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HIGH BURNUP IRRADIATION TESTING OF SPHERICAL BERYLLIUM OXIDE BASED FUEL ELEMENTS FOR A CONCEPTUAL HIGH TEMPERATURE AIR-COOLED REACTOR

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ABSTRACT

Fuelled beryllium oxide spheres, with a thin layer of porous BeO separating the fuelled core from the unfuelled shell, were irradiated at 500°C, 750°C and 1000°C to burnups of 13.4 to 15.6 per cent (U + Th) and fast neutron doses of 1.4×10^{20} to 1.9×10^{20} nvt.

The four spheres irradiated at 1000°C were apparently undamaged but the shell had fractured in all those irradiated at 500°C and 750°C. Failure is believed to have been caused by enhanced expansion of the inner regions of the unfuelled shell arising from exposure to both fast neutrons and energetic beta-particles.

Further work necessary to prove a fuel element design for the proposed application is briefly outlined.

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BERYLLIUM OXIDES; BURNUP; CERAMICS; COMPACTS; CRACKS; FISSION PRODUCTS; FUEL ELEMENTS; FUEL PELLETS; HTGR TYPE REACTORS; IRRADIATION; MATERIAL TESTING; SPHERES

CONTENTS

Page

1. INTRODUCTION 1

2. EXPERIMENTAL PROCEDURES 2

3. RESULTS 3

3.1 Specimen Temperatures 3
3.2 Burnup and Fast Neutron Doses 3
3.3 Macro-examination 3
3.4 Swelling of Unbroken Spheres 3
3.5 X-Ray Line Broadening and Lattice Parameters 3
3.6 Fission Gas Release 3

4. DISCUSSION 4

5. CONCLUSIONS 6

6. ACKNOWLEDGEMENTS 6

7. REFERENCES 7

Table 1 Nominal Composition, Dimensions and Other Details of Fuelled BeO Spheres

Table 2 Irradiation Conditions and Results for Fuelled BeO Spheres

Table 3 Irradiation Induced Swelling in Spheres Irradiated at 1000°C

Table 4 X-Ray Line Broadening and Lattice Expansion of Shell and Buffer Zone from Specimen 8427

Table 5 Calculated Irradiation Induced Expansions in Fuelled BeO Spheres (for 500°C)

Figure 1 Schematic diagram of fuelled BeO fuel element

Figure 2 Microstructure of fuelled BeO sphere

Figure 3 Schematic representation of the irradiation rig X-127

Figure 4 Diagram of the cans used to irradiate spheres in rig X-127-2

Figure 5 Sphere with broken shell showing exposed core and buffer zone (white) (X 4.4)

Figure 6 Fragment of shell from broken sphere showing exposed buffer zone (white) (X 4.4)

Figure 7 Unbroken sphere irradiated at 1000°C (X 4.4) Surface markings are fabrication scratches

Figure 8 Temperature profile through sphere irradiated in Can A at a surface temperature of 500°C

1. INTRODUCTION

This report describes high burnup irradiation tests on a spherical beryllium-oxide based fuel element developed for the conceptual high temperature gas cooled reactor ABORIGINE. The fuel element is shown schematically in Figure 1. It consists of a core of BeO containing up to 5 volume per cent of finely dispersed $^{235}UO_2$–ThO_2 solid solution, a porous BeO buffer zone to absorb the burnup-induced expansion of the core and to protect the shell from β-radiation, a shell of dense BeO to retain gaseous fission products and, if desired, a thin coating of Al_2O_3 to allow the fuel element to operate in a moist air coolant.

The buffer zone fuel element design was the outcome of radiation damage studies which gave a good understanding of the behaviour of BeO in various combinations of fast neutron, hard beta-particle, and fission fragment fluxes (see for example Walker and Hickman 1967; Hickman et al. 1968). Simply, the BeO within a fuel element can be divided into three zones on the basis of the type of irradiation each receives, namely:–

Zone A – material which is subject only to fast neutron bombardment; that is, the outer region of the shell in Figure 1.

Zone B – material which is bombarded by both fast neutrons and beta-particles generated by fission and fission product decay. The total range of beta-particles in BeO is about 1500 μm. In Figure 1, the inner region of the shell and most of the "buffer zone" will, to some degree, be subjected to these conditions. The macroscopic growth rate is higher than in Zone A.

Zone C – material which is bombarded by fast neutrons, beta-particles and fission fragments; that is, the core and the inner 15 μm or so of the buffer zone in Figure 1. The macroscopic growth rate is higher than in Zone B.

Thus the buffer zone serves two purposes; it absorbs the greater expansion of Zone C without transmitting stress to the shell and it prevents significant beta-particle damage in the shell.

The burnup required of the fuel element was specified as 20% of the ^{235}U content or 10% of all heavy metal atoms when the ^{235}U is present as the solid solution $(U_{0.5}\,Th_{0.5})O_2$. The corresponding fast neutron dose to the BeO would be $\sim 2 \times 10^{20}$ nvt. The fuel element was required to withstand these conditions over the temperature range 500 – 1100°C throughout its life with a cracking rate no higher than 1% and preferably closer to 0.1%. The fission gas retention of uncracked spheres should remain high; release to birth ratios (R/B) for noble gases should be less than 10^{-5}.

Previous in-pile tests of this fuel element concept were aimed at proving that the dense BeO shell could retain fission gases to the fast neutron dose required; these were sweep capsule experiments to low burnups at 1000°C (Hanna 1972). It was assumed that, provided a design could be evolved in which the BeO shell showed no sign of cracking at high burnup, the results of the low burnup (but high fast neutron dose) sweep capsule experiments would be applicable to the reference conditions.

