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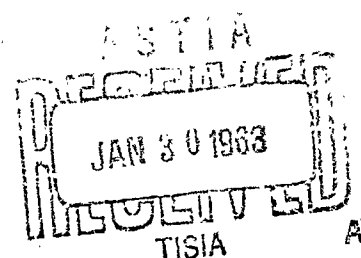
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SHEET METAL FORMING TECHNOLOGY

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Aeronautics and Missiles Division
CHANCE VOUGHT CORP.
A Division of Ling-Temco-Vought, Inc.
Dallas 22, Texas

Contract AF 33(657)-7314
ASD Project No. 7-871



Interim Technical Engineering Report
1 October 1962 to 31 December 1962

The purpose of this project is to determine the inherent limitations of sheet metal forming processes, to develop the knowledge to significantly advance these and to recommend the manner in which this can be accomplished. This report represents the results of the fourth period, consisting of three months, and covers the final experimental work on tensile testing and forming under combined conditions of high velocity, high temperature and high pressure. Results have been obtained on a projectile impact test fixture, a low-explosive closed system, a high-explosive open system, an electro-hydraulic open system, an electromagnetic system and conventional presses.

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AFSC Aeronautical Systems Division
United States Air Force
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December 1962

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The purpose of this project is to determine the inherent limitations of sheet metal forming processes, to develop the knowledge to significantly advance these, and to recommend the manner in which this can be accomplished. Principal areas of investigation are concerned with the effect that primary process variables such as velocity, temperature, and pressure have on various classes of metals and alloys. This report presents the results of the fourth period, consisting of three months, which covers the final experimental work on tensile testing and forming under combined conditions of high velocity, high temperature, and high pressure. Results have been obtained on a projectile impact test fixture, low explosive closed system, high explosive-open system, electro-hydraulic-open system, and electromagnetic system and conventional presses.

Results have been obtained for the available ductility for the various materials under combined conditions of velocity, temperature and pressure. In addition, optimum ranges of velocity have been obtained for each alloy and has been related to the high energy rate forming systems. This includes critical forming speeds beyond which negligible formability exists and immediately below which optimum formability usually exists.

Generally, the ultra high speed systems utilizing shock wave for forming produce superior formability when compared with lower speed systems such as low explosive and conventional presses. However, the formability of some materials has been found to be unimproved at these high velocities. Other materials, such as the titaniums and refractory metals, are not suitable for forming at high speeds except under suitable combined conditions with temperature.

FOREWARD

This Interim Technical Progress Report covers the work performed under contract AF 33(657)-7314 from 1 October 1962 through 31 December 1962. It is published for technical information only and does not necessarily represent the recommendations, conclusions, or approval of the Air Force.

This contract is being conducted by the Aeronautics and Missiles Division of the Chance Vought Corporation. It is entitled "Sheet Metal Forming Technology" and is being conducted under William W. Wood, Project Engineer. Others who participated in the research and in the preparation of the reports are: R. E. Goforth, Senior Manufacturing Research Engineer; J. R. Russell, R. A. Ford, D. L. Norwood, C. H. Cole Jr., C. R. Clifton, W. D. Moore, and W. A. Beck, all Manufacturing Research Engineers.

This contract was initiated by the Fabrication Branch, Manufacturing Technology Laboratory, AFSC Aeronautical Systems Division, Wright-Patterson Air Force Base, Ohio, and is being administered under the direction of Mr. B. B. Waters (ASRCTF).

This is the fourth of a series of four interim reports that will cover the progress of the research through the first fifteen months. A technical report will be written at the end of the fifteenth month and a development plan and handbook will be finished at the end of the nineteenth month.

PUBLICATION REVIEW

Approved by: William W. Wood
William W. Wood
Project Engineer

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INTRODUCTION

Designers of advanced vehicles of the high velocity aeronautic and aerospace types are placing greater demands on the sheet metal forming industry by designing parts from the high strength thermal resistant alloys that were once made from more formable materials. Added to this are those forming problems associated with the new thermal resistant alloys such as spring-back and buckling, requiring greater controls in order to maintain the necessary tolerances. A third type of current forming problem is the requirement for close tolerances in both thickness and contour for the more common materials.

These greater demands placed on the sheet metal forming industry has generally resulted in increased activity in development of new forming systems. This activity has been extremely great, with particular emphasis placed on the high velocity system such as explosive, electro-hydraulic, electromagnetic and gas expansion. Other high energy forming types such as high temperature, high rubber pressure, and vibration forming have received less attention. In addition, the development of the more conventional forming systems by increasing pressures, addition of heat, and other methods of adaptation has received less attention than the more sophisticated systems. It is now necessary to appraise the sheet metal forming systems by a systematic evaluation of the fundamental parameters governing formability of metals and alloys.

The primary purpose of this "Sheet Metal Forming Technology" program is to determine the inherent limitations of sheet metal forming processes, to develop the knowledge to significantly advance these, and to recommend the manner in which this can be accomplished. The approach is to first assess the current state-of-the-art for sheet metal forming by surveying literature and the industry. After the systems were determined that indicate considerable deficiencies as to formability knowledge of the process, a comprehensive experimental program was initiated in order to gain systematic data that will aid in overcoming these deficiencies. These data involve fundamental effects of pressure, temperature and velocity, on a broad range of metals and alloys. From this, recommendations can be made as to the forming systems which hold maximum potential for further development.

The program covers the broad class of forming types shown below:

- I. Conventional Forming
 - A. Brake Bending
 - B. Rubber Forming
 - C. Linear Contouring
 - D. Plane Contouring
 - E. Spinning
 - F. Bulging
 - G. Mechanical Die Drawing
 - H. Drop Hammer
 - I. Supplemental Forming

II. Advanced Methods of Forming

- A. High Pressure Liquid
- B. High Temperature
- C. Explosive
- D. Capacitor Discharge
- E. Gas Expansion
- F. Impact Rubber
- G. Vibration

Analytical procedures are being utilized to determine the limitations of the better known processes while experimental and analytical procedures are being used to establish the limitations of the more advanced processes, about which less is known from a formability standpoint. The effect of heat, velocity, and pressure is being investigated singularly and in combinations in the following ranges:

- 1. Temperature: Room temperature - 2500°F
- 2. Velocity: Static - 1000 Ft/sec.
- 3. Rubber pressure: Zero - 100,000 psi

Materials for the experimental part of the program have been selected from a broad class of alloys and metals as shown below:

- | | |
|--------------------|--------------------------------|
| 1. Aluminum Alloy | 2024-O |
| 2. Stainless Steel | 17-7 PH |
| | A-286 |
| | USS 12 MoV |
| 3. Titanium | 6Al-4V |
| | 13V-11Cr-3Al |
| 4. Beryllium | Pure Beryllium |
| 5. Tool Steel | Vascojet 1000 |
| 6. Super Alloys | Rene'41 |
| | L-605 |
| 7. Refractories | Molybdenum ($\frac{1}{2}$ Ti) |
| | Columbium (10 Mo-10 Ti) |
| | Pure Tungsten |

Previous effort has been in two directions: (1) securing state-of-the-art information from industry and others by personal interviews and a survey of literature and (2) conducting an extensive experimental program that will fill the gap between needed and existing information.

Longitudinal tensile specimens of three gage lengths, 1, 5, and 10 inch respectively and three gages, .020, .063, and 0.125 were tested at temperatures and velocities noted above. Free forming tests were conducted at various combinations of temperatures and velocities for 2 inch diameter tubes and 2-1/2 inch diameter domes. Parts were formed to various depths utilizing female dies at various combinations of temperature and velocity with 2 inch tubing, 6 inch diameter domes, and 6 inch diameter shallow recessed beaded panels.

Work in this quarter finalized the experimental phase of the program and the results are reported herein. A Technical Report will be submitted as a summary of all previous work. The last period of the contract will be used for finalizing a formability handbook and formulating a future development report. This report will be submitted for a clarification of current sheet metal forming processes and recommendations for future development work needed to significantly advance sheet metal forming technology.

LONGITUDINAL, HIGH VELOCITY TENSILE TESTING

Introduction

The test data contained in this report is in the velocity range from static to 620 ft/sec. and the temperature range from cryogenic (-320°F) to 2000°F . Using only 5" gage length tensile specimen, these combined velocity-temperature tests were completed for seven materials in the temperature range from ambient to 2000°F for all velocities. These seven materials are those which were not previously reported.

Strain distribution curves and uniform elongation vs forming velocity curves are shown in Appendix A, Graphs 1 through 14.

Cryogenic testing in the velocity range from static to 600 ft/sec. has been completed. Six materials, Titanium (6Al-4V), Titanium (13V-11Cr-3Al), Beryllium, Molybdenum (.5% Ti), Columbium (10 Mo-10 Ti), and Tungsten were not tested because of their brittle nature at cryogenic temperatures. Strain distribution curves and uniform elongation vs forming velocity for the tested materials are shown in Appendix A, Graphs 15 through 28.

Test Procedure

Two machines were used for the high velocity tests. The Projectile Impact Tester (CVC XMS 541.013) was used for all ambient and elevated temperature high velocity tests and all cryogenic testing above 150 ft/sec. (See Interim Report II, page 15.) For the cryogenic tests below 150 ft/sec. the Rotary Impact test machine (CVC XMS 541.014) was used with a special chamber around the test specimen for introducing liquid nitrogen as shown in Figure 24 on page 20 of Interim Report No. III. Cryogenic testing with the Projectile Impact Tester was accomplished by inserting the tensile specimens and their coupling tup in a plastic bag which was then filled with liquid nitrogen. The theoretical temperature of liquid nitrogen, -320°F , was verified by using a potentiometer.

Discussion

The data in this section is derived from the elongation vs. position curves obtained by measuring the grid marks on the tensile specimens. These curves are shown in Appendix A, Graphs 1-7 and 15-21. Because of the large number of specimens tested, it was necessary to show selected curves representative of the strain distribution found for the various velocities and temperatures. Although the interpretation of the data is somewhat arbitrary, the following rules were applied consistently throughout the test series.

- (1) The uniform elongation is taken as the average value of elongation outside the necked area.
- (2) The critical velocity region is established by the following criteria:
 - a) a strain distribution curve that shows a reasonably good reduction in area at fracture,
 - b) the fracture located at the impacted end of the specimen,
 - c) a small uniform strain value.

The critical velocity of the refractory metals, Columbium (10 Mo-10 Ti) and Molybdenum (.5% Ti), was difficult to determine because of the low value of elongation. For these two materials, particular weight was placed on the position of the fracture rather than the value of the uniform elongation.

Due to the increased strength of some materials at cryogenic temperatures, it was necessary to change the specimen size in order to insure a break in the gage section. This was accomplished by machining a specimen with a 2.5 inch gage length and a .125 inch gage width. Tests were performed which showed a correlation of uniform elongation and maximum elongation between these specimens and the standard specimens.

Results and Conclusions

Only those materials shown in Appendix A, Graphs 1 through 7 and 15 through 21 are considered in detail. Graphs 8 through 14, and 22 through 28 show the results of plotting uniform elongation versus forming velocity with a composite graph of the various temperatures given for each material. In Figure 1, the uniform static strain at various test temperatures is compared to the corresponding dynamic strain values.

Based on Figure 1, (shown on the next two pages), the following conclusions can be drawn concerning uniaxial deformation. Considering each material separately, it can be seen that:

- (1) Rene'41 and Columbium (10 Mo-10 Ti) show the same ductility for static and dynamic loading. Rene'41 shows a ductility decrease of approximately 25% from room temperature to cryogenic and a steady decrease from room temperature to 1000°F. Columbium (10 Mo-10 Ti) decreases in ductility from room temperature to 2000°F. Room temperature is the best forming temperature for both Rene'41 and Columbium (10 Mo-10 Ti).
- (2) 17-7 PH shows a ductility increase (dynamic loading compared to static loading) of 100% at cryogenic, 50% at room temperature. Both processes show the same ductility from 500°F to 1000°F. There is a ductility decrease of approximately 50% for both processes from room temperature to cryogenic with steady decrease to 1000°F. Dynamic loading at room temperature is the best forming condition for 17-7 PH.

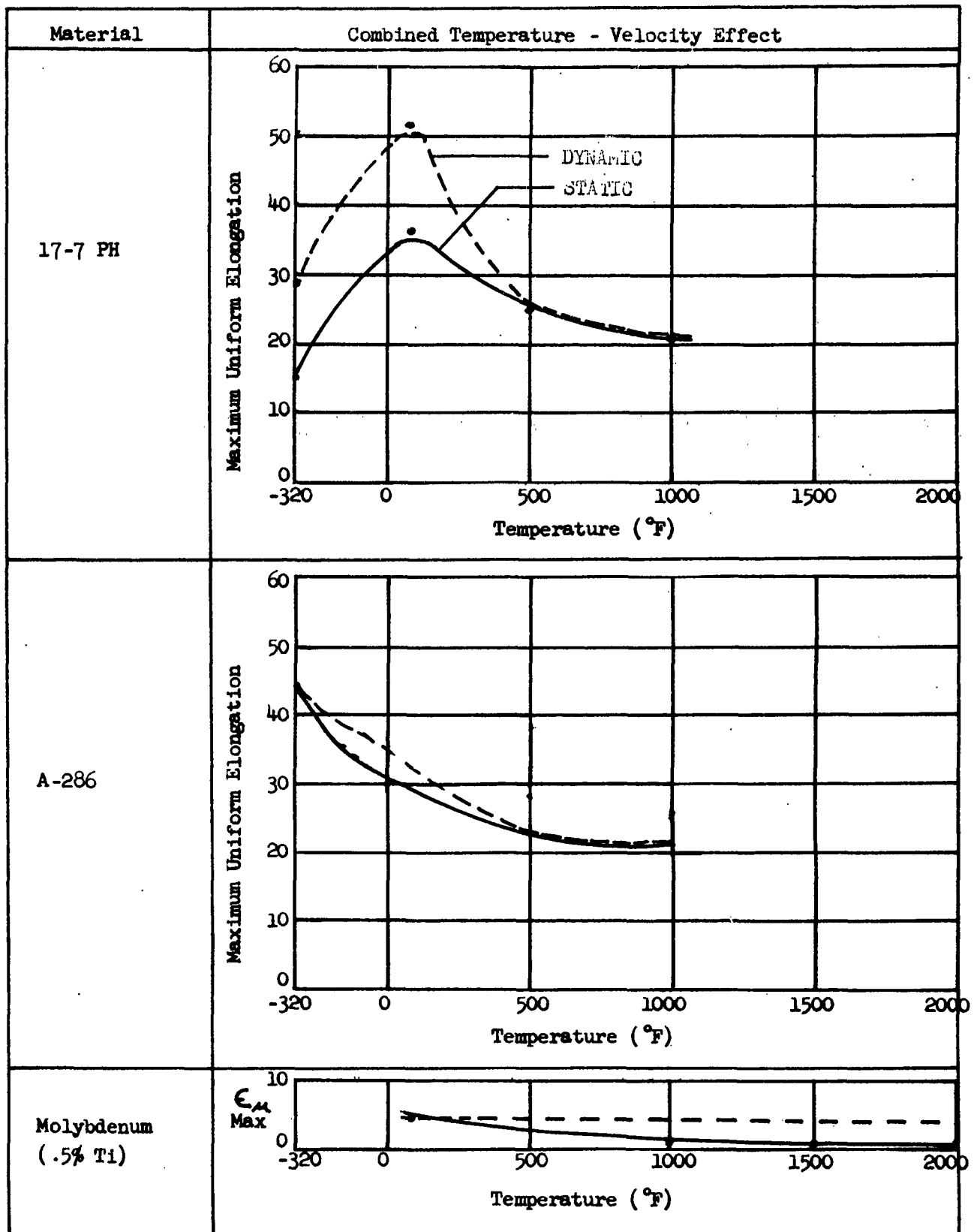


FIGURE 1: COMBINED VELOCITY TEMPERATURE EFFECT ON UNIFORM STRAIN FOR LONGITUDINAL TENSILE SPECIMENS

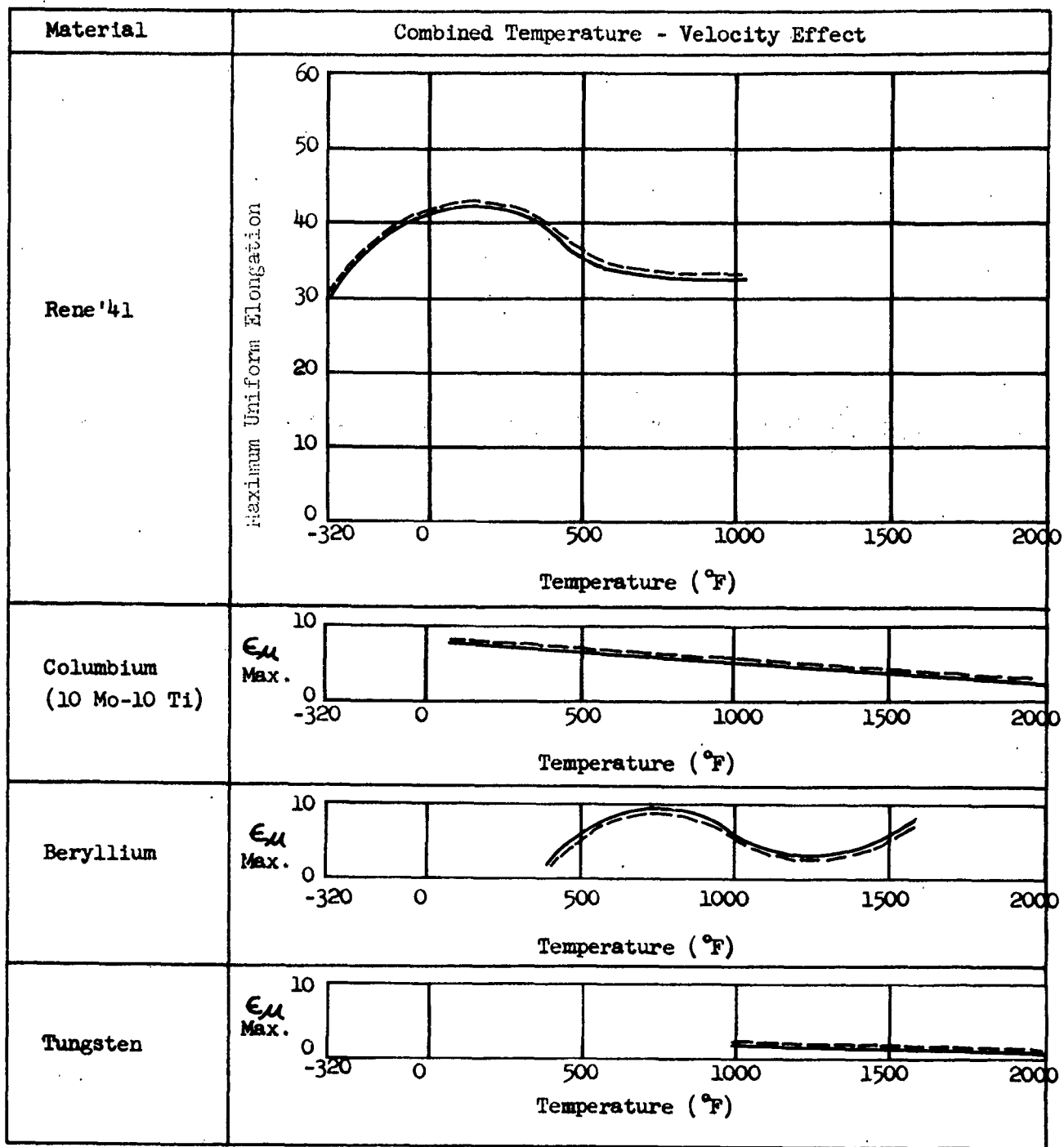


FIGURE 1: COMBINED VELOCITY TEMPERATURE EFFECT ON UNIFORM
(Concluded) STRAIN FOR LONGITUDINAL TENSILE SPECIMENS

- (3) Dynamic and static loading presents the same ductility for A-286 except for a 15% increase of dynamic over static at room temperature. A-286 shows a maximum ductility at cryogenic with a steady decrease thereafter. Dynamic or static loading at cryogenic (-320°F) is the best forming condition for A-286.
- (4) Tungsten and Beryllium show the same ductility for static and dynamic loading. An increase in temperature does not increase the ductility of Tungsten. The best ductility for Beryllium was shown at 800°F for static loading. If it is desirable to form Beryllium by a high energy method, the temperature of the metal should be raised to 1600°F .

