OCT 16 1967

MASTER

MASTER

WANL-TME-1619

June, 1967

Westinghouse Astronuclear Laboratory

THE CRYOGENIC AND AMBIENT TENSILE AND COMPRESSION PROPERTIES OF HOT-PRESSED BLOCK BERYLLIUM

UNCLASSIFIED NERVA RESEARCH
AND DEVELOPMENT REPORT.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

A. Makes any warranty or representation, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or

B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission, or employee of such contractor, to the extent that such employee or contractor of the Commission, or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.

WANL-TME-1619

June, 1967

THE CRYOGENIC AND AMBIENT TENSILE AND COMPRESSION PROPERTIES
OF HOT-PRESSED BLOCK BERYLLIUM

Prepared by: UNCLASSIFIED NERVA RESEARCH
AND DEVELOPMENT REPORT.

R. L. Kesterson
R. L. Kesterson

Approved by:

E. L. Layland
E. L. Layland, Manager
Materials Engineering
and Specifications

INFORMATION CATEGORY

UNCLASSIFIED

E. L. Layland 6/13/67
Authorized Classifier Date

D. E. Thomas
D. E. Thomas,
Engineering Manager

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:
A. Makes any warranty or representation, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or
B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.
As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission, or employee of such contractor, to the extent that such employee or contractor of the Commission, or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.

TABLE OF CONTENTS

		<u>Page</u>
I.	SUMMARY	1
II.	INTRODUCTION	2
III.	CONCLUSIONS AND RECOMMENDATIONS	6
IV.	EXPERIMENTAL PROCEDURE	7
V.	DISCUSSION OF RESULTS	9
VI.	ACKNOWLEDGEMENTS	14
VII.	REFERENCES	15
VIII.	TABLES	16
IX.	FIGURES	19

LIST OF TABLES

	<u>Page</u>
1. Compositions of S-200 Grade Beryllium	16
2. Vendor Reported Tensile Data	17
3. Tensile Properties	18
4. Compression Properties	18

LIST OF FIGURES

	<u>Page</u>
1. Vendor Tensile Data as a Function of Pressing Sequence	19
2. Microstructure of Transverse Block Pressing	20
3. Microstructure of Longitudinal Block Pressing	20
4. Microstructure of Transverse Ring Pressing	20
5. Microstructure of Longitudinal Ring Pressing	20
6. Beryllium Mechanical Test Specimens	21
7. Stress-Strain Diagram for Tension in the Transverse Direction of a Block Pressing at 70°F	22
8. Stress-Strain Diagram for Tension in the Transverse Direction of a Block Pressing at -320°F	23
9. Stress-Strain Diagram for Tension in the Transverse Direction of a Ring Pressing at 70°F	24
10. Stress-Strain Diagram for Tension in the Transverse Direction of a Ring Pressing at -320°F	25
11. Stress-Strain Diagram for Tension in the Longitudinal Direction of a Ring Pressing at 70°F	26
12. Stress-Strain Diagram for Tension in the Longitudinal Direction of a Ring Pressing at -320°F	27

13.	Stress-Strain Diagram for Tension in the Transverse Direction of a Block Pressing at -210°F	28
14.	Stress-Strain Diagram for Tension in the Transverse Direction of a Block Pressing at -110°F	28
15.	Stress-Strain Diagram for Tension in the Transverse Direction of a Block Pressing at -10°F	29
16.	Stress-Strain Diagram for Tension in the Longitudinal Direction of a Ring Pressing at -210°F	29
17.	Stress-Strain Diagram for Tension in the Longitudinal Direction of a Ring Pressing at -110°F	30
18.	Stress-Strain Diagram for Tension in the Longitudinal Direction of a Ring Pressing at -10°F	30
19.	Stress-Strain Diagram for Compression in the Transverse Direction of a Block Pressing at 70°F	31
20.	Stress-Strain Diagrams for Compression in the Transverse Direction of a Block Pressing at -320°F	32
21.	Stress-Strain Diagram for Compression in the Longitudinal Direction of a Ring Pressing at 70°F	33
22.	Stress-Strain Diagram for Compression in the Longitudinal Direction of a Ring Pressing at -320°F	34
23.	Stress-Strain Diagram for Compression in the Transverse Direction of a Ring Pressing at -320°F	35
24.	Stress-Strain Diagram for Compression in the Transverse Direction of a Ring Pressing at 70°F	35
25.	Stress-Strain Diagram for Compression in the Transverse Direction of a Block Pressing at -210°F	36

