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**SUMMARY OF BeO DEVELOPMENT WORK FOR THE
EXPERIMENTAL BERYLLIUM OXIDE
REACTOR PROGRAM**

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I. DESCRIPTION OF THE EXPERIMENTAL BERYLLIUM OXIDE REACTOR

The Experimental Beryllium Oxide Reactor (EBOR) has been designed and is being constructed to provide a full-scale working demonstration of the use of beryllium oxide as a reactor moderator material. The flow diagram⁽¹⁾ for the reactor system is presented in Fig. 1. The EBOR is a ten-megawatt (thermal) reactor and is cooled with helium. The helium coolant inlet pressure and temperature are 1150 psia and, nominally, 750°F. The helium is discharged from the reactor core at a nominal mixed mean temperature of approximately 1300°F and a pressure of approximately 1088 psia. All of the heat generated is rejected to the atmosphere through a helium-to-air heat exchanger. Some of the design operating conditions are presented in Table 1.

Table 1

TYPICAL DESIGN OPERATING CONDITIONS FOR THE EXPERIMENTAL BERYLLIUM OXIDE REACTOR

Helium inlet temperature	750°F (nom)
Helium outlet temperature	1300°F (nom)
Thermal power	10 Mw
Surface heat flux	210,000 Btu/(hr)(ft ²)
Maximum cladding temperature	1500°F

The schematic arrangement of the reactor core and pressure vessel is illustrated in Fig. 2. The design of the pressure vessel includes provisions for up-grading the reactor power by increasing the number of core and reflector elements. Adequate space is provided inside the pressure vessel to permit such an increase in the size of the reactor.

A typical core element is illustrated schematically in Fig. 3. The over-all length of the element is approximately 8 ft. The core element is composed of cylindrical BeO blocks approximately 2 in. in diameter and 7-1/2 in. long surrounded by an array of 18 fuel rods which are contained inside a Hastelloy-X shroud tube. The shroud tube defines the coolant flow passage and is the structural member of the core element. BeO blocks, approximately 3-1/2 in. square and 1-1/2 in. high, are fitted over the outside of the shroud tube. The assembly is held together by welds between the Hastelloy shroud tube and the Hastelloy top and bottom

Fig. 1--Flow diagram for the EBOR.

REACTOR ARRANGEMENT

Fig. 2

Fig. 3--Cutaway view of a typical EBOR core element.

end fittings. The Hastelloy-X-clad fuel rods are arranged in a "telephone dial" pattern in the annulus between the inner and outer BeO blocks. The core includes 36 such elements in a square array surrounded by a reflector region containing 52 elements. The reflector elements are similar to the core elements except that the fuel rods and central BeO blocks are replaced with larger-diameter BeO blocks. Appropriate space is provided in the reflector elements for coolant gas passage. The helium coolant flows from the bottom to the top of the reactor core. The reactor is controlled by four cruciform control rods, and the absorber material is dysprosia-alumina ceramic.

II. DESCRIPTION AND PROPERTIES OF BeO BLOCKS

The three basic block configurations that are used in the EBOR are illustrated in Fig. 4. As noted earlier, the square block is approximately 3-1/2 in. on a side and 1-1/2 in. thick, with an axial hole approximately 2-3/4 in. in diameter. The second type of block that is used in the core elements is approximately 2 in. in diameter and 7-1/2 in. long with an axial hole approximately 9/16 in. in diameter. The core-element instrumentation tube is inserted in the axial hole. The third type of block, which is used in the reflector only, is a disk approximately 2-3/4 in. in diameter by 1-1/2 in. thick. The disk also includes an axial hole for containment of the instrumentation for the reflector elements.

The composition of the BeO blocks for the EBOR has been specified as BeO plus 1 wt-% bentonite. The composition specification for the bentonite is given in Table 2. The specified density for the BeO blocks is 93% to 97% of theoretical density.

Table 2

COMPOSITION LIMITS FOR THE BENTONITE ADDITIVE USED IN THE FABRICATION OF EBOR BeO BLOCKS

<u>Constituent</u>	<u>Concentration (wt-%)</u>
SiO ₂	45-55
MgO	20-26
CaO	12-15
Al ₂ O ₃	8-11
Fe ₂ O ₃	0-2
Na ₂ O	0-1.5

Fig. 4 Photograph of BeO blocks of the type used in the Experimental Beryllium Oxide Reactor.