Four materials (Vascojet 1000, USS 12 MoV, 2024-O Aluminum and L-605) were tested at cryogenic temperature during this period. Elevated temperature testing was completed during the last period and were reported in Interim Report III. Graphs 24, 25, 26 and 28 in Appendix A show the uniform elongation as a function of forming velocity. In each case the uniform elongation is lower than that at room and elevated temperatures as presented in Graphs 1, 2, 5 and 6 in Interim Report III.

ELEVATED-TEMPERATURE LOW EXPLOSIVE
FREE BULGE DOME AND TUBE TESTING

Introduction

The objective of this phase of testing is to extend the temperature range of the previously determined room temperature data.

All materials tested are 0.020 in. and include:

Domes

- | | |
|-----------------------------|----------------------------|
| (1) 17-7 PH | (7) L-605 |
| (2) A-286 | (8) Rene '41 |
| (3) Vascojet 1000 | (9) 2024-O Aluminum |
| (4) USS 12 MoV | (10) Molybdenum (.5% Ti) |
| (5) Titanium (6Al-4V) | (11) Columbium (10Mo-10Ti) |
| (6) Titanium (13V-11Cr-3Al) | (12) Tungsten |

Tubes

- | | |
|-------------------|-----------------------|
| (1) 17-7 PH | (4) Titanium (6Al-4V) |
| (2) A-286 | (5) Rene '41 |
| (3) Vascojet 1000 | |

All tubing is annealed, welded two-inch I.D.

Since high explosive water forming is not readily adaptable to high temperature tests, the elevated temperature work is limited to low explosive testing. Several of the dome materials exhibited a critical velocity in the low explosive range at elevated temperature as shown in Graphs 29-40, Appendix B. Room temperature data, previously determined, are also shown. It should be noted, however, that no critical velocity was reached in the tubing tests at either room or elevated temperature. (See Graphs 41-45, Appendix B.)

Test Apparatus

The test specimens for both tubing and dome tests were resistance heated using a 100 KVA low-voltage transformer. All remaining apparatus used in room temperature testing is discussed in detail in previous Interim Reports. (See Interim Report II for tubing apparatus; Interim Report III for dome apparatus.)

Results and Conclusions

Domes

Eleven of the twelve materials tested showed a definite decrease in elongation at a specific respective critical velocity. Although L-605 exhibited no decrease in elongation, by comparison with the test specimens of other materials, it is felt that a critical velocity does exist approximately 100 fps above the highest L-605 test velocity. Additional conclusions can be based upon the results shown in Table 1 and Graphs 29 through 40 in Appendix B. The average elongation of all test materials, except Titanium (13V-11Cr-3Al), remains constant or increases with test temperature. Also for the materials exhibiting a critical velocity in the elevated temperature range, there is a definite decrease in critical velocity with increasing temperature. The only exception to this is molybdenum, as shown in Graph 38, Appendix B. It is also evident that a range of increased elongation exists immediately below the critical velocity for all materials except aluminum and refractories.

Tubes

Of the five tubing materials tested, Titanium (6Al-4V) showed an increase in elongation with temperature while 17-7 PH and A-286 decreased in elongation. The remaining materials exhibited no change. (See Table 2 and Graphs 41 through 45 in Appendix B.) Throughout the tubing tests no evidence of a critical velocity was observed.

FABRICATION OF PARTS

Introduction

These series of tests are intended to study and compare the validity of tensile testing and free forming against actual die forming operations. That is, when tensile testing and free forming establishes a given uniform elongation limit the formed part can be expected to fail when this limit is exceeded. Dies that were used in this series were female type tube bulge dies, dome dies, shallow recess dies, and free forming dome dies. Female type tube bulge die tests have been completed and discussed in Interim Report No. III. Dome and shallow recesses have now been completed. Elevated temperature tests, where applicable, are included in this report.

Five energy sources are included in these series. They are:

- (1) Low Explosive - Air
- (2) High Explosive - Water
- (3) Electro-Hydraulic
- (4) Electromagnetic
- (5) Static (Conventional Presses)

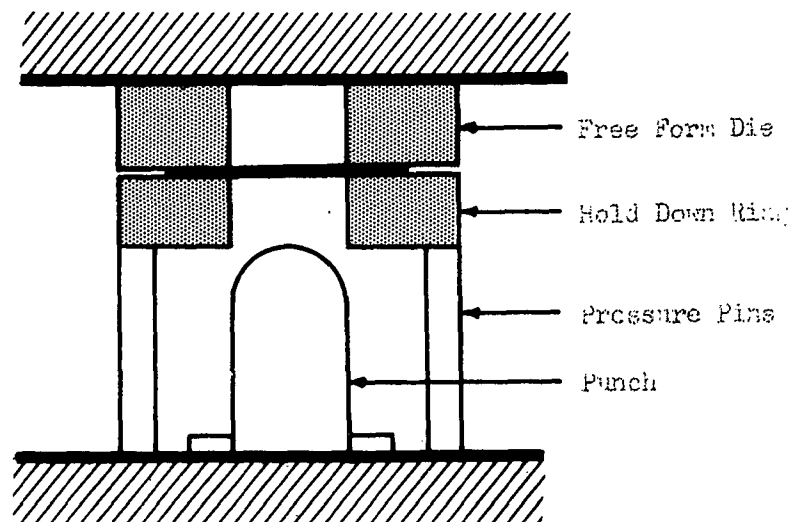
Materials tested include all those available for the experimental part of the program with the exceptions of those metals belonging to the Beryllium and Refractory classes of alloys.

Test Apparatus and Equipment

Forming Mediums:

Static - The punch and die setup shown below (Figure 2) together with a 1,000 ton press was used to form static, free form domes.

FIGURE 2: STATIC FREE
FORM DOME
SETUP



Static shallow recessed parts were formed using female dies on a 2,500 ton press equipped with a trapped rubber head. (Figure 3).

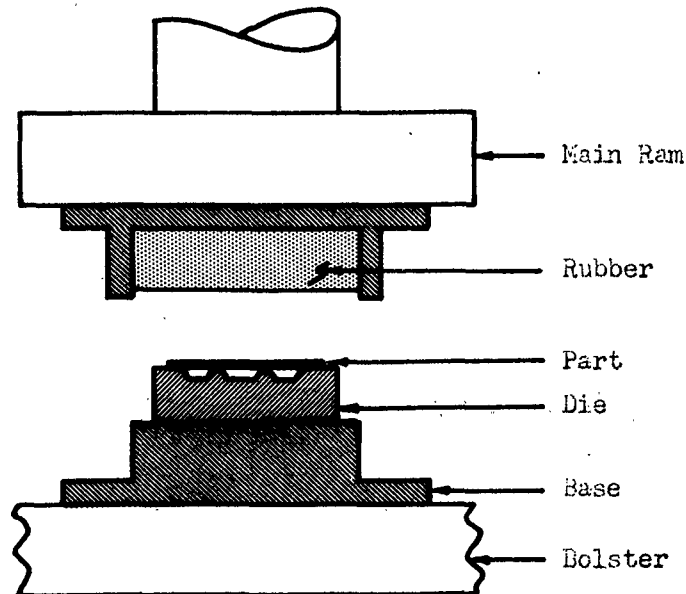


FIGURE 3: STATIC SHALLOW RECESSING SETUP

Low Explosive - Air - Both shallow recessed and domed parts were formed using the low explosive chamber and hold-down fixture in conjunction with the explosive press. These tools are discussed in Interim Report No. II.

High Explosive - Water - Both shallow recessed and domed parts were formed using the necessary tool and high explosive forming facility shown in Interim Report No. II.

Electro-forming - Both electrical forming methods utilized the capacitor discharge equipment shown in Interim Report No. II. The capacitor bank has a capacity of 18,400 joules (113.6 μ fd at 20 kilovolts). Capacitance during experimental forming varied from 85.2 μ fd to 113.6 μ fd due to the explosion and subsequent replacement of two capacitors. Electro-hydraulic parts were formed utilizing the explosive press in conjunction with the standpipe shown in Figure 4. Electromagnetic parts were formed utilizing the explosive press and a specially designed magnetic coil.

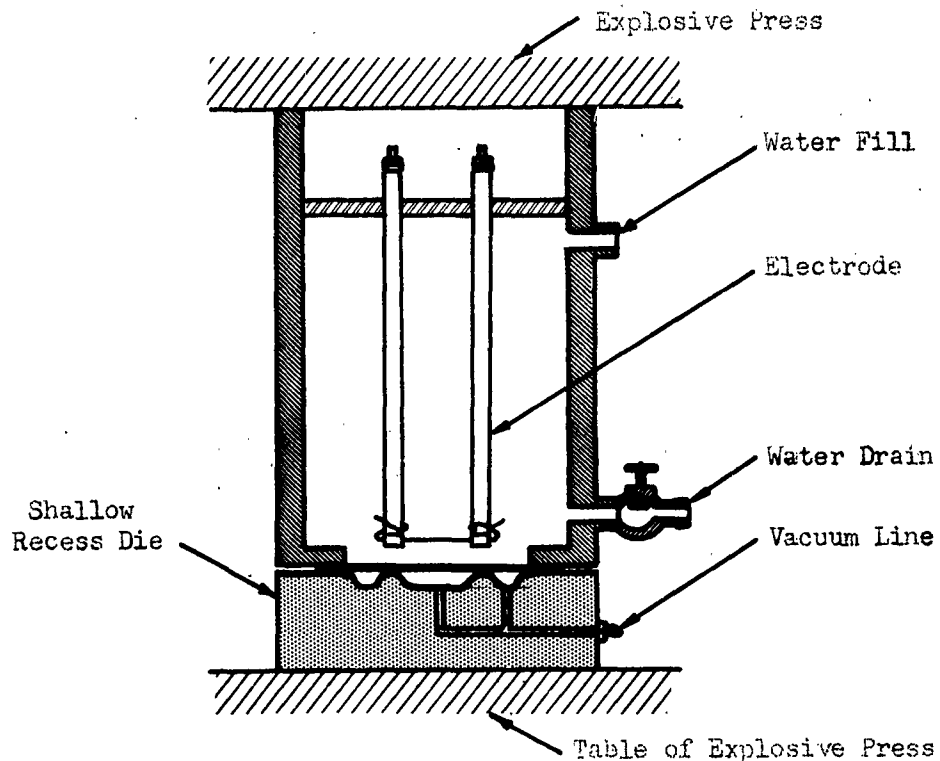


FIGURE 4: ELECTRO-HYDRAULIC FORMING SETUP

Dies:

Domes - High and low velocity forming of domes was performed in three different female dome dies with the following approximate elongations. (See Figure 5).

Dome Die #1 - 6%
 Dome Die #2 - 26%
 Dome Die #3 - 57%

Die Cavities were evacuated to approximately 28 inches of mercury for all tests. Those parts of the die contacting the material to be formed were flame sprayed with alumina prior to high temperature testing.

Static forming of domes was accomplished with a six-inch diameter free form dome die and plunger. Elevated temperature testing was accomplished by heating the plunger and the part to the required temperature.

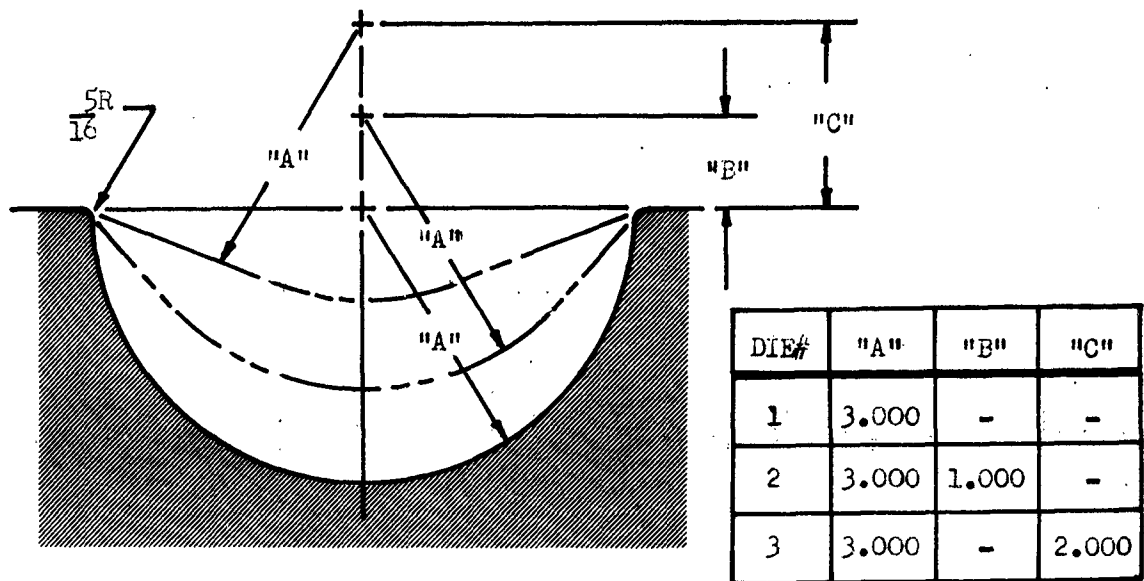


FIGURE 5: DEEP RECESSING DIE CONFIGURATIONS

Shallow Recessing - Parts were formed in three different female shallow recessing dies with the following approximate elongations. (See Figure 6).

Shallow Recess Die #1 - 5%
 Shallow Recess Die #2 - 15%
 Shallow Recess Die #3 - 30%

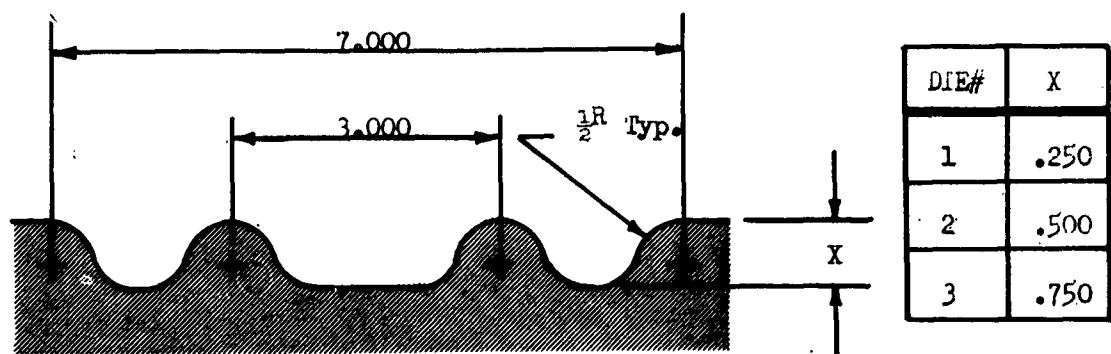


FIGURE 6: SHALLOW RECESSING DIE CONFIGURATIONS

Die cavities were evacuated to approximately 28 inches of mercury for all tests. Those parts of the die contacting the material to be formed were flame sprayed with alumina prior to high temperature testing.

Procedures and Preparation of Tests

Static Velocity Forming

Dome shaped parts were formed at static velocity using a conventional press setup in a Lake Erie 1,000 ton hydraulic press as shown in Figure 2.

Room temperature tests determined that depth to which the part could be recessed before fracture under conditions of ideal draw and complete clamping. For both draw and no-draw tests a lubricant (700 Draw Wax) was used on the punch. No lubricant was used on the drawing surfaces consistent with the experimental conditions of the high velocity tests. The recess depth at fracture was obtained by measuring the position of the main ram.

For the no-draw tests adequate blank size and/or hold down pressure was used to prevent drawing. On tests where the optimum draw pressure was used for concurrent flange buckling and fracture of the part, a blank diameter was used no larger than that required to provide material for the anticipated amount of draw.

For the elevated temperature tests, all parts were formed under no-draw conditions, heat was applied to the punch. Although the die and hold down ring were cooler than the punch, which remained at the test temperature during the forming operation, it was found that a very slow forming rate (approximately 2 inches/minute) was sufficient to allow the part to come up to temperature prior to contacting the punch. The surfaces of the punch, die and pressure ring were chrome plated to prevent changes in the surface condition of the tools during the test series. No lubricant was used.

Shallow recessed, static velocity parts were formed under high pressure by a trapped rubber head, mounted in a single action hydraulic press. No lubrication was used on either the rubber to part interface or on the die. Strain rate, as determined by the pressure build up in the rubber was on the order of 5 in/min. in the vertical direction. Sufficient blank size was used to prevent drawing.

Low Explosive - Air

The afore mentioned series of dome and shallow recessed dies mounted on a special, mechanical explosive press were used to conduct the low explosive - air tests. These tests were performed using Bullseye pistol powder contained in a 700 grain capacity firing chamber. The firing chamber was located approximately six-inches above the part. Explosive charges ranging from 100 to 700 grains, depending on material and gage, were compressed by hand into the firing chamber. Electrical detonation was achieved by use of an Atlas, M-100 match assembly. Velocities were approximated to be in the 100 to 300 fps range.

High Explosive - Water

Tests were conducted using the afore mentioned series of dome and shallow recessed dies, and facilities. A high explosive powder, RDX, with a 2% wax content, compressed to 18,000 psi was the energy force for all high explosive - water dome and shallow recess part forming. An electrical blasting cap fired by a dry cell battery was used to initiate this energy force. A series of tests indicate that $2D/3$ (where D = diameter of the formed part) was near the optimum stand-off distance. Therefore, this $2D/3$ value for stand-off distance was held constant in all subsequent testing. All testing in this series was conducted with the tool submerged approximately eight-feet under water. Velocities were approximated to be in the 500 to 800 fps range.

Electro-Hydraulic

Forming was performed using the $3\frac{1}{4}$ -inch gap and 2-inch stand-off distance which had been determined by previous testing. The initiating wire was a 0.030 diameter 5356 aluminum welding wire. Water head was 12 inches. Charging voltage varied from the absolute minimum of 6 kilovolts to the absolute maximum of 20 kilovolts. Energy can be calculated from:

$$E = \frac{1}{2} CV^2$$

where E is the energy in joules
C is the capacitance in farads
V is the voltage.

Velocities attained are estimated to be in the lower portion of the high explosive range.

Electromagnetic

All electromagnetic forming was accomplished with a full complement of eight capacitors. The coil is made up of 22 turns of #4 AWG copper wire wound on a three-inch core, to six-inches outside coil diameter. The coil is completely enclosed in glass-filled epoxy, with a 1/16 inch sheet of epoxy-glass over the coil face.

Initial attempts to form electromagnetically into a metal die were completely unsuccessful because of the "magnetic cushion" effect which returns the material to the coil face in a buckled condition. For this reason the free form deep recess die was used, and a #2 shallow recessing die was constructed of linen base phonolic. These dies eliminated the "magnetic cushion" effect.

Additional difficulty was encountered with the materials of high electrical resistivity; it was impossible to obtain sufficient force to deform the material. This problem was solved by the use of a sheet of .063 gage 2024-O aluminum overlay between the part to be formed and the coil. Using this procedure it was possible to fracture the stainless steels and one titanium alloy and to slightly form the super alloys. The remainder of the materials were exhausted before this portion of the program was reached.

Voltages used varied from 6 KV for aluminum to 12-18 KV for the balance of the materials.

Discussion

Deep Recessing:

Draw-Room Temperature - Part fabrication under draw conditions was accomplished by static, low explosive, high explosive, and electromagnetic means. Parts were not formed by electro-hydraulic means because it proved impossible to maintain a water head on one side of the part and a vacuum on the other. If the hold down pressure was increased enough to hold the vacuum then the part was not free to draw.

The best results were obtained from the static forming process because of slow loading and the ability to control draw. See Tables 3 through 6 Appendix C for the results of the deep recessed, draw testing. High explosive results approached those of static forming except in the Titanium alloys which are sensitive to strain rate. Low explosive - air results are generally lower than either static forming or high explosive results. This is partially due to a powder burning of the part and excessive hold down pressure encountered in the use of the explosive press. Figure 25 illustrates the increase in formability that may be gained by a part formed under a draw condition as opposed to a no-draw condition. Electromagnetic parts were run under draw conditions because the coil employed in these tests could not withstand those pressures necessary to prevent drawing. Coil design was the first major problem encountered in this part of the program. A useable coil for tube bulging was never devised; however, a coil for recessing, which is marginal, evolved slowly. High flux concentrations in the center of the coil and especially coil durability are still very pressing problems. The inability to form into metallic dies because of the "cushioning effect" and the poor applicability of most materials to this process place severe limitations on electromagnetic forming. Aluminum was best suited to this process due to its good conductivity. However, all those materials that were formed using aluminum overlays yielded results that were as good as the other forming processes. Much work must be done if this process is to become a useful tool of modern industry.