In brief, excellent fission gas retention was demonstrated in sweep capsule experiments on a few spheres at 1000°C at fast neutron doses up to three times that required. Also, the spheres tested were of an earlier design without a buffer zone (that is, they were of the "bonded shell" type) and thus would be expected to be more prone to shell cracking. Therefore these tests, although few in number, were more severe in most aspects (other than burnup) than necessary for ABORIGINE conditions. Unfortunately, a planned high burnup sweep capsule experiment on a fuel element with a buffer zone was unsuccessful because of a rig malfunction.

The present experiments were complementary to the sweep capsule experiments summarised above, the aim being to assess the effectiveness of the buffer zone in preventing cracking of the BeO shell at the burnups and fast neutron doses required, over a range of irradiation temperatures. Fission gas releases at the end of each experiment were to be measured by can puncture tests.

No alumina coating was included on any of the sweep capsule or high burnup elements. The Al_2O_3 was not expected to contribute to fission gas retention (because of its relatively low density, ~ 93% theoretical) and was too remote from the fuel to be subjected to other than fast neutron damage. The approach taken was therefore to test alumina coatings on BeO spheres in separate fast neutron irradiation experiments. Some of those results have been reported by Reeve, Ramm and Webb (1971).

2. EXPERIMENTAL PROCEDURES

Twelve identical fuelled spheres for irradiation (plus control specimens) were prepared by a method developed by Reeve and Ramm (1969) and based on isostatic pressing and sintering. Composition, dimensions and other details are given in Table 1. The nominal shell thickness (0.5 cm) was based on P.A.D. and sweep capsule test results (Roman, Randall and Hanna 1969, Hanna 1972). The nominal buffer zone thickness (0.09 cm) was based on an estimate of the total range of β-particles in BeO of 0.15 cm (Walker and Hickman 1967). It was not thought necessary to completely prevent all β-particles from reaching the shell. The buffer zone density was ~ 60% theoretical. An out-of-pile compression test at 600 °C on a cylinder of buffer zone material showed that the material compressed by 12% at a pressure of 6300 psi and 15% at 9000 psi, which was considered satisfactory for the proposed application. Figure 2 shows the microstructure of a control specimen.

The twelve spheres were irradiated in the rig (designated X-127-2) shown schematically in Figure 3; four spheres were contained in each of three cans of the type illustrated in Figure 4. The spheres were held in solid blocks of graphite (Can A) and stainless steel (Cans B and C) in which spherical seats had been machined to suit the dimensions of individual spheres. The blocks were a neat sliding fit inside the inner stainless steel can which was divided into two half-cans each containing two spheres. The inner can was located within a second stainless steel can and the gap between the two was of the required dimension to give the desired heat transfer rates and irradiation temperatures when filled with a helium-nitrogen mixture. All heat was derived from fission and gamma absorption and there was no auxiliary electrical heating. Three thermocouples were supplied to each half-can, two adjacent to the surface of the sphere nearer the end cap and one adjacent to the innermost sphere.

Irradiation was done in the HIFAR reactor over four reactor programmes with nominal temperatures of 500 °C (Can A), 750 °C (Can C), and 1000 °C (Can B). Temperatures were controlled by adjusting the composition of the He/N_2 gas mixture between the inner and outer specimen cans. Cobalt and titanium flux monitors were placed in each half-can for measurement of thermal and fast neutron fluxes respectively.

After irradiation, the six half-cans were punctured for gas sampling and determination of fission product gas release. Specimens were examined visually at up to 13 times magnification and the volumes of unbroken spheres were determined both from the mean of sixteen randomly chosen diameters and from displacement weighings in n-octanol. For the latter technique, specimens were immersed in the n-octanol and the weight recorded periodically over about twenty minutes and extrapolated to zero immersion time to obtain the unimpregnated weight and the displacement volume.

Selected specimens were given a post-activation diffusion test for periods of up to 5.75 hours at 1000 °C to measure the release of ^{85}Kr. In these tests the activities of the ^{85}Kr contained in gas samples were measured by beta counting after quantitatively transferring the gas sample to a specially constructed container incorporating a Geiger-Muller tube with a thin aluminium window.

Samples of the inner and outer sides of the shell of one sphere (No. 8427, Table 2) were extracted for X-ray diffraction measurements of line broadening and lattice parameters. Line broadening was measured on the solid samples using a diffractometer, and lattice parameters were obtained from powder photographs of the crushed samples.

3. RESULTS

3.1 Specimen Temperatures

Throughout the irradiation, specimen temperatures were held to within ± 10 °C of the design temperatures of 500 °C (Can A), 750 °C (Can C), and 1000 °C (Can B) except for the first nine days of the third programme when low reactor power reduced the temperature of Can B to 970 °C.

3.2 Burnup and Fast Neutron Doses

Average burnups achieved in Cans A, B and C were respectively 13.4, 15.6 and 14.3 atom per cent of heavy metal (see Table 2). Fast neutron doses were respectively 1.6 x 10^{20}, 1.9 x 10^{20}, and 1.4 x 10^{20} nvt.

3.3 Macro-examination

All the spheres irradiated at 500 °C and 750 °C exhibited BeO shell failure when recovered from the irradiation cans. As indicated in Table 2, some were recovered whole although large cracks were visible on the surface. The shells of other spheres had broken away from the cores, either wholly or partly, leaving buffer zone material adhering to both core and shell. This material was very soft and could be scratched easily. Examples of spheres from which pieces of shell had separated are shown in Figures 5 and 6. Two fuel cores taken from broken spheres were scrubbed with a stiff nylon bristle brush to remove the buffer zone material. Neither core showed evidence of cracking.

The four spheres irradiated at 1000 °C were recovered whole (Figure 7) and no cracks could be seen under the low power microscope (13 x magnification).

3.4 Swelling of Unbroken Spheres

Volume increases of 0.14 to 0.36 per cent (from dimensions) and 0.17 to 0.21 per cent (from displacement weighings) were measured on the four unbroken spheres. These increases are detailed in Table 3. The displacement volumes are the more consistent set of results and probably are more reliable than the volumes calculated from dimensions; in a hot cell it is difficult to read a micrometer and to obtain a truly random selection of diameters.

