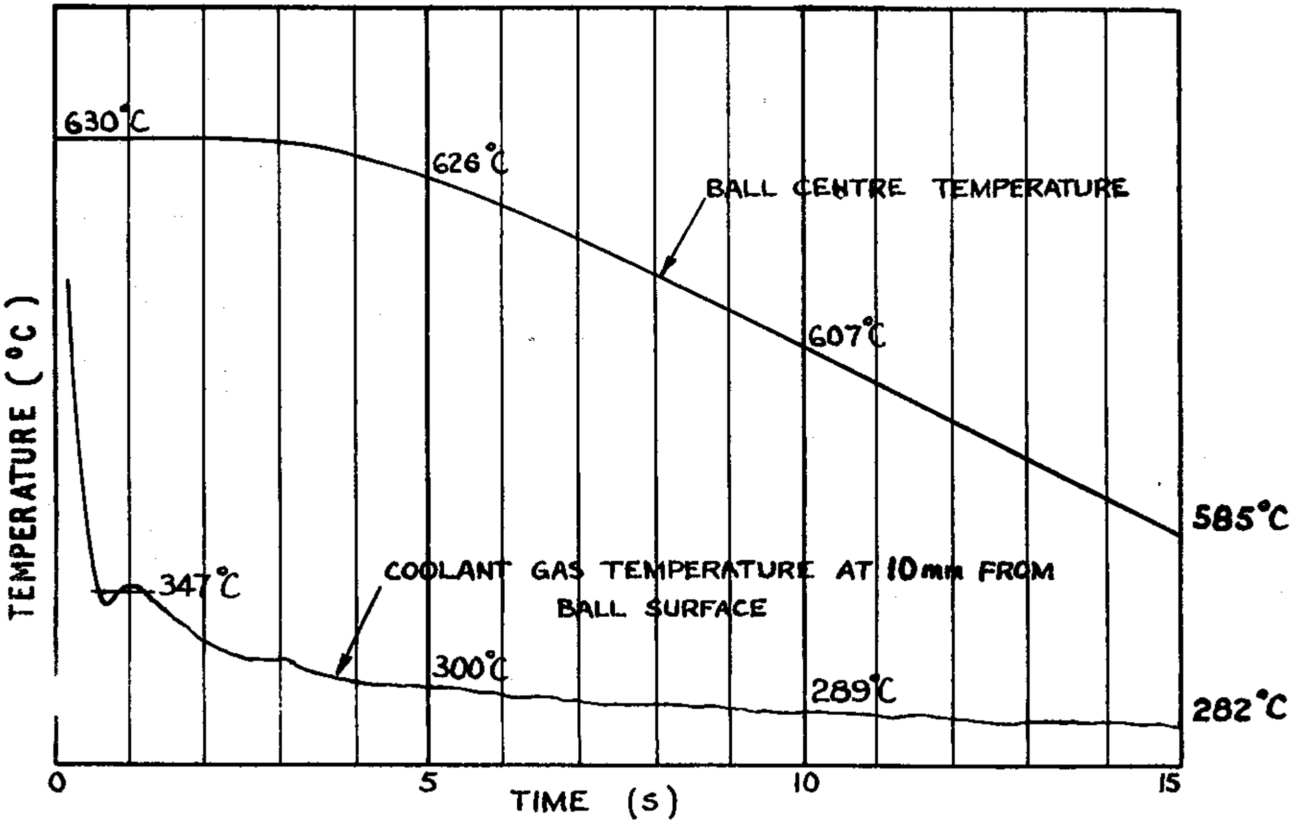

FIGURE 3. QUENCH RECORD

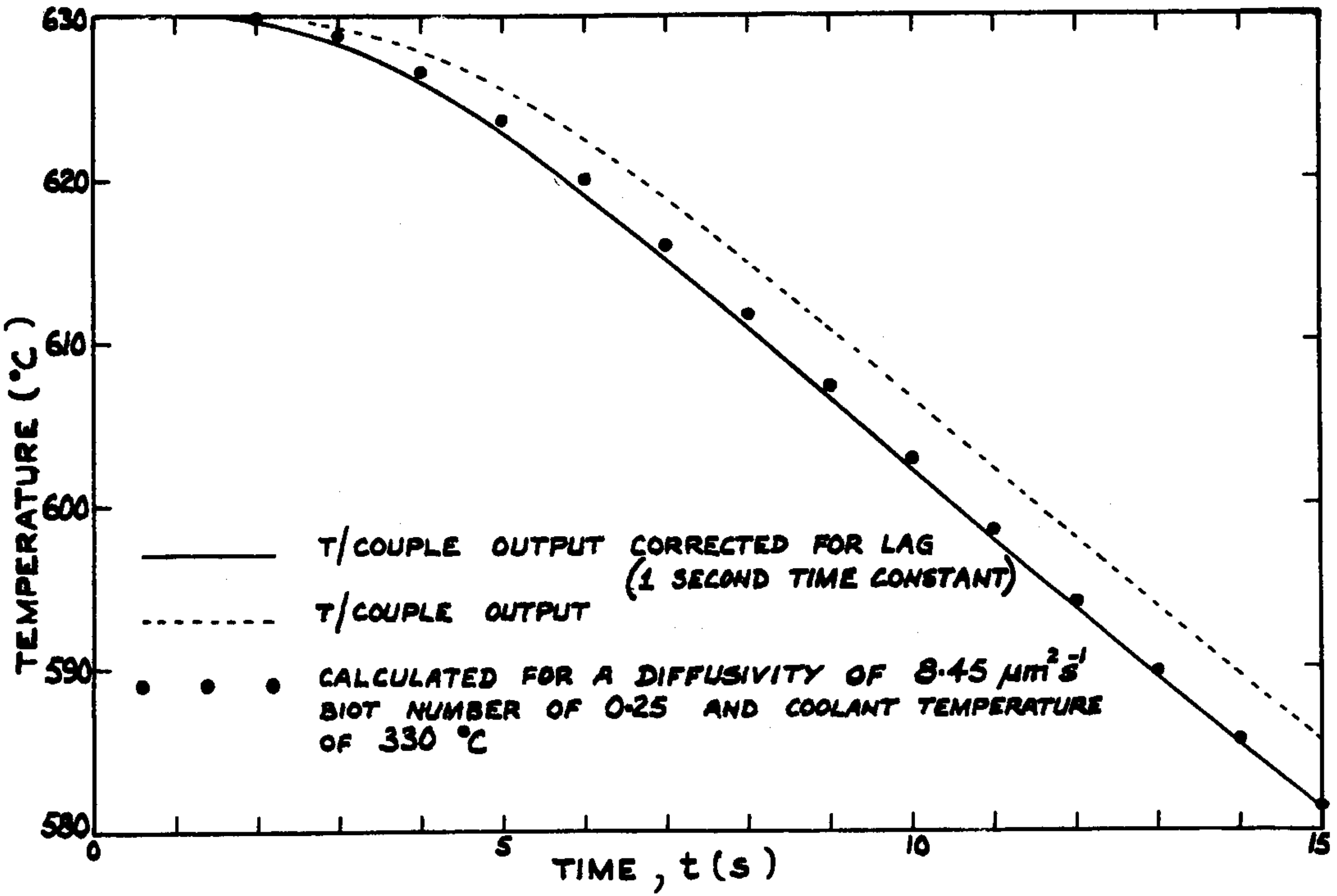