No Draw - Room Temperature - Part fabrication under no-draw conditions was accomplished by static, low explosive, high explosive, and electro-hydraulic means. Figures 7 through 15 illustrate the results of the testing for this portion of the program. The results also appear in Tables 7 through 12. The velocities shown for the different processes are based on those velocities measured in free form, dome testing. These velocities, though not exact, are reasonably accurate and close enough for discussion purposes. The velocities shown for electro-hydraulic forming were estimated since it was impossible to measure velocities electrically by an Eput Timer due to the extremely high voltages used in this process. The percentage of elongation attainable in each die is shown by a dashed line. Those parts, with the exception of static parts, which fall off one of the die elongation lines do so because of a slight drawing of the part and subsequent correction as to actual elongation. The curve shown in each figure is that curve obtained in the dome free forming portion of this program.

A graph of 17-7 Ph is shown in Figure 7. This graph shows a maximum elongation of 22% in a velocity range from 0 to 600 fps. From 600 fps to critical velocity the maximum elongation rises to 38%. Thus high explosive parts formed in the upper velocity ranges formed in the number two die while the other processes failed in that die.

A graph of A-286 is shown in Figure 8. This graph shows a maximum elongation of 25% at static velocity dropping to 17.5% at a velocity range of 60 to 530 fps. From 530 fps to critical velocity the maximum elongation rises to 27%. Once again the high explosive part formed at the upper velocities was good, whereas the other processes at a lower velocity yielded a split part.

A graph of Vascojet 1000 is shown in Figure 9. This graph shows a maximum elongation of 17.5% at static velocities, dropping to 15% from 75 to 500 fps. From 500 fps to critical velocity the maximum elongation rises to 20%. A high explosive part is shown to be a good part at 21.5%. This part falls so near the forming limit that it easily could have failed. Good and split part will both fall on the forming limit curve.

A graph of USS 12 MoV is shown in Figure 10. A maximum elongation of 16% is shown for velocities of from static to 600 fps. From 600 fps to critical velocity the maximum elongation rises to 22.5%. Once again a high explosive part formed at the forming limit. Had it not been for a slight amount of draw this part would probably have failed at 26% elongation.

A graph of Titanium (6Al-4V) is shown in Figure 11. A maximum elongation of 6% is shown for velocities from 0 to 250 fps. From 250 fps to critical velocity the maximum elongation rises to 10%. The electro-hydraulic and high explosive parts fall beyond the critical impact velocity. Both static forming and low explosive forming yielded split parts on the forming limit curve.

A graph of Titanium (13V-11Cr-3Al) is shown in Figure 12. A maximum elongation of 10% is shown from a velocity of static to 125 fps. From 125 fps to the critical impact velocity the maximum elongation rises to 13.5%. The electro-hydraulic and high explosive parts fall outside the critical impact velocity and thus failed. The low explosive part fell on the forming limit curve and yielded a split part.

A graph of L-605 is shown in Figure 13. From static to 625 fps the maximum elongation is 17.5%. From 625 fps to the critical impact velocity the maximum elongation rises to 22.5%. A good, high explosive part fell on the forming limit curve, thus indicating that good and bad parts will both fall on the curve. Had not some drawing been present this part would have failed at 26% elongation.

A graph of Rene'41 is shown in Figure 14. A maximum elongation of 18% is shown from 50 to 500 fps. From 500 fps to the critical impact velocity the maximum elongation increased to 22%. A good high explosive part falls on the forming limit curve.

A graph of 2024-O Aluminum is shown in Figure 15. Maximum elongation from static to critical velocity is 18.5%. The static formed part falls on the forming limit curve. Low and high explosive formed parts as well as the electro-hydraulic part all formed without splitting in the number one die. The forming limit curve is based on uniform or average strain. Thus it is possible to obtain a slightly greater strain than that shown. Such is the case where the electro-hydraulic and high explosive processes yielded good parts in an area where a split part would be expected.

No Draw - Elevated Temperature - Both static and low explosive results closely parallel each other. (See Tables 8 through 10). The most noteworthy increase in formability due to elevated temperature occurs in the two titanium alloys. At elevated temperature (1200°F) the titanium alloys are capable of forming a good part in Die #1 as opposed to a split part at room temperature. This is true for both static and low explosive forming. See Figure 26 for an example of increase in formability of titanium at elevated temperatures. At elevated temperatures the low explosive process yielded an increase in formability of .063 gage 17-7 Ph and A-286. Also an increase in formability for .020 gage L-605 and Rene'41. See Figures 16 through 24 for a comparison to free forming elevated temperature results.

Shallow Recessing:

Room Temperature - Part fabrication was accomplished by static forming, low explosive, high explosive, electro-hydraulic and electromagnetic means. High explosive forming yielded the better results. (See Tables 13 through 17 Appendix C). This was due to the better forming limits of some materials at high velocities and due to a slight drawing of the part. Only one electro-magnetic shallow recessed part was formed due to a lack of power. That being 2024-O Aluminum in the #2 phenolic die. The part failed. See Figure 27 for an example of parts formed in Dies #1, 2, and 3.

Elevated Temperature - The only noteworthy increase in shallow recess formability at elevated temperature occurs in the titanium alloys. These alloys at 1200°F formed a good part in die #1, as opposed to a split part at room temperature. (See Table 15 Appendix C).

FABRICATION OF PARTS
SYMBOL CHART
FOR FIGURES 7 THRU 24

PROCESS	RESULT	SYMBOL
Static Forming	Good Part	○
	Split Part	●
Low Explosive Air	Good Part	△
	Split Part	▲
Electro-Hydraulic	Good Part	⬡
	Split Part	⬢
High Explosive - Water	Good Part	□
	Split Part	■

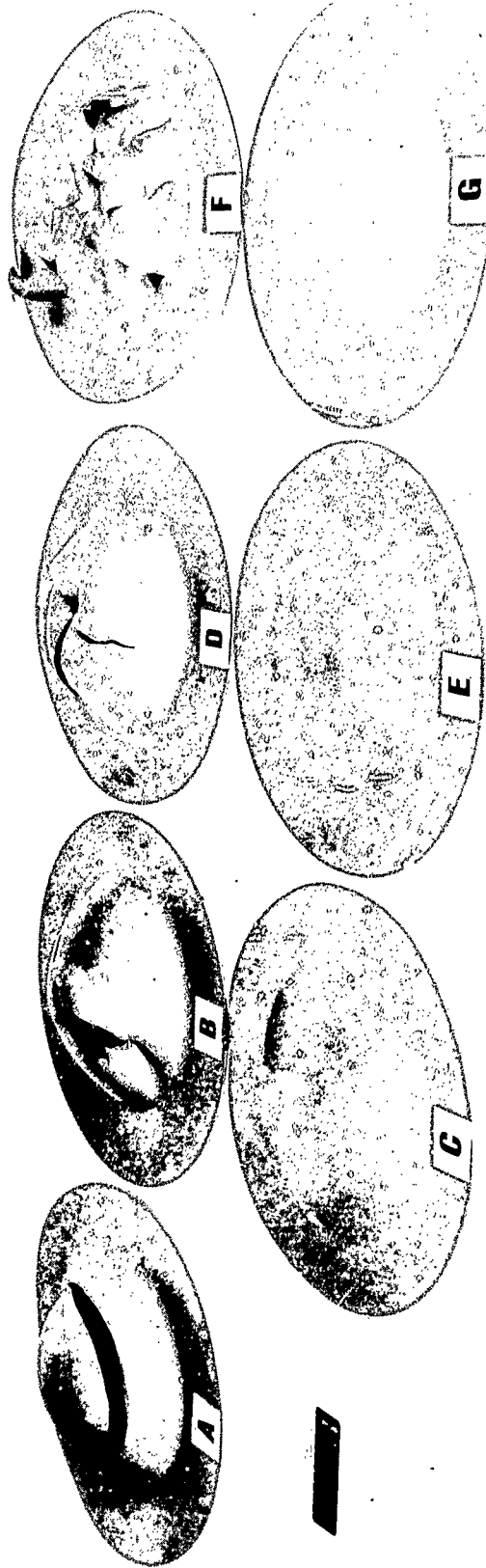


FIGURE 7(a). EXPERIMENTAL DIE FORMED PARTS - 17-7 PH

FIGURE 7(b)
 ELONGATION LIMIT CURVE
 SHOWING EXPERIMENTAL POINTS
 17-7 PH

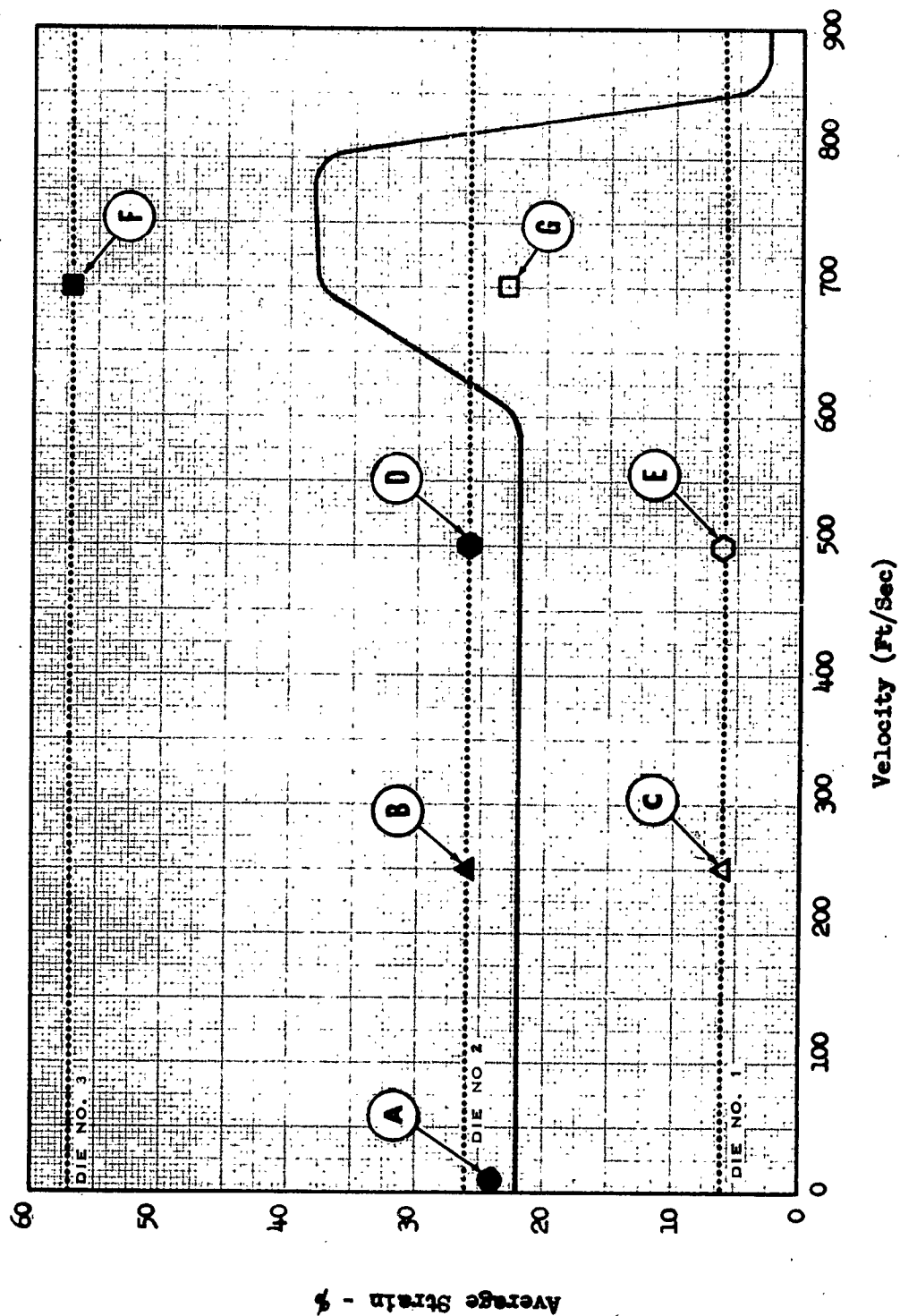


FIGURE 8
 ELONGATION LIMIT CURVE
 SHOWING EXPERIMENTAL POINTS
 A-286

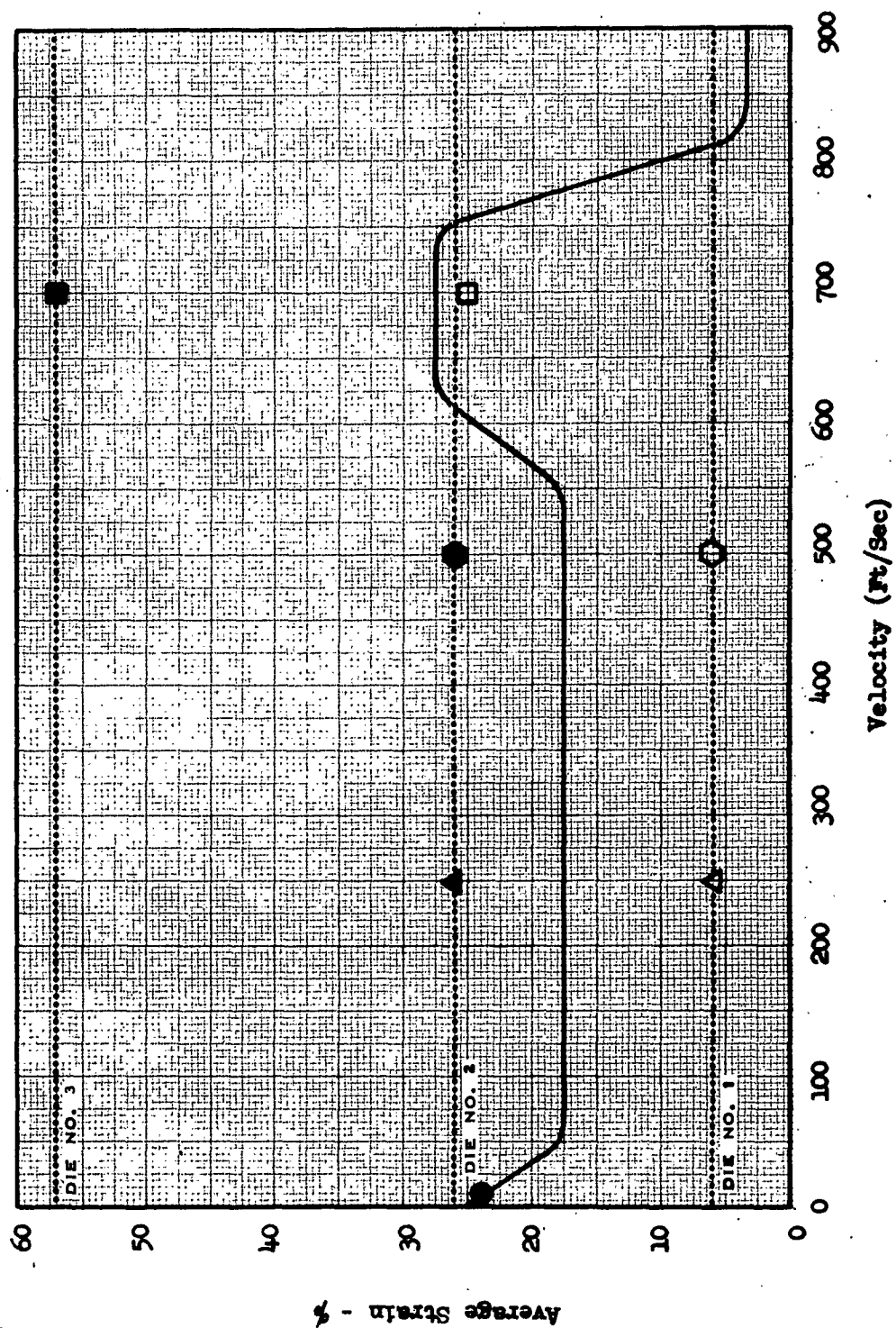
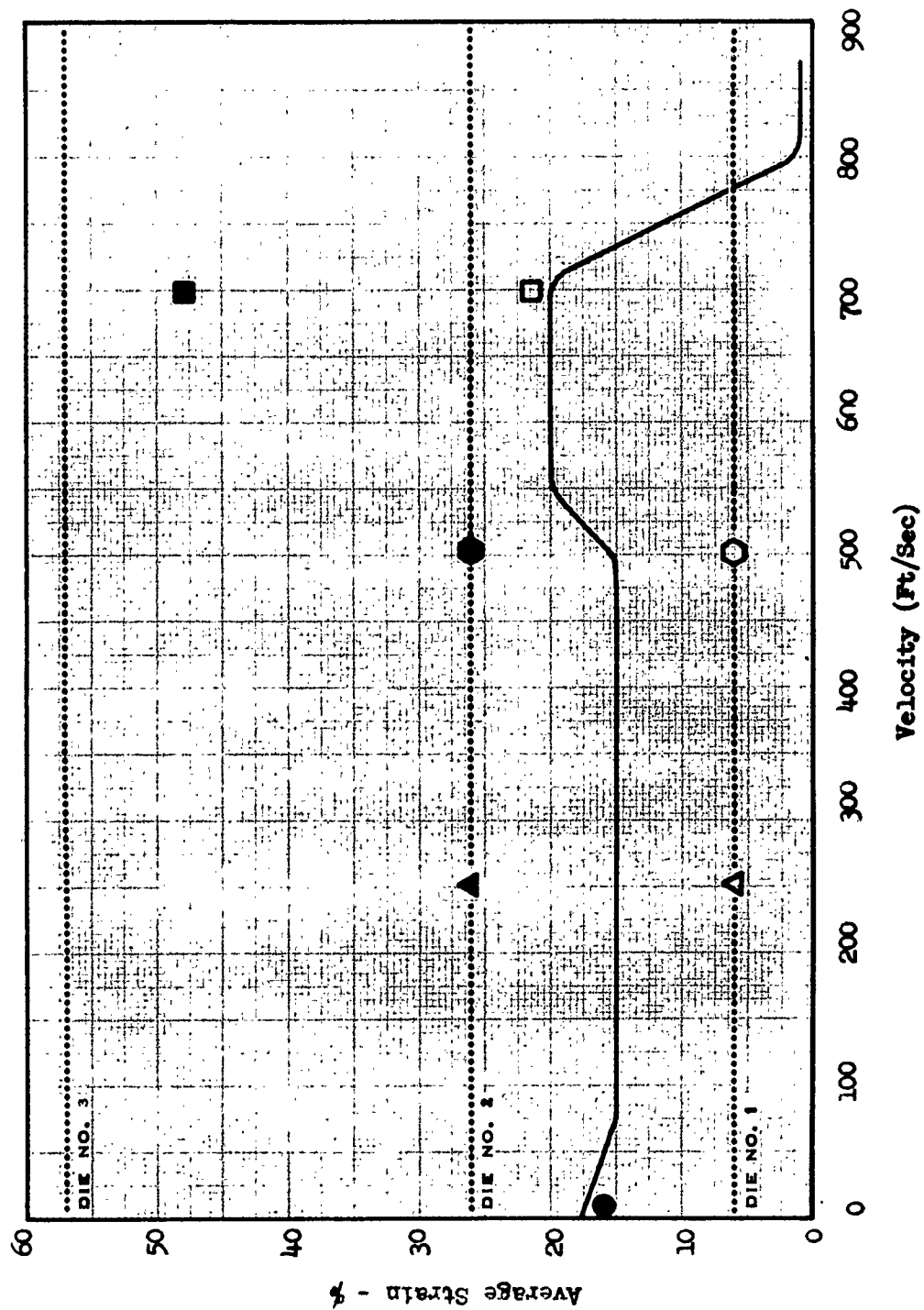