3.5 X-Ray Line Broadening and Lattice Parameters

Results of the X-ray line broadening and lattice parameter measurements are given in Table 4. Line broadening was calculated from the integral line breadths of the (203) and (300) reflections for cobalt and copper radiation respectively. In each case the broadening was about twice as great on the outer surface as on the inner surface of the shell.

Expansion of the c-spacing was significantly greater on the inner side of the shell ($\Delta c/c = 0.332\%$) than on the outer side ($\Delta c/c = 0.278\%$). The error in the a-parameter is greater and the a-expansion is only just significantly greater on the inner surface.

Lattice expansions in the buffer zone material were almost identical to those at the outer edge of the shell.

3.6 Fission Gas Release

Successful can puncture tests for fission gas release measurements were obtained on only three half cans as indicated in Table 2. Both samples from Can B (1000 °C) contained predominantly air, indicating that the can had leaked.

The successful samples from Can A and Can C gave gas releases in the range 0.9 to 3.0 per cent.

Of the selected specimens subjected to P.A.D. anneals at 1000 °C for ^{85}Kr release measurements, the two unbroken spheres (8421 and 8426) gave sample activities of 200 and 240 c.p.m. after 125 minutes annealing while the de-clad cores from specimens 8424, 8428 and 8430 gave activities of 36,000 to 66,000 c.p.m. These results are given in Table 2.

4. DISCUSSION

The experiment was successful in attaining the desired levels of burnup, fast neutron dose and temperature.

The can puncture tests indicate fission gas release parameters (release rate to birth rate ratios) of about 10^{-2} for broken spheres. This is comparable with the values measured in sweep capsule experiments on bare fuel particles but about 100 times higher than those measured on coarse dispersion type spheres after they had cracked at low fission burnup (Hanna 1972). This suggests that severe microcracking may have developed in the fuel cores at high burnup and that estimation of the allowable breakage rate in ABORIGINE should be based on a release parameter of about 10^{-2} (Hanna 1972).

The release of ^{85}Kr on post-irradiation annealing was 150 to 275 times higher from broken spheres than from the unbroken ones. If a similar difference existed during irradiation the release parameters for the unbroken spheres must have been in the range 10^{-5} to 10^{-4} (assuming 10^{-2} for broken spheres) which is two to three orders of magnitude higher than for the best spheres tested to low burnup in the sweep capsule experiments. This may mean that these fuel elements either had poorer retention throughout their life or that their gas retention deteriorated at moderate to high burnup. A successful measurement of the total gas release in Can B may have clarified this point.

The reasons for shell failure at 500 °C and 750 °C are not directly apparent from the experimental results. Possible causes which have been considered are thermal stress in the shell, failure of the buffer zone to absorb sufficient of the thermal and burnup induced expansion of the core, fission gas pressure within the porous buffer zone, and differential swelling of the shell arising from the effects of beta-particles, that is, from the presence of a significant volume of Zone B in the shell.

The relative magnitudes of stresses arising from each possible mechanism can be estimated at 500 °C, the only temperature for which there are adequate results on the relative expansion rates of BeO subjected separately to Zone A, B and C conditions. These results were reported by Hickman et al. (1968) from their studies on irradiated fuelled and unfuelled BeO.

The thermal stress in the shell was estimated to a first approximation by assuming it to be a hollow sphere with the inner and outer temperatures indicated by the calculated temperature profile in Figure 8 and a heat generation rate of 4.5 W cm^{-3} from gamma heating. The calculated value of stress was approximately 300 psi. This calculation assumes that the additional thermal expansion of the core (from its higher temperature) is taken up by the buffer zone. This is a reasonable assumption, since burnup-induced expansion is much higher (almost 1% on diameter compared with up to 0.05% on diameter from differential thermal expansion) and must be absorbed by the buffer zone. Thermal stress alone is therefore not a likely cause of cracking.

On the basis of can puncture tests it may be assumed that one per cent of the total fission gas yield migrated to pores in the buffer zone (which was 40 per cent porous) from which it escaped when the shell fractured. The calculated pressure in the pores is less than one atmosphere and would make an insignificant contribution to the hoop stress in the shell.

The stresses developed by radiation-induced volume changes can be calculated from the data of Hickman et al. (1968), adjusted for differences in the irradiation conditions, using the following assumptions –

(i) The swelling at the inner surface of the shell is the sum of the swelling arising from fast neutron and electron damage.

(ii) The incremental swelling from the beta damage is proportional to beta dose and has the same magnitude as that measured for coarse and medium dispersion fuels by Hickman et al. (Figure 5 of their paper).

(iii) The expansion in Zone C is proportional to fission density within the core.

For most of the coarse and medium dispersions investigated by Hickman et al., the range of the beta particles was larger than the distance between fuel particles. Under these conditions, the beta dose to the BeO matrix should be nearly uniform. For an average of six electrons per fission event, with a mean range of 0.15 cm, the beta-particle dose is given by :

$$\Phi = 0.9 \, P \text{ electrons cm}^{-2}$$

where P is the mean fission density. The corresponding doses for the buffer zone fuel element have been calculated by D. G. Walker (private communication) using Monte Carlo methods. From these, the mean value of beta dose in the inner region of the shell is given by:

$$\Phi = 0.12 \, P \text{ electrons cm}^{-2}$$

where P is the fission density in the core.

Values of swelling due to fast neutron damage alone were taken for all cases from data compiled by Hickman and Pryor (1964) and the component due to fission fragments was estimated from the Hickman et al. data. These fission density dependent components were then adjusted to the fission density encountered in this experiment, taking into account the burnup and fuel content (see Table 5). These figures are presented in Table 5 for 500 °C.