26.	Stress-Strain Diagram for Compression in the Transverse Direction of a Block Pressing at -110°F	36
27.	Stress-Strain Diagram for Compression in the Transverse Direction of a Block Pressing at -10°F	37
28.	Stress-Strain Diagram for Compression in the Longitudinal Direction of a Ring Pressing at -210°F	37
29.	Stress-Strain Diagram for Compression in the Longitudinal Direction of a Ring Pressing at -110°F	38
30.	Stress-Strain Diagram for Compression in the Longitudinal Direction of a Ring Pressing at -10°F	38
31.	The Effect of Cryogenic Temperatures on the Transverse Direction Ultimate Tensile Strength of a Block Pressing	39
32.	The Effect of Cryogenic Temperatures on the Longitudinal Ultimate Strength of a Ring Pressing	39
33.	The Effect of Cryogenic Temperatures on the Transverse 0.2% Yield Strength of a Block Pressing	40
34.	The Effect of Cryogenic Temperatures on the Longitudinal 0.2% Yield Strength of a Ring Pressing	40
35.	The Effect of Cryogenic Temperatures on the Transverse Elongation of a Block Pressing	41
36.	The Effect of Cryogenic Temperatures on the Longitudinal Elongation of a Ring Pressing	41
37.	The Effect of Cryogenic Temperatures on the Transverse 1.0% Compressive Yield Strength of a Block Pressing	42
38.	The Effect of Cryogenic Temperatures on the Longitudinal 1.0% Compressive Yield Strength of a Ring Pressing	42

39.	The Effect of Cryogenic Temperatures on the Transverse 0.2% Compressive Yield Strength of a Block Pressing	43
40.	The Effect of Cryogenic Temperatures on the Longitudinal 0.2% Compressive Yield Strength of a Ring Pressing	43
41.	The Effect of Cryogenic Temperatures on the Notch Sensitivity in the Transverse Direction of a Block Pressing	44
42.	The Effect on the Stress Concentration Factor on the Notched-Unnotched Strength Ratio	45

I. SUMMARY

The tensile and compression properties of S-200 grade beryllium were investigated in the temperature range of $+70^{\circ}\text{F}$ to -320°F . This hot-pressed block material is presently being used for both sector and ring types of NERVA outer reflectors.

The objectives of this investigation included:

1. A statistical comparison of the mechanical properties of ring and sector material.
2. A statistical comparison of the lot to lot variation in the mechanical properties of hot-pressed beryllium.
3. A statistical study of the testing temperature effect on the mechanical properties.
4. A study of the notched tensile behavior.

The experiment was designed such that a statistical data analysis would produce an optimum amount of information. The results from the analysis were used to develop stress-strain curves with 75%, 90%, 95% and 99% tolerance limits and with a 90% confidence factor.

The results indicate that on a statistical basis no real difference exists between the cryogenic mechanical properties of the ring and block pressings. However, there is less variance in properties of ring-type pressings, and thus this type of beryllium pressing is favored.

II. INTRODUCTION

Grade S-200, hot-pressed block beryllium, Westinghouse PDS-30018-E, is used for the outer reflector of the NERVA reactor. The choice of beryllium for this component was based mainly on two of its unique properties: a high modulus-density ratio and an excellent neutron reflecting capability. Since the outer reflector provides a lateral support along with its nuclear characteristic, it must have maximum strength with minimum weight. A good measure of this strength characteristic is the modulus to density ratio. When beryllium's ratio is compared to those of the stronger materials in extensive use today (such as steel and titanium), it is found that the modulus-density ratio of beryllium is larger than those of the other materials by at least a factor of 6.⁽¹⁾ Therefore, beryllium has been chosen as the primary reflector material. However, there is much to be learned about its mechanical properties, especially at the cryogenic temperatures where it will see most use, and so this program was initiated.

The major goal of this investigation was the construction of a series of stress-strain curves with 75%, 90%, 95% and 99% tolerance bands and a confidence factor of 90%. In developing these curves there were assumed to be three main factors of variability: the temperature, the specimen orientation and the pressing type. These factors are subdivided into test temperatures of -320°F , -210°F , -110°F , -10°F and 70°F , specimens of longitudinal and transverse orientation and pressings of block and ring type. These divisions produced a total of 20 possible sets of data. When considering that there were also two types of specimens, tensile and compression, the number of possible sets of data is increased to 40. However, not all of these sets were considered.

A statistical-based testing program was planned by Mr. W. L. Hafley, of the Westinghouse Research Laboratories,⁽²⁾ whereby the data would provide a maximum amount of information when examined by statistical analysis. This program was formulated to facilitate a regression analysis of the data. Upon testing and initial analysis,⁽³⁾ however, it was observed that the regression analysis would be inaccurate, due to a nonconformity of the measured properties to either linear or quadratic relationships. Therefore, it was decided to

use an analysis of variance of the data; Mr. W. H. Horton, of the WANL Reliability Department, analyzed the data.