FIGURE 9
 ELONGATION LIMIT CURVE
 SHOWING EXPERIMENTAL POINTS
 VASCOJET 1000



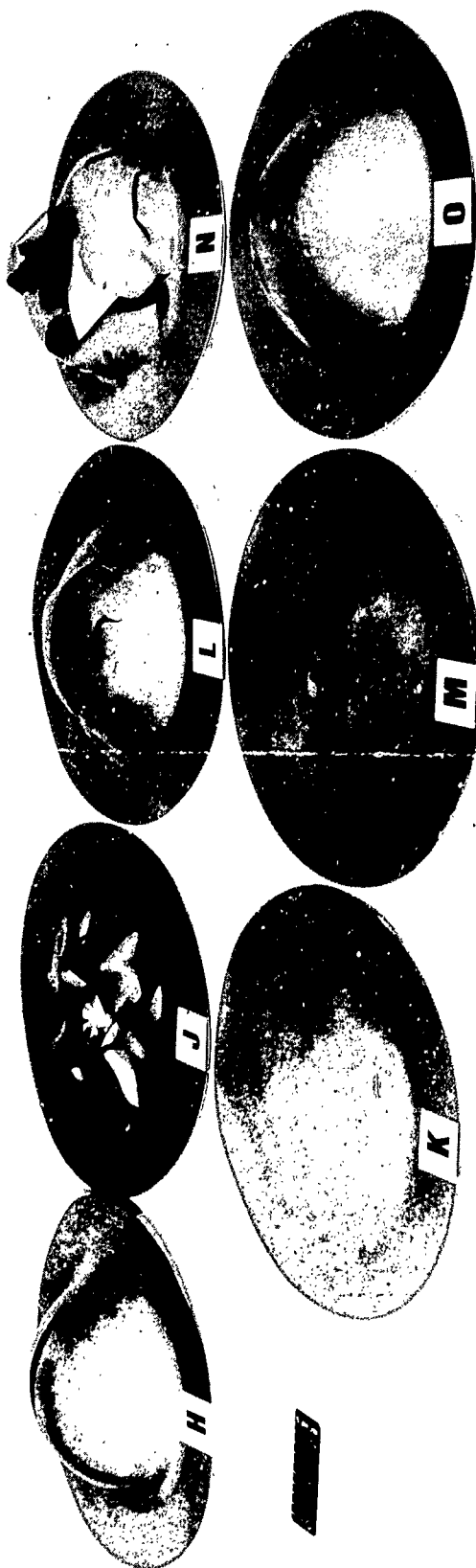


FIGURE 10(a). EXPERIMENTAL DIE FORMED PARTS - USS 12 MoV

FIGURE 10(b)
 ELONGATION LIMIT CURVE
 SHOWING EXPERIMENTAL POINTS
 USS 12 MoV

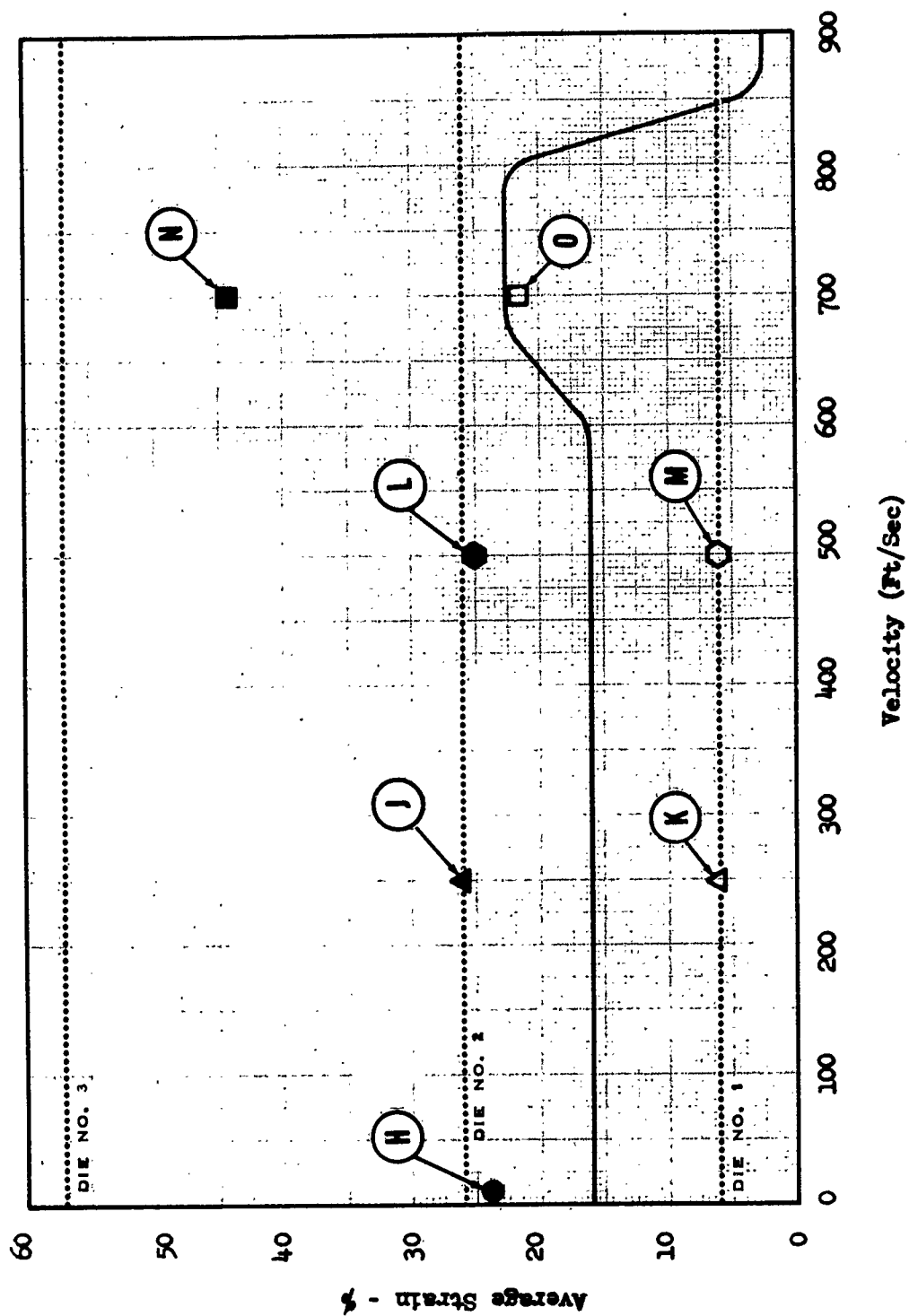




FIGURE 11(a). EXPERIMENTAL DIE FORMED PARTS - TITANIUM (6Al-4V)

FIGURE 11(b)
 ELONGATION LIMIT CURVE
 SHOWING EXPERIMENTAL POINTS
 TITANIUM (6AL-4V)

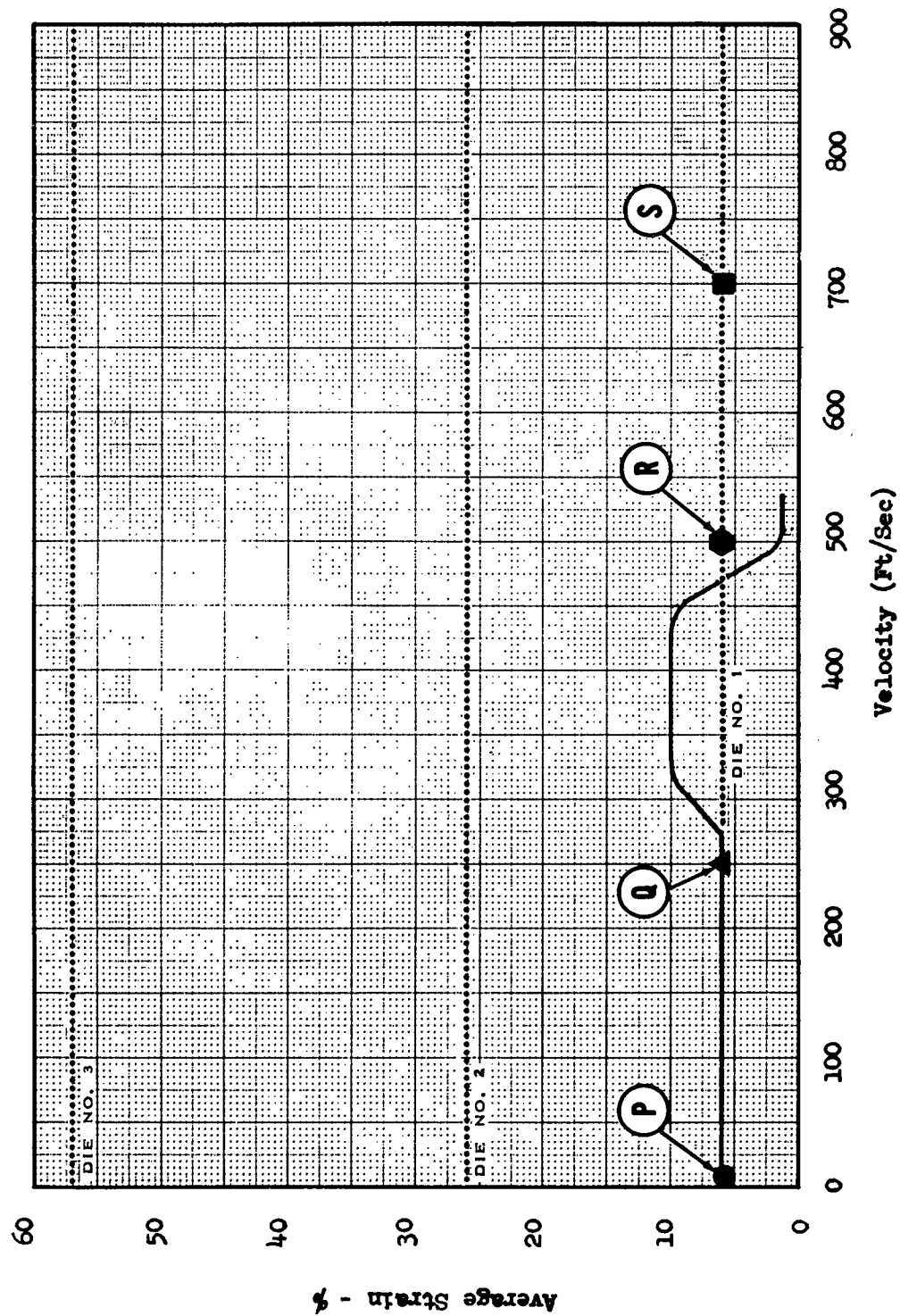


FIGURE 12
 ELONGATION LIMIT CURVE
 SHOWING EXPERIMENTAL POINTS
 TITANIUM (13V-11Cr-3Al)

