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# MECHANICAL PROPERTIES OF STRUCTURAL GRADES OF BERYLLIUM AT HIGH STRAIN RATES

AIR FORCE MATERIALS LABORATORY

OCTOBER 1975

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# MECHANICAL PROPERTIES OF STRUCTURAL GRADES OF BERYLLIUM AT HIGH STRAIN RATES

*METALS BEHAVIOR BRANCH*
*METALS AND CERAMICS DIVISION*



OCTOBER 1975

TECHNICAL REPORT AFML-TR-75-168
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AIR FORCE MATERIALS LABORATORY
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
Air Force Systems Command
Wright-Patterson Air Force Base, Ohio 45433

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T. Nicholas
Project Scientist

FOR THE COMMANDER

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Metals and Ceramics Division
Air Force Materials Laboratory

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An experimental technique is described for obtaining high rate tensile stress-strain data on materials with limited ductility. A modified split Hopkinson bar apparatus is used to obtain data on three advanced structural grades of beryllium at strain rates up to 500 $sec^{-1}$. The data indicate that there is no significant loss in ductility with increasing strain rate in any of the three grades of beryllium. Flow stress is shown to increase linearly with strain rate up to strain rates of 1-10 $sec^{-1}$ and then more abruptly at higher rates.

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# FOREWORD

This technical report was prepared by the Metals Behavior Branch, Metals and Ceramics Division, Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio. The research was conducted by Dr. T. Nicholas under Project No. 7351, Task No. 735106 during the period January 1975 to May 1975.

This investigation was supported, in part, with funds provided by SAMSO/ABRES/Capt. John Zawila/RSSE. The author would like to acknowledge the significant contributions of Mr. Jim G. Paine, Systems Research Laboratories, Dayton, Ohio in the development of the experimental apparatus and instrumentation.



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# SECTION I

# INTRODUCTION

The design of structures subjected to dynamic or impulsive loading requires information on the mechanical properties of materials at high rates of strain. In the design of beryllium shells using ultimate strength concepts, the details of the dynamic stress-strain behavior are necessary for an optimum design and accurate response prediction. While purely elastic analyses lead to overdesigned and overweight structures, the available plasticity in the material can be utilized to great advantage, provided it is known to some degree of certainty. Although elastic-plastic computer codes for dynamic loading of shell type structures are now available, dynamic material property information for incorporation into these codes is not widely available for structural materials. Little, if any, information is available on the behavior of beryllium at high strain rates, especially for the newer grades.

The relatively brittle behavior of beryllium combined with an extremely high modulus present unique challenges to the material tester. Special care must be taken to insure accurate alignment and adequate resolution of the small strains obtained. At high rates of strain, the difficulties of testing beryllium become even more pronounced. Techniques which were developed for and applied to more ductile materials are often no longer applicable to beryllium.

The split Hopkinson bar technique, developed by Kolsky, [Reference 1] has been used extensively, and with great success, in obtaining dynamic compressive stress-strain data on a large number of materials, including beryllium [References 2 and 3]. There are at least two cases where the apparatus has been modified to perform high rate tensile tests in which limited data on beryllium were generated. Lindholm and Yeakley [Reference 4] developed a tensile test using a complicated hat type specimen which is really a series of four very small tensile bars in parallel. They used this technique to obtain high rate tensile data on S-200E beryllium but experienced failures outside of the gage section of the specimen due to stress concentrations at fillet radii. Green and Schierloh [Reference 5] reported tensile test data on beryllium using another modification of a Hopkinson bar apparatus. In their technique, a compressive pulse was generated in a hollow tube which was attached to a solid inner rod by a mechanical joint. The compressive pulse reflected at the free end through the joint and returned as a tensile pulse through the solid inner rod. A threaded end specimen was attached to the solid inner Hopkinson bars and the test analyzed in the same manner as for the compression split Hopkinson bar. Although no details were given of the pulse shapes, magnitudes, etc, the authors reported that the stress wave which propagated through the elastic bars and into the test specimen gage section did not have a sharp rise. A subsequent study by Schierloh and Babcock [Reference 5] indicated that maximum strain rates of 200-400 $sec^{-1}$ could be achieved in beryllium using the same apparatus, although few data have been reported at the highest rates quoted.

The concept of using a threaded specimen and a tensile loading pulse, described by Green and Schierloh [Reference 5], has been applied in this investigation to develop still another modification of a split

Hopkinson bar apparatus. Using this relatively simple technique, stress-strain data have been obtained on several structural grades of beryllium at strain rates up to 500 $sec^{-1}$. In addition, quasi-static and intermediate strain rate data were obtained using a servo-controlled hydraulic testing machine, thus providing stress-strain data over nearly seven decades in strain rate. Results of these tests, as well as a description of the tensile split Hopkinson bar apparatus and instrumentation, are presented.

# SECTION II

## APPARATUS AND INSTRUMENTATION

The apparatus consists principally of a striker bar and two Hopkinson pressure bars mounted and aligned on a rigid base as shown schematically in Figure 1. Bar No. 1 is twice the length of bar No. 2, while the striker bar is less than half the length of bar No. 2. In the experiments reported here 0.5" diameter (12.7 mm) AISI 4130 steel bars of lengths 2.5, 6, and 12 feet (.06, .15, and .30 m) were used. Figure 2 shows a Lagrangian x-t diagram which depicts the details of the wave propagation in the bars and indicates how the experiment is performed. The striker bar is accelerated against bar No. 1, the impact generating a compression pulse whose amplitude depends on the striker velocity and whose length is twice the longitudinal elastic wave transit time in the striker bar. The pulse travels down the bar until it reaches the specimen. The threaded tensile specimen of Figure 3 is attached to the two pressure bars as shown in detail "A" of Figure 1. After the specimen has been screwed into the two bars, a split shoulder is placed over the specimen and the specimen is screwed in until the pressure bars are snug against the shoulder. The shoulder is made of the same material as the pressure bars, has the same outer diameter of 0.5"(12.7 mm), and has an inner diameter just sufficient to clear the specimen of .25" (6.4 mm). The ratio of the cross-sectional area of the shoulder to that of the pressure bars is 3:4 while the ratio of the area of the shoulder to the net cross-sectional area of the specimen is 12:1. The compression pulse travels through the composite cross-section of shoulder and specimen in an essentially undispersed manner. The tightening of the specimen by twisting the pressure bars, the relatively loose fit of the threaded