The calculated radial expansion in the core was 0.95 per cent whereas the expansion of the inner region of the shell (assuming that it is constrained to the same expansion as the outer part of the shell) is 0.08 per cent. If the difference is accommodated by compression of the buffer zone the reduction in thickness must be 0.0044 cm or about 4.5 per cent. The out-of-pile buffer zone compression test results (see Section 2) refer to 600°C, not 500°C At 600°C, the required compression should occur at about 2000 psi, which would induce in the outer surface a hoop stress of about 2500 psi. This is well below the fracture stress of BeO at 600°C. The situation would be better still at 750°C, but a higher stress would develop at 500°C.

The calculated differential expansion in the shell arising from combined beta and neutron irradiation of the inner shell is 0.08 per cent (Table 5). This is about twice the strain at fracture in BeO at 500°C. It is by far the most important factor of those considered and must be regarded as the most likely cause of shell failure in this experiment. The absence of failure at 1000°C can be attributed to the effects of higher temperature in reducing the damage rate (and swelling rate) due to particle bombardment, and in increasing the stress relaxation rate in the BeO (Walker, Rotsey and Wood 1971).

Some experimental support for the above argument is given by the observed increases in lattice parameters. The greater relative expansion of the "c" parameter at the inner surface of the shell and the small differences in expansion of the "a" parameter are both consistent with the results of Walker and Hickman (1967). Unfortunately the measurements do not allow a quantitative estimation of the macroscopic strain. The line broadening measurements, on the other hand, are in apparent disagreement with Walker and Hickman's results but are less accurate owing to the curvatures of the inner (concave) and outer (convex) surfaces. Another unexplained inconsistency is the lower "c" parameter expansion in the buffer zone compared with the inner surface of the shell.

If it is accepted that the shell failure was the result of combined beta-particle and fast neutron damage to the inner part of the shell, it can be calculated by the above methods that these fuel element spheres should have survived about 7 per cent burnup (14% of ^{235}U) and a corresponding fast neutron dose of 6.5×10^{19} nvt. Alternatively, a buffer zone about 0.18 cm thick should have been sufficient to prevent cracking in our experiments.

It should be noted that although the burnup was 1.3 to 1.5 times that required for ABORIGINE fuel elements the fast neutron dose was 5 to 30% lower. This arises from the difficulty of simulating ABORIGINE conditions in a HIFAR irradiation rig. The largest element which was considered for the ABORIGINE reactor was 3.8 cm in diameter; this would have a fuel content of 1.2 volume per cent $(U,Th)O_2$ and would be irradiated to 10 atom per cent (U + Th) and 2×10^{20} nvt (> 1 MeV). Thus, the shell strain at 500°C would be different from that in the 2 cm spheres considered above and, by the same type of calculation, would be 0.05 per cent (Table 5). This is approximately equal to the BeO fracture strain and indicates that the larger sphere may almost survive the ABORIGINE requirements. A buffer zone only slightly thicker might give adequate irradiation resistance by increasing the attenuation of beta-particles and thereby reducing the differential expansion in the shell.

5. CONCLUSIONS

The experiments described above were intended to prove the validity of the buffer zone concept in the design of a BeO based fuel element for high burnup operation in the temperature range 500 – 1000°C.

In the experiment at 1000°C to 50% higher burnup than required, the four spheres irradiated showed no signs of cracking, suggesting that the fuel element design was satisfactory for this temperature. Unfortunately, fission gas release could not be measured because of an irradiation can leak.

In the experiments at 500°C and 750°C all spheres cracked. Although the buffer zone concept was not proved at these temperatures, an argument is presented which suggests that the shells of these spheres may have cracked approximately half way through their irradiation life, and that a buffer zone approximately twice as thick may have prevented shell cracking altogether.

To prove a fuel element design concept for the proposed irradiation conditions at the lower temperatures would thus require further irradiation testing of fuelled spheres with a range of buffer zone thicknesses.

Finally, some comments should be made on the status of the development of the BeO-based ABORIGINE fuel element. Assuming that the buffer zone concept were to be proved in further irradiation experiments at 500°C and 750°C on spheres with thicker buffer zones, much additional work would be required to completely prove a fuel element design, since the fuel element would still have been made only by laboratory techniques and would have been subjected to only a limited range of tests. Areas requiring most attention would be large scale fabrication methods, including inspection techniques to detect pre-existing cracks in the shell, irradiation dose and temperature limitations of the alumina coating (if a corrosion resistant coating is required), the effects of thermal cycling and mechanical stresses in service, and experiments to allow prediction of the proportion of fuel elements which crack in service and to reduce this cracking rate if necessary. A considerable amount of high burnup testing of the complete fuel element, including sweep capsule tests, would be required, covering the whole range of conditions to be expected in service.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

Hanna, G. L. (1972). – AAEC/E230.

Hickman, B. S. and Pryor, A. W. (1964). – J. Nucl. Mater. 14: 196.

Hickman, B.S., Rotsey, W. B., Hilditch, R.J. and Veevers, K. (1968). – J. Amer. Ceram. Soc. 51: 63.

Reeve, K. D. and Ramm, E.J. (1969). – AAEC/TM521.

Reeve, K. D., Ramm, E. J. and Webb, C.E. (1971). – AAEC/E216.

Roman, D., Randall, C. H. and Hanna, G. L. (1969). – AAEC/E201.

Walker, D. G. and Hickman, B. S. (1967). – J. Nucl. Mater. 24: 60.

Walker, D. G., Rotsey, W. R. and Wood, B. R. A. (1971). – J. Mater. Sci. 6: 281.