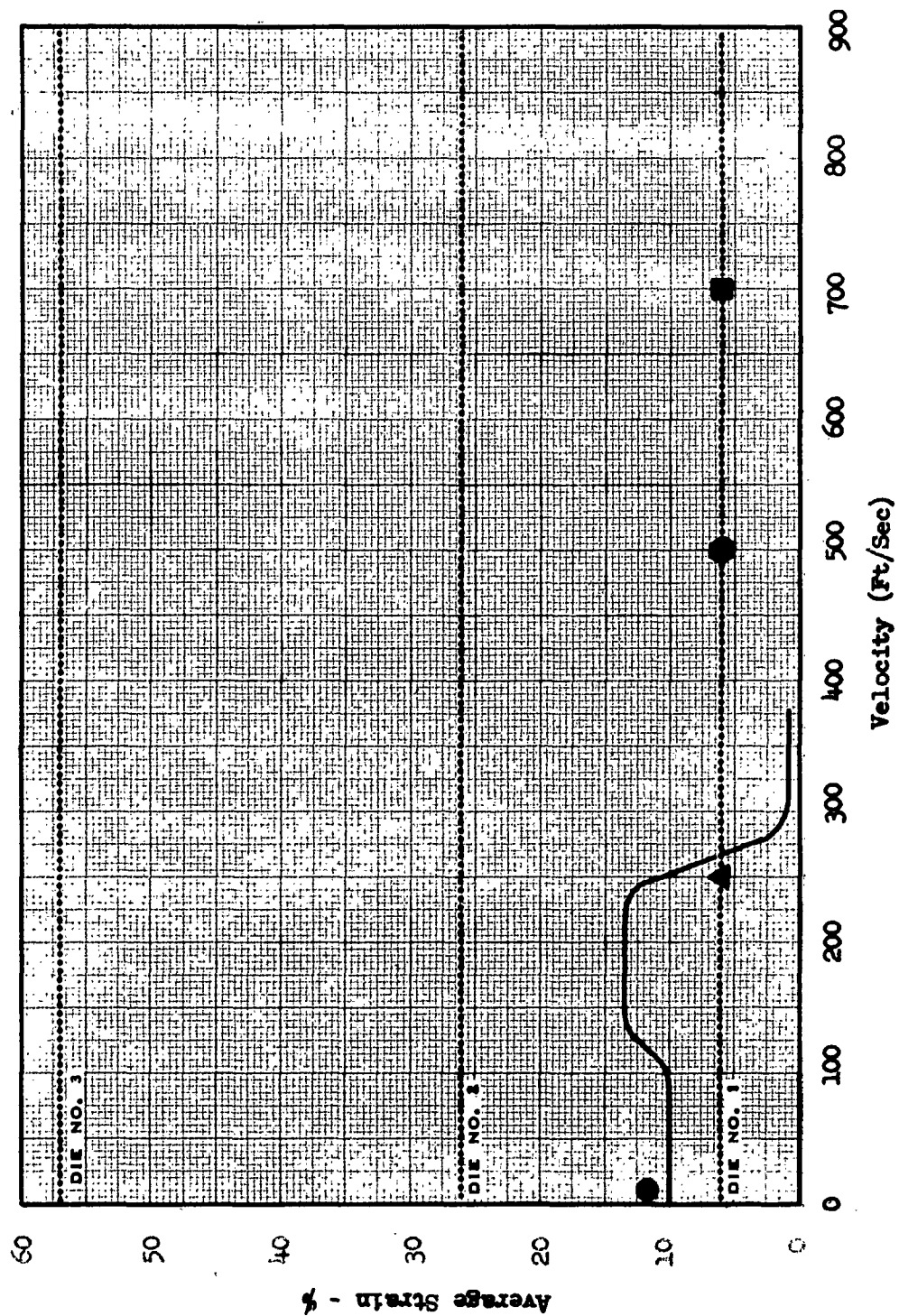


FIGURE 13
ELONGATION LIMIT CURVE
SHOWING EXPERIMENTAL POINTS
L-605

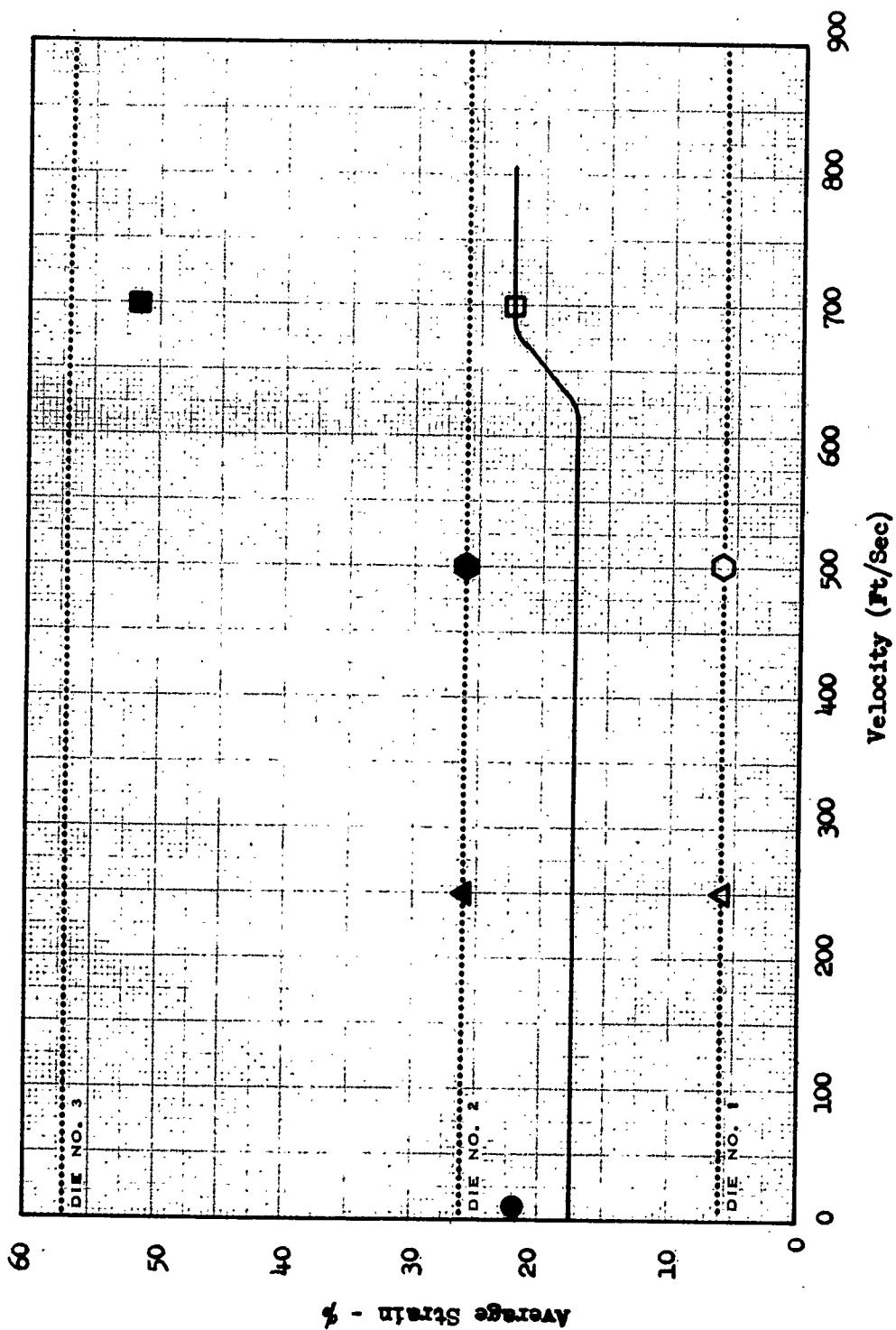


FIGURE 14
 ELONGATION LIMIT CURVE
 SHOWING EXPERIMENTAL POINTS
 REE '41

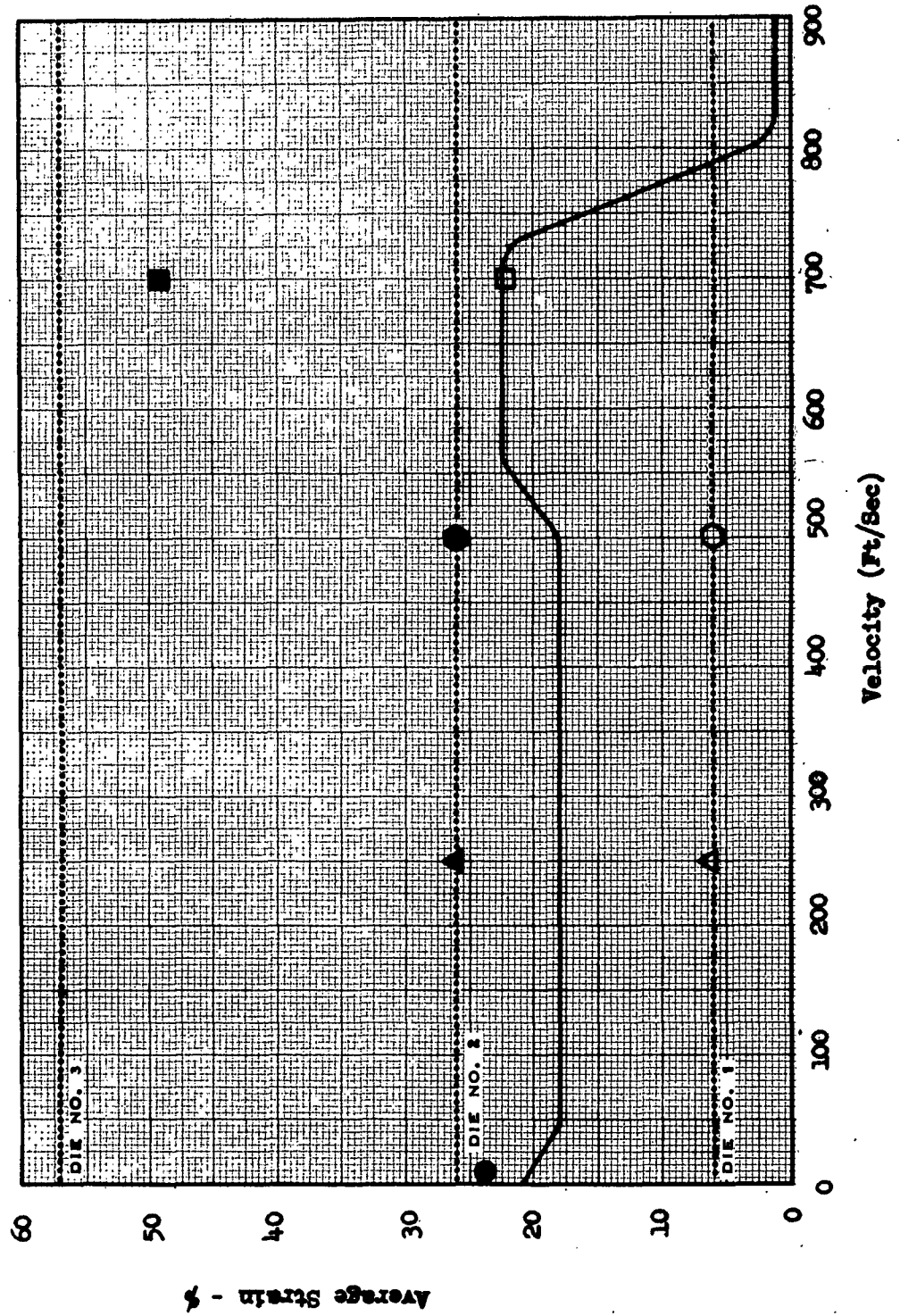


FIGURE 15
 ELONGATION LIMIT CURVE
 SHOWING EXPERIMENTAL POINTS
 2024-O ALUMINUM

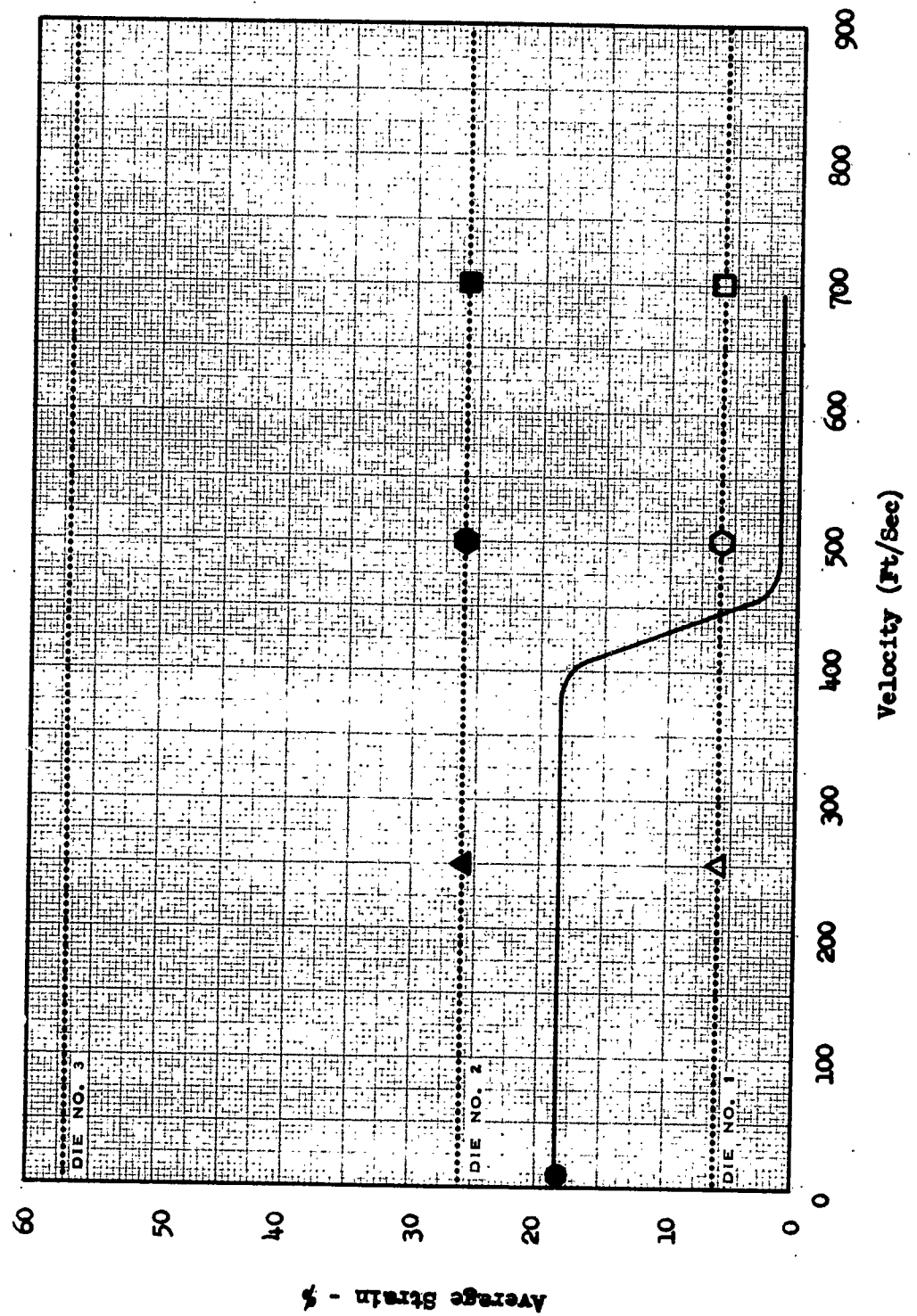


FIGURE 16
 ELONGATION LIMIT CURVE
 SHOWING EXPERIMENTAL POINTS
 17-7 PH
 (ELEVATED TEMPERATURE - 1000°F)

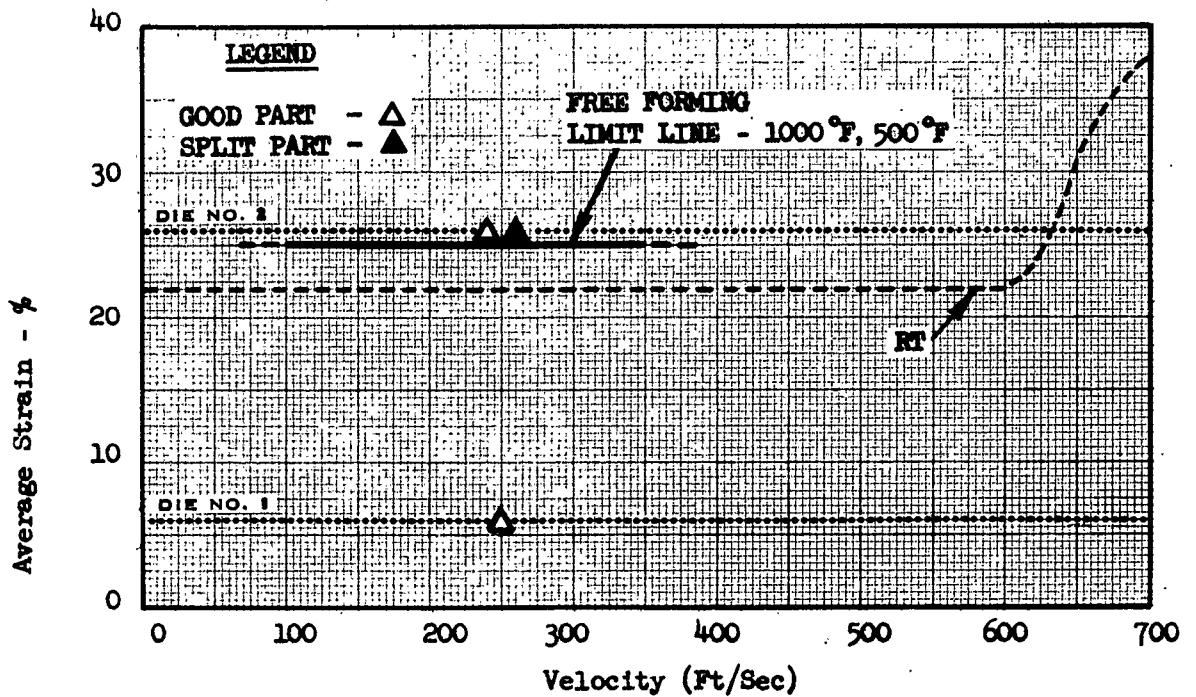


FIGURE 17
 ELONGATION LIMIT CURVE
 SHOWING EXPERIMENTAL POINTS
 A-286
 (ELEVATED TEMPERATURE - 1000°F)

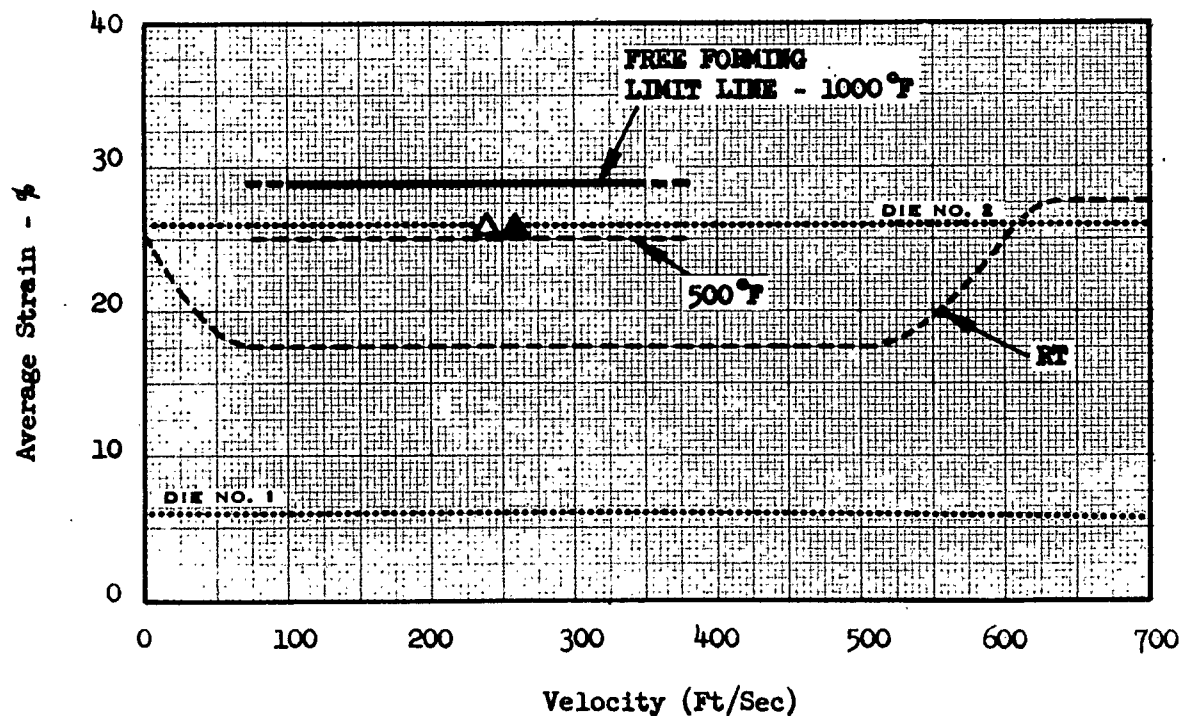


FIGURE 18
 ELONGATION LIMIT CURVE
 SHOWING EXPERIMENTAL POINTS
 VASCOJET 1000
 (ELEVATED TEMPERATURE - 1000°F)

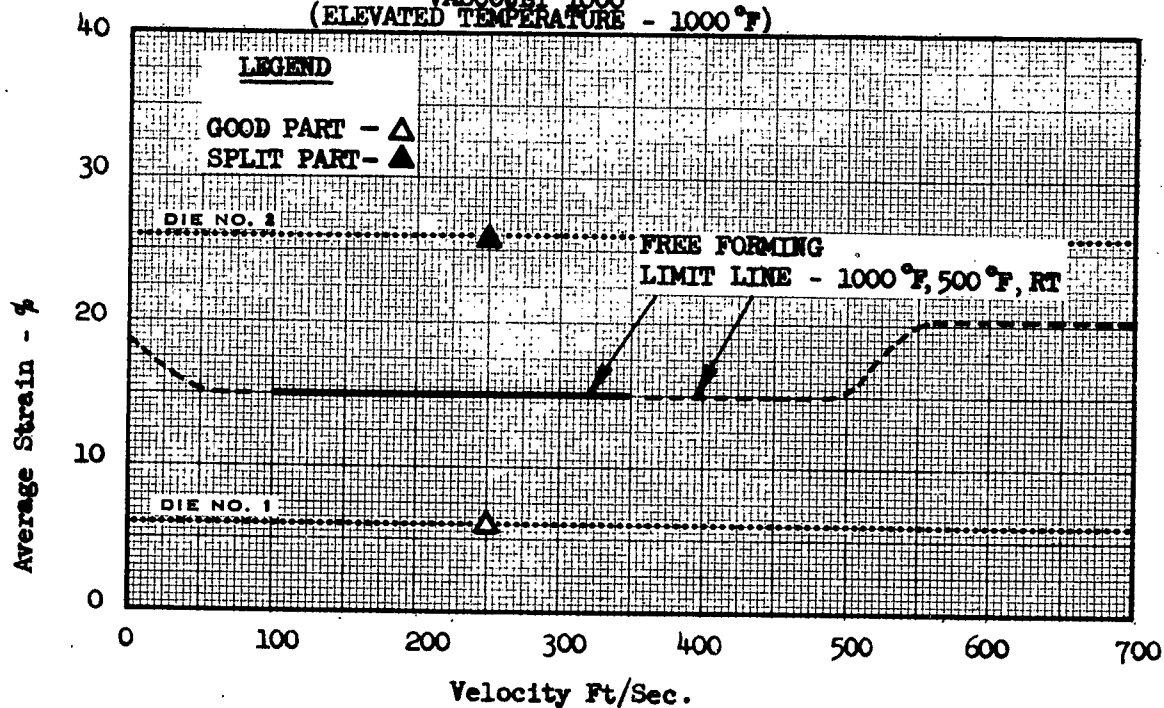


FIGURE 19
 ELONGATION LIMIT CURVE
 SHOWING EXPERIMENTAL POINTS
 USS 12 MoV
 (ELEVATED TEMPERATURE - 1000°F)

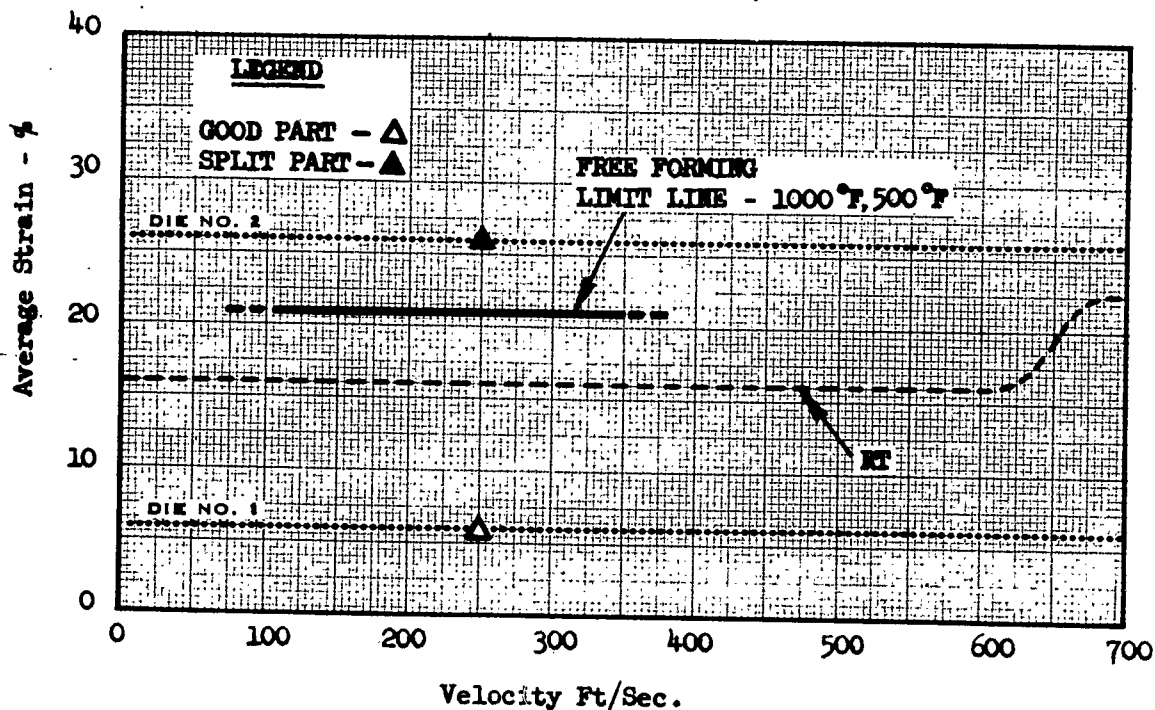


FIGURE 20
 ELONGATION LIMIT CURVE
 SHOWING EXPERIMENTAL POINTS
 TITANIUM (6Al-4V)
 (ELEVATED TEMPERATURE - 1200°F)

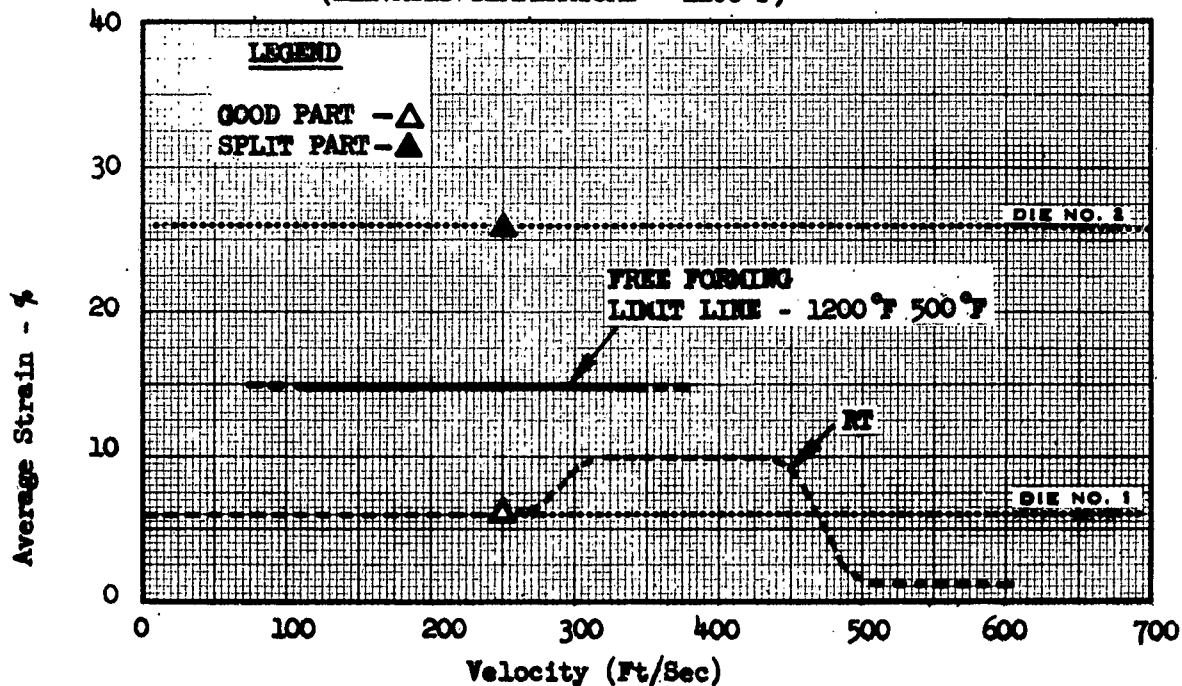


FIGURE 21
 ELONGATION LIMIT CURVE
 SHOWING EXPERIMENTAL POINTS
 TITANIUM (13V-11Cr-3Al)
 (ELEVATED TEMPERATURE - 1200°F)

