



**AUSTRALIAN ATOMIC ENERGY COMMISSION  
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**THE MECHANICAL PROPERTIES OF  $\text{BeO}-(\text{UTh})\text{O}_2$  DISPERSION FUELS**

by

**K. VEEVERS  
W.B. ROTSEY**



**AUGUST 1966**

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ABSTRACT

Dispersions of (UTh)O<sub>2</sub> in BeO were fabricated using (UTh)O<sub>2</sub> particles made from mixed powders of UO<sub>2</sub> and ThO<sub>2</sub> or by co-precipitation of UO<sub>2</sub> and ThO<sub>2</sub>. The behaviour of the dispersions was studied by measuring the modulus of rupture and Young's modulus. Modulus of rupture measurements were made by four-point bending of cylindrical specimens, and Young's modulus was calculated from the deflection of rectangular beams.

The out-of-pile control specimens for two irradiation experiments, X121 and X105, were also tested. Examination of matching fracture faces showed that cracks passed through (UTh)O<sub>2</sub> particles, indicating that they were bonded to the matrix.

The results were compared with previous results on BeO-ThO<sub>2</sub> dispersions. The strength of dispersions of (UTh)O<sub>2</sub> in BeO decreased with increasing (UTh)O<sub>2</sub> particle size and increasing (UTh)O<sub>2</sub> concentration. For dispersions of 1.7 v/o (UTh)O<sub>2</sub> made from mixed oxides in BeO, the strength increased with

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increasing temperature while for dispersions of (UTh)O<sub>2</sub> made by co-precipitation, the strength remained unchanged with temperature up to 500°C and decreased as the temperature was raised to 1000°C. Young's modulus decreased with increasing (UTh)O<sub>2</sub> concentration. Young's modulus of 1.7 v/o (UTh)O<sub>2</sub> dispersions remained unchanged up to about 600°C, then decreased slightly as the temperature was raised to 1000°C. Increasing the (UTh)O<sub>2</sub> concentration from 1.7 to 20 v/o displaced the curve to lower values. In general, the behaviour of dispersions of (UTh)O<sub>2</sub> in BeO was similar to that of ThO<sub>2</sub> in BeO. The differences in behaviour between dispersions of (UTh)O<sub>2</sub> made from mixed oxides and by co-precipitation, observed in modulus of rupture tests, were attributed to variations in matrix grain size caused by iron contamination of the co-precipitated (UTh)O<sub>2</sub>.

It was concluded that to obtain maximum strength, the particle size of the (UTh)O<sub>2</sub> should not exceed 5 $\mu$ , and the particles should contain no impurity which could cause grain growth in the beryllia matrix.

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## 1. INTRODUCTION

The mechanical properties of dispersions of thoria in beryllia have been investigated by Veevers and Rotsey (1966). This report describes a similar investigation on  $(UTh)O_2$  dispersed in beryllia. Particles of  $(UTh)O_2$  of various sizes were made by two different techniques: mechanical mixing and chemical co-precipitation. The particles were then dispersed in a beryllia matrix in the same way that the thoria particles were. In addition a number of dispersions were made, using the co-precipitation technique, for irradiation experiments.

Mechanical mixing of  $UO_2$  and  $ThO_2$  powders by grinding with beryllia balls, followed by sintering, produced particles which were heavily contaminated with  $BeO$ . With the co-precipitation method, the purity of the product varied from batch to batch, with iron being a major contaminant. Beryllia was again present from grinding operations on the sintered product, but to a lesser extent than in the first method. The overall result was that each batch of fuel particles differed slightly, and the resulting dispersions revealed variations in the mechanical properties. Each batch, therefore, is treated separately in the text.

This report describes the results of modulus of rupture and Young's modulus measurements on these two types of dispersion and the unirradiated control specimens for irradiation experiments designated X121 and X105. The results are compared with, and discussed in terms of, the results on dispersions of thoria in beryllia.

## 2. DISPERSIONS CONTAINING $(UTh)O_2$ MADE FROM MIXED OXIDES

This series of specimens was made by Ceramics Group by a route outlined in Appendix 1. In particular, the solid solution of  $(UTh)O_2$  was made by grinding the urania and thoria together with beryllia balls, then sintering the mixed powder.

### 2.1 Structure

Only one concentration, 1.7 volume per cent. of  $(UTh)O_2$  was used, in which the ratio of U:Th:Be was 1:10:2000. The size of the fuel particles used was  $5\mu$ ,  $33-53\mu$ ,  $152-211\mu$ , or  $422-600\mu$ . The structures were examined metallographically and the salient features were:

- (a) The particles were rounded but irregular in shape. Their porosity was about 5 per cent. and finely dispersed, and they contained about 20  $\%$  beryllia from the mixing operation (Figure 1a).
- (b) The particles were uniformly dispersed in the matrix.
- (c) The matrix grain size remained uniform, for all particle sizes, at about  $5\mu$  (Figure 2a).

## 2.2 Mechanical Properties

### 2.2.1 Modulus of rupture v. fuel particle size

The results are given in Table 1 and shown in Figure 3. The strength of the dispersions decreased with increasing fuel particle size. The results are in excellent agreement with those obtained on BeO-ThO<sub>2</sub> dispersions (Veevers and Rotsey 1966).

### 2.2.2 Modulus of rupture v. temperature

Five batches of 60 specimens containing 200 $\mu$  particles, and one each of specimens containing 50 and 500 $\mu$  particles, were tested in the range 20 to 1000°C. The results are given in Tables 2 and 3 and shown in Figure 4. The results on BeO-ThO<sub>2</sub> are also shown in Figure 4. The strength of the 152-211 $\mu$  dispersion increased linearly from about 20,000 p.s.i. at 20°C to about 25,000 p.s.i. at 1000°C. Up to 400°C, the behaviour was similar to that of the BeO-ThO<sub>2</sub> dispersions. The behaviour of the ~50 and ~500 $\mu$  dispersions was similar to that of the 200 $\mu$  dispersions but the lines were displaced to a higher and a lower level, respectively.

### 2.2.3 Fractography

Examination of adjacent fracture faces showed that the fracture had passed through the fuel particles, indicating that the fuel particles were bonded to the matrix. A typical example is shown in Figure 5.

### 2.2.4 Young's modulus v. temperature

Four specimens containing 1.7 volume per cent., ~200 $\mu$  particles were tested in the range 20 to 1000°C. The results are given in Table 4 and shown in Figure 6. The behaviour was similar to that of BeO-ThO<sub>2</sub>. The results were slightly lower than the BeO-ThO<sub>2</sub> results because the (UTh)O<sub>2</sub> was dispersed in a matrix of lower density and hence lower Young's modulus.

## 3. DISPERSIONS CONTAINING CO-PRECIPIATED (UTh)O<sub>2</sub>

### 3.1 Structure

This series of specimens was made by the Ceramics Group by a route outlined in Appendix 2. In particular, the solid solution of (UTh)O<sub>2</sub> was made by chemical co-precipitation of the oxides. Specimens were made using ~200 $\mu$  particles in concentrations of 1.7, 5, 10, and 20 volume per cent. In addition, specimens were made containing 1.7 volume per cent. of particles with sizes 3-5, 10-15, 15-20, 25-35, 53-63, 104-124, 210-250, 250-300, 300-400, and 450-500 $\mu$  diameter. The following general comments can be made about the structures:

- (a) The particles contained about 10 volume per cent. of BeO from the milling operation (Figure 1b).
- (b) The porosity in the particles was about 5 per cent., and finely dispersed.
- (c) The particles were irregularly shaped with rounded corners.
- (d) The matrix grain size varied both within specimens and between specimens. The particles contained about 1,600 p.p.m. of iron, which caused grain growth in the adjacent matrix during sintering. The finer the particle size of the fuel or the greater the concentration, the worse the grain growth, and, in the extreme, at a particle size of about 5 $\mu$ , the matrix grain size was about 10-35 $\mu$  (Figure 2b).

## 3.2 Mechanical Properties

### 3.2.1 Modulus of rupture v. fuel particle size

The results are given in Table 5 and shown in Figure 3. The strengths of the dispersions decreased with increasing fuel particle size in a similar manner to the strengths of the dispersions containing (UTh)O<sub>2</sub> made from mixed oxides (Section 2.2.1) and of thoria; generally the strengths were slightly higher.

### 3.2.2 Modulus of rupture v. concentration

Dispersion containing ~200 $\mu$  particles in concentrations of 1.7, 5, 10, and 20 volume per cent. were used. The porosity varied from 2.0 per cent. at 1.7 volume per cent. (UTh)O<sub>2</sub> to 9.0 per cent. at 20.0 volume per cent. (UTh)O<sub>2</sub>. The results are given in Table 6 and shown in Figure 7. The modulus of rupture decreased linearly with increasing (UTh)O<sub>2</sub> content. The behaviour was similar to that of the BeO-ThO<sub>2</sub> dispersions, but the modulus of rupture was 2 - 3,000 p.s.i. higher.

### 3.2.3 Modulus of rupture v. temperature

Specimens of different concentrations of ~200 $\mu$  particles were tested in the range 20-1000°C. The results are given in Table 6 and shown in Figure 8. The modulus of rupture of all the dispersions remained constant with temperature up to 500°C, then decreased slightly as the temperature increased to 1000°C.

### 3.2.4 Fractography

Fracture was similar to that in mixed oxides as shown in Figure 5.

### 3.2.5 Young's modulus v. concentration

Specimens containing 0, 5, 10, and 20 volume per cent. of ~200 $\mu$  particles of

(UTh) $O_2$  were used. The porosity varied from 2.0 per cent. at 1.7 volume per cent. (UTh) $O_2$  to 8.5 per cent. at 20.0 volume per cent. (UTh) $O_2$ . The results are given in Table 7 and shown in Figure 9. Young's modulus decreased linearly with increasing (UTh) $O_2$  content. The results showed excellent agreement with those for BeO-Th $O_2$  (Veevers and Rotsey 1965).

### 3.2.6 Young's modulus v. temperature

One specimen of each of the concentrations used in the modulus of rupture tests was tested in the range 20-1000°C. The results are given in Table 7 and shown in Figure 6. The behaviour was similar to that of BeO-Th $O_2$  but the absolute values were different because of varying amounts of porosity in the matrices.

## 4. RIG X 121 (UTh) $O_2$ CO-PRECIPITATED PARTICLES DISPERSED IN BeO

### 4.1 Experiment

Rig X121 is the designation of an experimental irradiation rig in which dispersions of (UTh) $O_2$  in BeO were irradiated to a burnup of 4 to 8 per cent. of heavy metal atoms at temperatures between 300 and 600°C. The results of the tests on irradiated material have been reported by Hilditch et al. (1966). The results reported below refer to the unirradiated control specimens.