TABLE 1

NOMINAL COMPOSITION, DIMENSIONS AND OTHER DETAILS OF FUELLED BeO SPHERES

Sphere diameter	2.16 cm
Core diameter	1.09 cm
Buffer zone thickness	0.09 cm
Shell thickness	0.50 cm
Core composition U:Th:Be	5:5:2000
	$(U,Th)O_2$ = 1.5 vol.% of core
Core density	95% of theoretical
Buffer zone density	60% " "
Shell density	97% " "
Mean BeO grain size in shell	13 μm
Sintering temperature	1370°C
Sintering time	6 hours

TABLE 2

IRRADIATION CONDITIONS AND RESULTS FOR FUELLED BeO SPHERES

Specimen No.	Integrated Neutron Doses		Burnup Atom % (U + Th)	Irrad. Temp. °C	Post Irradiation Condition	Fission Gas Release to Can (%)	^{85}Kr Release in P.A.D. After 125 mins. (c.p.m.)
	Thermal n. cm^{-2}	Fast n. cm^{-2}					
8425	6.0 x 10^{20}	1.6 x 10^{20}	13.4	500	Cracked	2–3	ND
8424	"	"	13.4	500	Shell broken away from core; core sound.		36,000
8422	"	"	13.4	500	Cracked	3.0	ND
8419	"	"	13.4	500	Cracked		ND
8421	7.2 x 10^{20}	1.9 x 10^{20}	15.6	1000	Good	No Sample	220
8420	"	"	15.6	1000	Good		ND
8426	"	"	15.6	1000	Good	No Sample	240
8423	"	"	15.6	1000	Good		ND
8430	6.5 x 10^{20}	1.4 x 10^{20}	14.3	750	Shell broken away from core; core sound.	No Sample	66,000
8429	"	"	14.3	750	Shell broken away from core; core sound.		38,000
8428	"	"	14.3	750	Shell broken away from core; core sound.	0.9	ND
8427	"	"	14.3	750	Shell broken away from core; core sound.		ND

ND – Not Determined

TABLE 3

IRRADIATION INDUCED SWELLING IN SPHERES IRRADIATED AT 1000°C

Sphere No.	Radius		Δr	$\frac{\Delta r}{r_u}$	$\frac{\Delta v}{v_u}$	$\Delta v/v_u$ from Displacement %
	Unirrad. r_u, cm	Irrad. r_i, cm				
8421	1.0824	1.0832	0.0008	0.074	0.22	0.17
8420	1.0809	1.0816	0.0005	0.046	0.14	0.17
8426	1.0808	1.0821	0.0013	0.12	0.36	0.21
8423	1.0786	1.0796	0.0010	0.093	0.28	0.17

TABLE 4

X-RAY LINE BROADENING AND LATTICE EXPANSION OF SHELL AND BUFFER ZONE FROM SPECIMEN 8427

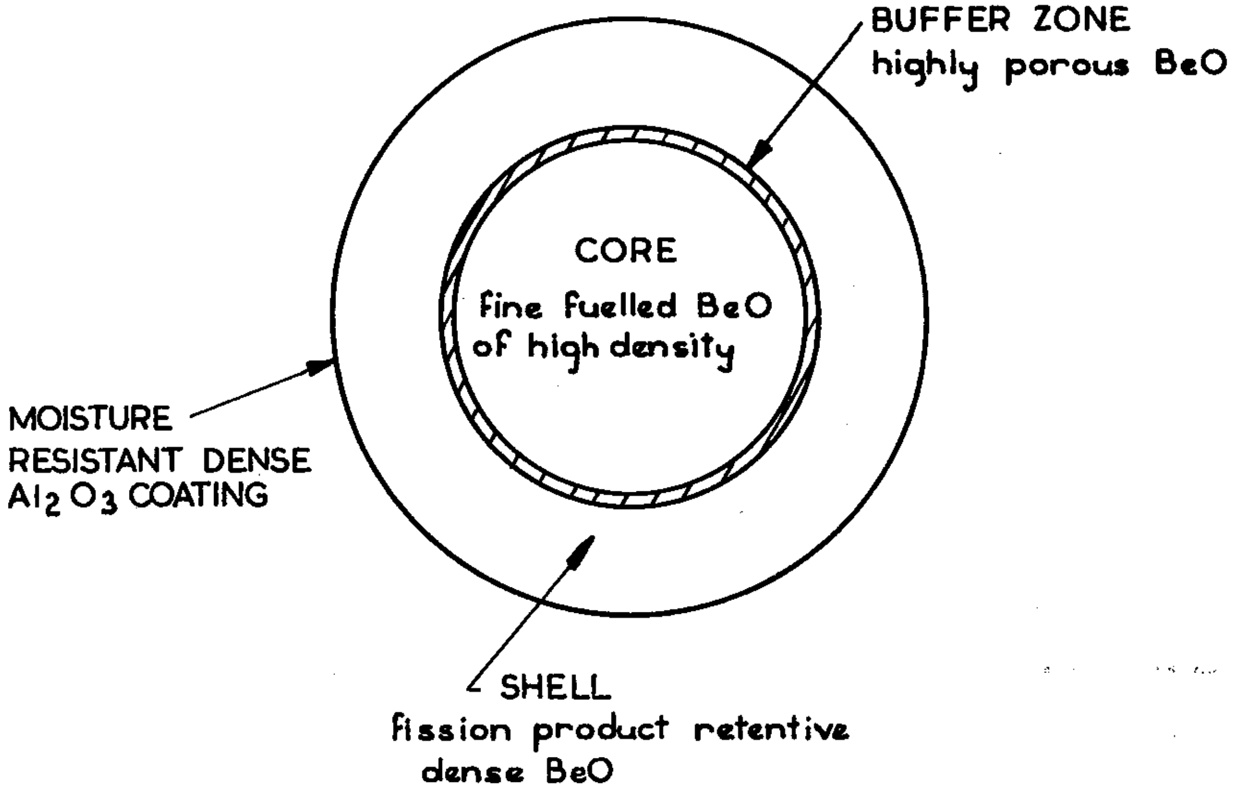
Sample	Line Broadening % Increase in Breadth		Lattice Expansion	
	Co203	Cu300	$\frac{\Delta a}{a}$	$\frac{\Delta c}{c}$
Outer Shell Zone A	173	103	0.007	0.287
Inner Shell Zone B	89	45	0.016	0.332
Buffer Zone	N.D.	N.D.	0.006	0.290