In addition to the composition and density requirements for the BeO blocks, there is also a minimum strength requirement. This strength requirement includes provisions that (1) no specimen tested may exhibit a modulus-of-rupture strength of less than 20,000 psi and (2) the average modulus-of-rupture strength for the test specimens for any block must not be less than 25,000 psi. Blocks that fail to meet either of these requirements are rejected. Modulus-of-rupture specimens are cut from each of the blocks that are fabricated for the reactor, and tests are performed on them. An illustration of the manner in which the modulus-of-rupture test specimens are obtained for the square block is presented in Fig. 5. Note that during manufacture a projection is pressed into the shape at one corner of each block. After the sintering operation is completed this projection is removed by diamond sawing, and test specimens are machined from it. These specimens are subsequently tested by the three-point modulus-of-rupture loading method.

As a part of the EBOR program, various BeO shapes were fabricated at General Atomic and by selected vendors to (1) identify the problems associated with the fabrication of the required shapes, (2) obtain a sufficient number of blocks for the assembly of model core elements, and (3) fabricate pilot-plant quantities of the blocks. Subsequent to the fabrication some of the blocks were machined to obtain test specimens⁽²⁾ as illustrated in Fig. 6. These blocks were produced before the requirement for the 1% bentonite addition had been established, and the test results for the specimens, which are presented in Table 3, are therefore not representative of the properties of the material being used in the construction of the EBOR. However, a number of these blocks were used in thermal-stress tests described below to verify the thermal-stress calculation methods and results. To provide reference data for these tests, modulus-of-rupture tests of the machined specimens were performed at room temperature and at 1400°F. Modulus-of-rupture strengths of approximately 18,000 psi were obtained at both test temperatures.

Additional data have been obtained during the course of the manufacture of the BeO blocks for EBOR.⁽³⁾ Some of these data are discussed below.

In order to qualify a given batch of powder for the production process, modulus-of-rupture bars are pressed and fired in a manner similar to that used in the fabrication of the blocks. The bars are then ground to provide a surface finish similar to that required on the blocks. The finished bars are tested at room temperature under three-point loading. In order to qualify the batch of powder, no modulus-of-rupture specimen may exhibit a strength of less than 27,500 psi. Some of the results obtained in the qualification process are presented in Table 4.

As noted above a special projection is pressed into the blocks and subsequently removed by diamond sawing to obtain modulus-of-rupture

Fig. 5 Sketch of a square BeO block illustrating the method for obtaining modulus-of-rupture specimens from each block.

Fig. 6 BeO blocks with illustration of locations from which test specimens were taken.

Table 3
STRENGTH DATA FOR BeO SPECIMENS MACHINED FROM FABRICATED BeO BLOCKS^a

Moderator Shape	Lot ^b	Avg. Grain Size (μ)	Bend-test Specimens ^c									Cylinders ^d					
			2-in. Span (70°F)			2-in. Span (1400°F)			1-in. Span (70°F)			Diametral Loading			Axial Loading		
			No. Tests	Avg. Strength (psi)	Std. Dev. (psi)	No. Tests	Avg. Strength (psi)	Std. Dev. (psi)	No. Tests	Avg. Strength (psi)	Std. Dev. (psi)	No. Tests	Avg. Strength (psi)	Std. Dev. (psi)	No. Tests	Avg. Strength (psi)	Std. Dev. (psi)
Square-annular block	GA	35	22	18,000	2,800	16	18,900	3,500	5	18,500	2,200	--	-----	-----	--	-----	-----
	B	10	17	18,600	1,900	10	17,700	1,300	5	18,100	1,200	18	11,140	3,200	10	122,000	47,400
Spine tube	C	60	9	12,300	500	--	-----	-----	5	12,000	900	--	-----	-----	--	-----	-----
Sleeve	B	--	--	-----	-----	--	-----	-----	5	14,700	1,900	--	-----	-----	--	-----	-----
	D	45	--	-----	-----	--	-----	-----	6	21,300	2,700	--	-----	-----	--	-----	-----

^aShapes were sintered powder compacts with a density of 94% $\pm$ 2% of theoretical.

^bLot GA was fabricated at General Atomic; lots B, C, and D were fabricated by commercial suppliers.

^cRectangular bars with a span-to-depth ratio of 8, broken by third-point loading.

^dSpecimens 0.240 in. in diameter and 0.4 in. long, broken between tungsten carbide pads.

Table 4
MODULUS-OF-RUPTURE VALUES FOR BeO POWDER LOTS
USED IN EBOR BLOCK FABRICATION

	Modulus-of-rupture Strengths (psi $\times 10^{-3}$)	
	Initial 16 Lots ^a	36 Lots ^b
Average modulus of rupture	28.4	30.5
Range of lot averages	26.1-30.7	26.1-34.8
Range of individual sample values	21.8-33.7	21.8-37.6

NOTE: Sample size, 0.125 by 0.300 by 2 in.; 1-1/2-in. specimen support span.
Modulus-of-rupture specimens were pressed from a 2-lb sample from each lot.