FIGURE 4. BALL CENTRE TEMPERATURE

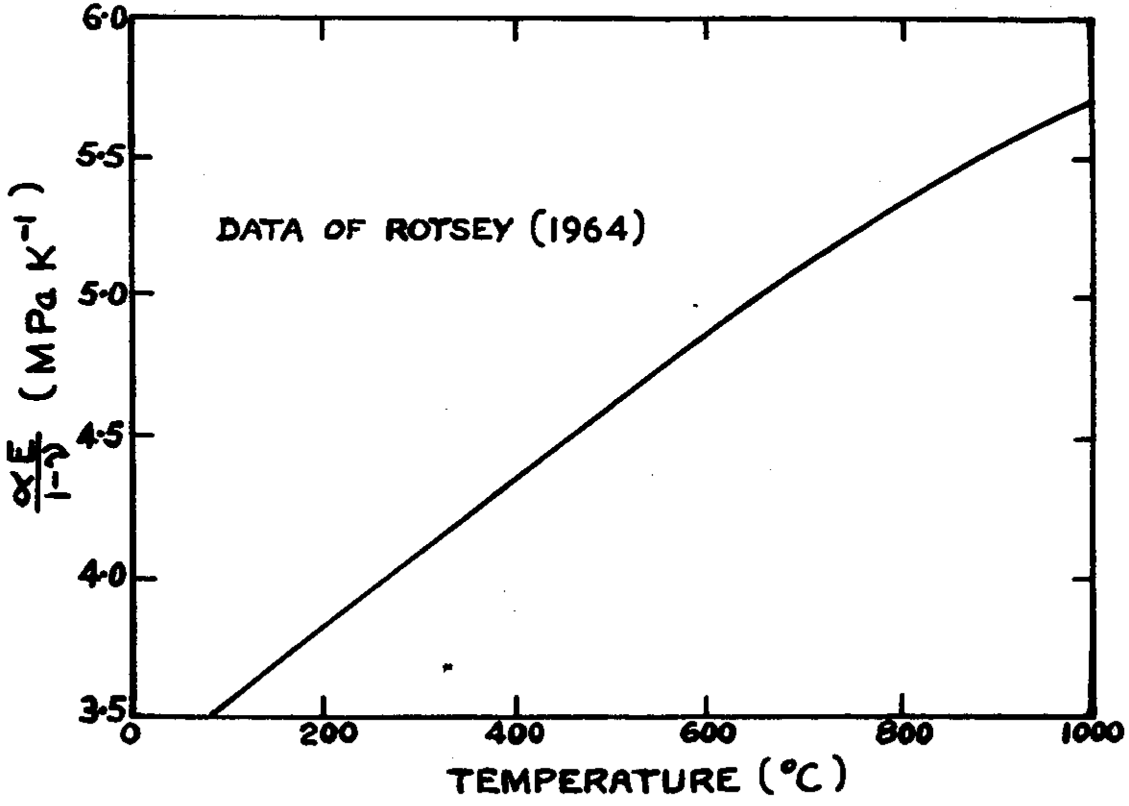

FIGURE 5. $\frac{\alpha E}{1-\nu}$ FOR BeO