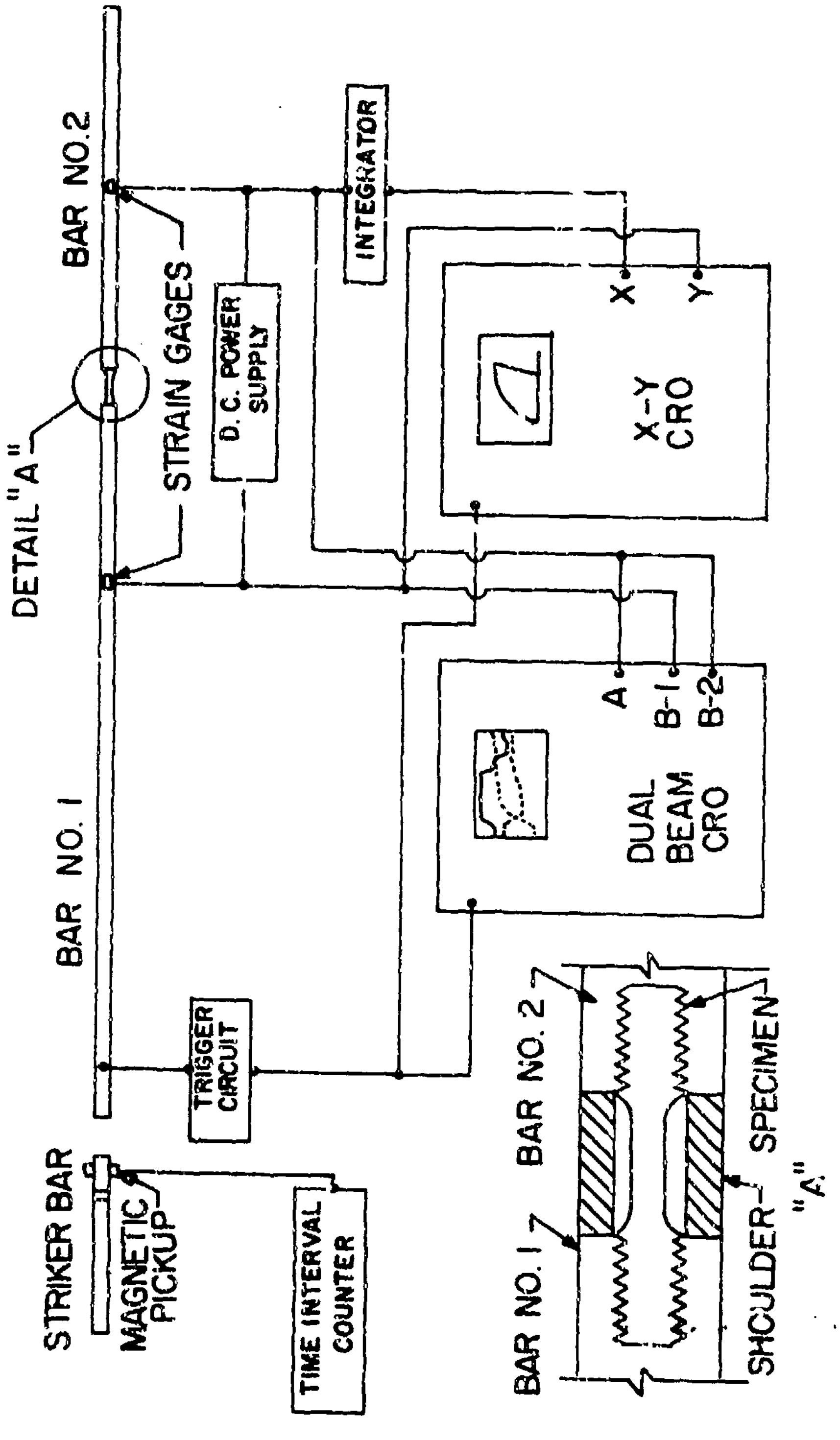



Figure 1. Schematic of Apparatus and Instrumentation

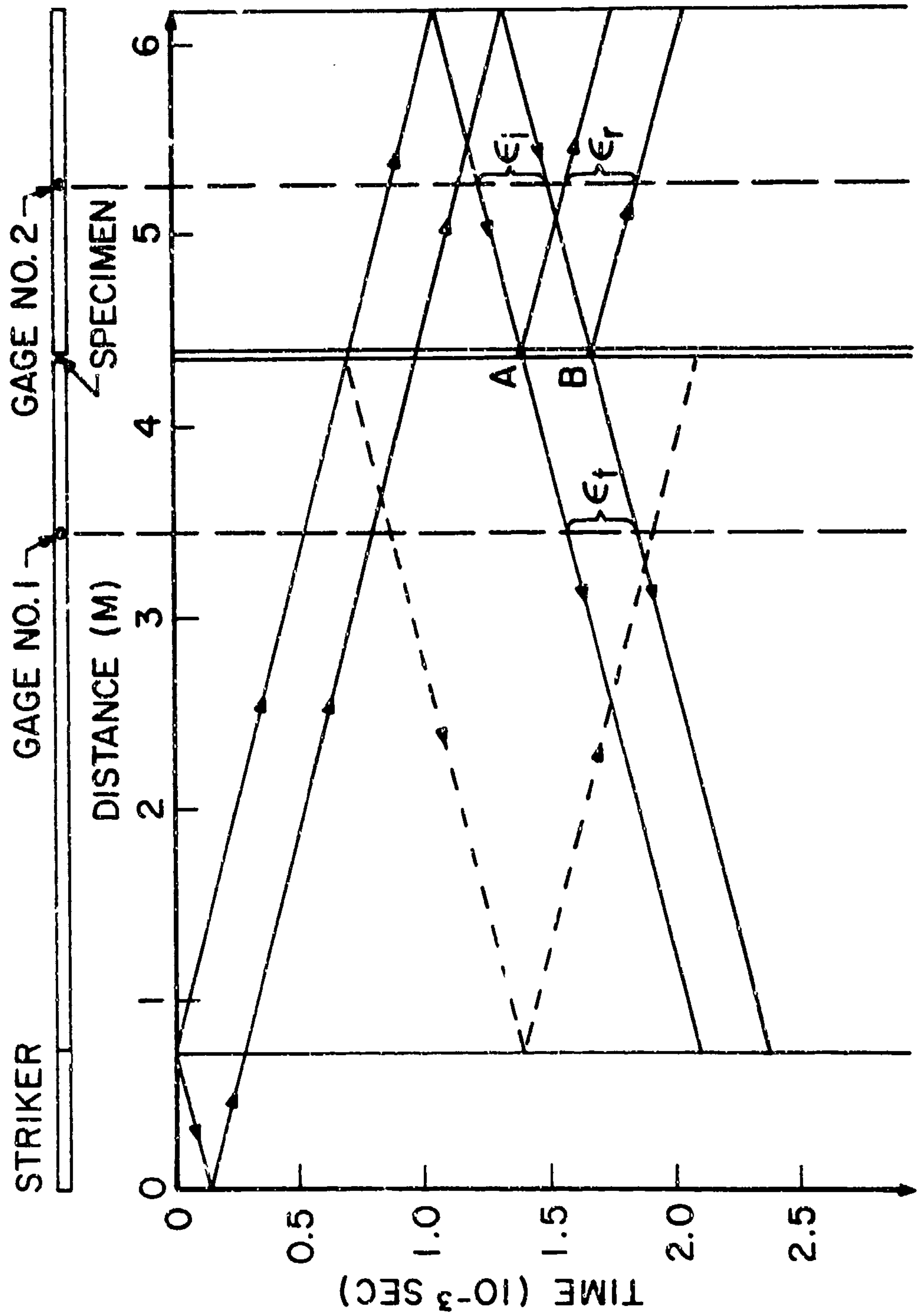
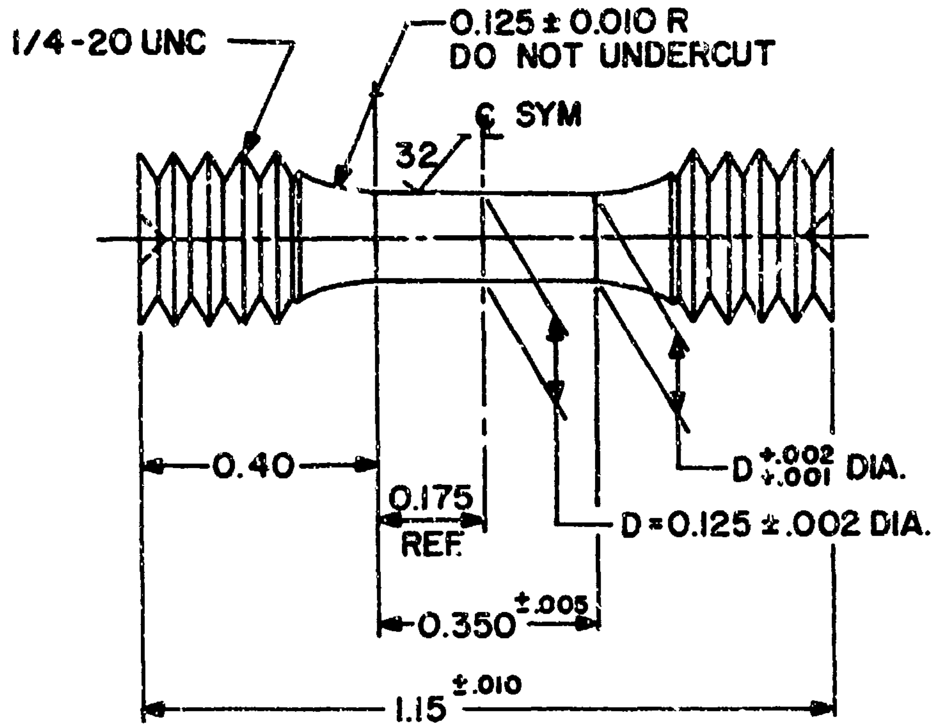



Figure 2. Lagrangiar x-t Diagram




NOTES:

1. ALL DIMENSIONS IN INCHES AFTER ETCHING
2. FINAL MACHINING CUT NOT TO EXCEED 0.003"
3. ETCH TO REMOVE 0.004" ± .0005" (.008" ON DIA.)
4. FINISH REQUIREMENT MUST BE MET AFTER ETCHING

THREADED TENSION HOPKINSON BAR SPECIMEN (BE)

Figure 3. Specimen

joint of the specimen into the bars, and the large area ratio of shoulder to specimen all help to insure that no compression beyond the elastic limit is transmitted to or through the specimen. In effect, the entire compression pulse passes through the supporting shoulder as if the specimen were not present. Referring again to Figure 2, the compression pulse continues to propagate until it reaches the free end of bar No. 2. There, it reflects and propagates back as a tensile pulse, shown as $\varepsilon_i$, as it passes gage No. 2. The tensile pulse, upon reaching the specimen at point A, is partially transmitted through the specimen ($\varepsilon_t$) and partially reflected back into bar No. 2 ($\varepsilon_r$). Note that the shoulder, which carried the entire compressive pulse around the specimen, is now unable to support any tensile loads because it is not fastened in any manner to the bars.

In performing the experiments, a tight fitting nylon cylinder or collar, approximately 6" (150 mm) long, is slipped over the split shoulder around the specimen and the two ends of the Hopkinson bars to insure accurate axial alignment. It was found that this technique was necessary because the threads of the beryllium specimen will not insure axiality since there is always some play between specimen and bar even when screwed in fully. The tightening of the specimen against the split shoulder, in addition to the use of a nylon alignment collar, insures a snug interface and accurate axial alignment. In all of the Hopkinson bar tests where specimens were loaded to failure, the failure was always within the gage section, generally within one diameter of the center of the specimen. No failures were experienced at the fillet radii of the specimen or in the threaded section.

The experimental setup at the instant the tensile pulse is reflected from the free end and starts to propagate back down the bar is identical to the compression split Hopkinson bar apparatus except for the change in sign of the loading pulse and the use of a threaded joint to attach the specimen as opposed to the use of a cylindrical compression specimen. In essence, the shoulder is no longer there. Referring to the incident tensile pulse as $\varepsilon_i$, the pulse transmitted through the specimen and down bar No. 1 as $\varepsilon_t$ and the reflected pulse $\varepsilon_r$, the Hopkinson bar equations are identical to those of the compression test (see References 2 and 3).

$$u_s = -2c \int_0^t \varepsilon_r dt \qquad (1)$$

$$F_s = EA\varepsilon_t \qquad (2)$$

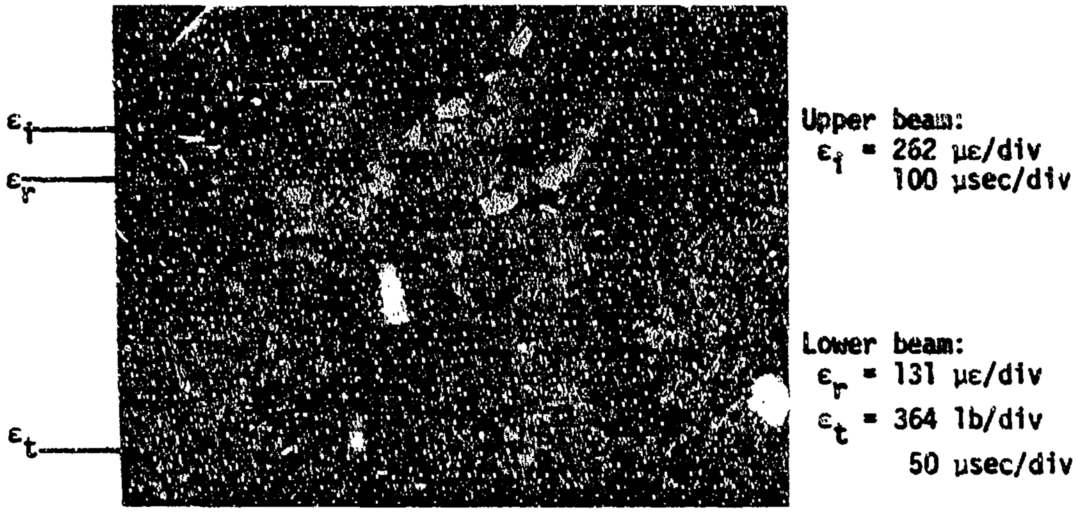
where $u_s$ is displacement in the specimen, $F_s$ specimen force, c the longitudinal wave speed in the bar, E Young's modulus, and A the cross-sectional area of the pressure bar.