N.D. – Not determined

TABLE 5

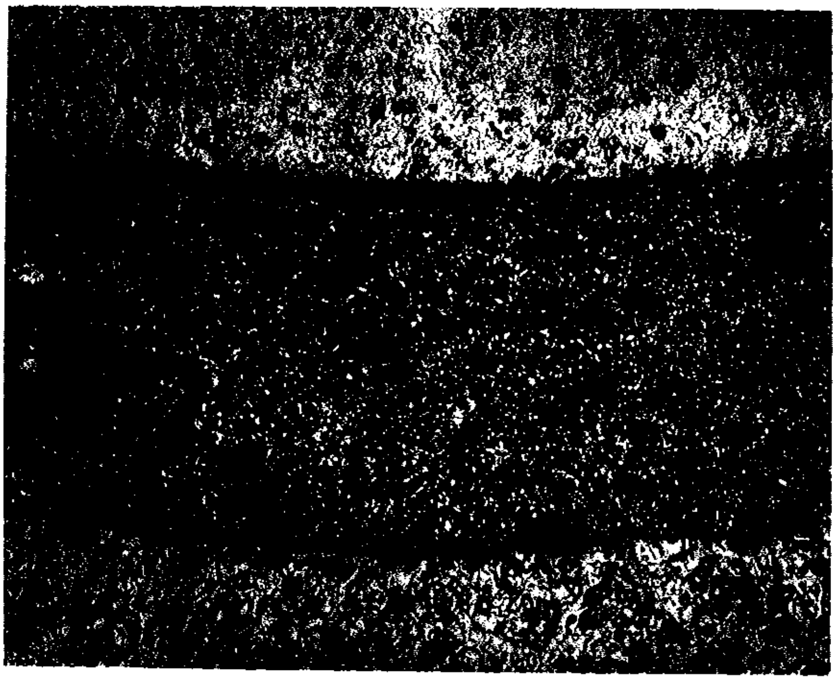
CALCULATED IRRADIATION INDUCED EXPANSIONS IN FUELLED BeO SPHERES (FOR 500°C)

	Reference Data	X–127 (2 cm sphere)	ABORIGINE (3.8 cm sphere)
Volume % $(U,Th)O_2$	1.7	1.5	1.2
Burnup, atom % (U + Th)	5	13.4	10
Fast neutron dose ($n.cm^{-2}$)	4×10^{20}	1.6×10^{20}	2×10^{20}
Irradiation Temperature	500°C	500°C	500°C
Expansions (lin %)			
Zone A	0.2	0.08	0.1
Inner region of shell, n	0.20	0.08	0.10
β	0.07 (Zone B)	0.08	0.05
Total	0.27	0.16	0.15
Zone C	0.4	0.95	0.56



SCALE : 2-4 TIMES FULL SIZE

FIGURE 1. SCHEMATIC DIAGRAM OF THE FUELLED BeO FUEL ELEMENT



(X 50)