^aRepresenting 5,600 lb of material.

^bRepresenting 12,600 lb of material.

Table 5
COMPARISON OF MODULUS-OF-RUPTURE VALUES FOR "IN-PROCESS" CONTROL
BARS WITH VALUES FOR FABRICATED BeO BLOCKS

Lot No.	Modulus-of-rupture Values (psi $\times 10^{-3}$)		
	In-process Control Bars	Individual Bars from Fired Blocks	Averages for Fired Blocks
1	Average for 8 bars, 30.4	Average for 33 bars, 27.8	Average for 4 blocks, 27.8
	Range, 27.6-33.5	Range, 24.0-35.8	Range, 26.1-30.1
2	Average for 8 bars, 37.4	Average for 30 bars, 36.0	Average for 12 blocks, 36.0
	Range, 30.0-41.3	Range, 22.9-45.7	Range, 25.4-43.0 ^a

NOTE: Size of specimens machined from fired blocks was 0.120 by 0.120 by 1 in. Surface finish was 30-60 RMS.

^aOnly one block exhibited an average of 25,400 psi. The next lowest block average was 30,900 psi.

specimens. These specimens are tested and the results are used as a measure of the strength of the respective BeO blocks. Some of the initial results obtained for blocks from the production process are presented in Table 5. In this case the specification requires that no specimen tested shall exhibit a modulus-of-rupture strength of less than 20,000 psi, and the average modulus-of-rupture strength for all the specimens from any given block shall not be less than 25,000 psi. As indicated in the table, the strength requirements are being routinely achieved.

Measurements of the thermal conductivity of specimens pressed from various BeO powder lots as well as of specimens machined from selected BeO production blocks have also been made at 100°C. The values obtained are presented in Table 6. These values indicate that the addition of 1% bentonite does not have a marked effect on the conductivity of the material at the test temperature. Measurements of the thermal diffusivity of samples machined from selected blocks are being obtained at General Atomic over a range of temperatures.

Table 6

THERMAL CONDUCTIVITY OF EBOR BeO BLOCK MATERIAL^a

Lot Sample ^b		Fabricated Block ^c	
Lot Number	K (cal/cm-sec-°C)	Lot Number	K (cal/cm-sec-°C)
3	0.474	1	0.44
4	0.478	5	0.452
5	0.465	5	0.448
7	0.415	10	0.435
10	0.46	10	0.448
11	0.44		

^aAll measurements were made at a temperature of 100°C. BeO density range was approximately 93% to 95% of theoretical density.

^bMeasured values for 1/2-in. right circular cylinders that were cold-pressed and sintered for each lot of powder to qualify the material.

^cMeasured values for 1/2-in. right circular cylinders that were core-drilled from fabricated blocks. Approximately 2000 lb of fabricated material is represented.

One of the potential sources of failure of the BeO in the EBOR core is fracture due to thermal stresses generated in the BeO blocks as a result of gamma heating in the material. Because of the geometry of the piece,

the calculation of thermal-stress levels in the square block is very difficult. A number of these blocks were therefore tested under simulated reactor conditions and the results were compared with the results of modulus-of-rupture tests of specimens that had been machined from similar blocks.⁽⁴⁾ For the tests, an array of blocks was heated on their outside surfaces by electrical resistance heaters and cooled on their inside surfaces by a high-velocity air stream. The temperature distribution around the periphery of a test block was measured with thermocouples that were inserted through holes in an adjacent block that was used as an end shield. This arrangement is illustrated schematically in Fig. 7. Figure 8 is a photograph of an array of blocks that were subjected to such a test. The results of the thermal-stress tests are summarized in Fig. 9. It should be recalled that the BeO blocks that were fabricated for use in the core element mockups were not produced in accordance with the specifications for the EBOR production blocks. Tests designated C, D, E, F, and G were performed on blocks that had a modulus-of-rupture strength at 1400° F of 17,700 psi, as noted in Table 3. Tests designated H, I, J, and K were performed on blocks fabricated in accordance with the EBOR block specification. As expected from a comparison of the modulus-of-rupture strength for EBOR blocks and the thermal-stress level achieved, no failures were observed with the EBOR-type blocks. The excellent agreement between the calculated thermal stresses achieved and the measured modulus-of-rupture strengths for the materials provides assurance that the calculational methods and results are reliable.