The beryllium used in this study was obtained from the trepanned cores of actual reflector pressings. Briefly, the production of such pressings consists of ore reduction, vacuum melting of the metal, attritioning to powder and vacuum, hot-pressed sintering. The main ore, beryl, contains about 5% beryllium and is mined largely as a secondary product. Because of large grain size and poor as-cast properties, the metal is subsequently attritioned to an average particle size of 35 microns. The powder is then hot pressed at about 100 psi and at a temperature of 2000°F while under a vacuum of 50 microns.⁽⁴⁾ The chemical composition of typical, finished material is 98.3% beryllium (including that present in the oxide) with 1.8% beryllium oxide and about 0.4% additional metallic impurities. Table 1 shows the actual and average compositions,⁽⁵⁾ as well as densities, for both the ring and the block pressings.

The size of the beryllium pressing required for the NERVA reactor is among the largest produced; the rough machined ring pressing has an outside diameter of about 50 inches and is 18 inches long with a 6 inches thick wall. The finished reflector is a 54 inches long cylinder constructed of three beryllium rings.

In the experimental program 332 specimens were tested. Of these, 132 were compression samples and 200 were tensile with 56 of the tensile specimens being notched. The notch radius was varied to provide data concerning the effect of the notch stress concentration factor on the ultimate strength. The samples were obtained from 10 lots of material (or pressings) with the majority of the longitudinal specimens machined from ring pressings and most of the transverse specimens from block pressings. Since it is possible that the difference in properties between the transverse and longitudinal orientations could be attributed to the type of pressing, as well as to the orientation, some specimens of opposite orientation were also examined.

With the production of every pressing, the vendor supplies a certification of its mechanical and physical properties as determined by appropriate sampling of the material. Table 2 contains the average reported⁽⁵⁾ tensile properties of the pressings that were used

in this investigation. From this listing it appears that the average block pressing is slightly superior to the ring pressing. This characteristic was discussed with the vendor⁽⁶⁾ who observed that, when the mechanical properties of the individual pressings were plotted as a function of the chronological order of pressing, a series of curves, as seen in Figure 1, was generated.

The block pressing data show essentially no change in properties as a function of time of pressing, while the ring data show an increase in strength as more pressings are made. On this basis, the vendor concluded that the difference in properties is largely a function of production experience. There has been considerable background experience with the block pressings, while the rings are a relatively new product. The vendor feels that, with the experience that has now been gained, they can produce ring pressings of comparable, if not of superior, quality to the block pressings.

Beryllium data is often reported for both the longitudinal and transverse pressing directions, with the transverse direction exhibiting the better mechanical properties. This difference in the observed properties is attributed to the basal plane fracture mode of the hexagonal lattice structure of beryllium. In the hot-pressed form there is a fair degree of basal plane orientation perpendicular to the pressing direction. Since the basal plane in beryllium has the lowest critical shear stress of any crystallographic plane,⁽⁷⁾ it is the preferred fracture system. With the basal type fracture predominant, the amount of plasticity is severely limited by the plane's very low capacity for sustaining deformation before fracture.

The inherent difference between transverse and longitudinal properties of hot-pressed beryllium is explained by the different fracture mechanisms. When testing a longitudinally-oriented specimen in tension or compression, the major stress is normal to the basal plane producing a cleavage between the planes at low stress with little slip or deformation. When testing in the transverse direction, the major stress is parallel to the basal plane, with the deformation and fracture mode being one of planes sliding over each other. This larger amount of deformation allows a higher stress to be obtained before fracture.

The orientation effects on properties is a factor that has been considered in the NERVA outer reflector design. The beryllium used has some degree of preferred basal

orientation, thereby producing an inherent property variability dependent upon orientation.

The microstructures of the two types of pressings investigated are very similar. For typical examples of each microstructure refer to Figures 2 through 5.

III. CONCLUSIONS AND RECOMMENDATIONS

1. There is less variance in the ring data than in the block data, indicating the ring type to be more consistent.
2. The transverse properties of the ring pressing are equal to the transverse block properties.
3. The ultimate tensile strength of S-200 grade beryllium shows only small changes over the temperature range studied.
4. The 0.2% yield strength in tension and the 0.2% and 1.0% yield strengths in compression show a general increase with decreasing temperature.
5. The tensile elongation shows a large decrease with decreasing temperature. For the transverse direction the average elongation varies from 2% at +70°F to 0.5% at -320°F, while the longitudinal elongation varies from 1% at 70°F to 0.5% at -320°F.
6. Beryllium is strongly notch sensitive at cryogenic temperatures. A K_t of 5.5 and a temperature of -320°F reduce the strength by 50%.
7. On a statistical basis the ring material is recommended as the better material for use in design.