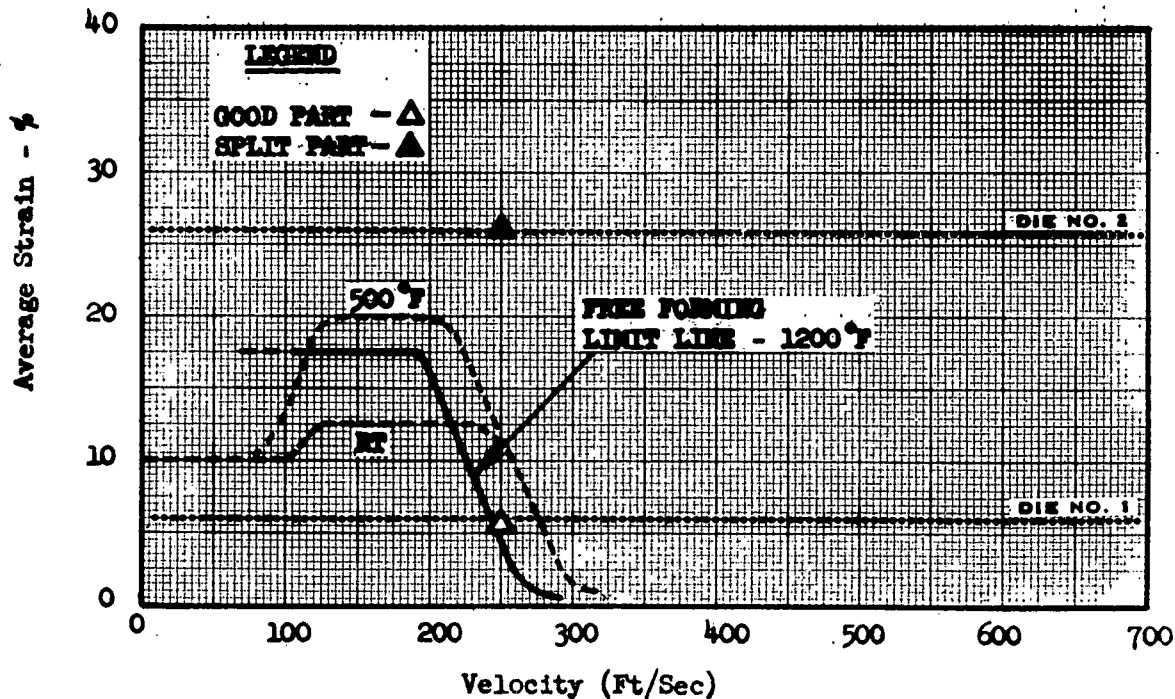


FIGURE 22
 ELONGATION LIMIT CURVE
 SHOWING EXPERIMENTAL POINTS
 L-605
 (ELEVATED TEMPERATURE - 500°F)

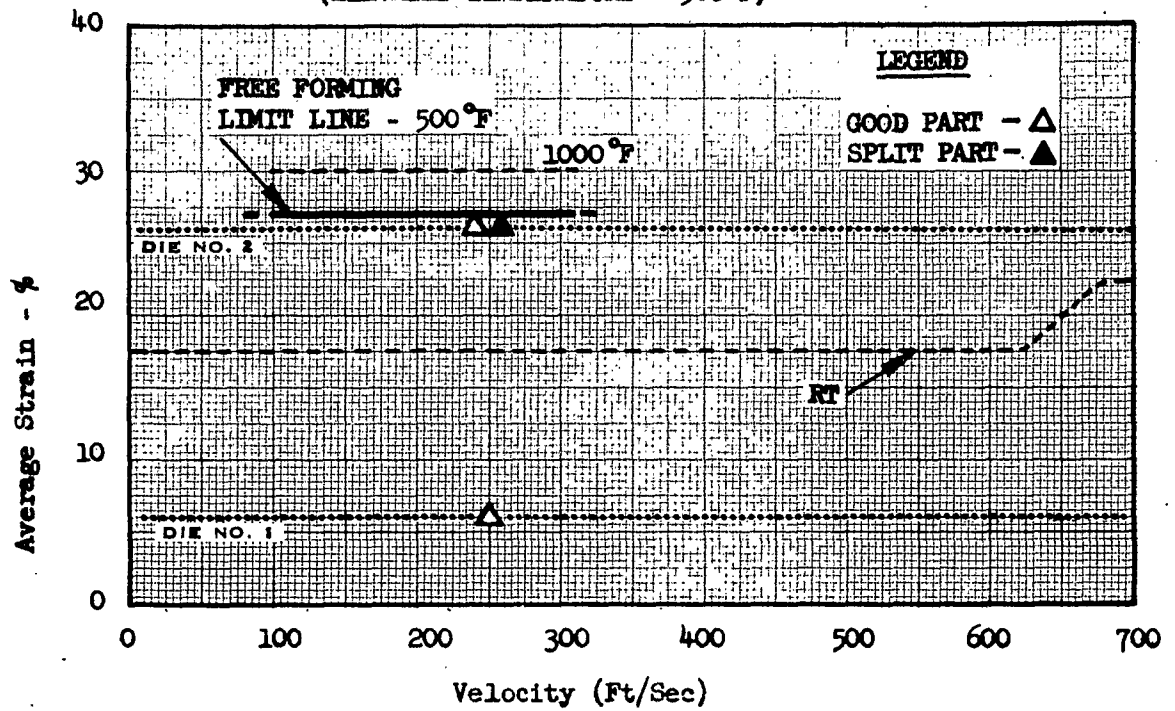


FIGURE 23
 ELONGATION LIMIT CURVE
 SHOWING EXPERIMENTAL POINTS
 RENE 41
 (ELEVATED TEMPERATURE - 500°F)

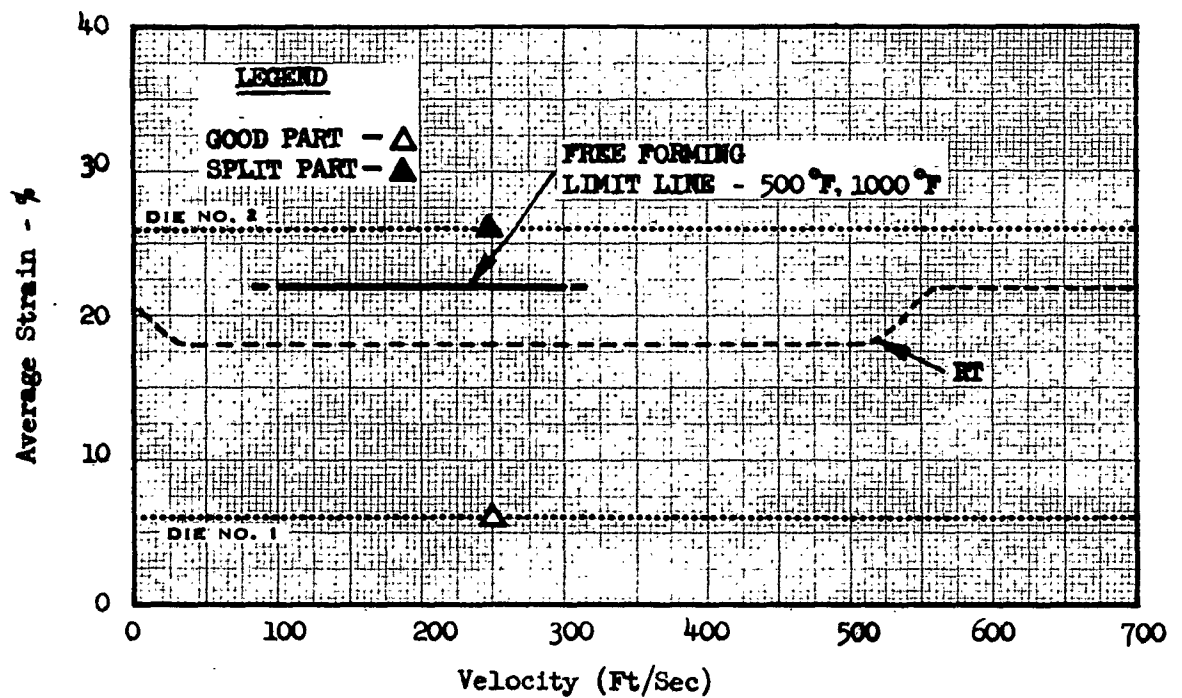
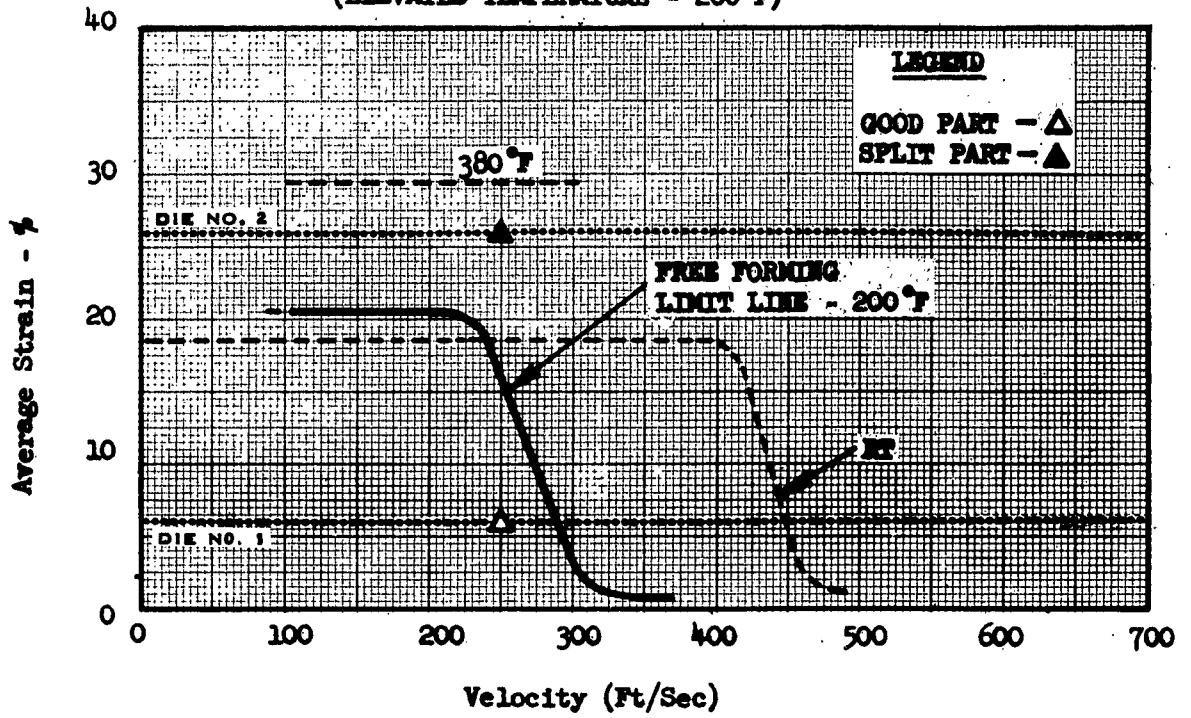
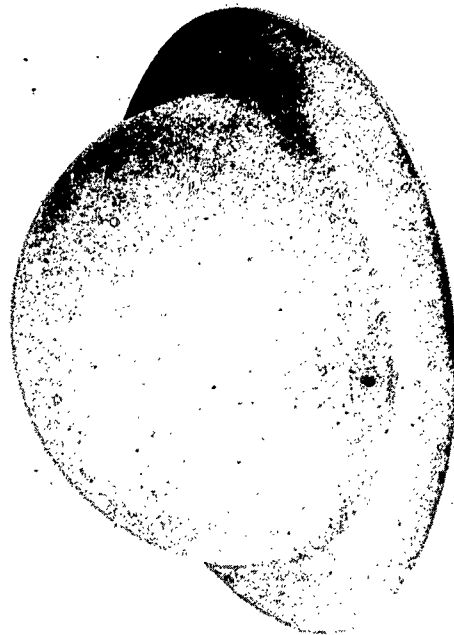


FIGURE 24
 ELONGATION LIMIT CURVE
 SHOWING EXPERIMENTAL POINTS
 2024-O ALUMINUM
 (ELEVATED TEMPERATURE - 200°F)





T



U



FIGURE 25. COMPARISON BETWEEN DRAW (T) AND NO-DRAW (U), STATIC FORMED 2024-O ALUMINUM PARTS



FIGURE 26. COMPARISON BETWEEN STATIC FORMED TITANIUM (6Al-4V) PARTS
AT 1200°F (V) AND ROOM TEMPERATURE (W)

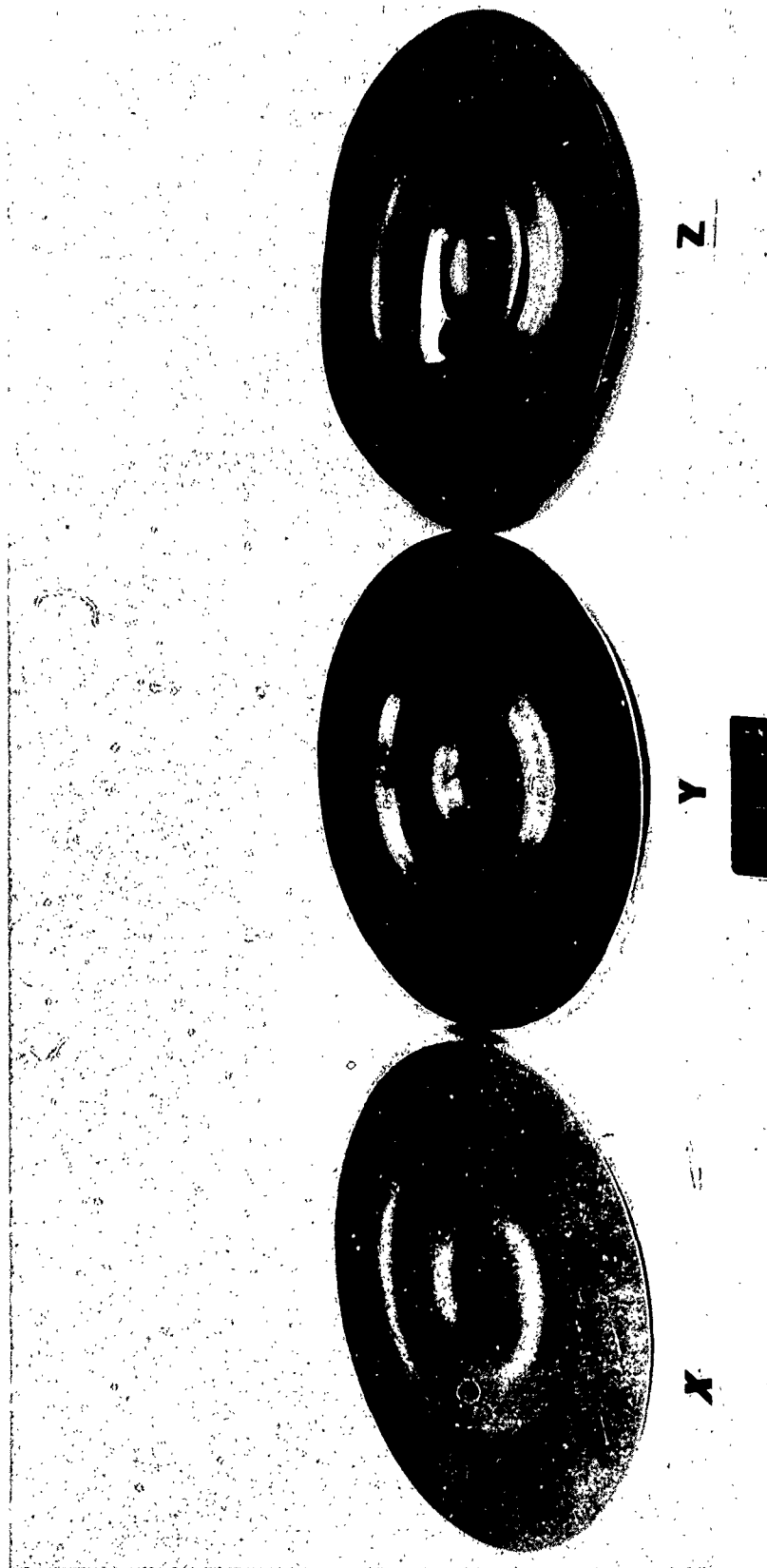
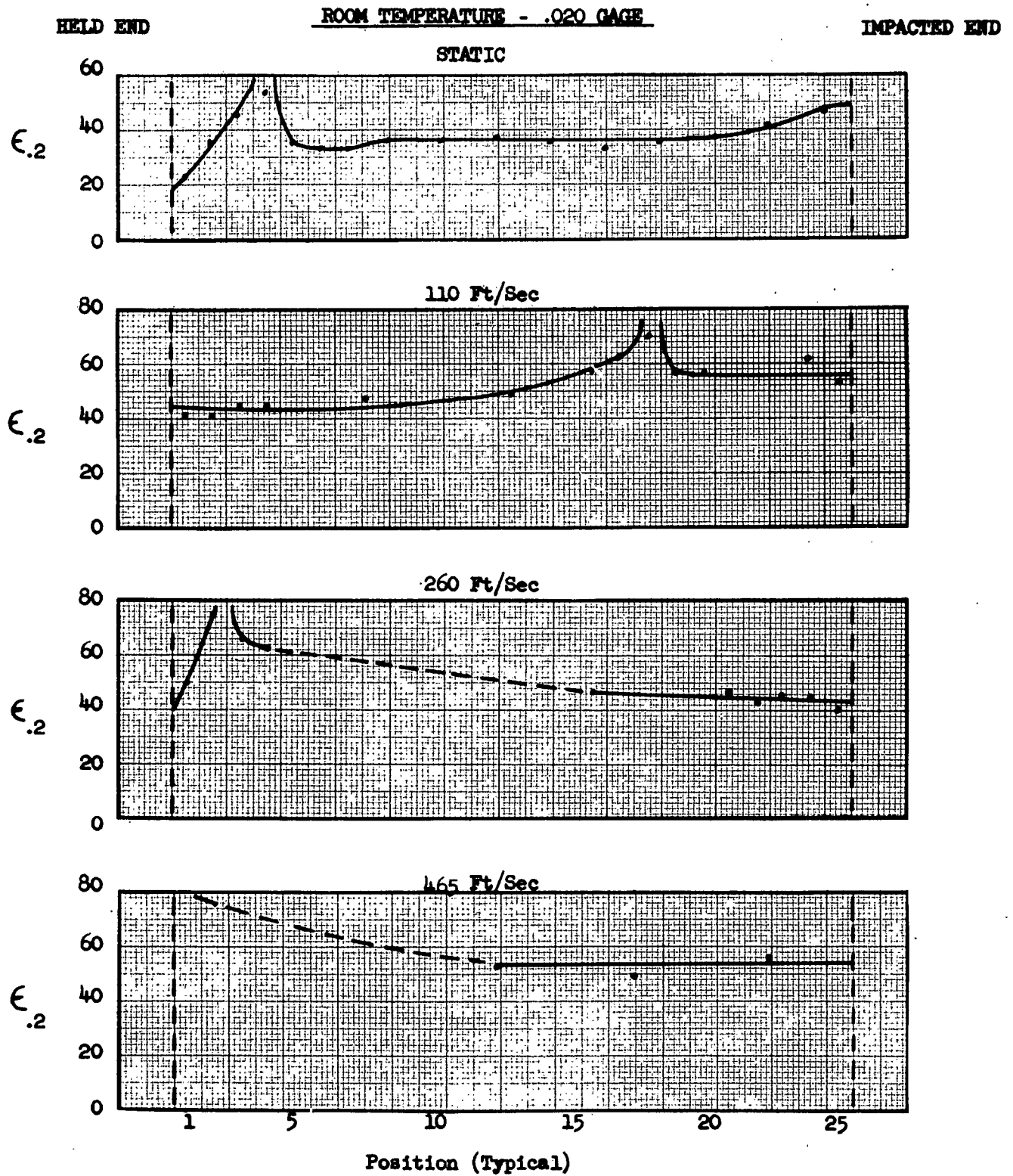


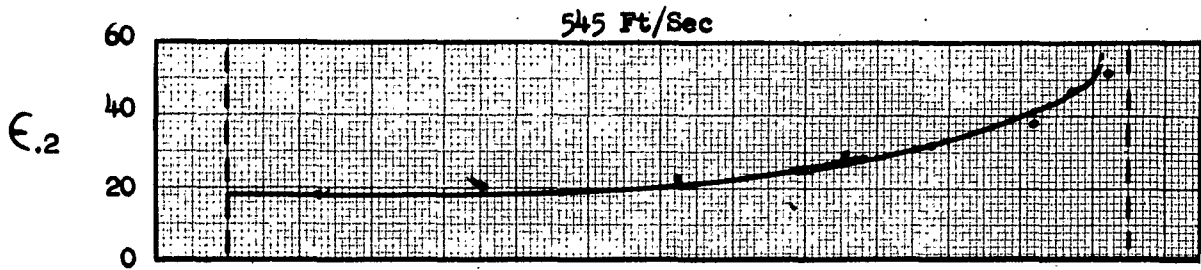
FIGURE 27. EXAMPLE OF PART FORMING IN THE SHALLOW RECESS DIES #1(X), #2(Y), AND #3(Z)