The strain gage bridge on bar No. 2 is located at the center of that bar while the gages on bar No. 1 are at the quarter point, precisely equidistant from the specimen as gage No. 2. In this manner, the transmitted and reflected pulses are time coincident (see Figure 2).

The striker and pressure bar lengths have been chosen so that no spurious reflections interfere with the three pulses being recorded during the experiment ($\varepsilon_i$, $\varepsilon_r$, and $\varepsilon_t$). Referring again to the wave diagram of Figure 2, it can be seen that the entire compression pulse traveling down the bars due to the striker bar impact has passed gage No. 2 before the tensile pulse, $\varepsilon_i$, arrives at the gage. In a similar manner, the complete incident pulse, $\varepsilon_i$, passes the gage befo reflected pulse, $\varepsilon_r$, arrives. The first pressure bar has been chosen very long to avoid any strain gage signals due to possible small wave reflections from the shoulder and specimen interface interfering with the recording of the transmitted pulse, $\varepsilon_t$, with gage No. 1. That possible reflection is shown as a dashed line in the wave diagram. The entire tensile loading of the specimen takes place between points A and B in the wave diagram.

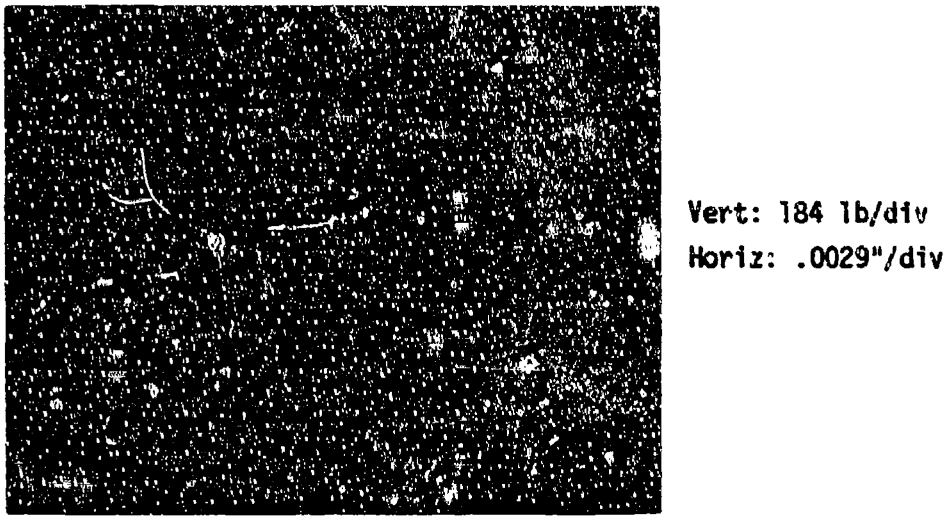
The two pressure bars are each instrumented with two active arm strain gage bridges, to cancel bending, which are powered by a stable DC power supply. The three pulses, $\varepsilon_i$, $\varepsilon_r$, and $\varepsilon_t$, are recorded on a dual-beam oscilloscope by delaying the second beam with respect to the first by an amount equal to the wave transit time between the strain gage bridges. The two traces, $\varepsilon_r$ and $\varepsilon_t$, which are time coincident by virtue of the placement of the gages equidistant from the specimen, are recorded by using the chopped mode of the oscilloscope preamplifier. A typical set of strain gage traces is shown in Figure 4a.

An X-Y oscilloscope is used to record directly a load-displacement curve. The signal from gage No. 2 is electronically integrated and fed to the X axis of the oscilloscope. The signal from the other gage, proportional to load in the specimen, is fed to the Y axis. Displacement rate is proportional to the reflected pulse, $\varepsilon_r$, and is obtained from the dual-beam oscilloscope trace by virtue of Equation (1). A typical X-Y photo is shown in Figure 4b.




(a)

Specimen No. UCAR DD-6




(b)

Figure 4. Typical Oscilloscope Photos

The strain gage bridges each consist of two active elements placed diametrically opposite to cancel bending waves should any be present. Strain gage calibration is performed by measuring the velocity of the striker bar and recording the signal from the resulting pulse on both strain gage bridges. Since the striker and pressure bars are of the same material and same cross-section, the resulting strain amplitude due to a striker velocity v is

$$\varepsilon = \frac{v}{2c} \tag{3}$$

The longitudinal wave velocity, c, is obtained experimentally by accurately measuring the wave transit time in the bar as a pulse reflects back and forth using a time mark generator for the time base measurement. Density is also determined experimentally, and Young's modulus is calculated from

$$E = \rho c^2 \tag{4}$$

The horizontal axis of the X-Y oscilloscope, which records the time-integral of the strain pulse from gage No. 2, is also calibrated dynamically by sending a pulse of known amplitude and time duration down the bars. The amplitude is determined from the measured striker velocity from Equation (3); the time duration is twice the wave transit time in the striker bar.

All data were recorded on Polaroid film from the two oscilloscope displays and reduced digitally with the aid of a Hewlett Packard Model 9820 calculator, digitizer, and plotter system.

## SECTION III

## MATERIALS AND EXPERIMENTS

Three structural grades of beryllium were tested in this investigation, each one being a controlled purity grade consolidated by a different process. P-1 grade beryllium was consolidated by Battelle Columbus Laboratories (BCL) from high purity electrolytic refined P-1 powder obtained from Kawecki Berylco Industries (KBI), using the cold isostatic pressing-hot isostatic pressing (CIP/HIP) process described in Reference 7. S-65 grade beryllium obtained from Brush Wellman Inc. (BW) was fabricated by hot pressing low oxide chemically purified impact pulverized powder. Union Carbide Corporation, Linde Division (UCAR) supplied samples of beryllium fabricated by plasma spraying and sintering a blend of powders obtained from KBI, designated DD to denote the blend and sintering treatment. The chemistries of the three grades of beryllium are presented in Table I. Note that two different batches of P-1 powder were consolidated for this program. The first batch, designated BCL-VS, was pressed into the shape of a hollow cylinder approximately 12" (.3 m) high, 8" (.2 m) diameter, with a wall thickness of approximately 1" (25 mm). The second batch, designated DC-1, was formed on a mandrel into the frustum of a cone approximately 30" (.76 m) long, having fore and aft diameters of 6" (.15 m) and 12" (.3 m), respectively, and a nominal wall thickness of 1" (25 mm). Specimens were machined from 2" (50 mm) high sections cut from the fore (F) and aft (A) ends of the frustum and are thus designated as DC-1F and DC-1A, respectively. All specimens of P-1 beryllium were machined so that their axes were parallel to the axis of the cylinder of frustum; these are normally referred

TABLE I

BERYLLIUM CHEMISTRY

(Weight Percent)

| | P-1 | | | |
|---|---|---|---|---|
| | VX | DC-1 | S-65 | DD |
| BeO | 0.52 | 0.65 | 0.80 | 1.45 |
| C | .02 | .026 | .03 | .021 |
| Fe | .026 | .015 | .07 | .083 |
| Al | .0056 | .003 | .03 | .007 |
| Mg | .0045 | .001 | .01 | |
| Si | .0073 | .004 | .02 | .024 |
| Cr | .0016 | | | .011 |
| Cu | .005 | | | .015 |
| Mn | .0017 | | | .019 |
| Ni | .0175 | | | .020 |
| Ti | | | | .011 |

to as the longitudinal or axial directions of the material. The specimens from the DC-1 pressing were used to obtain design data for a structural component fabricated from the remainder of the billet and subsequently tested under dynamic loading conditions. Since the worst loading conditions on the structure happened to be in the axial directions, the specimens were chosen with that orientation.

The S-65 grade beryllium specimens were cut from a pressing (No. 0902) approximately 26" (0.66 m) high and 17" (0.43 m) diameter. The specimens were oriented with their axes in the transverse direction, i.e., in a direction in a plane normal to the axis of the cylinder or pressing direction. This (transverse) is generally the direction of maximum elongation in hot pressed beryllium and was chosen to study the effect of strain rate on the elongation with maximum accuracy. There was no attempt made to compare one grade against another but rather just to examine the rate phenomenon in several different materials and to develop and demonstrate the experimental technique. The highest elongation direction permitted the experiment to take place over the longest period of time at a given high strain rate.

The plasma consolidated beryllium samples, DD, were obtained from a thick-walled hollow cylindrical billet and were oriented with their axes in the longitudinal or axial direction, again for maximum elongation in that material. Limited experience has shown that elongations in the circumferential and axial directions in plasma consolidated beryllium are essentially the same, only the radial direction showing some decrease in elongation to failure.