### 4.2 Structure

The specimens were fabricated by the route outlined in Appendix 2. Specimens were made at 1.7 volume per cent. using ~200 $\mu$ , ~50 $\mu$ , and <5 $\mu$  diameter particles of (UTh) $O_2$  with U $O_2$ :Th $O_2$  ratio of 1:10. In addition specimens containing ~50 $\mu$  diameter particles of (UTh) $O_2$  with a U:Th ratio of 2:6 were supplied. The structures showed the following general features:

- (a) Some particles contained a small amount of BeO, 2-3 per cent., from the milling operations (Figure 1c).
- (b) The porosity within the particles was about 5 per cent., and finely dispersed.
- (c) The particles were irregularly shaped but with rounded corners.
- (d) The matrix grain size of the ~200 $\mu$  particle dispersion was variable and in the range <3 $\mu$  to 10 $\mu$ . The ~50 $\mu$  dispersion had a matrix grain size of 3-5 $\mu$ , but the <5 $\mu$  dispersion had a coarser matrix grain size of about 8 $\mu$  (Figure 2c).

### 4.3 Mechanical Properties

#### 4.3.1 Modulus of rupture v. temperature (1:10:2000)

Dispersions containing three particle sizes, <5 $\mu$ , ~50 $\mu$ , and ~200 $\mu$ , were tested in the range 20-1000°C. The results of at least 10 tests at each temperature are

given in Table 8 and shown in Figure 10. The ~200 $\mu$  material was of the same order of strength as the previous batches tested at room temperature, but the strength showed no significant change with temperature. The ~50 $\mu$  material was stronger than the ~200 $\mu$  material and results again agreed very well with previous data at room temperature; the strength remained approximately constant with increasing temperature. The <5 micron material was much weaker than both the BeO - Th $O_2$  (Veevers and Rotsey 1966) and the co-precipitated dispersions (Section 3.2.1). Once again, the strength did not vary significantly with temperature.

#### 4.3.2 Modulus of rupture v. temperature (2:6:2000)

The results of tests in the temperature range 20-1000°C, are given in Table 8. The strength was similar to that of the 1:10:2000 material, and did not vary significantly over the temperature range.

#### 4.3.3 Fractography

Fracture was similar to that in mixed oxides as shown in Figure 5.

## 5. RIG X105 (UTh) $O_2$ CC-PRECIPITATED PARTICLES DISPERSED IN BeO

### 5.1 Experiment

Rig X105 is the designation of an experimental irradiation rig in which dispersions of (UTh) $O_2$  in BeO and (UTh) $O_2$  + Th $O_2$  in BeO were irradiated to a burnup of 4 - 10 per cent. of heavy metal atoms at temperatures between 500 and 950°C.

### 5.2 Structure

Two types of material, types A and B, were supplied for these tests. Both materials were 1.7 volume per cent. fuel in the form of ~200 $\mu$  particles dispersed in BeO. Material A was similar to that used in Rig X121 and described in Section 4. In material B, the thoria was divided so that half was combined in the ~200 $\mu$  (UTh) $O_2$  particles, and the remainder existed as ~200 $\mu$  particles of pure Th $O_2$ . In both materials the U:Th ratio was 1:10. The structures had the following features:

- (a) The fuel particles contained about 10 volume per cent. of BeO from the milling operation (Figure 1d).
- (b) The porosity within the particles was about 5 per cent., and finely dispersed.
- (c) The particles were irregularly shaped but with rounded corners.
- (d) In all cases, the matrix grain size was uniform at about 5 $\mu$  diameter (Figure 2d).

### 5.3 Modulus of Rupture v. Temperature

Results on irradiated material were obtained by Hilditch (Unpublished 1965), who also tested the unirradiated specimens at 20°C and 500°C; his results are given in Table 9 and shown in Figure 11. All the specimens of the three separate sintering batches increased in strength in the temperature range 20 to 500°C. In this respect the behaviour was similar to that of the 200 $\mu$  mixed oxides (Section 2.2.2) and BeO-ThO<sub>2</sub> series.

### 5.4 Fractography

Fracture was similar to that in mixed oxides as shown in Figure 5.

## 6. DISCUSSION

### 6.1 Previous Work

The general conclusions from the work on BeO-ThO<sub>2</sub> dispersions by Veevers and Rotsey were:

1. The behaviour of BeO-ThO<sub>2</sub> dispersions indicated that the thoria particles were bonded to the beryllia matrix.
2. The differing coefficients of thermal expansion of beryllia and thoria gave rise to internal stresses at low temperatures.
3. Young's modulus of dispersions decreased as thoria concentration increased; the observed values agreed well with those predicted by Hashin and Shtrikman's (1963) method for coherent inclusions.
4. Additions of thoria to beryllia caused a reduction in modulus of rupture: the greater the concentration of thoria, the weaker the dispersion. At a constant concentration of thoria the strength of the dispersion depended on the thoria particle size: the larger the particle, the weaker the dispersion.
5. The strength of a two-phase ceramic system in which the dispersed phase has a smaller strain to fracture than the matrix, is controlled by the properties of the dispersed phase, unless the particle size of the dispersed phase is limited to that of a Griffith crack in the matrix. For BeO-ThO<sub>2</sub> dispersions, the maximum permissible size of ThO<sub>2</sub> particles is about 5 $\mu$ .

The results and reasoning leading to these conclusions will not be repeated here, but the results obtained in the present work are compared with those for the BeO-ThO<sub>2</sub> dispersions.

### 6.2 Fractography

In all the dispersions in which the fuel particles were large enough to permit examination of matching fracture faces, the crack was found to have passed through the particles. This behaviour was similar to that of BeO-ThO<sub>2</sub> and it was concluded that the fuel particles were bonded to the matrix.

### 6.3 Effect of Fuel Particle Size on Modulus of Rupture

The variation of modulus of rupture with particle size for BeO-(UTh)O<sub>2</sub> (mixed oxides) dispersions shown in Figure 3 was in excellent agreement with the BeO-ThO<sub>2</sub> results. For BeO-(UTh)O<sub>2</sub> (co-precipitated) dispersions, the curve was generally displaced to a higher strength, but the strengths of the dispersions containing 5 $\mu$  and 10 $\mu$  particles were abnormally low. The higher strengths observed in dispersions having particles larger than 10 $\mu$  may be due to the fuel particles themselves being stronger. No data are available on the strengths of the various (UTh)O<sub>2</sub> phases alone. The low strengths of the 5 $\mu$  and 10 $\mu$  dispersions can be attributed to the coarse matrix grain size which resulted from the iron impurity in the fuel particles. In these cases, failure probably initiated in the coarse matrix rather than in the fuel particle.

For the BeO-(UTh)O<sub>2</sub> (co-precipitated) dispersions used for Rig X121, the strengths of the ~50 $\mu$  and ~200 $\mu$  dispersions agreed well with that of BeO-ThO<sub>2</sub>, but the 5 $\mu$  dispersion was relatively weak (Table 8). Again the reason is probably that failure initiated in the coarse grained matrix.

Summarising, dispersions made from pure ThO<sub>2</sub>, "mixed oxide" (UTh)O<sub>2</sub>, and co-precipitated (UTh)O<sub>2</sub> all showed a similar variation of strength with particle size. Anomalies occurred only if the beryllia matrix grain size was accidentally coarsened by impurities. The smaller the fuel particle, the stronger the dispersion, and 5 $\mu$  particles caused a negligible loss of strength.

### 6.4 Effect of Concentration on Modulus of Rupture

The BeO-(UTh)O<sub>2</sub> (co-precipitated) dispersions showed a variation in modulus of rupture with concentration similar to that of BeO-ThO<sub>2</sub> (Figure 7). The strengths of the (UTh)O<sub>2</sub> dispersions were higher than those of the pure ThO<sub>2</sub> dispersions, which was consistent with the observations on the effect of varying particle size.

### 6.5 Effect of Temperature on Modulus of Rupture

The effect of temperature on the dispersions is shown in Figures 4, 8, 10, and 11. BeO-ThO<sub>2</sub> dispersions increased in strength over the temperature range 20-400°C, then decreased slightly over the range 400-1000°C (Veevers and Rotsey 1965). The dispersions made from mixed oxide (UTh)O<sub>2</sub> and those made from co-precipitated



(UTh) $O_2$  used for Rig X105 (Figures 4 and 11) both showed an increase in strength over the range 20-400°C, and, by analogy with the BeO-Th $O_2$  work, it was concluded that internal stresses were present as would be predicted for bonded fuel particles.

The other dispersions made from co-precipitated (UTh) $O_2$  (Figures 8 and 10) did not show an increase in strength as the test temperature increased. In both dispersions the fuel particles were contaminated with iron, and patchy grain growth had taken place in the matrices. It is known that the relationship between strength and temperature for pure BeO depends on grain size (Bentle and Knifel 1965; Rotsey and Veevers 1965), as does the absolute value of strength. Thus, in these specimens, not only did internal stresses arise from the differing coefficients of expansion between the matrix and the fuel, but additional internal stresses resulted from grain size variations in the matrix. A very complicated relation between total internal stress and temperature would therefore exist, precluding a quantitative rationalisation of the data. Nevertheless, the fracture behaviour (Figure 5) indicated that the fuel particles were bonded to the matrix.

The structural differences between the four dispersions made direct comparisons difficult; further work on dispersions having much more closely controlled structures is required, and is in progress. Tentatively, it was concluded that in all the dispersions the fuel particles were bonded to the matrix and all had internal stresses in the fuel particles to a greater or lesser extent.

#### 6.6 Young's Modulus v. Concentration

The comparison between BeO-(UTh) $O_2$  (co-precipitated) dispersions and BeO-Th $O_2$  dispersions is shown in Figure 9. The agreement was excellent; this was interesting because Young's modulus is independent of grain size, so that in this case, unlike the modulus of rupture tests, the major difference between the dispersions, that is matrix grain size, was unimportant. The same conclusions as for BeO-Th $O_2$  were therefore valid, that is the fuel particles were bonded to the matrix.

#### 6.7 Young's Modulus v. Temperature

The results shown in Figure 6 again agreed well with the BeO-Th $O_2$  data. The decreases of Young's modulus with temperature for both mixed oxides and co-precipitated (UTh) $O_2$  dispersions was less than that observed for equivalent amounts of porosity, and indicated that the fuel particles were bonded.