In addition to the high-temperature thermal-stress tests, a number of blocks were subjected to water quench tests. These tests were designed to evaluate the behavior of the BeO blocks under conditions simulating the insertion of a warm core element into a water storage pool following removal of the element from the reactor. The experimental apparatus is illustrated schematically in Fig. 10. The blocks were insulated on their top and bottom surfaces and heated to a selected temperature in an insulated tank. Boiling water was then introduced at a controlled rate into the tank and the level raised until the block was covered. The tank was then drained and cooled and the block assembly was inspected for cracks. The results of the quench tests are illustrated in Fig. 11. In addition to the quench tests on the square blocks, one of the 2-in. -diameter shapes was also tested in a similar manner. The results of this test are illustrated in Figs. 12 and 13. It was observed that crack propagation occurred in some cases without the occurrence of complete fracture of the specimen. As a result of this observation, a series of tests was initiated to determine if a fatigue mechanism is likely to influence the effective strengths of the BeO blocks used in EBOR. The results of this study are being evaluated.

For the BeO blocks that were fabricated for use in the EBOR core element mockups, it was found that the calculated fracture strength of the

Fig. 7 Schematic arrangement of square BeO blocks that were used in steady-state thermal-stress tests.

Fig. 8 Photograph of an array of square BeO blocks that were subjected to steady-state thermal-stress tests.

Fig. 9 Graphical summary of steady-state-thermal-stress test results (MR = modulus of rupture; σ = standard deviation).

Fig. 10 Schematic arrangement of BeO quench-test apparatus.

○ INITIAL CRACKING
 ⊗ ADDITIONAL CRACKING
 ● FRACTURE
 ABSCISSA DENOTES RUN NUMBER
 ORDINATE DENOTES INITIAL SPECIMEN TEMPERATURE (°F)
 $\Delta T = \text{INITIAL TEMPERATURE} - 212^{\circ}\text{F}$

Fig. 11 BeO square-block quench-test results.

Fig. 12 Quench-test results for a two-inch-diameter BeO block.

Fig. 13 Crack pattern developed in a two-inch-diameter BeO block after repeated quench testing.

blocks corresponded closely with the modulus-of-rupture strength for specimens from similar blocks. In addition it was found that in general the fractures that occurred in the square blocks during steady-state thermal-stress testing were located in the thin ligament of the shape, as predicted from the calculations. However, some fractures also occurred at the corners of the square blocks during the quench tests.

III. IRRADIATION TEST RESULTS

As a part of the EBOR program, BeO specimens of selected compositions and densities were irradiated. The initial irradiation test involved pellets that were fabricated by several vendors as well as at General Atomic and had a range of compositions, ⁽⁵⁾ including various additives. The additives were selected in order to include solid-solution formers (such as MgO), compound formers (Al₂O₃), and glass formers (bentonite). Both hot-pressed materials and cold-formed and sintered materials were contained in the irradiation capsule. Some of the results of tests on Capsule MGCR-1 are presented in Table 7 and in Figs. 14 and 15. From the results obtained it was concluded that those specimens containing additives in general exhibited a higher postirradiation strength and thermal conductivity than did specimens containing no additives. In addition, there appears to be an indication that the specimens containing bentonite (a glass former) exhibited somewhat higher strength and slightly higher thermal conductivity after irradiation than did the remaining specimens in the experiment. Diametral expansions of the specimens of less than 1% were generally observed.

A second capsule (MGCR-2) containing 134 BeO specimens has been irradiated and the specimens are being evaluated. The BeO specimen compositions included are listed in Table 8. The arrangement of the specimens in the capsule is illustrated in Fig. 16. The specimens were solid disks 0.5 in. thick and up to 1.68 in. in diameter. Other specimens were rings and smaller cylinders with dimensions chosen to provide a selected thermal stress during irradiation and to facilitate complete utilization of the space in the capsule. Thermal stresses of up to 20,000 psi were calculated for the specimens during the design of the capsule. The maximum exposure achieved in the capsule is estimated to be approximately 1×10^{21} nvt ($E > 1$ Mev) based on the analysis of the dosimeters.