The specimens were machined in accordance with the dimensions, tolerances, and specifications of Figure 3, and were provided by the producers in fully machined and etched condition. Several specimens from each batch were strain gaged with a 0.062" (1.6 mm) length gage and tested quasi-statically to failure. In addition to load-strain and load-deflection recordings on X-Y plotters, a deflection-strain plot was obtained in each case. The deflection-strain plots were compared for the three different materials and found to be nearly identical. Several least-square fitting attempts resulted in obtaining an equation

$$\varepsilon = .265\delta - .5(1-\exp^{-.55\delta}) \qquad (5)$$

which closely represents all the strain-deflection data obtained on the three different grades of beryllium. In this equation, $\varepsilon$ represents the strain in percent, and $\delta$ represents the deflection in mils (.001") between the grips which are identical in size to the threaded ends of the Hopkinson bars as shown in Figure 1. The strain-deflection plot, shown in Figure 5 and represented by Equation (5) above, was used in all subsequent experiments to calculate strain from experimentally observed deflections. In this manner, the tedious task of bonding small strain gages on each sample was eliminated. In addition, the Hopkinson bar tests could be performed in a manner where a load-deflection trace was obtained directly and this, in turn, could easily be transformed into a stress-strain curve in the data reduction with the aid of a digitizer. It was determined that strains could be obtained to an accuracy of better than ±5 percent using this procedure for strains up to 0.03. There was no verification of the strain-deflection curve beyond 0.03

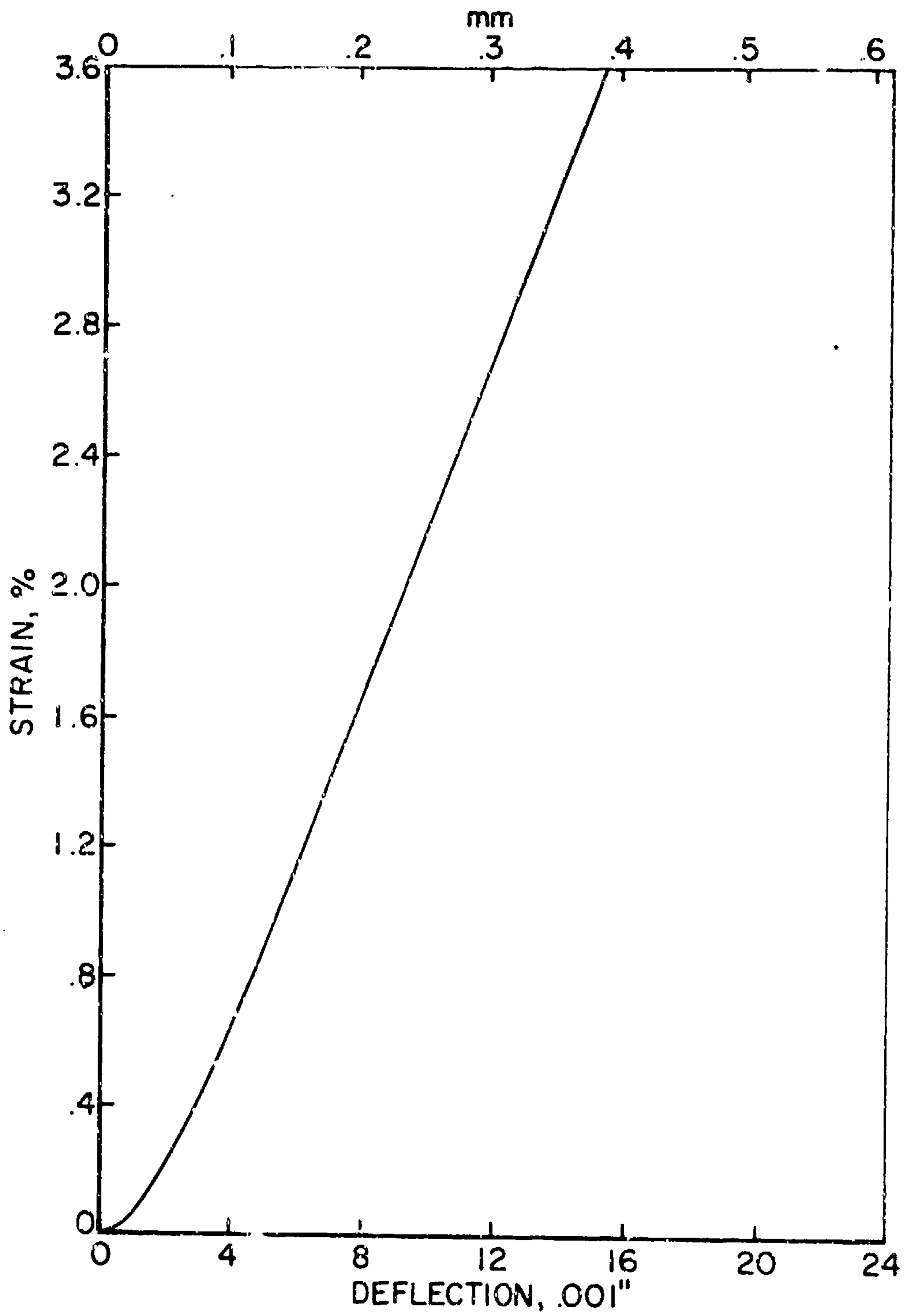



Figure 5. Strain-Deflection Relationship

strain because the strain gages peeled off the beryllium at larger strains in the static tests. Except for very small strains, the strain-deflection curve is linear as can be seen in Figure 5. The linear portion of the curve corresponds to an effective gage length of approximately 0.38" (9.6 mm) compared to a true gage length of 0.35" (8.9 mm) as shown in Figure 3. The difference is due obviously to the strain contribution of the portion of the specimen outside the points of tangency of the fillet radii and appears quite reasonable.

Quasi-static tests were run on an MTS servo-controlled hydraulic testing machine over a range of cross-head velocities corresponding to strain rates from approximately $10^{-4}$ $sec^{-1}$ up to 10 $sec^{-1}$. Although higher velocities could be achieved with the machine, no meaningful data could be obtained because of inertia effects and load cell ringing. Load was recorded on the MTS load cell while deflection was recorded using an LVDT mounted on a special fixture which was made to hold the specimen in perfect alignment. Load versus deflection was recorded on an X-Y plotter at the lower loading rates and on an X-Y oscilloscope at the higher MTS machine rates. Strain rate was obtained from the (constant) cross-head deflection rate as measured separately with the LVDT output against time using the linear portion of the strain-deflection curve, i.e., an effective gage length of 0.38" (9.6 mm).

High rate, split Hopkinson bar tests were conducted over a range in strain rates from approximately 100 to 500 $sec^{-1}$. The lowest strain rate obtainable is governed by the total time available for the test corresponding to AB in Figure 2. This is the total time of the loading pulse, which is twice the wave transit time in the striker bar of approximately 300 μsec. Since $\varepsilon = \dot{\varepsilon}t$, an average strain rate, $\dot{\varepsilon}$, of 100 $sec^{-1}$ for 300 μsec corresponds to a total strain of .03 in the specimen. Since the upper limit of t is fixed in the experiment by the length of the striker bar, continual decreasing of $\dot{\varepsilon}$ will eventually reach a loading condition where failure of the specimen will not be achieved. The upper limit of strain rate of 500 $sec^{-1}$ was governed by practical considerations including the rise-time of the loading pulse, the maximum pulse amplitude governed by the strength of the input bars and, most important, the split shoulder configuration. At the highest loading rates, wave reflections and interactions started to obscure the experimental data.

# SECTION IV

# RESULTS AND DISCUSSION

Typical stress-strain curves are shown in Figure 6 for P-1 beryllium and in Figure 7 for DD and S-65 beryllium. The average strain rates are shown in parenthesis next to each curve. In some cases a single curve best represents a range of strain rates because of the scatter and the oscillations from wave reflections present in the curves at the highest strain rates. Note that the elastic region of the high rate curves is not shown. This is because during the first few wave reflections in a Hopkinson bar test stress equilibrium through the specimen is not achieved. Thus, the data near the origin have no significance. This point is more fully discussed in Reference 3 for the case of compression testing and in Reference 6 for tensile testing of beryllium. It can be seen from Figures 6 and 7 that the flow stress increases as a function of strain rate for all grades of beryllium tested. The ultimate tensile strength is plotted as a function of strain rate in Figures 8 and 9 which show this trend of increasing strength with increasing strain rate. This is significant from a design point of view for impulsively loaded structures when stress dependent failure criteria are used. It can be seen, however, that the experimental scatter is much more pronounced at higher rates of strain. The scatter is mainly in the value of strain to failure and not in the shape of the stress-strain curves. This can be seen more clearly in Figures 10 and 11 where strain to failure is plotted as a function of strain rate. In these, and the previous two figures, arrows indicate a lower bound of stress or strain obtained from Hopkinson bar tests where