#### 6.8 Summary

The behaviour of the BeO-(UTh) $O_2$  dispersions was generally similar to that observed for BeO-Th $O_2$  dispersions. Agreement was particularly good for those properties, for example, Young's modulus, where variations in the matrix grain size between specimens is less important. Discrepancies in modulus of rupture tests can all be ascribed to a coarse matrix grain size: where the matrix grain size was maintained at 3-5 $\mu$ , the results showed good agreement over the whole series. Some variation in the absolute strengths of the dispersions can be attributed to variations in the strength of the fuel material itself, about which little is known.

#### 7. CONCLUSIONS

The mechanical properties of BeO-(UTh) $O_2$  dispersions are very similar to those of BeO-Th $O_2$  dispersions, and vary in a similar manner with changes in fuel particle size and concentration. The same conclusions about the dispersions are therefore drawn, and are listed in Section 6.1.

The major variation between the dispersions tested was the matrix grain size. Coarse grain sizes appear to be related to the iron impurity in the fuel particles. The result was that dispersions containing 5 $\mu$  particles which should have been almost as strong as pure beryllia were considerably weaker, since fracture initiated in the matrix rather than the fuel particle. In those dispersions in which the matrix grain size remained at 3-5 $\mu$ , the dispersions having small fuel particles (~5 $\mu$ ) gave high strengths.

#### 8. ACKNOWLEDGEMENTS

The authors express their thanks to members of Ceramics Group who supplied the specimens, to Mr. J.G. McCracken for the metallography, and to Mr. W.J. Wright for helpful discussions throughout the work.

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APPENDIX 1

MANUFACTURE OF DISPERSIONS OF URANIA-THORIA MADE FROM MIXED OXIDES IN BeO

The oxides of urania and thoria are milled for 24 hours with BeO balls. The product is pressed at 20 t.s.i., crushed, and graded (-60 + 85 mesh). The powder is then sintered for 3 hours at 1700°C in flowing hydrogen. The sintered product is regraded (-72 + 100 mesh), dispersed in BeO, and the dispersion sintered for  $1\frac{1}{2}$  hours at 1500°C in flowing nitrogen.

The particles were contaminated with about 20 volume per cent. of BeO during the milling operation.

APPENDIX 2

MANUFACTURE OF DISPERSIONS OF URANIA-THORIA, MADE BY CO-PRECIPITATION, IN BeO

The co-precipitated sludge, containing about 1,600 p.p.m. of iron and trace quantities of nickel, chromium, and fluorine, is dried at about 85°C for 24 hours. The dried powder is crushed to 85 mesh, reduced at 700°C, and ground for 4 hours with BeO balls. The product is pressed at 20 t.s.i., crushed, and graded (-60 + 85 mesh). The powder is then sintered for 2 hours at 1700°C in flowing hydrogen. The sintered product is then regraded (-72 + 100 mesh), dispersed in BeO, and the dispersion sintered for 1½ hours at 1500°C in flowing nitrogen.

The particles were contaminated with about 10 volume per cent. of BeO during the milling operation.

TABLE 1

MODULUS OF RUPTURE VERSUS PARTICLE SIZE FOR DISPERSIONS OF (UTh)O<sub>2</sub> MADE FROM MIXED OXIDES IN BeO

(UTh)O <sub>2</sub> Particle Size (μ)	Porosity (%)	No. Tested	Modulus of Rupture (p.s.i.)	Standard Deviation (p.s.i.)
~5	3.5	8	29,700	3,362
35-53	4.0	8	26,100	3,267
152-211	4.0	9	18,500	1,351
422-600	3.5	8	15,100	1,282

TABLE 2

MODULUS OF RUPTURE VERSUS TEMPERATURE FOR DISPERSIONS OF 1.7  $v/o$ , 152-211 $\mu$   
 PARTICLES OF (UTh) $O_2$  MADE FROM MIXED OXIDES IN BeO

Temperature (°C)	Modulus of Rupture (p.s.i.) for Batch:					Standard Deviation (p.s.i.) for Batch:				
	1	2	3	4	5	1	2	3	4	5
20	19,700(9)	19,600(10)	22,800(11)	24,100(11)	19,500(9)	1,762	1,500	790	1,605	1,350
200	23,300(10)	21,600(10)	19,400(12)	21,200(11)	18,500(9)	2,009	2,540	1,190	2,810	1,550
400	24,800(10)	22,900(9)	22,000(12)	22,400(11)	20,400(9)	2,812	2,210	1,029	2,890	2,170
600	24,250(10)	23,600(10)	20,900(12)	23,480(11)	22,100(8)	2,969	2,850	2,873	3,740	2,260
800	23,600(9)	27,000(11)	26,400(11)	26,900(11)	25,200(9)	4,217	2,770	1,795	3,810	3,180
1000	26,400(9)	23,450(10)	23,660(10)	27,350(11)	24,300(9)	4,202	2,460	2,460	2,015	2,950

Numbers in brackets denote number of specimens tested.

TABLE 3

MODULUS OF RUPTURE VERSUS TEMPERATURE FOR DISPERSIONS OF  
 1.7  $v/o$ , ~50 $\mu$  AND ~500 $\mu$  PARTICLES OF (UTh) $O_2$  MADE FROM MIXED OXIDES IN BeO

Temperature (°C)	Modulus of Rupture (p.s.i.) for Particle Size:		Standard Deviation (p.s.i.) for Particle Size:	
	35-53 $\mu$	422-600 $\mu$	35-53 $\mu$	422-600 $\mu$
20	26,100(8)	15,100(9)	3,270	1,280
200	25,950(8)	16,700(9)	3,340	2,800
400	26,800(8)	19,400(9)	2,700	4,700
600	27,000(8)	18,900(8)	4,670	2,980
800	27,300(8)	17,000(9)	4,360	2,160
1000	30,700(8)	20,600(9)	1,080	4,330

Numbers in brackets denote number of specimens tested

TABLE 4

YOUNG'S MODULUS VERSUS TEMPERATURE FOR A DISPERSION OF 1.7 V/o 200 $\mu$   
PARTICLES OF (UTh)O<sub>2</sub> MADE FROM MIXED OXIDES IN BeO

Temperature (°C)	Young's Modulus (10 <sup>6</sup> p.s.i.) for Specimens Numbered:			
	1	2	3	4
20	49.2	49.4	48.7	48.6
200	49.2	49.4	48.7	
210				48.6
400	49.2	49.4	48.7	48.6
600	49.2	48.7	48.7	48.6
650	48.7	48.4	48.2	
700	48.3		47.8	
710		48.2		47.5
750	48.0		47.4	
760		47.4		
800	46.0	46.6	46.6	46.9
850	45.4	46.2	46.2	
895		44.7		
900	43.4		45.7	45.6
950	43.3			
1000				43.8

TABLE 5

MODULUS OF RUPTURE VERSUS PARTICLE SIZE FOR DISPERSIONS  
OF (UTh)O<sub>2</sub> MADE BY CO-PRECIPITATION IN BeO

(UTh)O <sub>2</sub> Particle Size ( $\mu$ )	Porosity (%)	No. Tested	Modulus of Rupture (p.s.i.)	Standard Deviation (p.s.i.)
3-5	1.5	9	26,700	2,460
10-15	1.5	8	25,500	2,650
15-20	1.5	14	32,000	3,018
25-35	1.5	9	30,700	3,350
53-63	1.5	9	32,400	2,360
104-124	1.5	9	24,500	3,810
210-250	2.5	9	22,600	2,540
250-300	2.5	9	21,800	3,480
300-400	2.0	8	22,600	2,000
450-500	2.0	16	19,600	2,559

TABLE 6

MODULUS OF RUPTURE VERSUS TEMPERATURE FOR DIFFERENT CONCENTRATIONS OF (UTh)<sub>2</sub>O<sub>7</sub> MADE BY CO-PRECIPIATION IN BeO

(UTh) <sub>2</sub> O <sub>7</sub> Concentration (volume per cent.)	Modulus of Rupture (p.s.i.) at Temperature:				Standard Deviation (p.s.i.) at Temperature:					
	20°C	250°C	500°C	750°C	1000°C	20°C	250°C	500°C	750°C	1000°C
1.7	20,400(10)		22,500(11) (400°C)	20,000(9) (700°C)	19,500(10)	2,103		2,880 (400°C)	3,200 (700°C)	2,210
5.0	19,100(5)	18,700(5)	19,000(5)	18,940(5)	17,500(5)	1,174	1,740	2,220	2,750	3,220
10.0	15,800(5)	16,200(5)	15,200(5)	15,180(5)	14,430(5)	1,460	2,810	1,760	970	2,860
20.0	11,500(5)	10,100(5)	10,200(5)	8,390(5)	8,214(5)	830	730	1,345	624	1,010

Figures in brackets denote number of specimens tested.

TABLE 7

YOUNG'S MOD'ULUS VERSUS TEMPERATURE FOR VARIOUS CONCENTRATIONS  
OF 200 $\mu$  PARTICLES OF (UTh)<sub>2</sub>O<sub>7</sub> MADE BY CO-PRECIPIATION IN BeO

Concentration (Volume per cent.)	Porosity (per cent.)	Young's Modulus (10 <sup>6</sup> p.s.i.)							
		20°C	200°C	400°C	600°C	700°C	800°C	900°C	1000°C
Nil	2.5	51.2							
	2.5	53.2							
	2.0	53.4							
5.0	4.0	49.5	49.8	49.0	49.0	49.0	47.8	45.9	45.4
	4.0	50.0							
	4.0	49.4							
10.0	4.5	46.6							
	4.5	47.4	48.3	48.7	47.2	46.0	45.2	44.4	42.9
20.0	8.5	39.0							
	8.5	40.7	40.7	40.7	41.0	40.3	38.7	38.1	35.3

TABLE 8

MODULUS OF RUPTURE V. TEMPERATURE AND FUEL PARTICLE SIZE FOR (UTh)<sub>2</sub>O<sub>7</sub>  
MADE BY CO-PRECIPITATION IN BeO

X121 RESULTS

1 : 10 : 2000

Temperature (°C)	Modulus of Rupture (p.s.i.)			Standard Deviation (p.s.i.)		
	<5μ	~50μ	~200μ	<5μ	~50μ	~200μ
20	25,570	25,800	18,440	3,271	3,200	1,510
200	26,000	27,784	20,180	1,040	2,550	1,495
400	22,805	22,455	19,550	2,065	2,388	1,925
600	24,200	24,700	20,880	2,933	2,121	2,342
800	26,100	25,200	20,500	2,929	3,508	1,313
1000	24,600	23,985	18,200	2,580	1,870	1,685