IV. EXPERIMENTAL PROCEDURE

A. Specimen Machining

The raw material used in this investigation was obtained as sections of cores trepanned from ten beryllium pressings. Due to the toxicity of beryllium and the necessary precautions involved during the cutting of specimens, an outside vendor was used for machining the specimens.

From the beryllium sections were machined both compression and tensile specimens, with the compression specimen being a solid cylinder, 0.360 inch in diameter and 1.06 inches long. For the purpose of obtaining good axiality, the ends of the compression specimens were parallel to each other to within 0.0001 inch.

Of the 200 tensile specimens, 144 were plain bar and 56 were notched. The unnotched specimens were 2 inches long with nominal gage diameter and length of 0.250 inch and 1.00 inch, respectively. Of the notched specimens, there were five different types. Four types were similar in size, each being 3.00 inches long, having a notch diameter of 0.250 inch and a major diameter of 0.354 inch; they differed only in their notch radii of 0.003, 0.005, 0.010 and 0.035 inch. The remaining type was smaller in size, being only 2.00 inches in length, having a notch diameter of 0.178 inch, a major diameter of 0.250 inch and a notch radius of 0.003 inch. Figure 6 is a picture of the specimens used.

B. Etching

The surface damage produced during the machining operation must be removed before testing to prevent spurious results. An etch-polish solution was used to remove approximately four mils from the specimen diameter. The solution used was:

125 ml	Phosphoric Acid
15 ml	Sulphuric Acid
250 gm	Chromic Oxide
1000 ml	Water

The solution was magnetically stirred and heated to 100°F. The etching time was about 15 minutes, depending on the temperature and the changing strength of the solution. A precaution was taken to maintain the axially of the compression specimens by protecting their ends with Stoner Mudge Lacquer. This compound resists attack by the etchant and is easily removed with acetone. Dimensional measurements were made on the specimens before and after etching.

C. Mechanical Testing

A few specimens were strain gaged, both for a determination of loading eccentricity and for a more accurate elastic modulus determination. The eccentricity determination was performed, using three strain gages equally spaced around the circumference of the specimen. From the difference between the individual gage readings, the amount of eccentricity was calculated to be less than 5% upon fracture.

Most of the specimens were strained at a rate of 0.005 inch/inch/minute on a Wiedemann Mark G 60,000 lb. tensile machine. It was felt that this rate was approximately that experienced in a reflector during use. An attempt was made to obtain data, using an extremely slow strain rate of 0.00005 inch/inch/minute; however, due to exterior electrical interference, accurate results were not obtainable.

The specimens were tested at temperatures of +70°F, -10°F, -110°F, -210°F and -320°F. The cryogenic temperatures were maintained within 2°F by a controlled flow of vaporized liquid nitrogen. The temperatures were measured with an iron-constantan thermocouple, the output from which was fed into an electronic, on-off controller which actuated a solenoid valve, thus regulating the flow of the nitrogen vapor into the cryostat. The cryostat consisted of a double-walled cylinder with orifices placed in the inner wall so that gas impinged on the specimen and load train. The -320°F temperature tests were performed while the specimen was submerged under liquid nitrogen.

V. DISCUSSION OF RESULTS

Following the mechanical testing of all specimens, the majority of the data was subjected to an analysis of variance. From this analysis, information was obtained concerning the variability within and between pressings. It was evident that the significant variance was not within pressings, but between pressings. Tables 3 and 4 contain a tabulation of the more significant data. The mean value and the 90%, 95% and 99% minimum tolerance values are listed as a function of temperature for each of the mechanical properties.

Considering the amount of data generated, a graphical approach provides the clearest presentation. As previously stated, all statistical data were calculated with a 90% confidence factor; therefore, the graphs are interpreted as follows:

It can be assumed with 90% confidence that 75% (90%, 95% or 99%) of all future results will fall within the appropriate band.

Stress-Strain Diagrams

The graphs found in Figures 7 through 30 are stress-strain diagrams for both tension and compression. Each figure represents a specific type pressing, orientation and temperature. The tension curves were generated by plotting an experimentally determined modulus and then drafting lines parallel to this modulus, representing the 0.01% and 0.2% yields. A similar line was drawn for the average plastic strain, which was also experimentally determined. The statistically analyzed 0.2% yield and ultimate strengths were then plotted on the 0.2% yield and elongation lines, respectively.

The stress-strain curves of the strain gaged specimens indicated that the 0.01% yield occurred at an approximate value of 0.5 of the 0.2% yield strength in tension and at 0.6 of the yield strength in compression. These 0.01% yield strengths provided a third point on the stress-strain curve and gave some indication of the point of tangency with the modulus line.