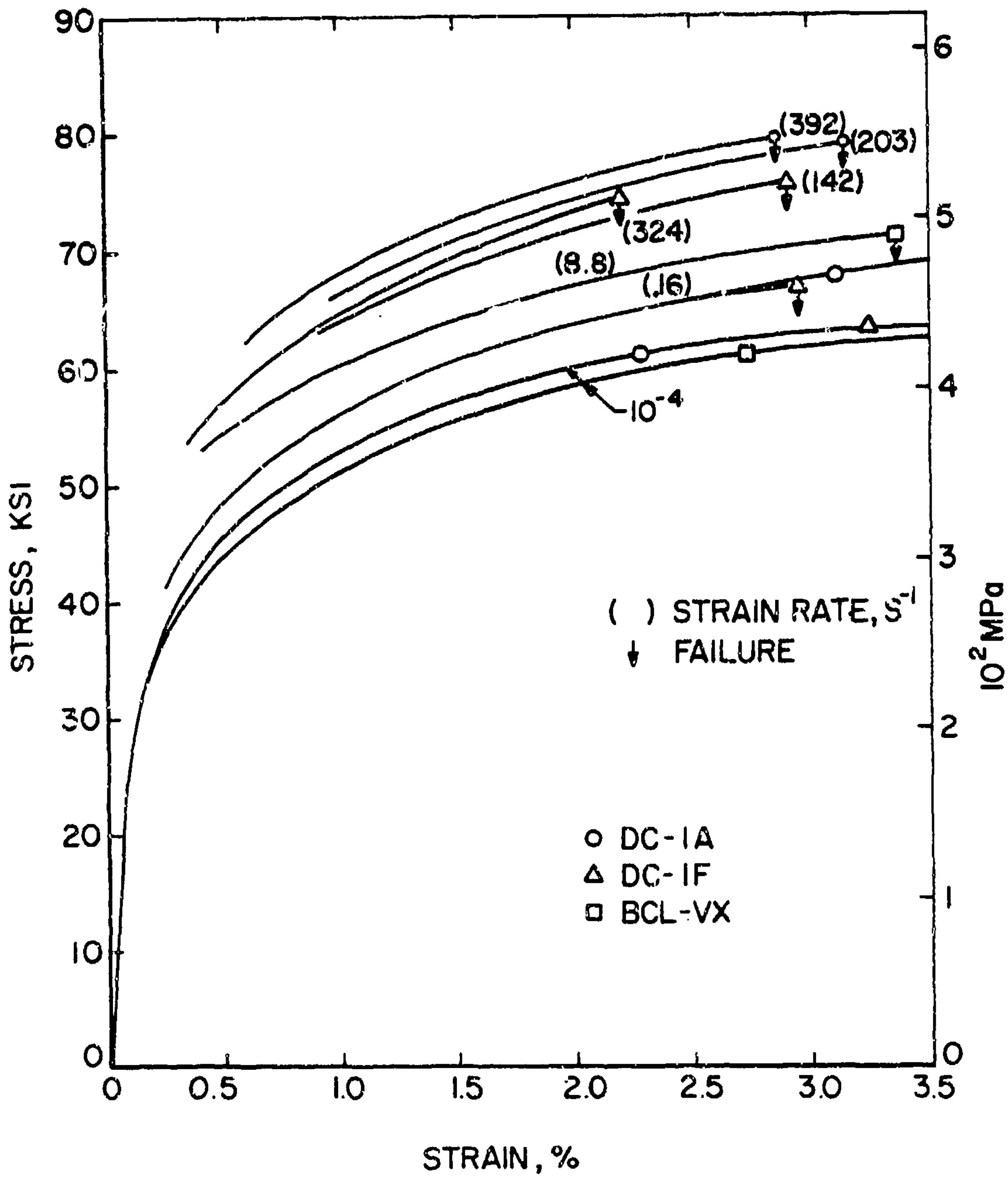



Figure 6. Typical Stress-Strain Curves, P-1 Beryllium

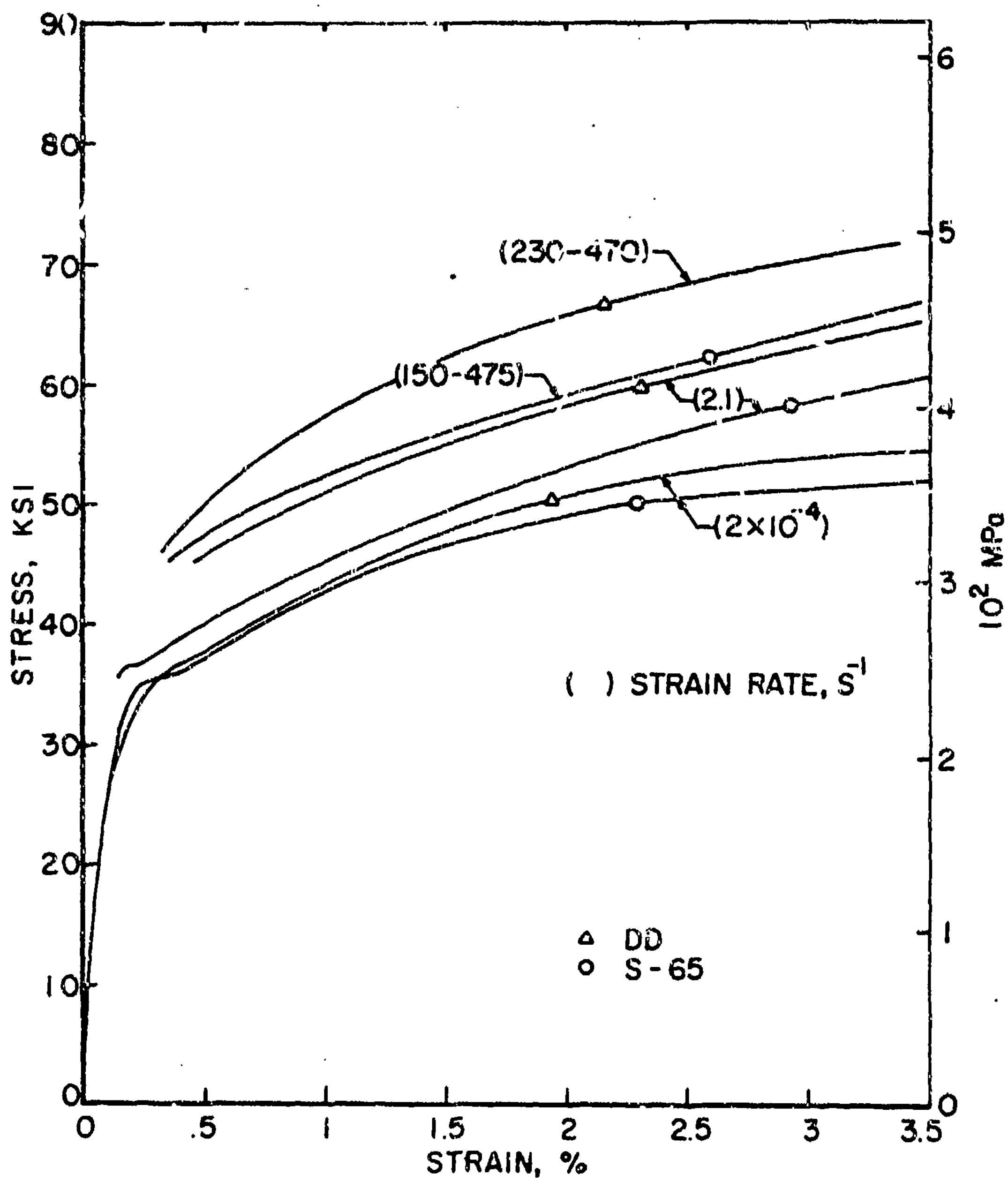



Figure 7. Typical Stress-Strain Curves, DD, S-65 Beryllium

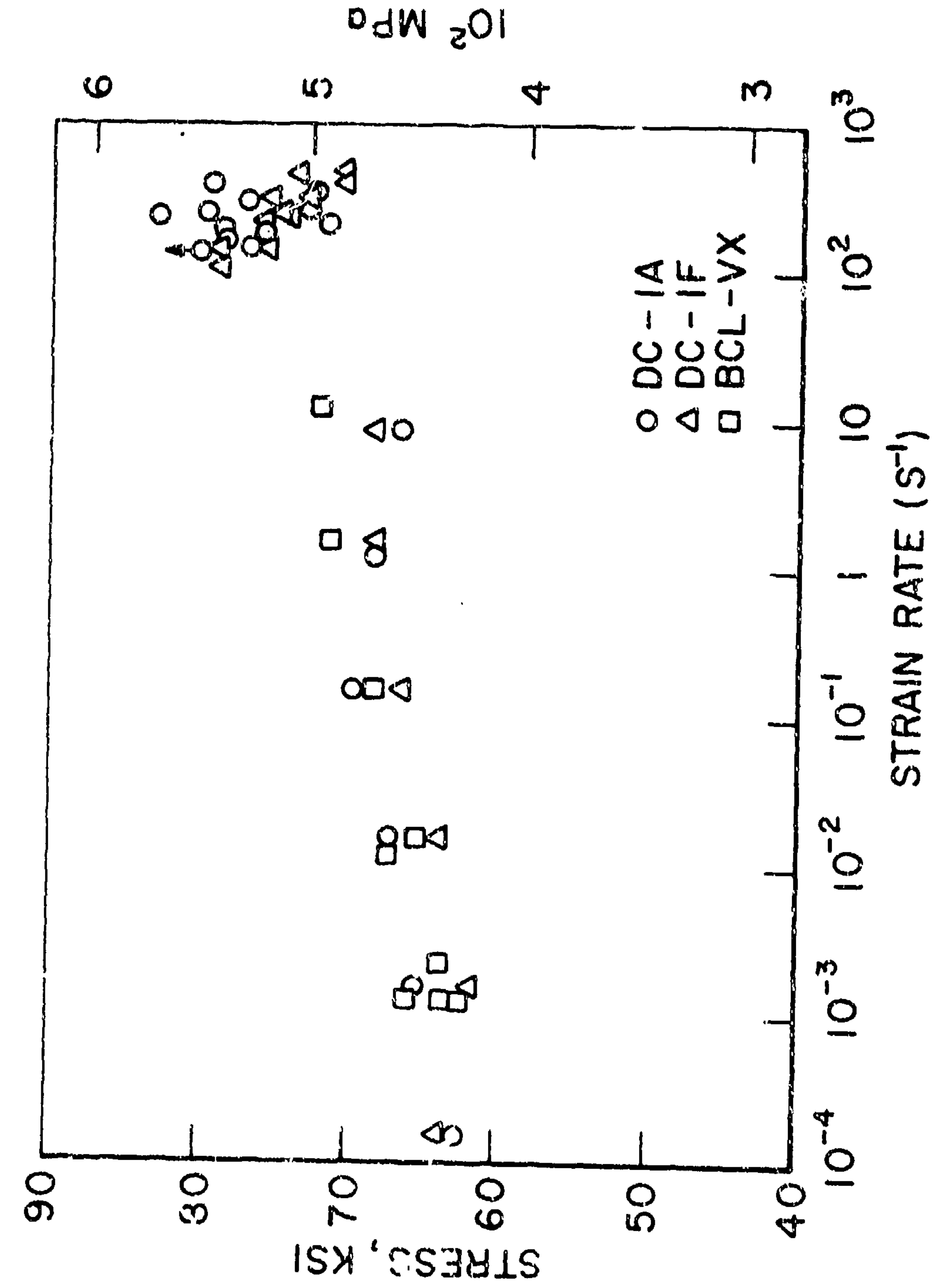



Figure 8. Ultimate Tensile Strength versus Strain Rate, P-1

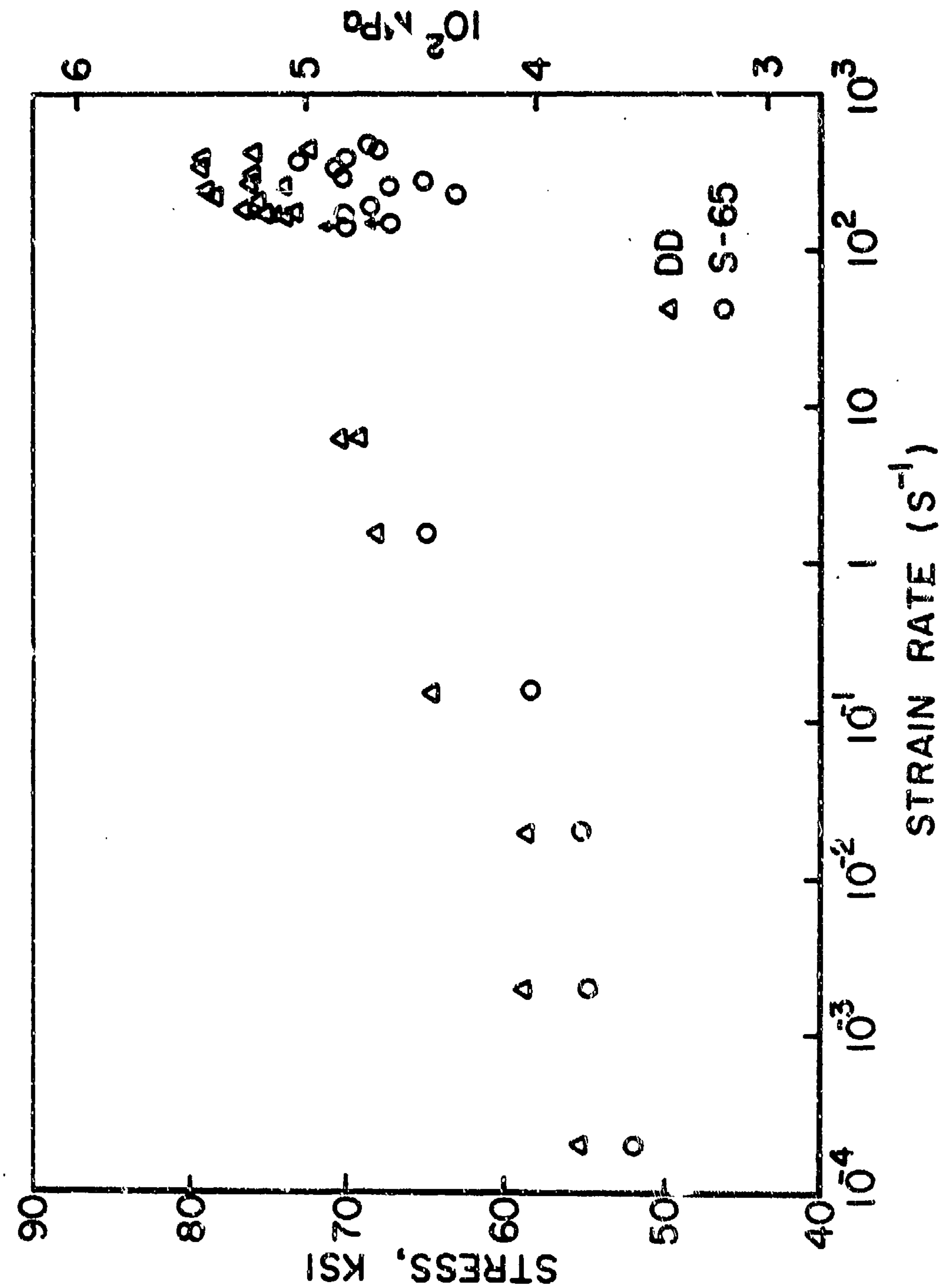



Figure 9. Ultimate Tensile Strength versus Strain Rate, DD, S-65

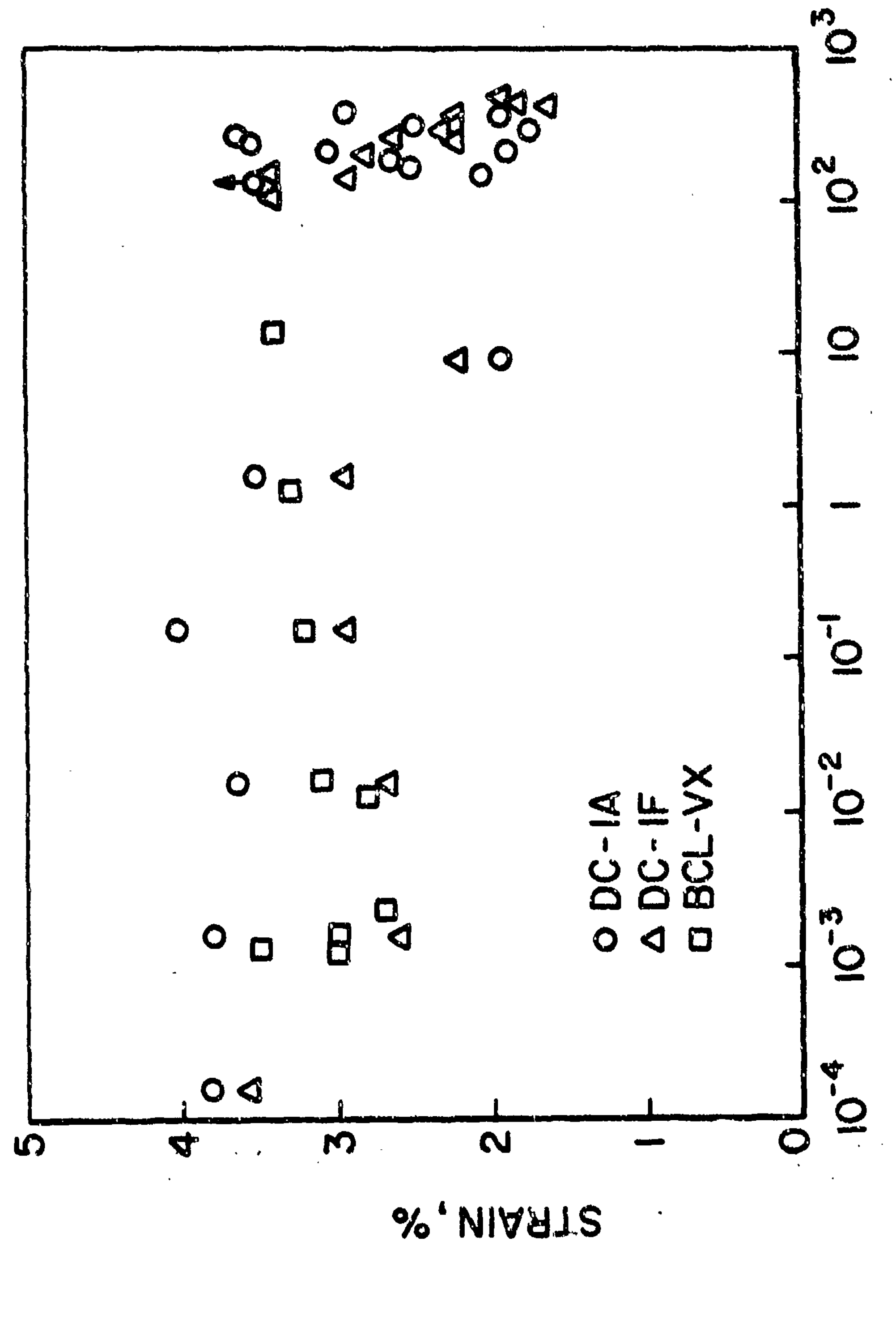



Figure 10. Strain to Failure versus Strain Rate, P-1

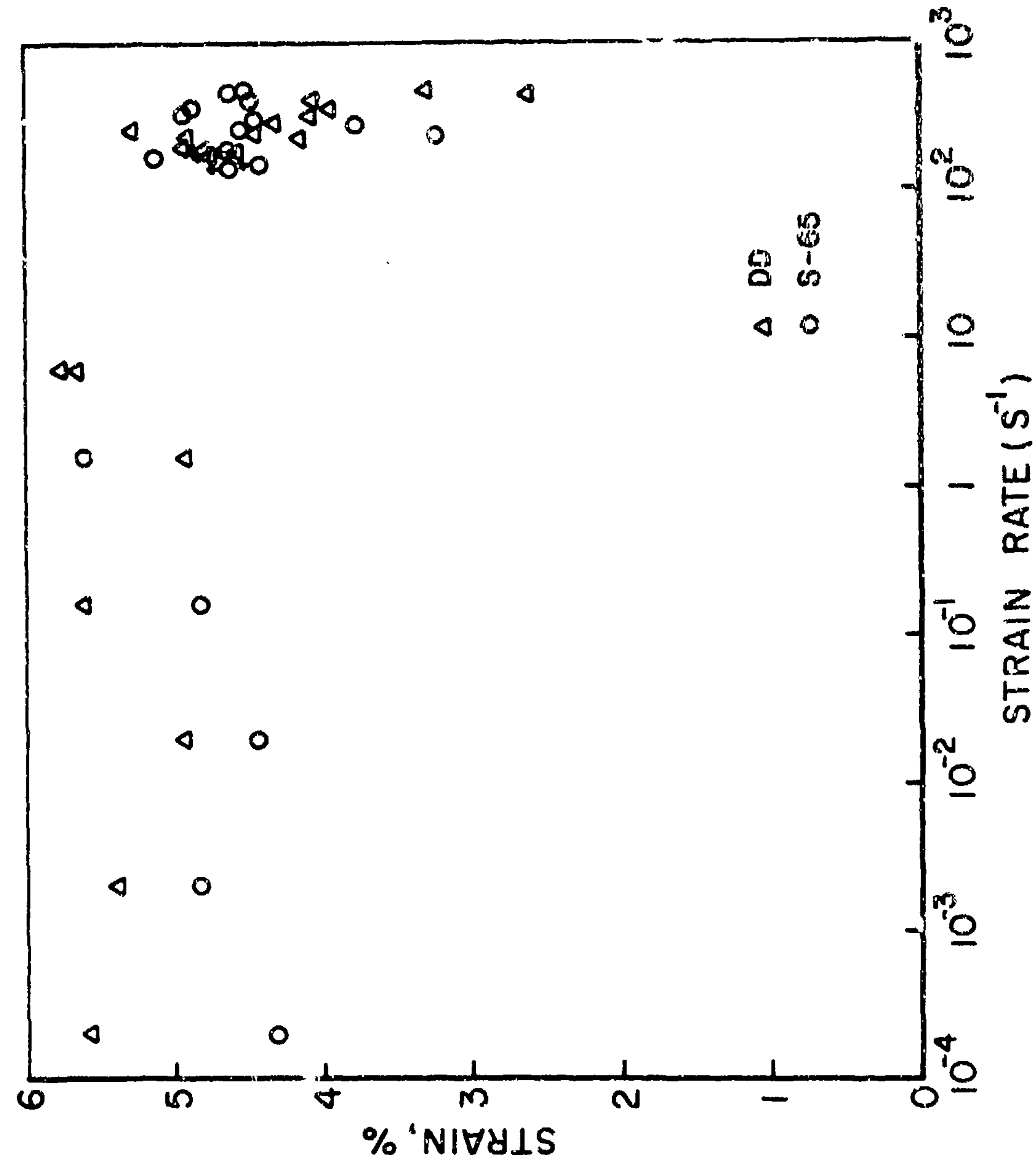



Figure 11. Strain to Failure versus Strain Rate, DD, S-65

the specimen did not fail because of insufficient energy in the loading pulse. The scatter in strain to failure is quite large, especially at the high rates of strain. Whether