2 : 6 : 2000

Temperature (°C)	Modulus of Rupture (p.s.i.)	Standard Deviation (p.s.i.)
	~50μ	~50μ
20	22,600	3,751
200	24,815	2,430
400	24,265	2,025
600	23,990	1,740
800	23,640	2,233
1000	24,950	1,625

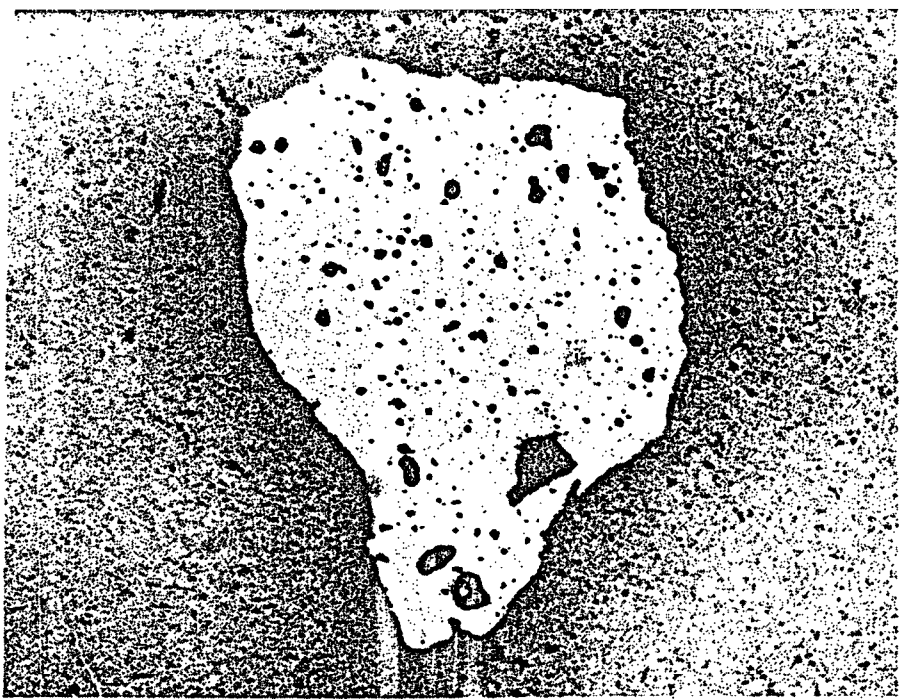
TABLE 9

MODULUS OF RUPTURE OF MATERIALS USED IN RIG X105

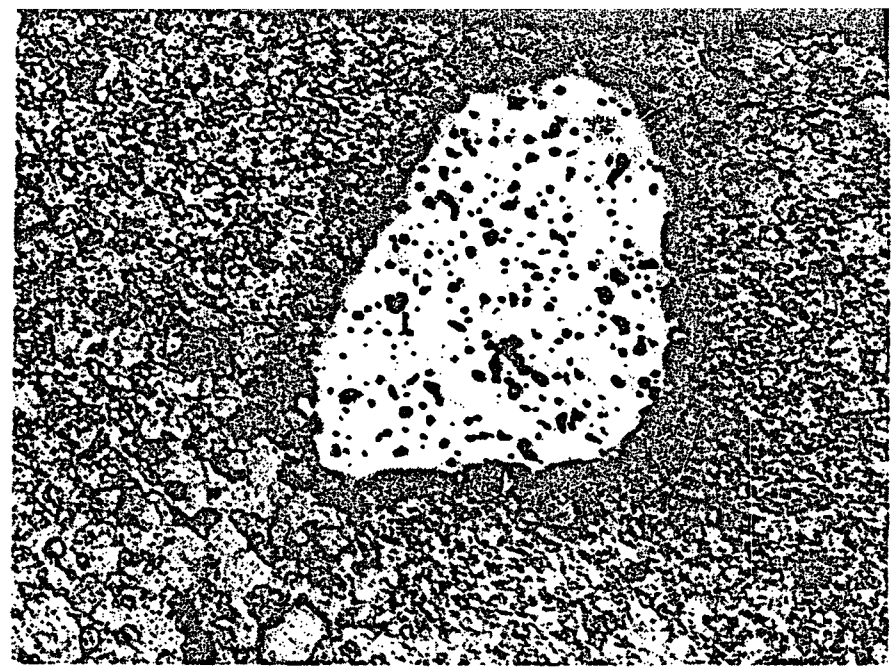
Temperature (°C)	Modulus of Rupture (p.s.i.)					
	Material A			Material B		
	Batch No.			Batch No.		
	45	38	42	50	52	47
20	15,200	16,118	13,740	17,026	17,356	16,632
500	18,490	18,905	19,521	17,470	18,418	19,650

MATERIAL A: 1.7 volume per cent. (UTh)<sub>2</sub>O<sub>7</sub> in BeO; 200μ particles dispersed in BeO.

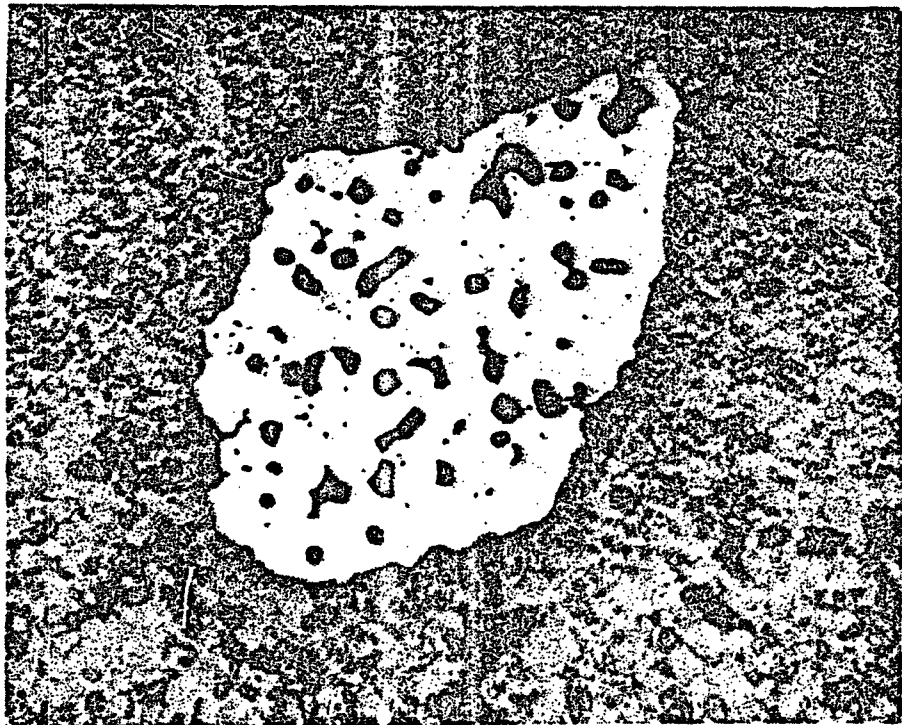
MATERIAL B: 1.7 volume per cent. fuel in BeO. 200μ particles of UO<sub>2</sub> + 50% ThO<sub>2</sub> and 200μ particles of 50% free ThO<sub>2</sub>.



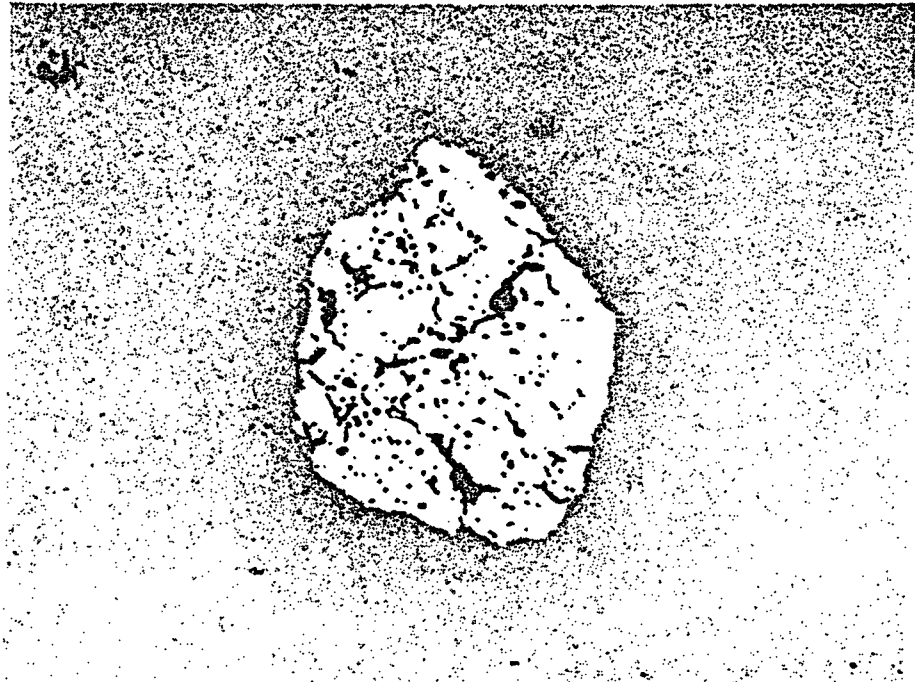
a) (UTh)O<sub>2</sub> PARTICLE MADE FROM MIXED OXIDES ×250



b) (UTh)O<sub>2</sub> PARTICLE MADE BY CO-PRECIPITATION ×250



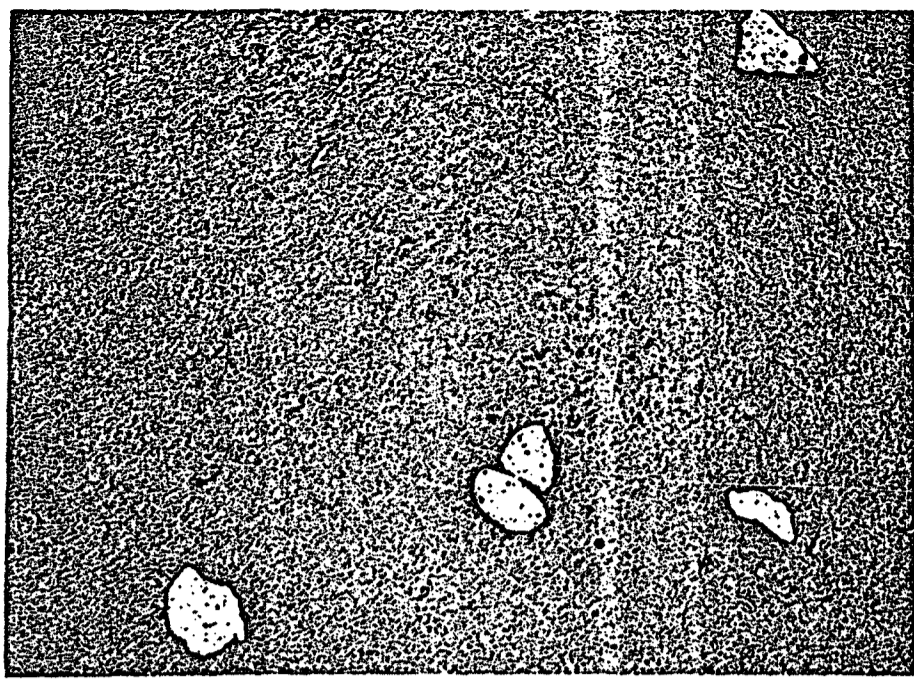
c) (UTh)O<sub>2</sub> PARTICLE MADE BY CO-PRECIPITATION AND USED IN RIG X121 ×250