Figures 7 through 12 are curves for the two major temperatures considered: -320°F and 70°F . The intermediate temperature curves are plotted on a smaller scale with fewer tolerance limits. The same range of tolerance values was determined for the intermediate as for the major temperatures, but are not presented here.

The tolerance ranges for the total strain or elongation have also been deleted from the series of stress-strain curves to provide a more distinct diagram. Had these ranges been included, the fracture point or the ultimate stress and total elongation tolerance regions would have consisted of vague areas of concentric rectangles covering the majority of the diagram.

The curves are self-explanatory and can be used to derive a large quantity of information for a specific set of conditions. The effects of cryogenic temperatures on the properties of yield and ultimate strengths and elongation are of considerable interest and will be discussed in detail in the following sections.

Cryogenic Temperature Effects

Figures 31 through 40 are graphs of mechanical properties as a function of temperature with the appropriate tolerance bands. The first two graphs, Figures 31 and 32, show the effect of temperature on the ultimate strength in tension. For both the ring and block pressings, the relationship appears constant with a slight increase in strength at the lower temperature.

Figure 32 has two additional points which represent the mean transverse properties of a ring pressing. From this data the transverse tensile strengths of the ring pressings appear to be approximately 15% greater than the longitudinal strength. When comparing the transverse tensile strengths of the block and ring pressings, there is less than 5% difference in their means. This small difference makes it tempting to conclude that there is little or no real difference in the tensile properties of the block and ring pressings.

The effect of temperature on the 0.2% yield strength is shown in Figures 33 and 34. The general trend of increasing yield strength with decreasing temperature is caused by the increased stresses required to initiate deformation at the lower temperatures.

Also plotted on Figure 34 for the ring pressing are two points representing the transverse properties. These strengths are within 5% of the corresponding yield strengths reported for the block pressings. Again, there is little difference in properties between the two types of pressings.

Figures 35 and 36 show the effect of temperature on the total plastic elongation. The general trend of decreasing elongation as temperature decreases is noted. Beryllium has the disadvantage of very low elongation or ductility, especially at cryogenic temperatures, which is attributed mainly to the very low capacity of the lattice to accommodate slip before fracture.

When the tolerance bands of each type pressing are compared, it is seen that the ring has much less range or variance in data. This small variance, when combined with the good transverse strength, produces very advantageous properties. At $+70^{\circ}\text{F}$ the 99% tolerance band for the block pressings indicate a possible ductility of zero, while for a ring pressing in the transverse direction, the lowest value in the 99% tolerance range would be 1.5% elongation. In this respect the ring is a superior pressing.

The compression data consist of 0.2% yield and 1.0% "yield" strengths. There were no ultimate strengths obtained, due to two factors. The accurate determination of the point of ultimate strength and fracture is questionable and the additional information is not of sufficient value to warrant the added complications.

Figures 37, 38, 39 and 40 show the effect of cryogenic temperatures on the compression properties of 0.2% and 1.0% yield strengths. The trend is the same as in the 0.2% tensile yield, as one would expect. The temperature effect appears to be stronger in the 1% yield values than in the 0.2% yield.

Another noticeable feature is the relatively smaller temperature effect on the transverse properties, when compared to those in the longitudinal direction. This is seen especially in the ring pressing; at $+70^{\circ}\text{F}$ the longitudinal strengths are lower than the transverse, while at -320°F the reverse is true.

In considering all the data, there appear to be two general trends. One concerns the apparent equality between the ring and block pressings in the transverse direction. The other trend concerns the smaller variance in the ring data, as compared to the block. Upon combining these two factors and from a statistical view, the ring pressings have better transverse mechanical properties than the transverse block.

Notch Effects

The remaining two figures, 41 and 42, are concerned with the effects of temperature and the stress concentration factor on the notch strength of beryllium. The first shows the relationship of temperature on notch sensitivity. For a constant stress concentration factor, K_t , of 5.8, a 20% loss in strength is encountered in going from room temperature to liquid nitrogen.

Figure 42 indicates the effects of various K_t factors and temperatures on the notched strength ratio. For a given K_t , the large notch strength sensitivity to temperature is indicated by the difference in the two curves. For a K_t value of 5.0, a 50% decrease in strength is encountered when going from room temperature to -320°F .

The notched-unnotched strength ratios observed in Figure 41 for specific temperatures ($+70^{\circ}\text{F}$ or -320°F) appear smaller than the corresponding ratios in Figure 42. The only differences between the two sets of specimens were their size and pressing. The specimens used in Figure 41 were the smaller diameter, notched samples. Both figures represent block pressings; and, although obtained from different lots, the data should not show as large a variance. The differences in temperature sensitivity between the two figures may be an indication of the size difference instead of a material difference. It is hard to obtain a clear conclusion on this effect from the present data.