this represents a significant strain rate effect at very high rates of strain, i.e., a tendency towards brittle behavior at some limiting strain rate, or simply material scatter, is not clear from the figures. What is significant, however, is that no brittle failures were observed in any tests at high rates of strain up to nearly 500 $sec^{-1}$. No tests were conducted at any higher rates. The minimum strain seen in any individual test was approximately 1.6 percent for P-1, 2.6 percent for DD, and over 3 percent for S-65. Note, again, the preferred specimen orientation used for both DD and S-65 grades, making comparisons with P-1 unrealistic. These minimum observed strains are for three materials and orientations; P-1, DD, and S-65, which have nominal quasi-static elongations to failure of approximately 3, 4, and 4.5 percent, respectively, in these tests. Thus, strain rates up to 500 $sec^{-1}$ have succeeded, at most, in reducing the strain to failure to half the quasi-static value. This observation certainly has to be encouraging to designers who have worried about the "brittle" behavior of beryllium at high rates of strain, especially since the elastic strains in these grades of beryllium are less than 0.2 percent.

To further investigate the possibility of a limiting or transition strain rate beyond which brittle behavior might be encountered, the data for ultimate stress and strain to failure are replotted for only the Hopkinson bar tests, which cover an approximate range from 100 to 500 $sec^{-1}$, in Figures 12 and 13. In this expanded plot, one can see a