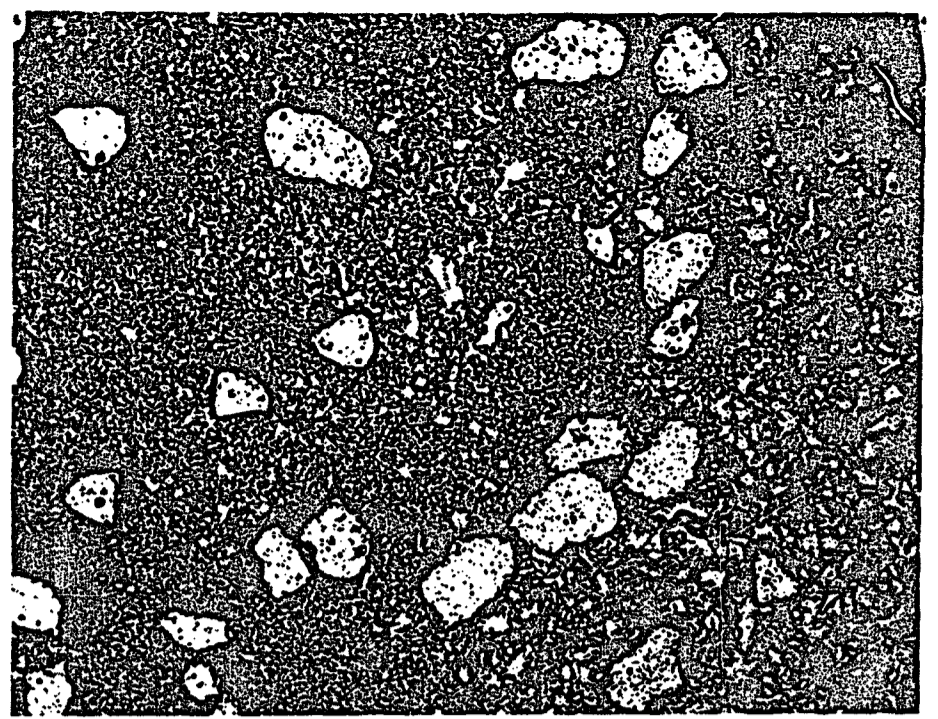
d) (UTh)O<sub>2</sub> PARTICLE MADE BY CO-PRECIPITATION AND USED IN X105 ×250

FIGURE 1. (UTh)O<sub>2</sub> PARTICLES

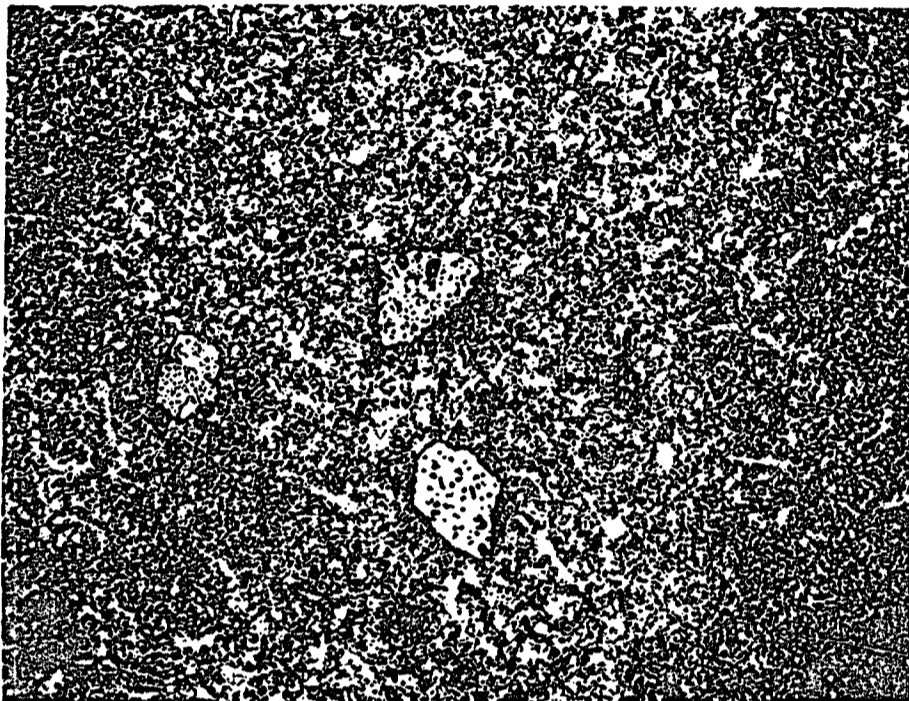




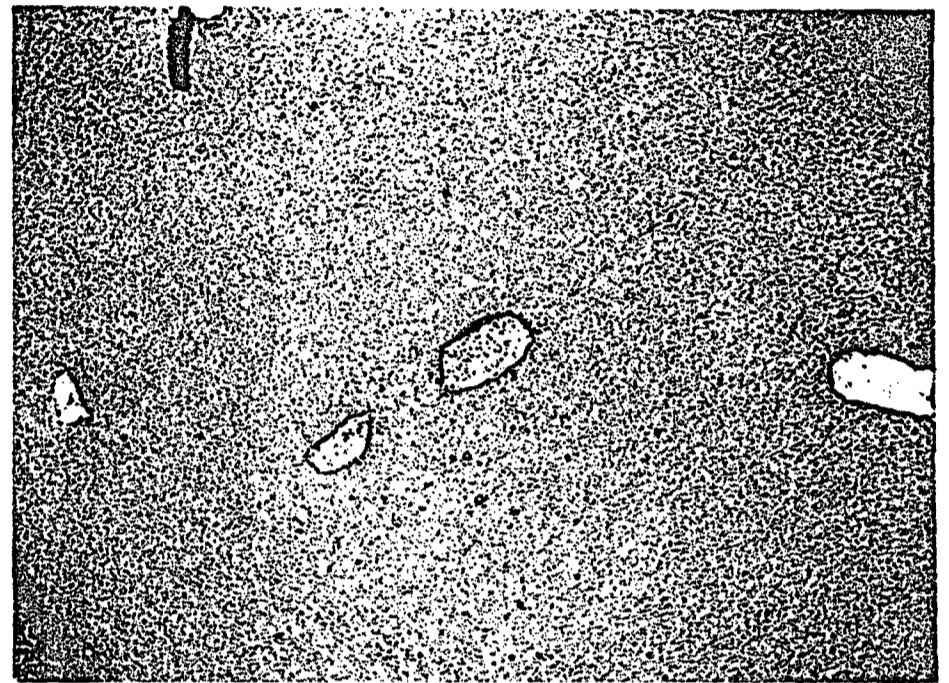
a) DISPERSION OF (UTh)O<sub>2</sub> MADE FROM MIXED OXIDES IN BeO x50