The slopes of the two curves in Figure 42 show the strong influence of cryogenic temperatures on the notched strengths. At 70°F a notch concentration factor as great as 5.0 appears to have no harmful effect, while at -320°F a K_t of 2.5 is deteriorating. Likewise, any K_t of less than 2.5 appears not to be harmful except at temperatures lower than liquid nitrogen.

In Figure 42 there are extrinsic points, separate from the two temperature curves, which represent longitudinal ring properties, as compared to the transverse block data used to generate the curves. At a temperature of 70°F the ring data show good agreement with the block data; however, at -320°F the notched strength ratio of the ring is considerably larger than the block. This indicates that the ring material is less notch sensitive than the block, particularly at cryogenic temperatures. However, further experimentation should be

performed before a conclusive statement is made.

VI. ACKNOWLEDGEMENTS

The author wishes to acknowledge and thank Mr. E. F. Vandergrift and Mr. W. H. Horton for their contributions of mechanical testing and data analysis, respectively. Also, Mr. R. A. Nadler, who planned and initiated this work.

VII. REFERENCES

1. Bulletin 2125, "Properties of Beryllium," The Beryllium Corporation.
2. Hafley, W. L., "Test Program for Strength Data on Beryllium at Low Temperatures," Westinghouse Research Memo 66-8C3-MCONS-M2, April, 1966, Proprietary Class 2.
3. Kussmaul, K. L., "Analysis of Strength Data on Beryllium at Low Temperatures," Westinghouse Research Report 67-8C3-MCONS-R1, February, 1967, Proprietary Class 2.
4. Darwin, G. E. and Buddery, J. H., Beryllium, Butterworth's Scientific Publications, London, 1960.
5. Vendor certifications of chemical composition and mechanical properties.
6. Wyatt, H., Brush Beryllium Company, Private communication.
7. Conrad, H. and Perlmutter, I., "Beryllium as a Technical Material." Air Force Materials Laboratory, Wright-Patterson AFB, Ohio.

TABLE 1
Compositions of S-200 Grade Beryllium, %

Block Pressings	Total Be	BeO	Fe	Al	Mg	Si	C	Density gm/cc
2099	98.1	1.71	0.12	0.07	0.01	0.04	0.12	1.855
2931	98.6	1.64	0.14	0.08	0.01	0.04	0.12	1.870
3027	98.4	1.82	0.16	0.10	0.01	0.04	0.12	1.862
3052	98.2	1.71	0.18	0.09	0.01	0.04	0.13	1.858
3277	98.2	1.96	0.15	0.12	0.02	0.04	0.12	1.857
3517	98.4	2.06*	0.17	0.10	0.01	0.04	0.12	1.862
3968	98.2	1.80	0.15	0.10	0.01	0.02	0.13	1.860
Average	98.3	1.81	0.15	0.09	0.01	0.04	0.12	1.861

Ring Pressings	Total Be	BeO	Fe	Al	Mg	Si	C	Density gm/cc
4015	98.30	1.92	0.15	0.09	0.06	0.04	0.13	1.860
4022	98.58	1.79	0.15	0.07	0.01	0.02	0.08	1.858
4055	98.33	1.85	0.13	0.07	0.01	0.03	0.09	1.859
4065	98.28	1.81	0.14	0.06	0.01	0.02	0.10	1.858
Average	98.37	1.84	0.14	0.07	0.02	0.03	0.10	1.859
		Max.	Max.	Max.	Max.	Max.	Max.	Min.
WANL PDS-30018-E		2.00	0.20	0.18	0.08	0.12	0.15	1.84

* Out of specification

TABLE 2

Vendor Reported Tensile Data
Room Temperature

	Ultimate Strength (KSI)		0.2% Yield Strength (KSI)		Elongation (%)	
	Long.	Trans.	Long.	Trans.	Long.	Trans.
Block Pressing						
2099	45.1	50.1	34.0	33.2	1.0	2.2
2931	52.9	49.2	33.1	33.3	2.8	1.8
3027	42.8	47.6	30.7	30.9	1.3	2.3
3052	42.7	42.6	31.2	30.5	1.3	1.2
3517	49.0	52.2	34.2	34.8	2.0	2.8
3968	44.3	51.2	33.2	33.9	1.3	3.0
Average	46.1	48.8	32.7	32.8	1.6	2.2

Ring Pressing						
4015	40.5	43.9	29.0	29.3*	1.4	2.3
4022	40.9	46.3	30.7	30.9	1.1	2.6
4055	44.8	47.5	33.2	34.5	1.5	2.4
4065	41.5	48.4	31.7	32.5	1.2	2.5
Average	41.9	46.5	31.2	31.8	1.3	2.5