APPENDIX A

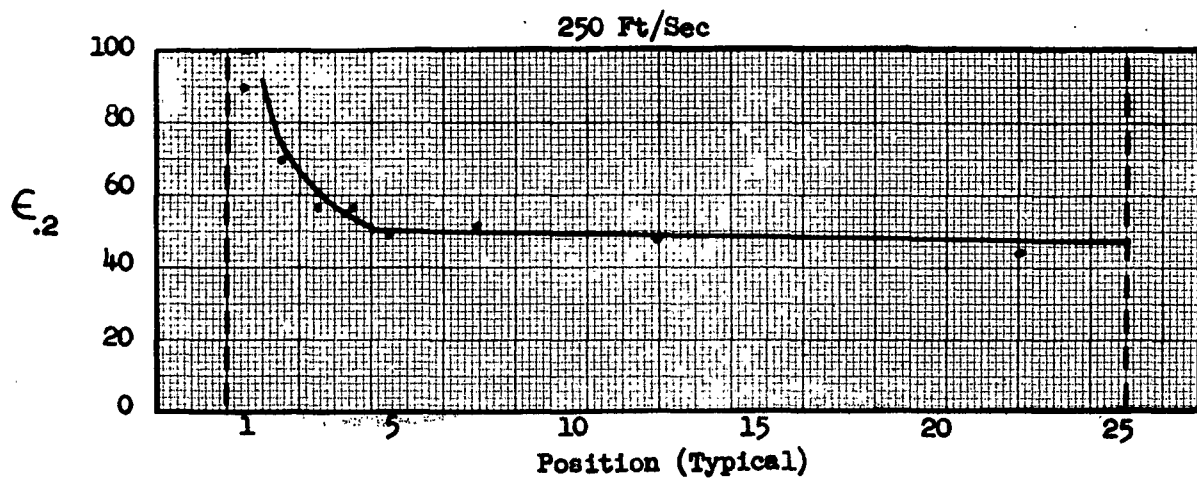
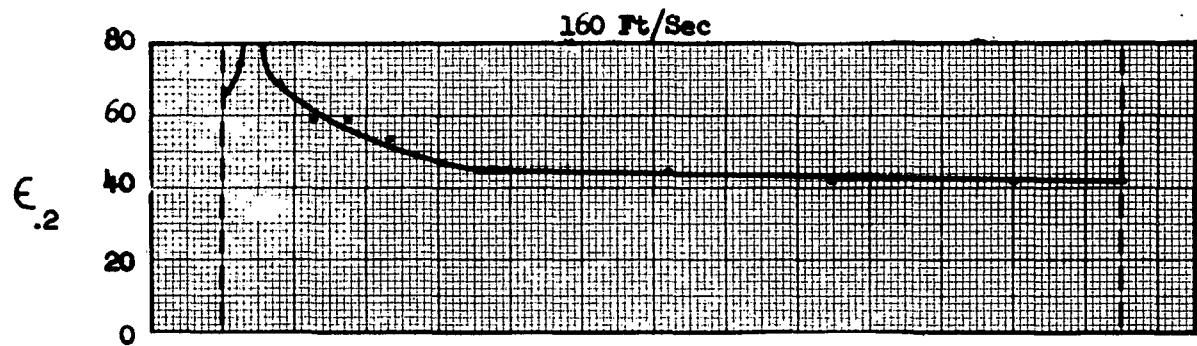
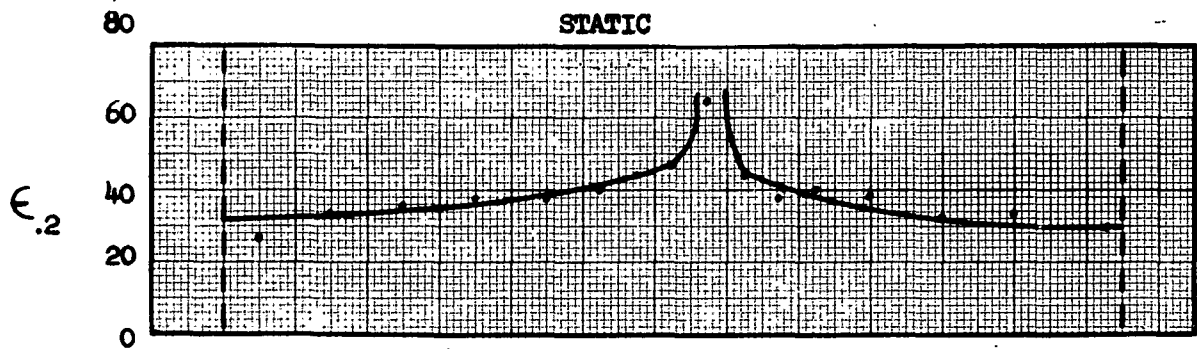
GRAPH 1
 LONGITUDINAL TENSILE SPECIMENS
 ELONGATION VS POSITION OF .2 INCH GAGE LENGTH
 AT VARIOUS TEST TEMPERATURES AND VELOCITIES
 17-7 PH - 5" GAGE LENGTH



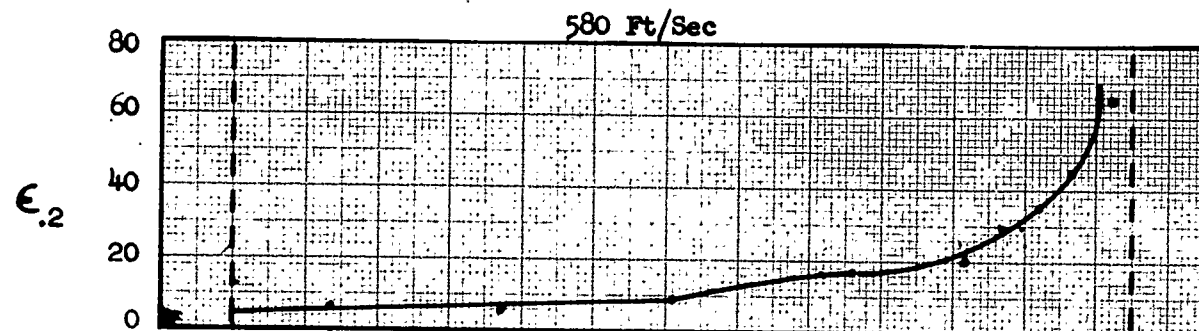
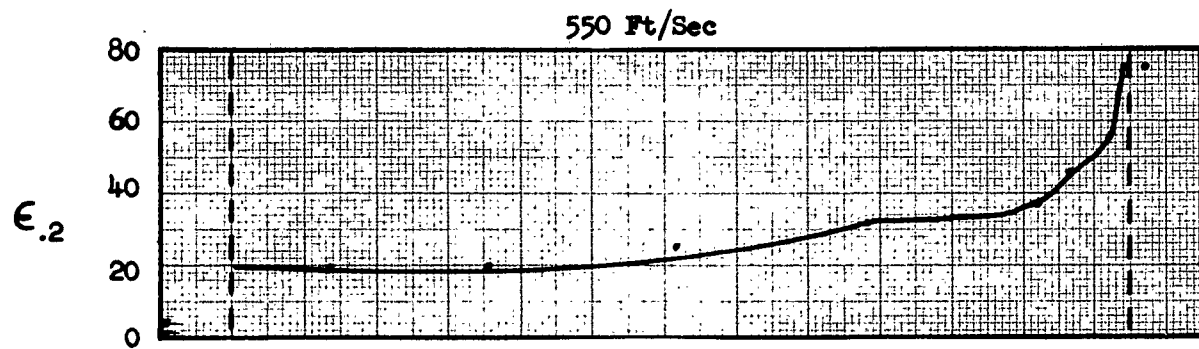
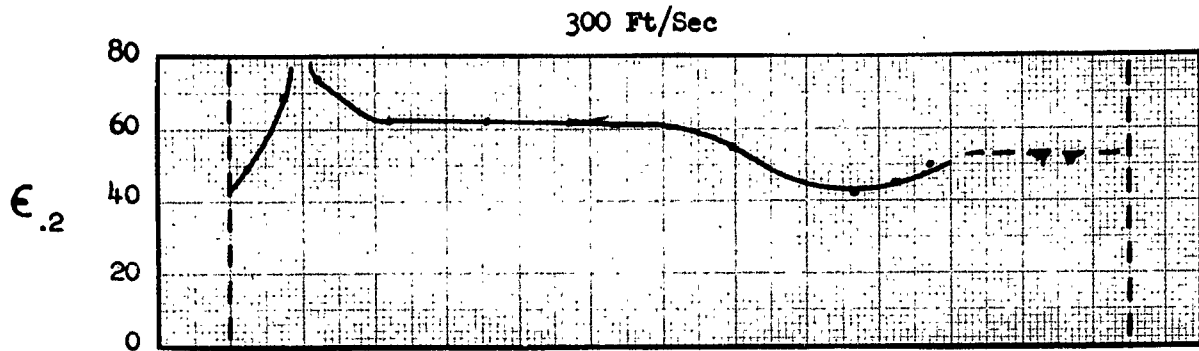
GRAPH 1 (Continued)



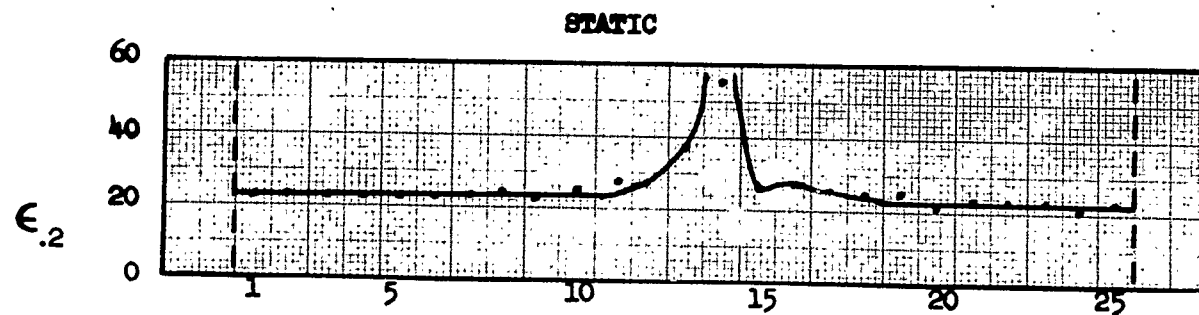
ROOM TEMPERATURE - .063 GAGE



GRAPH 1 (Continued)

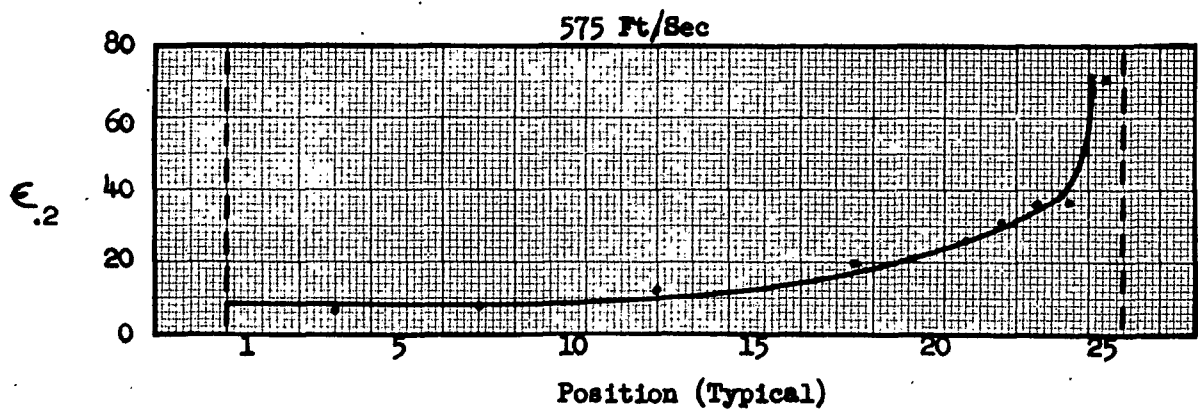
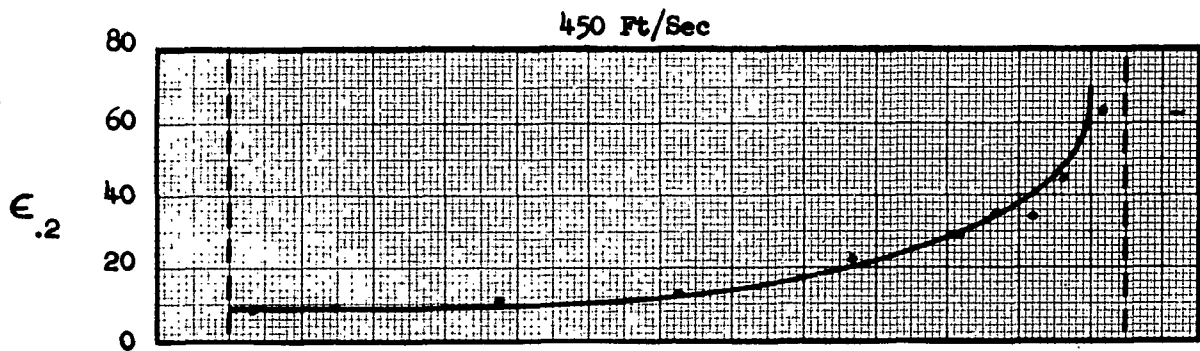
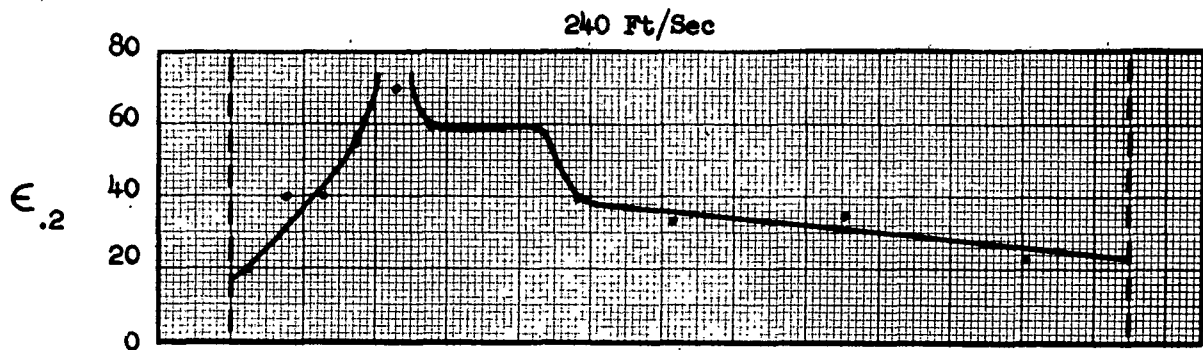
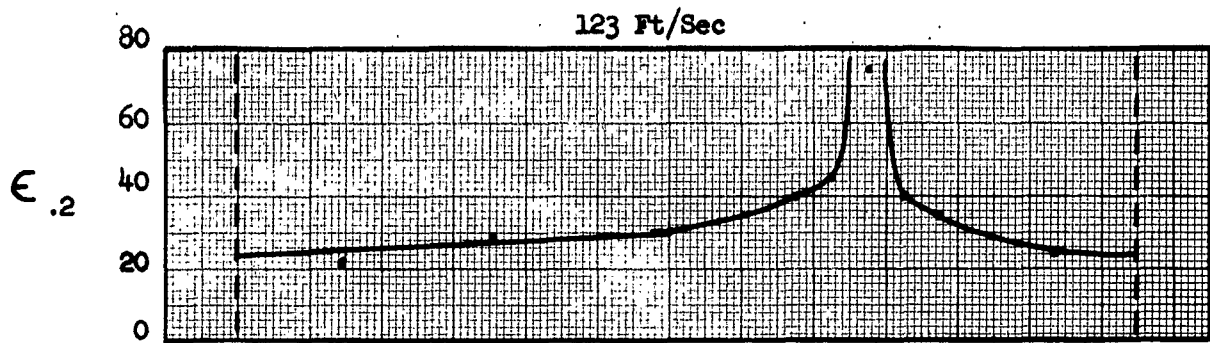


500°F - .063 GAGE



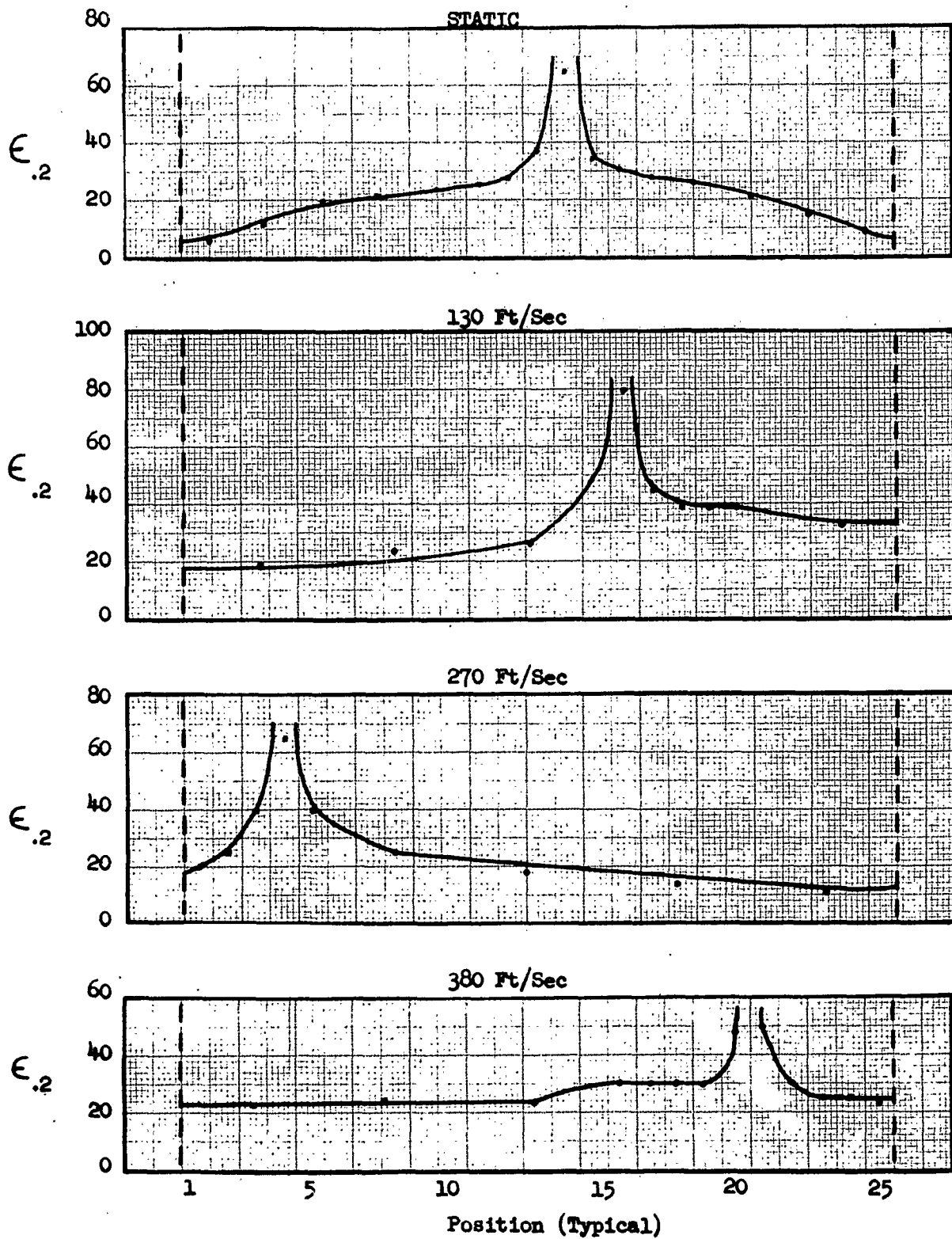
Position (Typical)

GRAPH 1. (Continued)

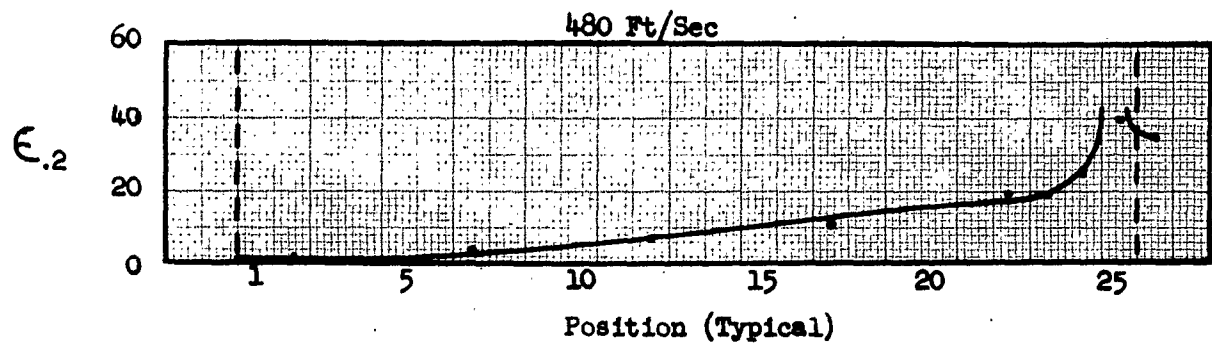


GRAPH 1 (Continued)