FIGURE 2 MICROSTRUCTURE OF FUELLED BeO SPHERE

UPPER STRATUM : FUELLED CORE
CENTRE STRATUM : BUFFER ZONE
LOWER STRATUM : BeO SHELL

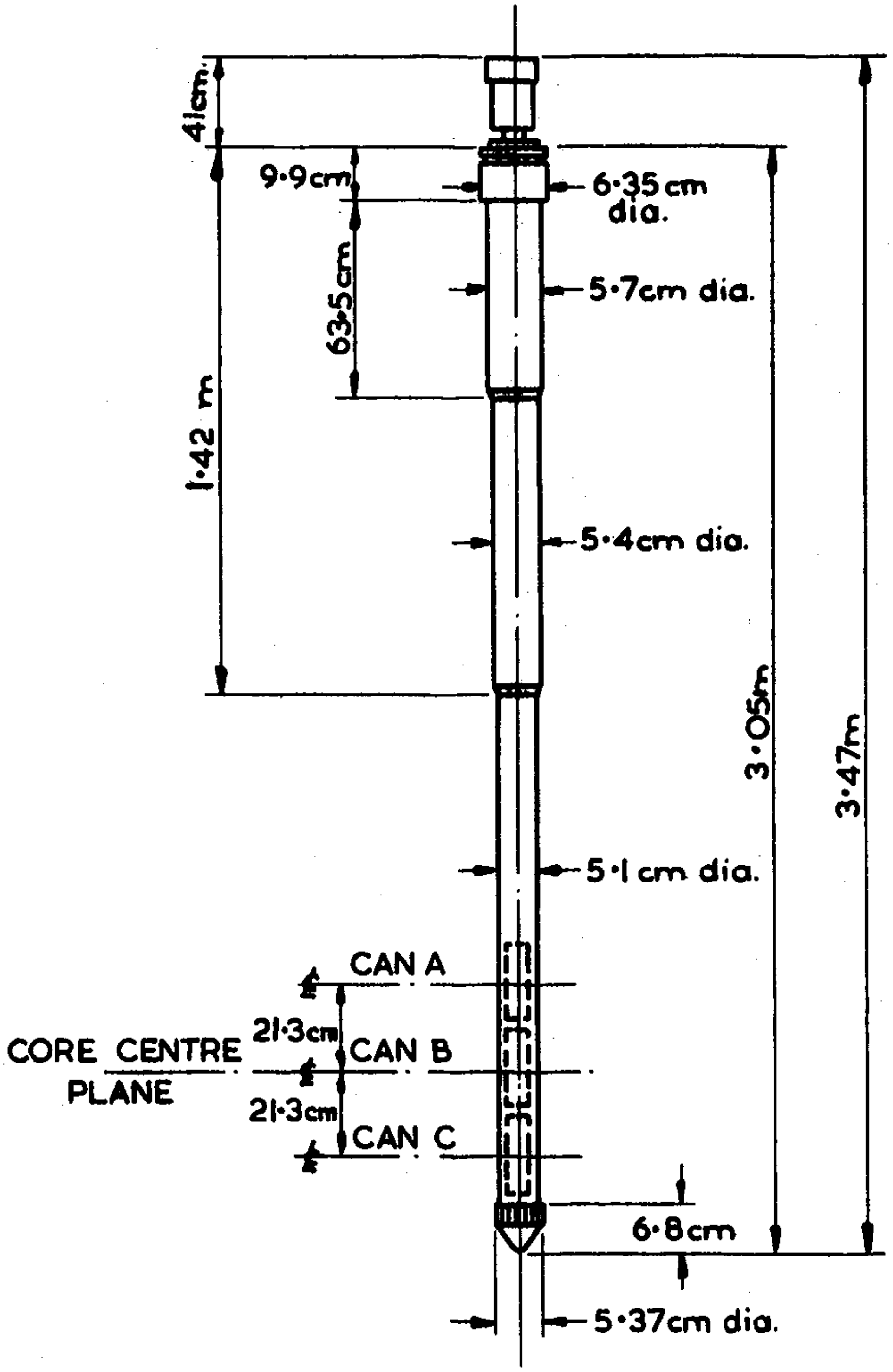


FIGURE 3. SCHEMATIC REPRESENTATION OF THE IRRADIATION RIG X-127

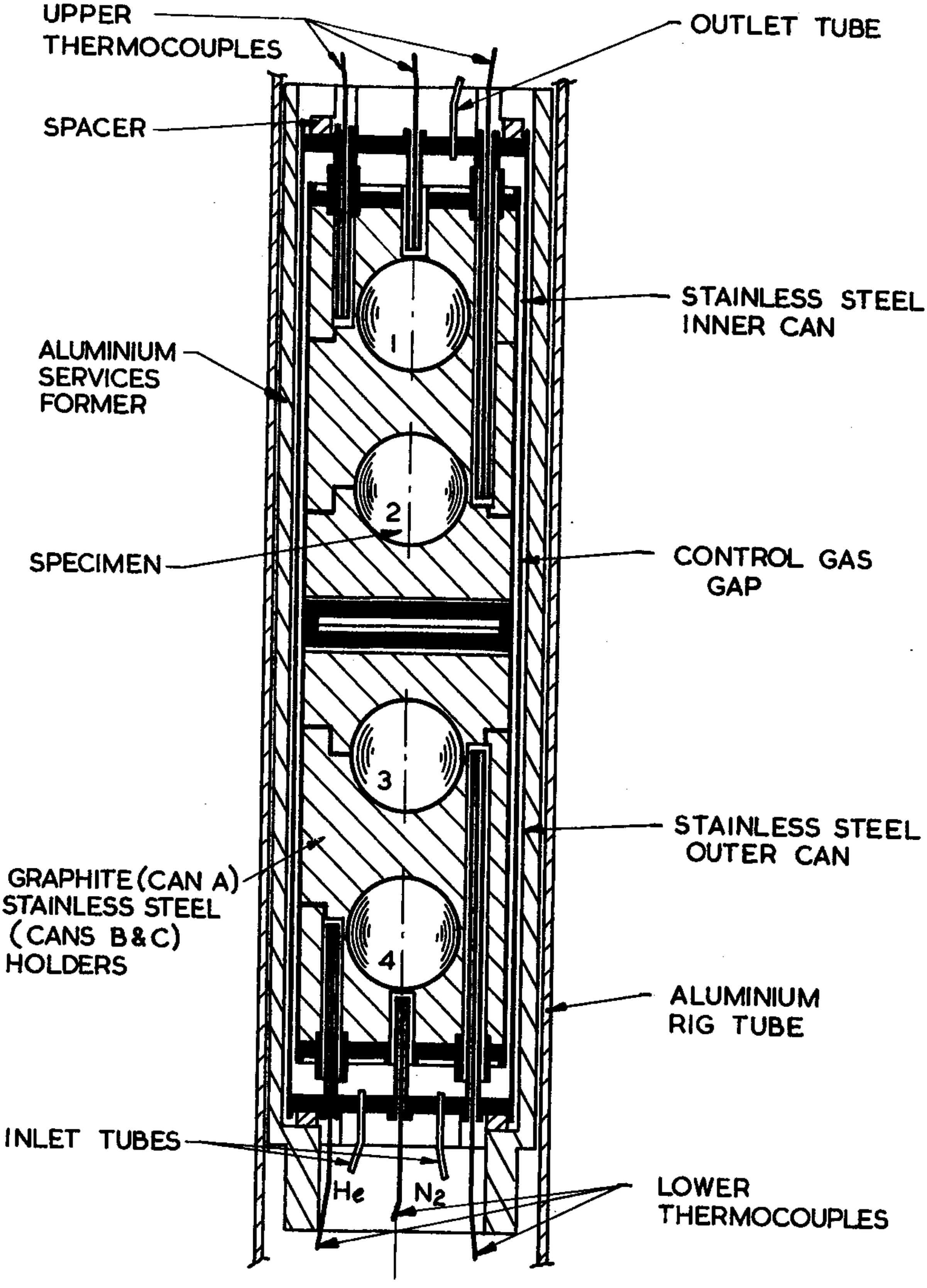


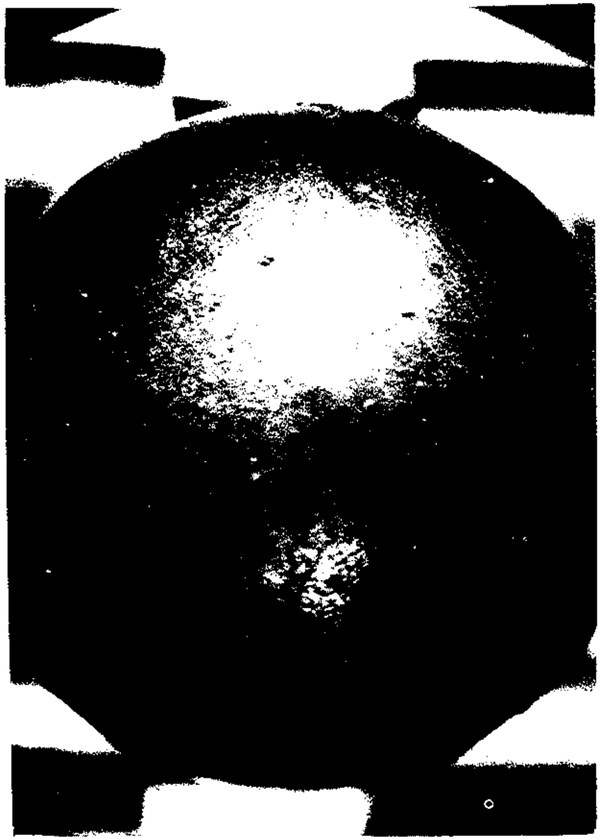
FIGURE 4. DIAGRAM OF THE CANS USED TO IRRADIATE SPHERES IN RIG X-127-2

(X 4.4)