WANL PDS-30018-E	Min. 35.0	Min. 40.0	Min. 27.0	Min. 30.0	Min. 0.75	Min. 1.0

* Out of specification

TABLE 3
Tensile Properties

Pressing Type	Test Temp.	Ultimate Strength (KSI)				0.2% Yield Strength (KSI)				0.01% Yield Strength (KSI)				Elongation (%)			
		$\bar{X}$	90	95	99	$\bar{X}$	90	95	99	$\bar{X}$	90	95	99	$\bar{X}$	90	95	99
Block Transverse	+ 70	47.9	40.1	38.6	35.7	34.9	30.0	29.0	27.2	17.4	14.9	14.5	13.6	2.17	0.57	0.28	0.00
	- 10	50.7	42.8	41.3	38.4	34.5	29.7	28.7	26.9	17.3	14.8	14.4	13.5	2.18	0.68	0.39	0.00
	-110	51.8	44.7	43.3	40.7	35.0	30.3	29.3	27.6	17.5	15.1	14.7	13.8	1.98	0.72	0.48	0.01
	-210	49.7	41.2	39.6	36.4	36.3	31.5	30.6	28.8	18.1	15.7	15.3	14.4	1.55	0.29	0.05	0.00
	-320	48.8	40.4	38.8	35.6	41.1	36.5	35.6	33.7	20.5	18.2	17.8	16.9	0.61	0.12	0.02	0.00
Ring Longitudinal	+ 70	41.2	36.6	35.7	34.0	31.7	29.5	29.0	28.2	15.9	14.7	14.5	14.1	1.09	0.66	0.58	0.42
	- 10	41.7	37.1	36.2	34.4	34.2	30.3	29.6	28.2	17.1	15.2	14.8	14.1	1.03	0.58	0.49	0.33
	-110	43.4	38.9	38.1	36.5	31.8	28.0	27.3	25.8	15.9	14.0	13.6	12.9	1.04	0.64	0.55	0.39
	-210	43.0	37.2	36.1	34.0	34.9	29.0	27.9	25.7	17.5	14.5	14.0	12.8	1.02	0.57	0.48	0.32
	-320	43.6	37.9	36.8	34.6	38.0	32.1	31.0	28.9	19.0	16.1	15.5	14.4	0.48	0.12	0.05	0.00
Ring Transverse	+ 70	46.9	42.3	41.4	39.7	33.2	30.9	30.5	29.7	16.6	15.5	15.3	14.8	2.20	1.77	1.69	1.53
	-320	47.8	42.0	40.9	38.8	39.9	34.0	32.9	30.7	20.0	17.0	16.4	15.4	0.70	0.34	0.27	0.14

TABLE 4

Compression Properties

	Test Temp. °F	1.0% Compressive Yield (KSI)				0.2% Yield Strength (KSI)				0.01% Yield Strength (KSI)			
		$\bar{X}$	90	95	99	$\bar{X}$	90	95	99	$\bar{X}$	90	95	99
Block Transverse	+ 70	49.1	41.8	40.4	37.7	33.8	26.7	25.3	22.6	20.3	16.0	15.2	13.6
	- 10	49.8	42.5	41.1	38.4	34.5	27.4	26.0	23.3	20.7	16.4	15.6	14.0
	-110	51.0	45.4	44.4	42.3	34.4	29.5	28.6	26.8	20.6	17.7	17.1	16.0
	-210	53.1	47.5	46.4	44.3	35.7	30.0	28.9	26.8	21.4	18.0	17.3	16.1
	-320	59.9	54.5	53.5	51.5	39.2	33.5	32.4	30.3	23.4	20.0	19.3	18.1
Ring Longitudinal	+ 70	49.3	46.5	46.0	45.0	33.1	31.2	30.8	30.1	19.9	18.7	18.5	18.1
	- 10	51.5	48.6	48.0	47.0	34.3	30.7	30.0	28.7	20.6	18.4	18.0	17.2
	-110	52.1	49.2	48.6	47.5	33.8	30.2	29.5	28.2	20.3	18.1	17.7	16.9
	-210	52.6	49.1	48.4	47.1	34.1	30.5	29.8	28.5	20.5	18.3	17.9	17.1
	-320	62.2	58.7	58.1	56.7	39.1	37.1	36.8	36.0	23.4	22.2	22.0	21.5
Ring Transverse	+ 70	50.3	47.6	47.1	46.1	34.5	32.6	32.2	31.4	20.7	19.5	19.3	18.9
	-320	57.7	54.2	53.6	52.2	36.4	34.4	34.0	33.3	21.9	20.7	20.5	20.0

FIGURE 1
Vendor Tensile Data as a Function of Pressing Sequence

FIGURE 2
Microstructure of Transverse
Block Pressing
(200X)

FIGURE 3
Microstructure of Longitudinal
Block Pressing
(200X)