Some of the preliminary observations that have been made may be summarized as follows:

1. Dimensional changes were in the range below 1.4% as determined from micrometer measurements. Length measurements of the specimens revealed that significantly larger dimensional changes occurred near the

Table 7

SUMMARY OF IRRADIATION TEST RESULTS FOR BeO SPECIMENS FROM THE MGCR-1 CAPSULE

Pellet No. ^a	Additive (%)	Preirrad. Density (% T.D.)	Avg. Grain Size (μ)	Irrad. Temp. ($^{\circ}\text{C}$)	Instantaneous Flux ($\text{nv} \times 10^{-14}$)	Integrated Exposure ($\text{nvt} \times 10^{-21}$)	Diameter Change ^b (%)	Density Change (%)	Crushing Strength ($\text{psi} \times 10^{-3}$)
13	None	95.6	20	960	2.1	2.1	0.4	-2.72	34.3
19,20	None	93.0	40	770	1.7	1.7	0.7-0.9	-2.5-2.8	21.3, 22
36, 37, 40	1.0 MgO	96.0	30	930	2.0	2.0	0.5-0.6	-1.77	40.6, 23.0, 32.3
44, 46	1.0 MgO	83.7, 87.7	10	900	2.0	2.0	0.1	-----	Not measured
61, 62	0.5 MgO	94.7	40	950	2.1	2.1	0.4	-1.8, -1.4	18.3, 51.7
67, 68, 70	1.0 MgO	95.0, 95.3	40	930	2.1	2.1	0.1, 0.4, 0.6	-2.1, -2.7, -1.7	35.0, 42.5, 18.9
74, 75	1.5 MgO	94.6	40	970	2.1	2.1	0.4, 0.5	+0.74, -1.37	25.9, 60.2
A-1	1.5 Al_2O_3	97.0	30	900	1.9	1.9	0.3	-1.75	-----
B-1	None	97.0	40 ^c	660	1.4	1.4	0.8	-----	-----
C-1	None	96.0	50 ^c	890	1.9	1.9	0.1	-2.7	-----
E1, E2, E4	0.2 MgO	88.7, 89.0, 88.0	20	960	2.1	2.1	0.9, 0.1, 0.6	-1.47, +1.12, +0.68	4.1, 22.9, 38.8
G1, G2, G3	1.0 bent.	94.6, 94.3, 94.0	25	960	2.0	2.0	0.8, 0.8, 1.0	-0.32	49.8, 78.2, 51.0
H1, H6	2.0 bent.	94.3, 94.0	25	970	2.0	2.0	0.3	-0.64, -0.32	10.4, 88.0
J2, J3, J4	1.0 bent.	92.0, 92.6	10	860	1.9	1.9	0.5	-1.0, +1.8, -2.3	6.2, 159.7, 67.3
K1, K2, K5	2.0 bent.	92.4, 93.0, 92.6	20	810	1.8	1.8	0.3, 0.2	-0.2, 7.1, -1.4	80.7, 81.1

^a All pellets were pressed and sintered except C-1, which was isostatic-pressed and sintered.

^b All values are increases in diameter.

^c Average grain length-to-diameter ratio was approximately five.

Fig. 16 Arrangement of BeO specimens in the MGCR-2 irradiation capsule.

periphery of a specimen or specimen array than were observed near the axis of the specimen (or specimen array). This behavior has been tentatively attributed to a temperature effect.

Table 8
MATERIAL DATA FOR THE BeO SPECIMENS FROM THE
MGCR-2 CAPSULE

Additive		Measured Density (g/cm ³)	Grain Size (mm)
Compound	Wt-%		
Bentonite	1.25	2.88	0.030
MgO	1.0	2.90	0.020
MgO	1.0	2.84	0.045
MgO	1.0	2.66	Not measured
MgO	1.0	2.61	0.018
Al ₂ O ₃ + MgO	0.5 ea	2.86	0.022
Al ₂ O ₃ + MgO	0.5 ea	2.92	0.035
Al ₂ O ₃ + MgO	0.5 ea	2.65	Not measured
Al ₂ O ₃ + MgO	0.5 ea	2.55	0.018

2. Some of the specimens in the highest exposure region of the capsule (also highest gamma-heating region) exhibited radial fractures. However, because of the stress distribution that results from the observed dimensional changes it has not yet been fully determined that the observed fractures were or were not the result of thermal stresses. The results of some initial calculations indicate that the stresses due to the dimensional changes alone would be sufficient to cause fracture (these stresses are of the opposite sign from the stresses due to temperature gradients).

3. All of the specimens that contained 1.25% bentonite additive were found to be in good condition except for the radial fractures described above. No gross fragmentation or powdering of the bentonite-containing specimens was observed.

4. Two of the large-diameter high-density ring specimens that contained 1% MgO and had the large grain size were found to be powdered when the capsule was opened. These specimens were immediately adjacent to specimens containing the bentonite additive in the high-exposure portion of the capsule.

The evaluation of the specimens from the second BeO irradiation experiment is continuing. The observations that have been made to date suggest that an additive that would be expected to form a "glassy" phase

is attractive from the standpoint of achieving satisfactory behavior of the BeO during irradiation.

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