b) DISPERSION OF (UTh)O<sub>2</sub> MADE BY CO-PRECIPITATION IN BeO x50



c) DISPERSION OF (UTh)O<sub>2</sub> MADE BY CO-PRECIPITATION IN BeO AND USED IN RIG X121 x50



d) DISPERSION OF (UTh)O<sub>2</sub> MADE BY CO-PRECIPITATION IN BeO AND USED IN RIG X105 x50

FIGURE 2. MICROSTRUCTURES OF DISPERSIONS OF (UTh)O<sub>2</sub> IN BeO

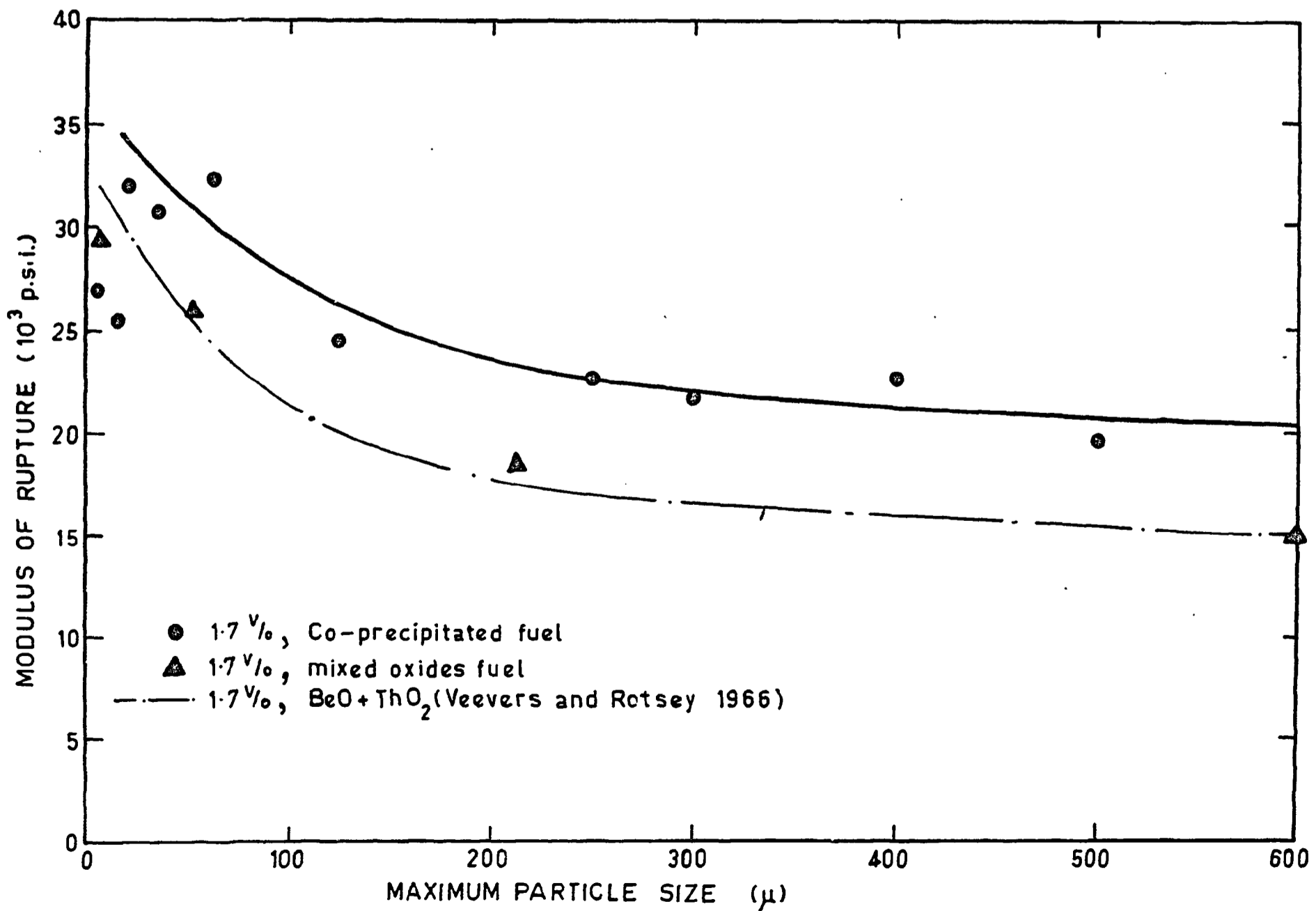


FIGURE 3. MODULUS OF RUPTURE VERSUS MAXIMUM PARTICLE SIZE

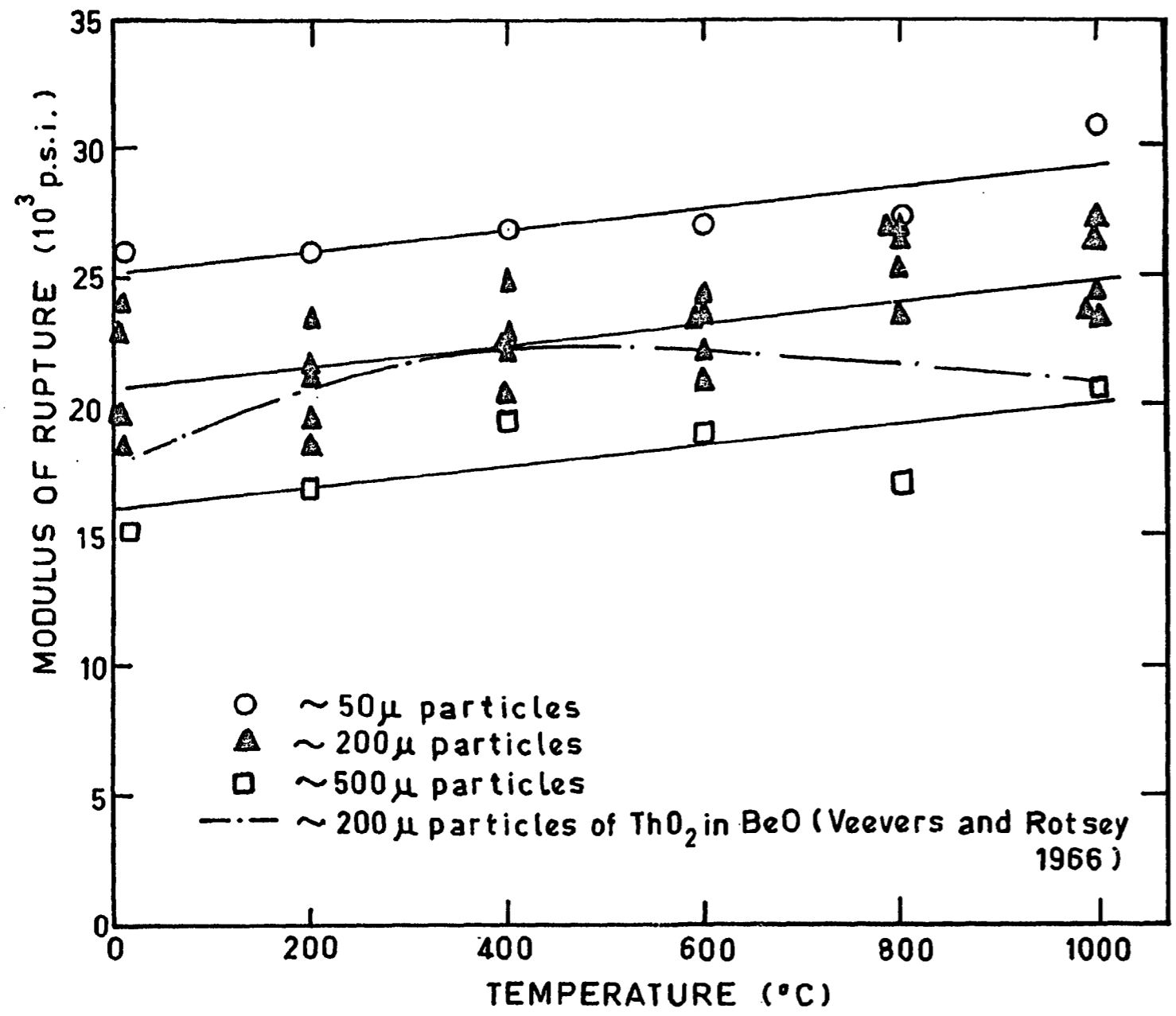


FIGURE 4. MODULUS OF RUPTURE VERSUS TEMPERATURE FOR 1.7 VOLUME PER CENT  $\sim 50\mu$ ,  $\sim 200\mu$ , AND  $\sim 500\mu$  PARTICLES OF  $(\text{UTh})\text{O}_2$  IN  $\text{BeO}$