FIGURE 4
Microstructure of Transverse
Ring Pressing
(200X)

FIGURE 5
Microstructure of Longitudinal
Ring Pressing
(200X)

FIGURE 6
Beryllium Mechanical Test Specimens

FIGURE 7
Stress-Strain Diagram for Tension in the Transverse
Direction of a Block Pressing at 70°F

FIGURE 8

Stress-Strain Diagram for Tension in the Transverse Direction
of a Block Pressing at -320°F

FIGURE 9
Stress-Strain Diagram for Tension in the Transverse Direction
of a Ring Pressing at 70°F

FIGURE 10
 Stress-Strain Diagram for Tension in the Transverse Direction
 of a Ring Pressing at -320°F

FIGURE 11
Stress-Strain Diagram for Tension in the Longitudinal Direction
of a Ring Pressing at 70°F

FIGURE 12
Stress-Strain Diagram for Tension in the Longitudinal Direction of a
Ring Pressing at -320°F

FIGURE 13

Stress-Strain Diagram for Tension in the Transverse Direction of
a Block Pressing at -210°F

FIGURE 14

Stress-Strain Diagram for Tension in the Transverse Direction
of a Block Pressing at -110°F

FIGURE 15

Stress-Strain Diagram for Tension in the Transverse
Direction of a Block Pressing at -10°F

FIGURE 16

Stress-Strain Diagram for Tension in the Longitudinal
Direction of a Ring Pressing at -210°F

FIGURE 17

Stress-Strain Diagram for Tension in the Longitudinal
Direction of a Ring Pressing at -110°F

FIGURE 18

Stress-Strain Diagram for Tension in the Longitudinal
Direction of a Ring Pressing at -10°F

FIGURE 19

Stress-Strain Diagram for Compression in the Transverse
Direction of a Block Pressing at 70°F

FIGURE 20

Stress-Strain Diagrams for Compression in the Transverse
Direction of a Block Pressing at -320°F

FIGURE 21
 Stress-Strain Diagram for Compression in the Longitudinal
 Direction of a Ring Pressing at 70°F

FIGURE 22

Stress-Strain Diagram for Compression in the Longitudinal Direction
of a Ring Pressing at -320°F

FIGURE 23

Stress-Strain Diagram for Compression in the Transverse
Direction of a Ring Pressing at -320°F

FIGURE 24

Stress-Strain Diagram for Compression in the Transverse
Direction of a Ring Pressing at 70°F

FIGURE 25

Stress-Strain Diagram for Compression in the Transverse
Direction of a Block Pressing at -210°F

FIGURE 26

Stress-Strain Diagram for Compression in the Transverse
Direction of a Block Pressing at -110°F

FIGURE 27

Stress-Strain Diagram for Compression in the Transverse
Direction of a Block Pressing at -10°F

FIGURE 28

Stress-Strain Diagram for Compression in the Longitudinal
Direction of a Ring Pressing at -210°F

FIGURE 29

Stress-Strain Diagram for Compression in the Longitudinal
Direction of a Ring Pressing at -110°F

FIGURE 30

Stress-Strain Diagram for Compression in the Longitudinal
Direction of a Ring Pressing at -10°F

FIGURE 31

The Effect of Cryogenic Temperatures on the Transverse
Ultimate Tensile Strength of a Block Pressing

FIGURE 32

The Effect of Cryogenic Temperatures on the Longitudinal
Ultimate Strength of a Ring Pressing

FIGURE 33

The Effect of Cryogenic Temperatures on the Transverse
0.2% Yield Strength of a Block Pressing

FIGURE 34

The Effect of Cryogenic Temperatures on the Longitudinal
0.2% Yield Strength of a Ring Pressing

FIGURE 35

The Effect of Cryogenic Temperatures on the Transverse Elongation of a Block Pressing

FIGURE 36

The Effect of Cryogenic Temperatures on the Longitudinal Elongation of a Ring Pressing

FIGURE 37

The Effect of Cryogenic Temperatures on the Transverse
1.0% Compressive Yield Strength of a Block Pressing

The Effect of Cryogenic Temperatures on the Longitudinal
1.0% Compressive Yield Strength of a Ring Pressing

FIGURE 39

The Effect of Cryogenic Temperatures on the Transverse
0.2% Compressive Yield Strength of a Block Pressing

FIGURE 40

The Effect of Cryogenic Temperatures on the Longitudinal
0.2% Compressive Yield Strength of a Ring Pressing

FIGURE 41
The Effect of Cryogenic Temperatures on the Notch Sensitivity
in the Transverse Direction of a Block Pressing

FIGURE 42
The Effect on the Stress Concentration Factor on the
Notched-Unnotched Strength Ratio