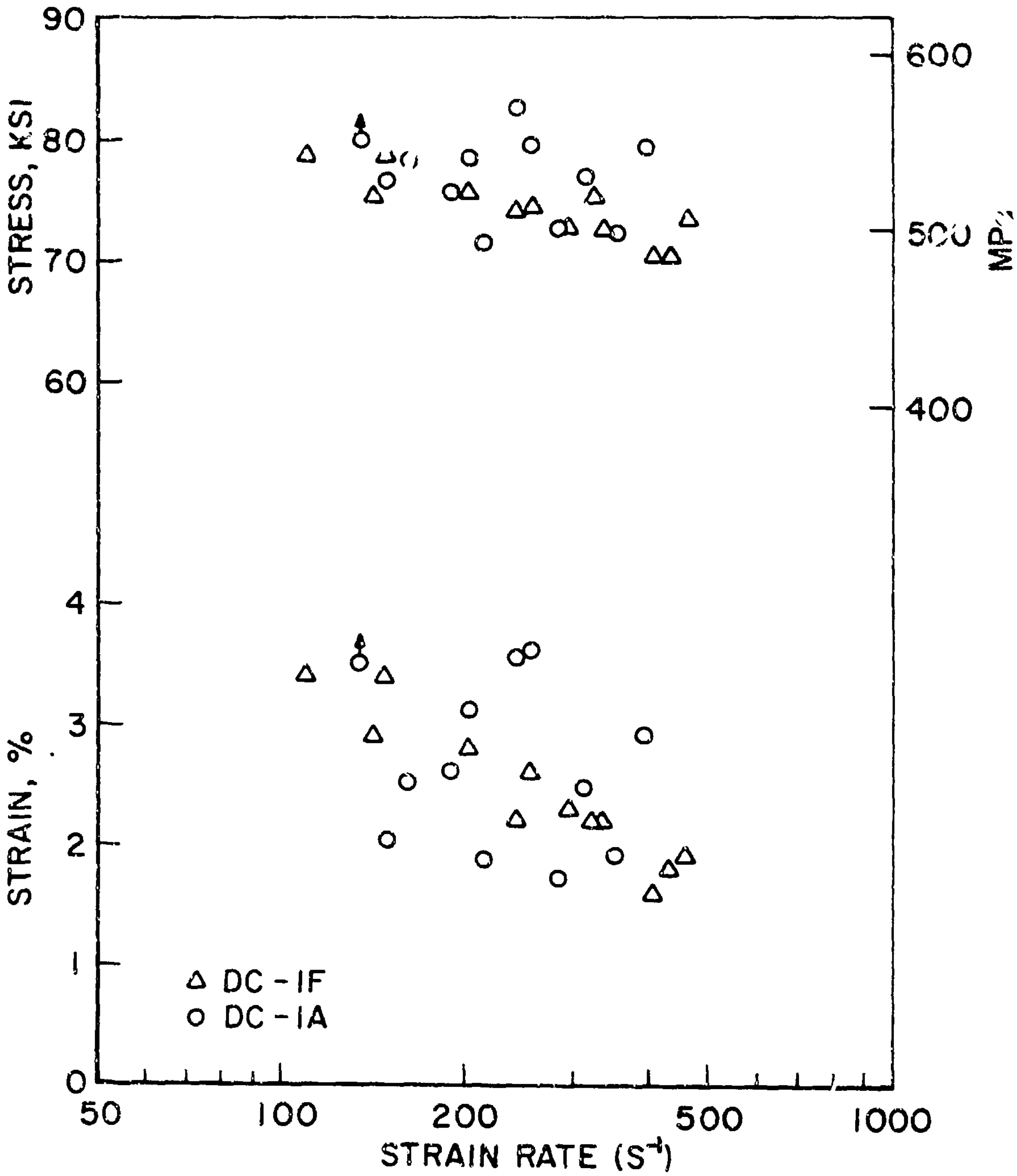



Figure 12. High Strain Rate Data, P-1

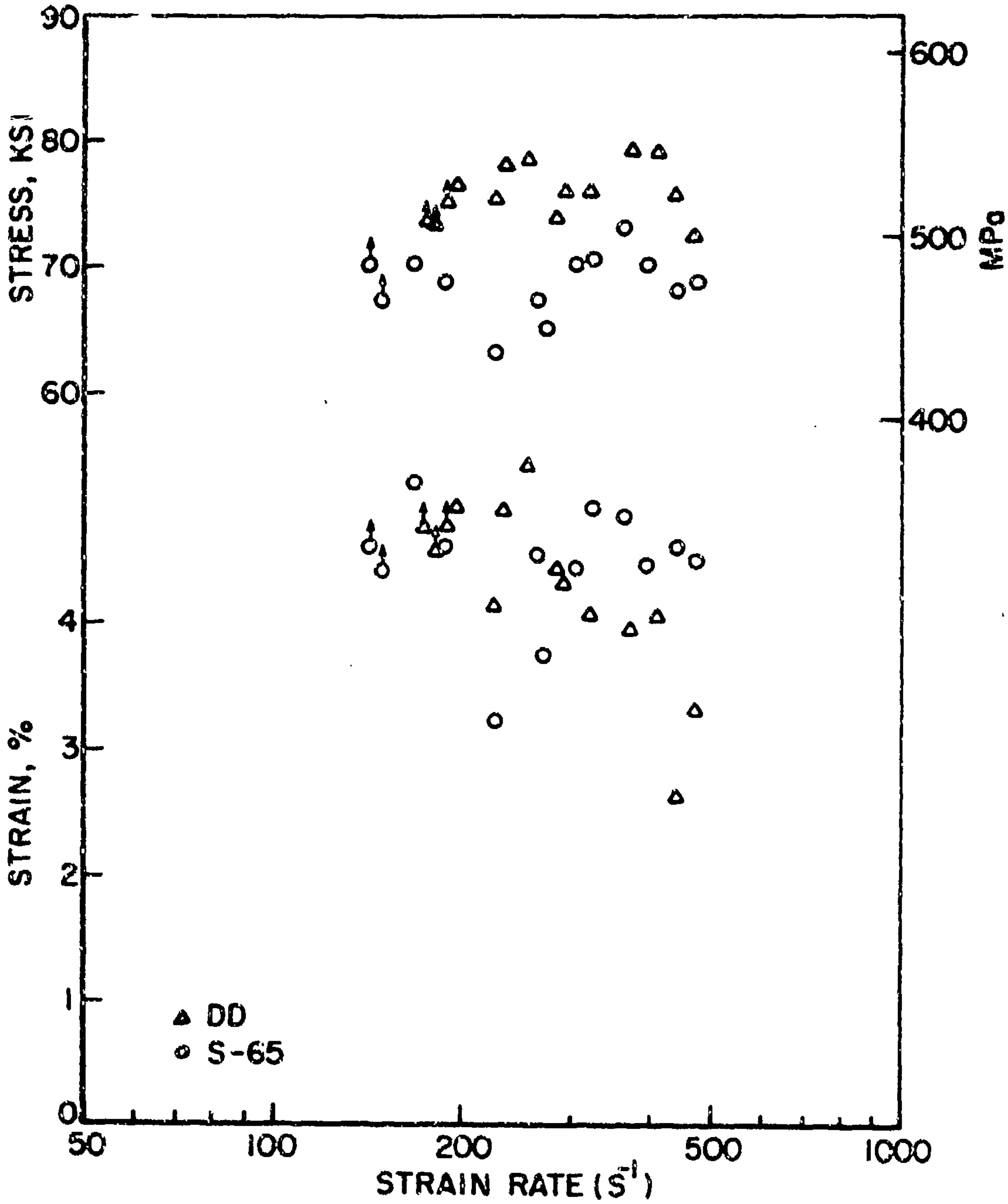



Figure 13. High Strain Rate Data, DD, S-65

possible trend of decreasing strain to failure with increasing strain rate for P-1 and DD grades of beryllium, while such a trend is not apparent for S-65. However, the scatter in the data appears to be as significant, if not more so, than a possible trend towards brittle behavior at higher rates of strain. At this point, it is extremely difficult to extrapolate the existing data to determine what the uniaxial tensile properties of beryllium are like at strain rates greater than 500 $sec^{-1}$.

From the individual stress-strain curves for each test, the flow stress at an arbitrary value of $\varepsilon = 0.02$ was obtained and plotted in Figure 14 for each of the three grades as a function of strain rate. This is a more realistic and accurate method of representing the rate sensitivity of a material than plotting ultimate stresses or strains. It gives a clearer picture of the change in the stress-strain or flow stress behavior of the material and can often be used to deduce the rate controlling processes in a material. It can be seen that flow stress increases linearly with (log) strain rate over the range of strain rates from $10^{-4}$ to approximately 1 to 10 $sec^{-1}$. At higher strain rates, the strain rate sensitivity or rate of increase of stress with (log) strain rate appears to increase. This observation is consistent with the results of previous investigations on S-200E hot pressed black beryllium [Reference 6] both qualitatively and quantitatively. It is to be noted that the degree of rate sensitivity is approximately equal for all three grades tested in this program. The information obtained on the degree of rate sensitivity of the flow stress should be of use in modelling the strain-rate sensitive behavior of beryllium for design and analysis purposes.

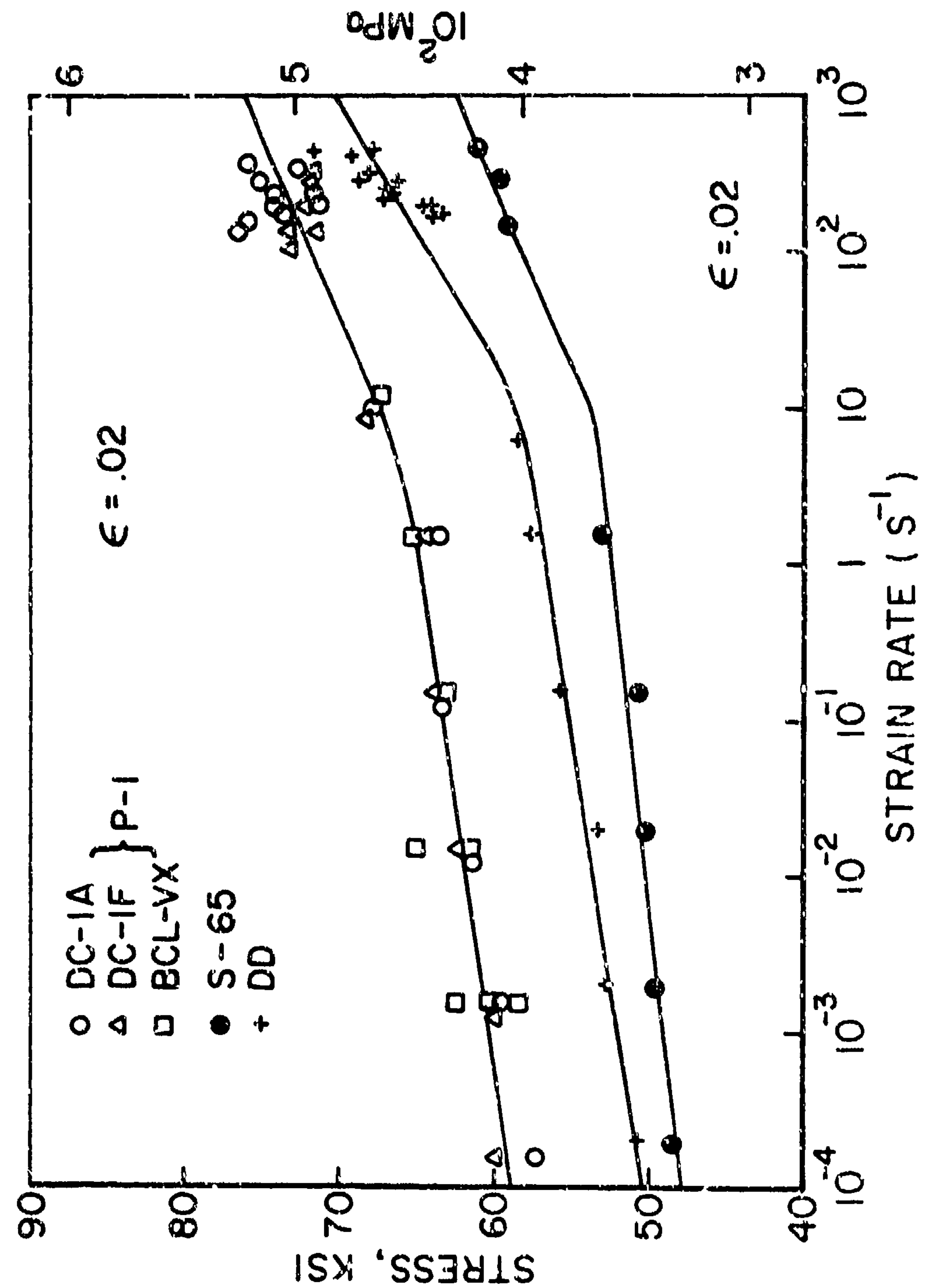



Figure 14. 0.2% Flow Stress versus Strain Rate

Based on the results presented herein, it is felt that the split Hopkinson bar technique described can be a valuable tool for obtaining data on high strain rate uniaxial tensile properties of materials with limited ductility. Although the range of strain rates obtained is rather narrow, it allows the obtaining of data in a region of strain rates where data are scarce, or often non-existent. The data obtained in this investigation were subsequently used in the design and analysis of a dynamic structural response experiment and have made possible the further definition of the dynamic load carrying capabilities of advanced structural grades of beryllium.

# REFERENCES


1. H. Kolsky, "An Investigation of the Mechanical Properties of Materials of Very High Rates of Loading", Proc. Phys. Soc., B 62, 676-700, 1949.

2. U. S. Lindholm, "Some Experiments with the Split Hopkinson Pressure Bar", J. Mech. Phys. Solids, 12, 317-335, 1964.

3. T. Nicholas and M. J. Sever, "Dynamic Compressive Strain Rate Tests on Several Grades of Beryllium", AFML-TR-74-224, Wright-Patterson AFB, Ohio, November 1974.

4. U. S. Lindholm and L. M. Yeakley, "High Strain-Rate Testing: Tension and Compression", Expt. Mech., 8, 1-9, 1968.

5. S. J. Green and F. L. Schierloh, "Uniaxial Stress Behavior of S-200 Beryllium, Isotropic Pyrolytic Boron Nitride, and ATJ-S Graphite at Strain Rates to $10^3$/sec. and 700°F", Report No. MSL 68-11, Manufacturing Development, General Motors Technical Center, Warren, Michigan, March 1968.

6. F. L. Schierloh and S. G. Babcock, "Tensile Properties at High Strain Rates and Temperatures", AFML-TR-69-273, Wright-Patterson AFB, Ohio, October 1969.

7. J. P. Denny, et al, "Manufacture of Beryllium Structures", AFML-TR-73-251, Wright-Patterson AFB, Ohio, November 1973.

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