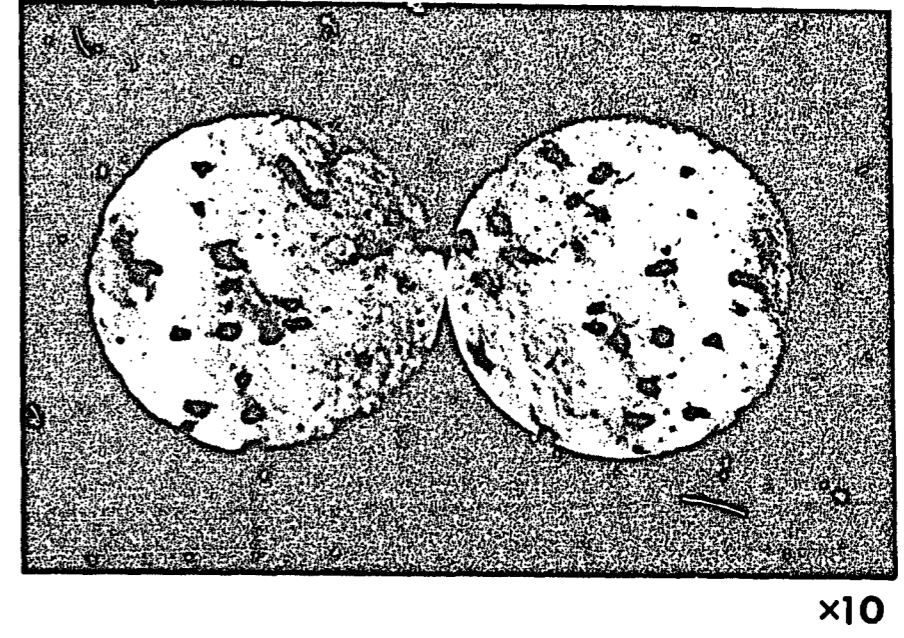


FIGURE 5. FRACTURE FACES OF A MODULUS OF RUPTURE SPECIMEN SHOWING FRACTURE THROUGH THE URANIA-THORIA PARTICLES

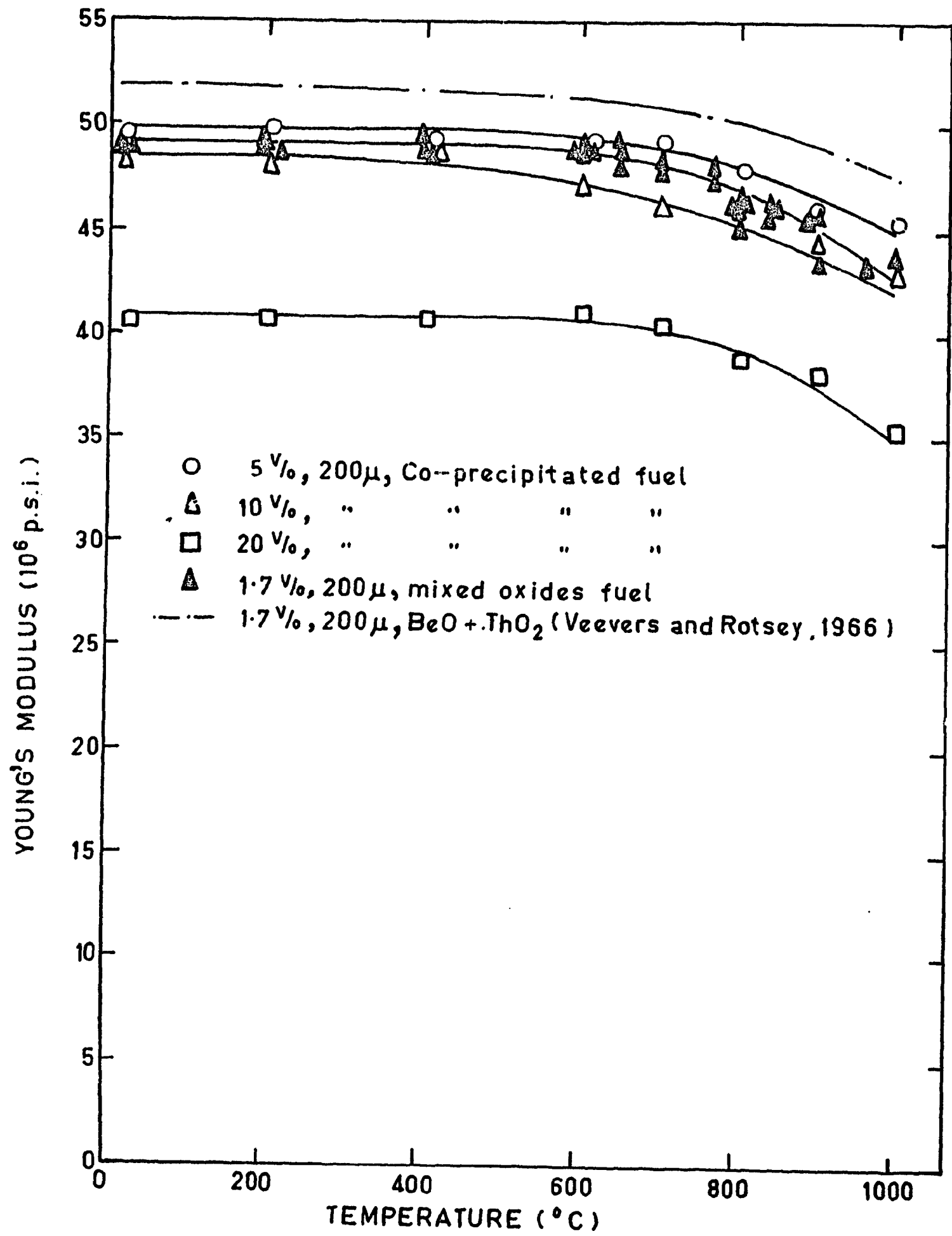


FIGURE 6. YOUNG'S MODULUS VERSUS TEMPERATURE

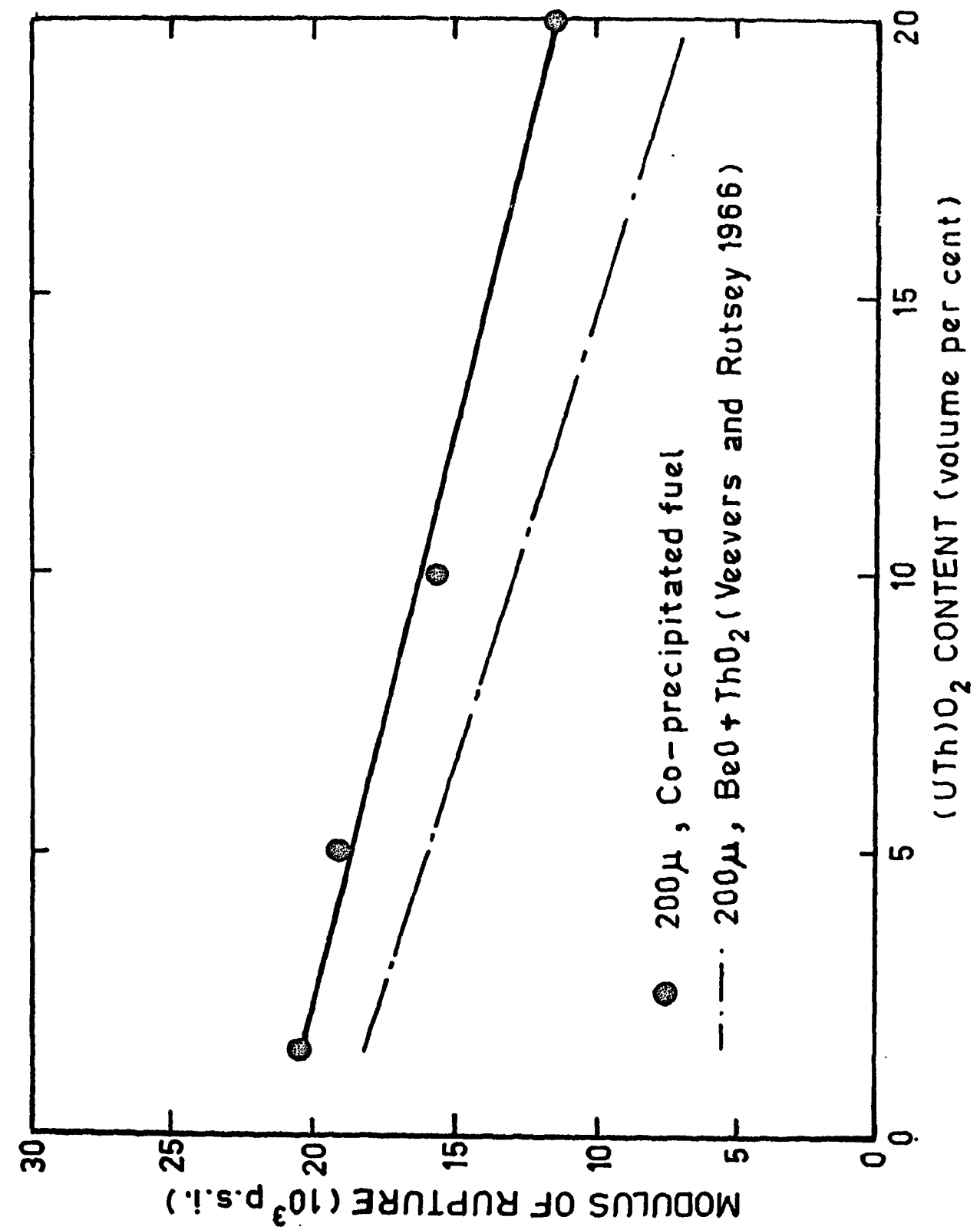


FIGURE 7. MODULUS OF RUPTURE VERSUS (UTh)O<sub>2</sub> CONTENT

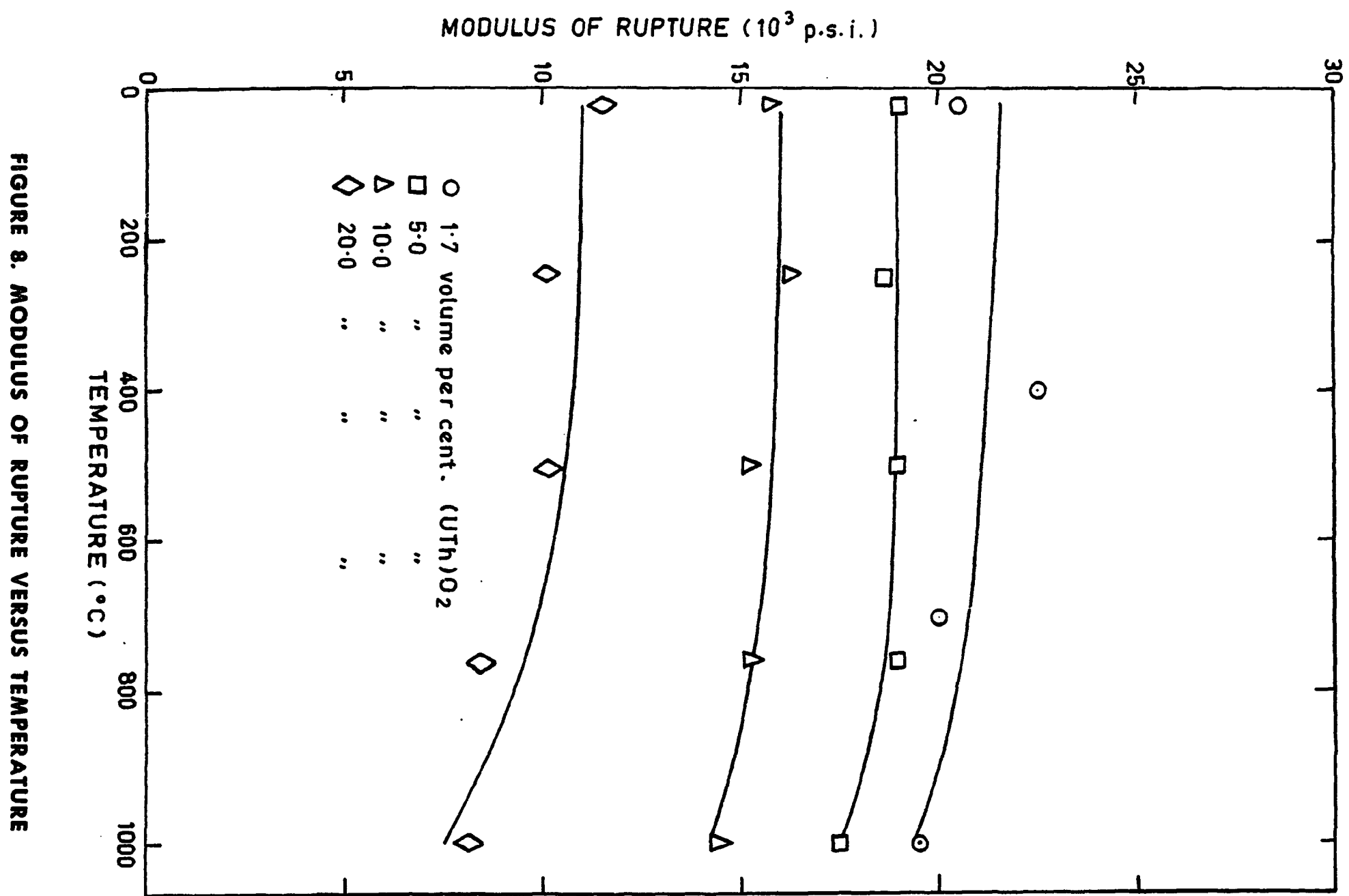