FIGURE 5 SPHERE WITH BROKEN SHELL SHOWING EXPOSED CORE AND BUFFER ZONE (WHITE)

(X 4.4)

FIGURE 6 FRAGMENT OF SHELL FROM BROKEN SPHERE SHOWING EXPOSED BUFFER ZONE (WHITE)



(X 4.4)

FIGURE 7 UNBROKEN SPHERE IRRADIATED AT 1000 °C. SURFACE MARKINGS ARE FABRICATION SCRATCHES

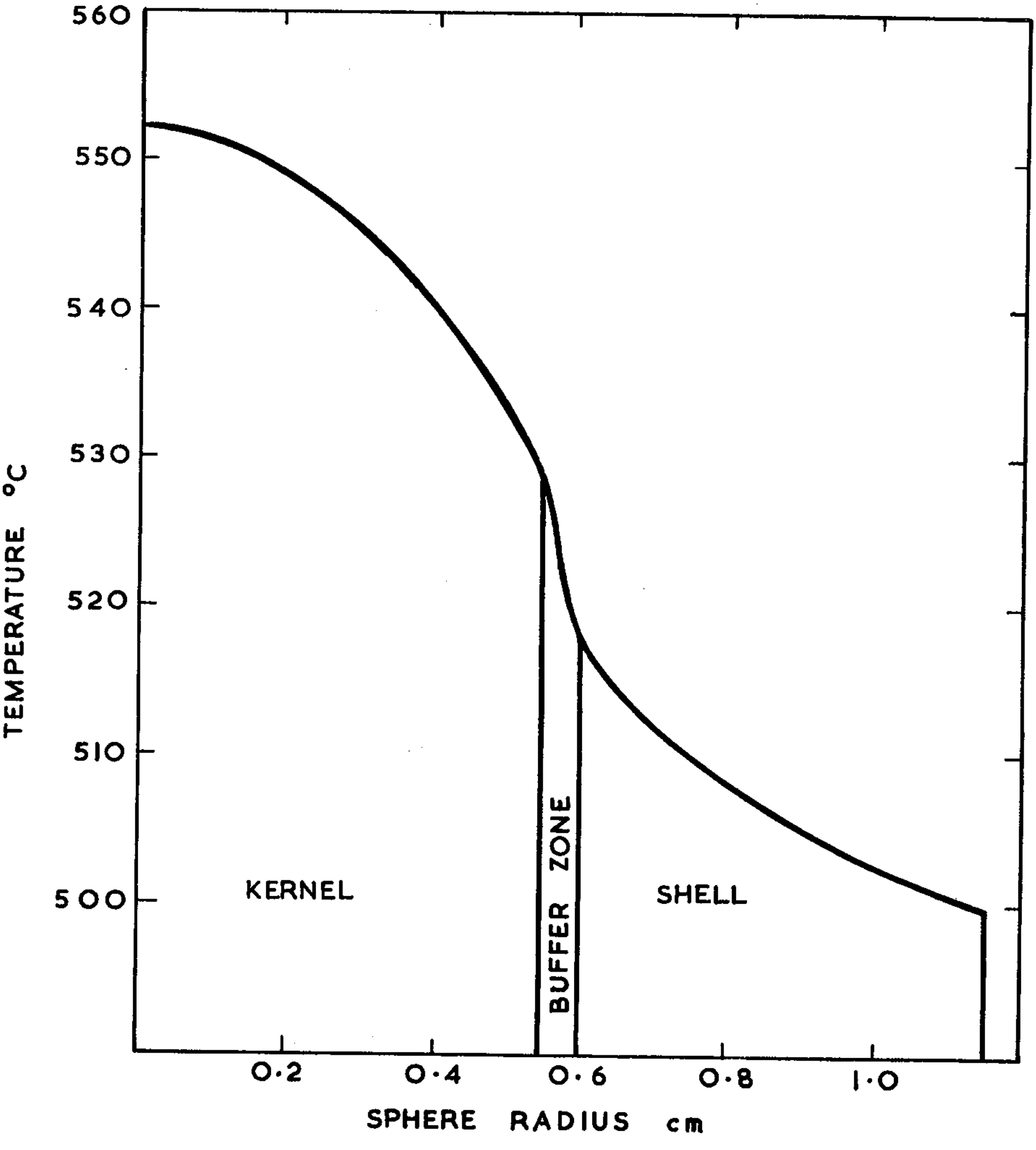


FIGURE 8. TEMPERATURE PROFILE THROUGH SPHERE IRRADIATED IN CAN A AT A SURFACE TEMPERATURE OF 500°C