FIGURE 8. MODULUS OF RUPTURE VERSUS TEMPERATURE

P 570

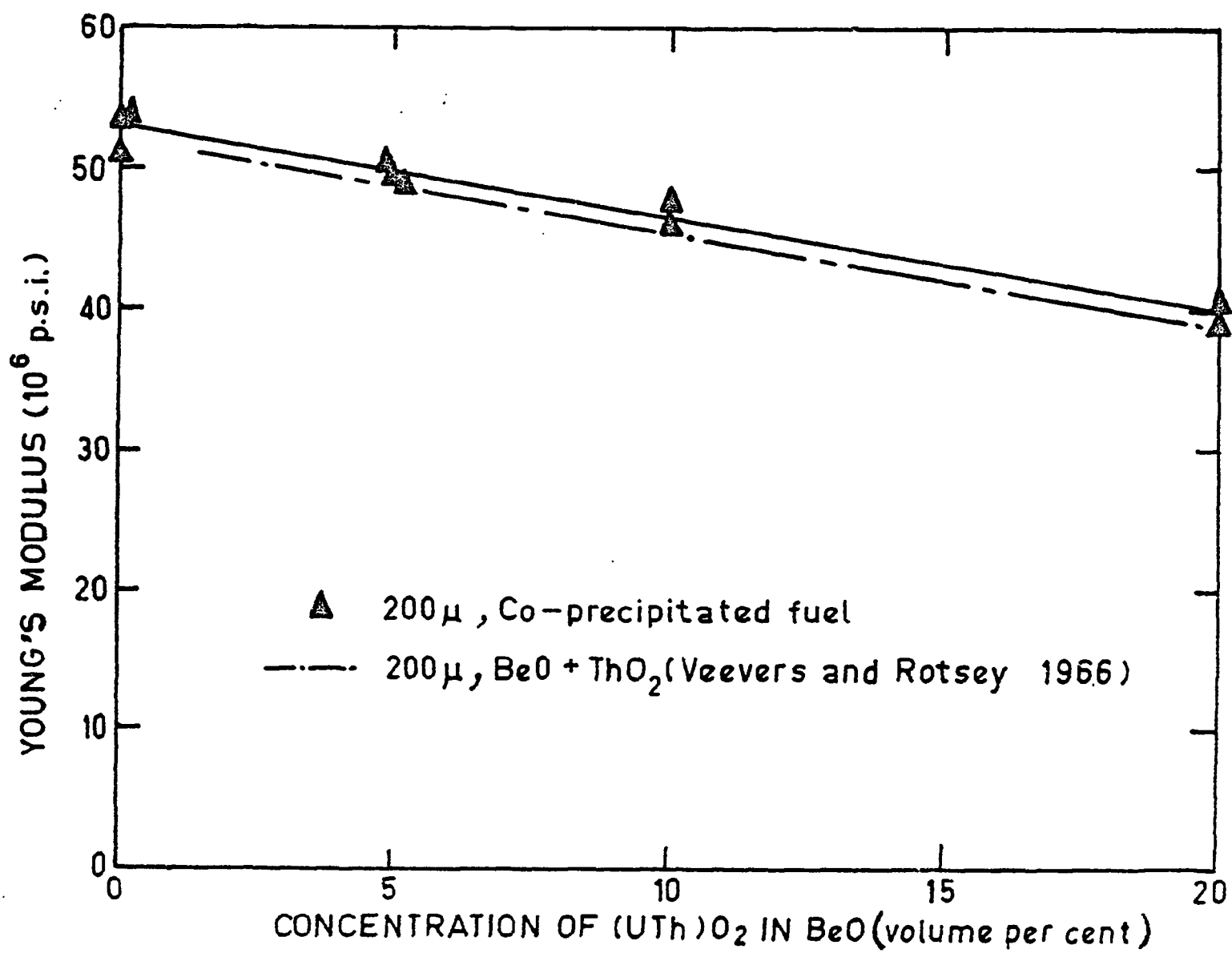


FIGURE 9. YOUNG'S MODULUS VERSUS  $(\text{UTh})\text{O}_2$  CONCENTRATION

P 570

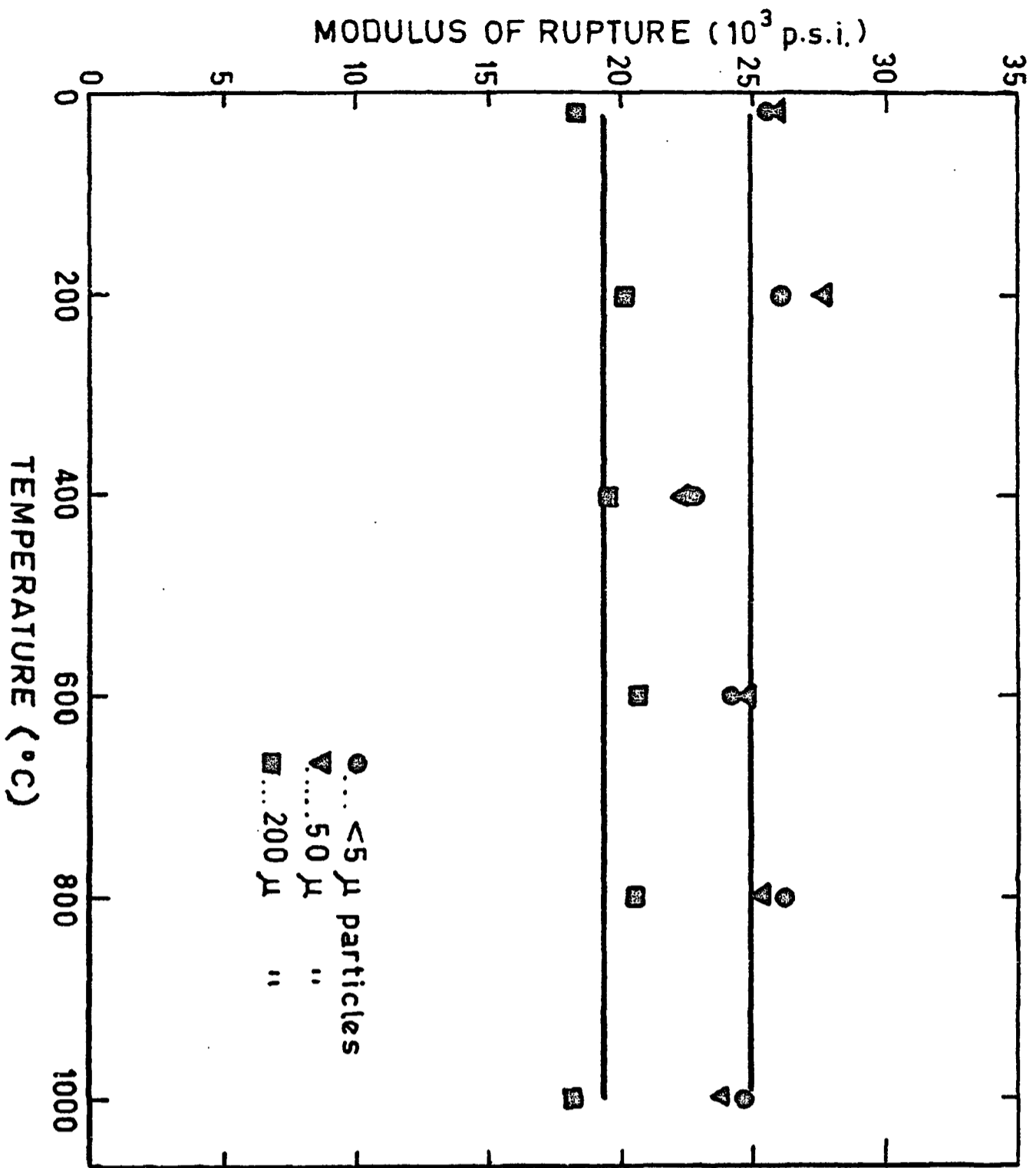


FIGURE 10. MODULUS OF RUPTURE VERSUS TEMPERATURE FOR RIG X121 SPECIMENS

P970

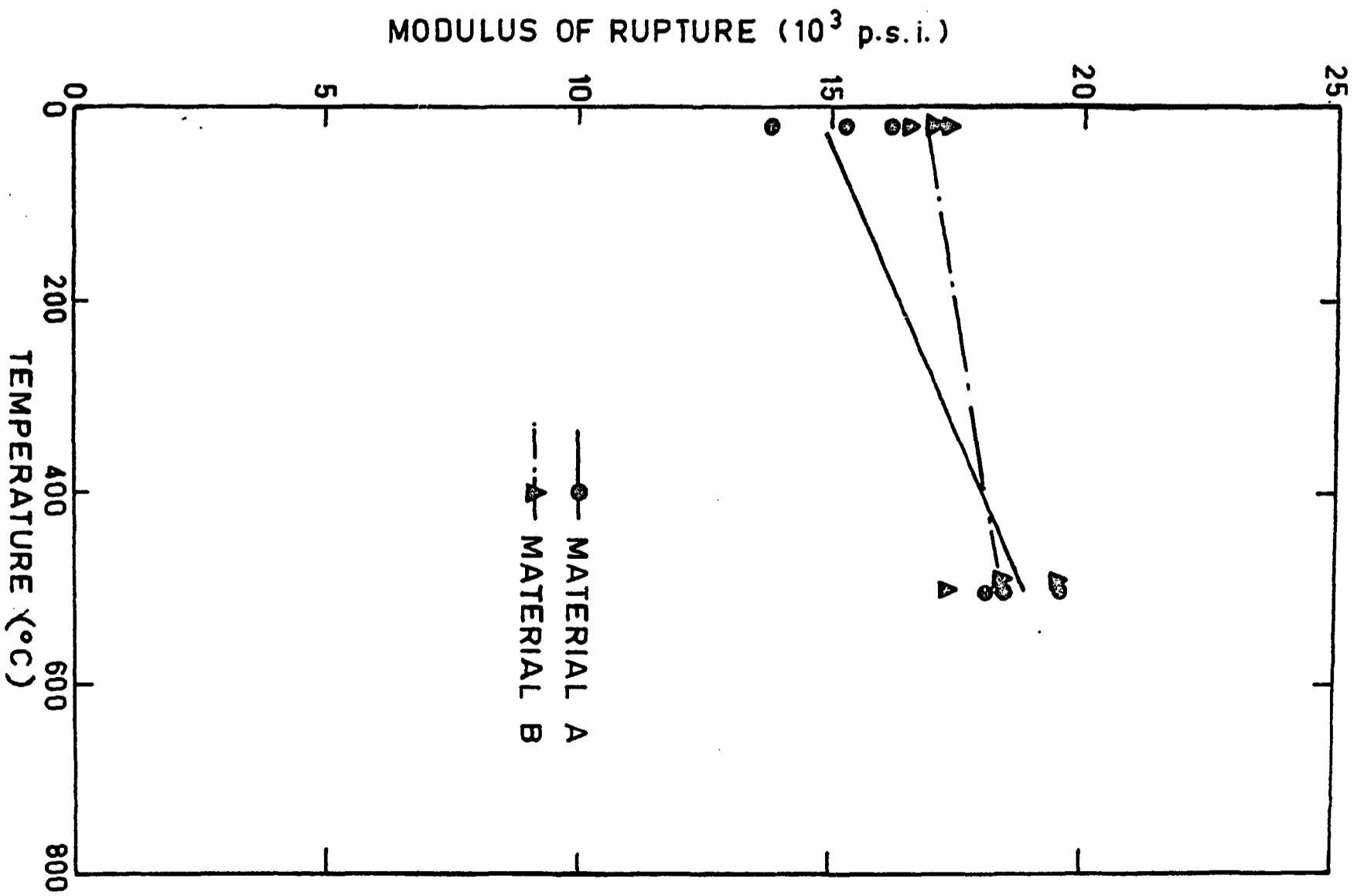


FIGURE 11. MODULUS OF RUPTURE VERSUS TEMPERATURE FOR X105 SPECIMENS