1000°F - .063 GAGE

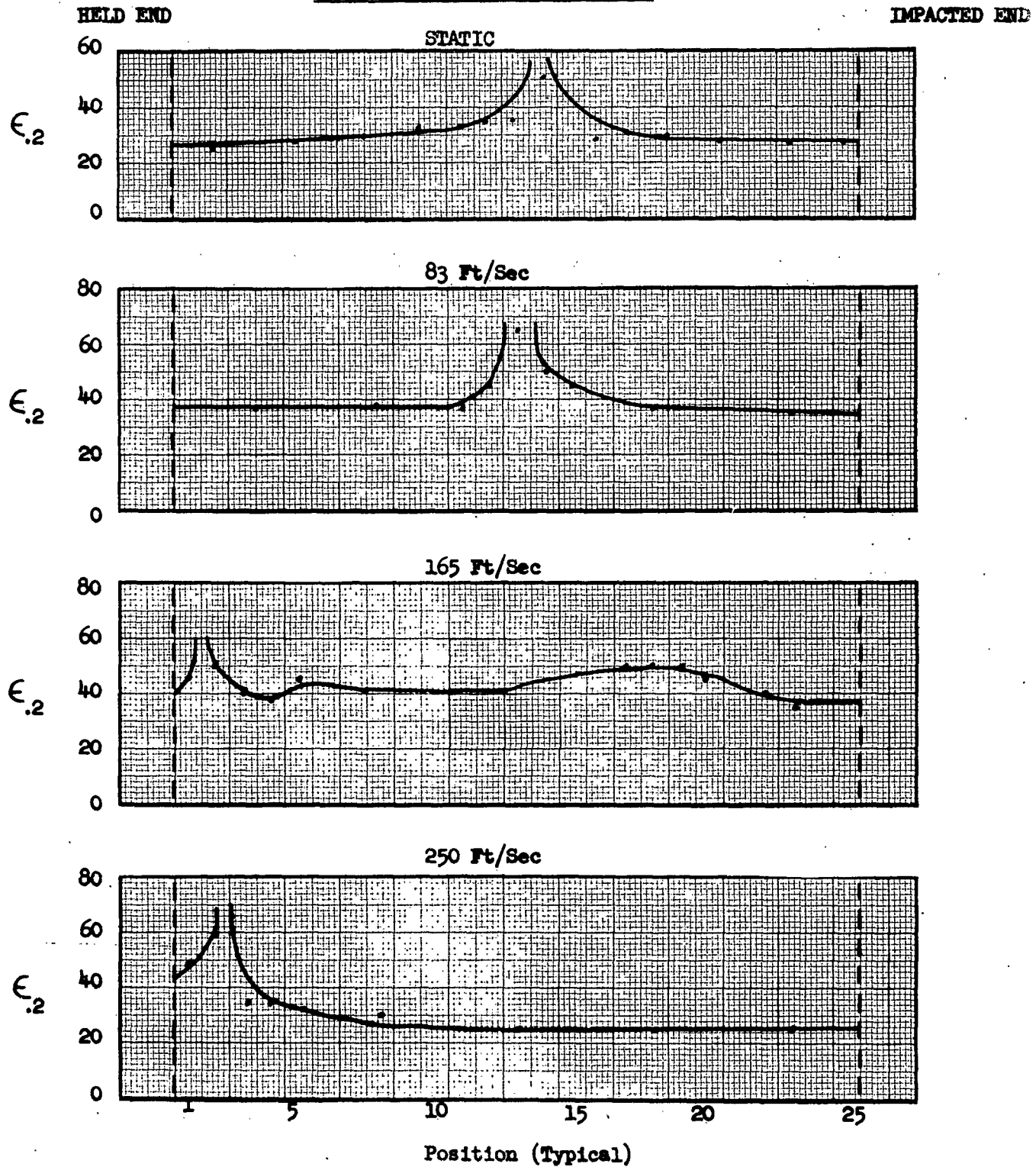


GRAPH 1 (Concluded)

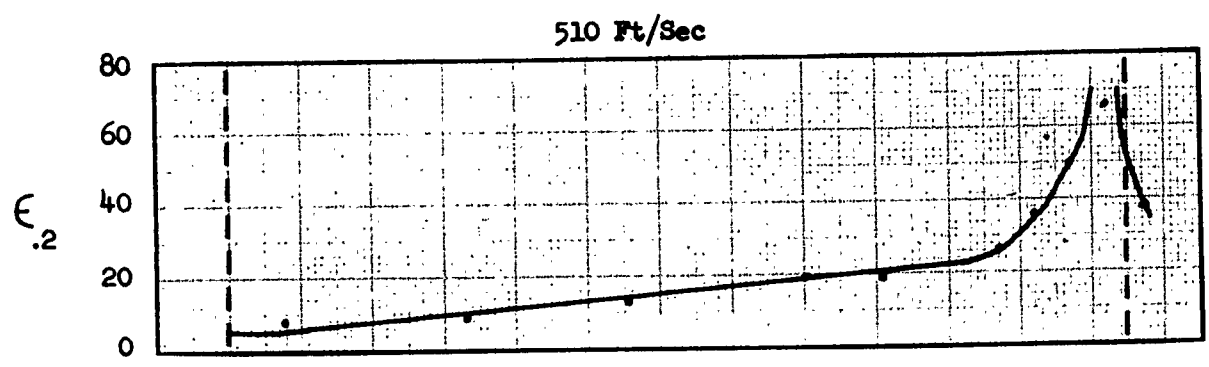
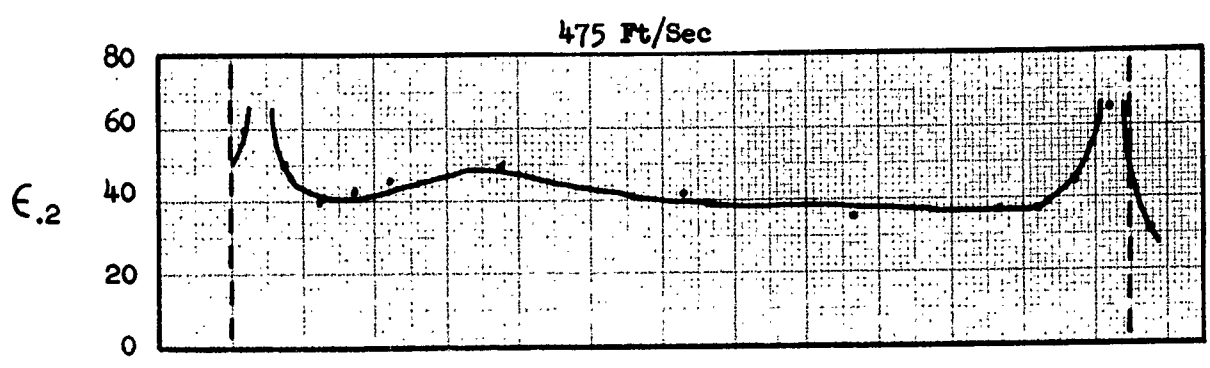
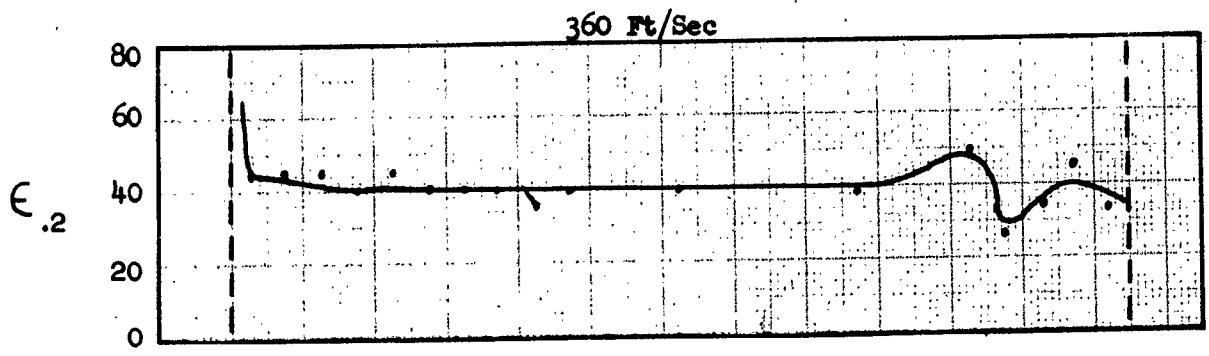


GRAPH 2
 LONGITUDINAL TENSILE SPECIMENS
 ELONGATION VS POSITION OF .2 INCH GAGE LENGTH
 AT VARIOUS TEST TEMPERATURES AND VELOCITIES
 A-286 - 5" GAGE LENGTH

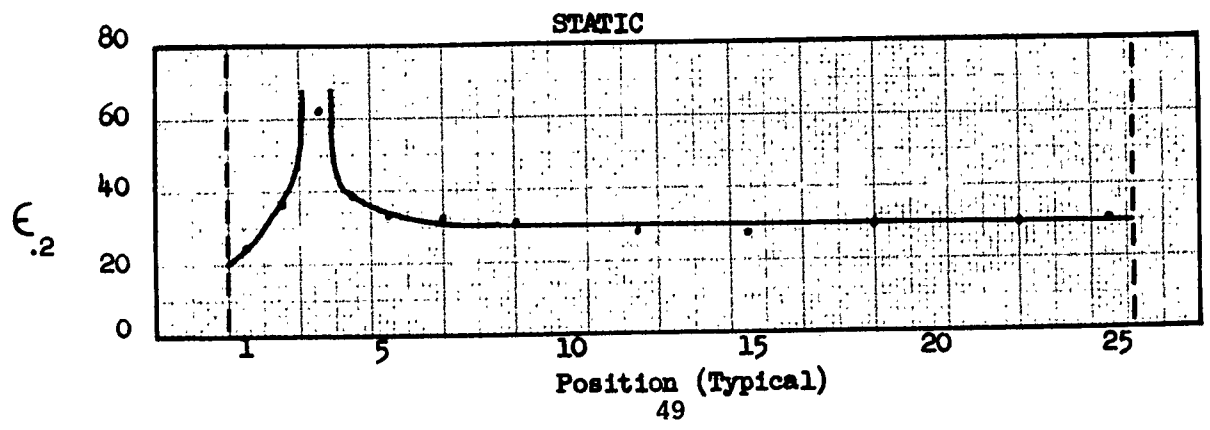
ROOM TEMPERATURE - .020 GAGE



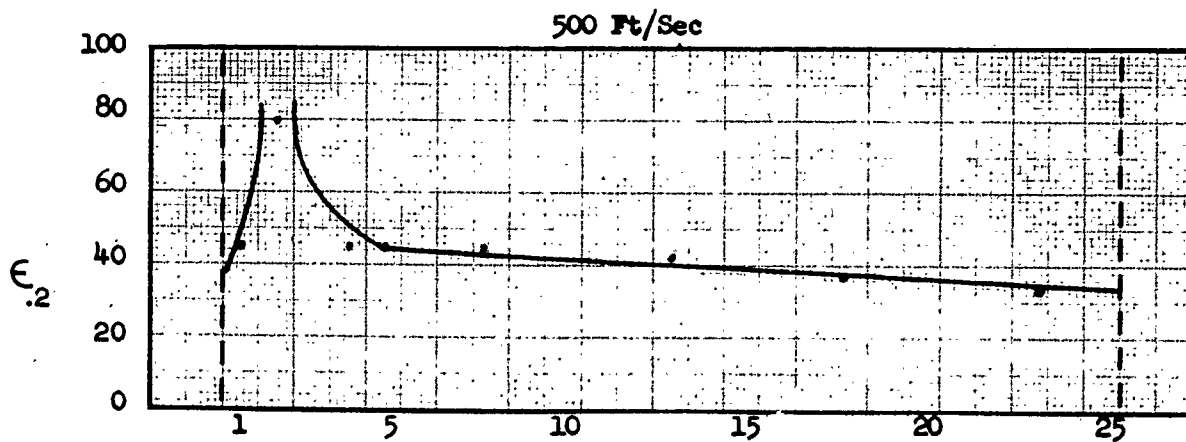
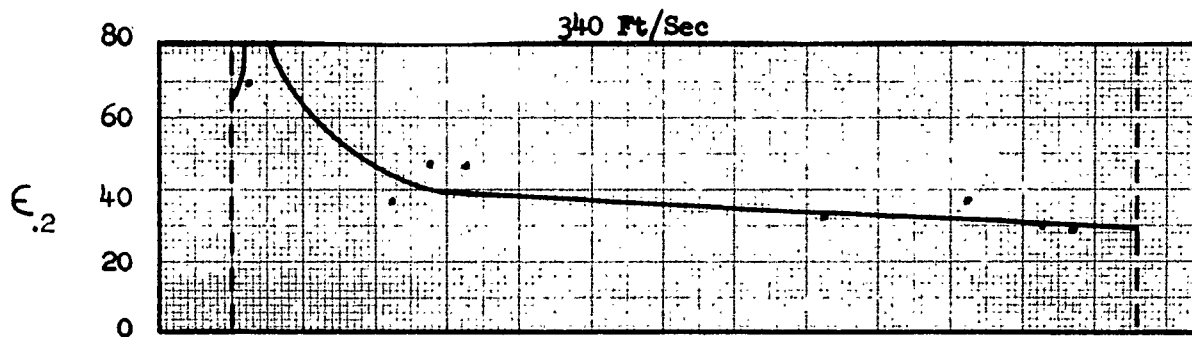
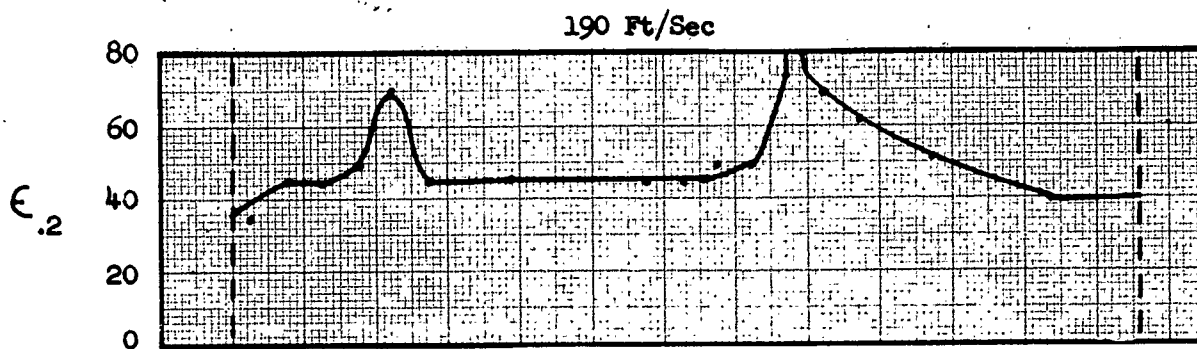
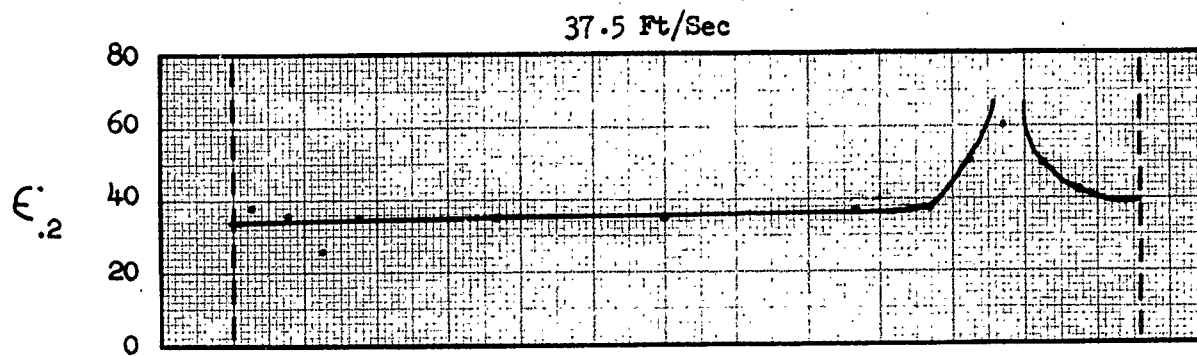
GRAPH 2 (Continued)



ROOM TEMPERATURE - .063 GAGE

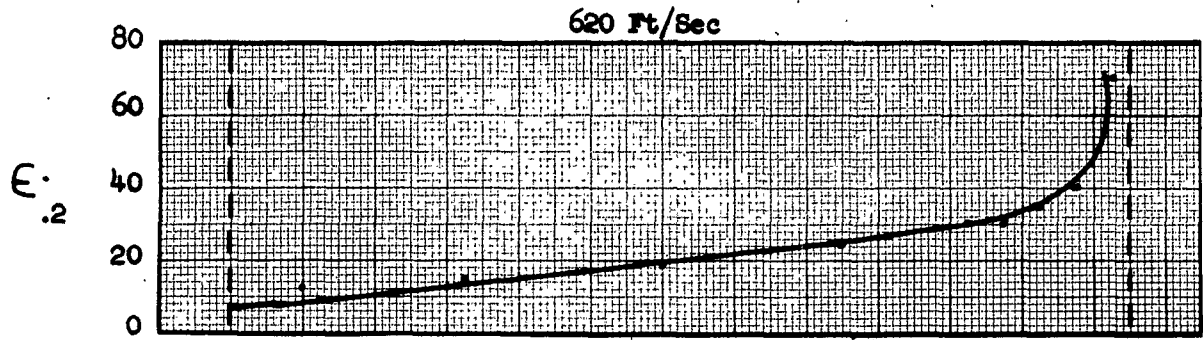


GRAPH 2 (Continued)

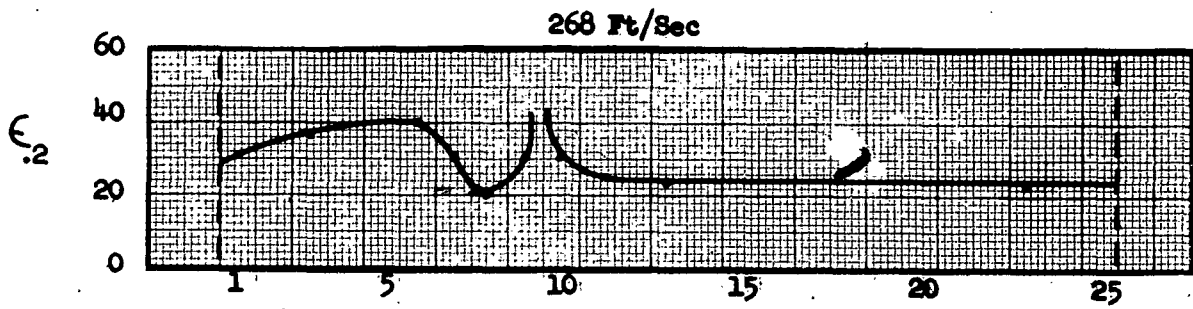
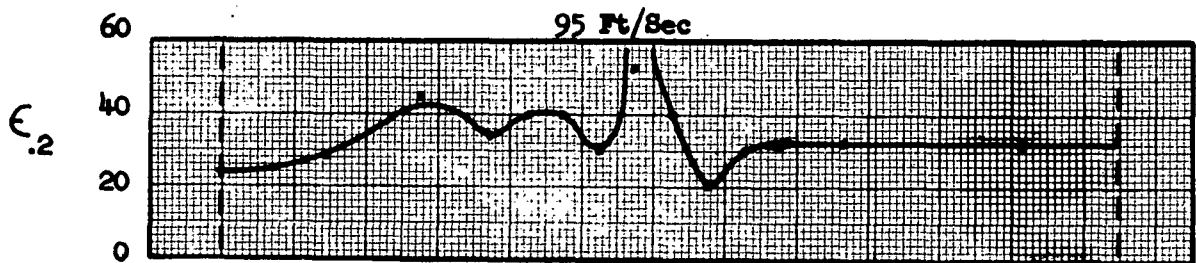
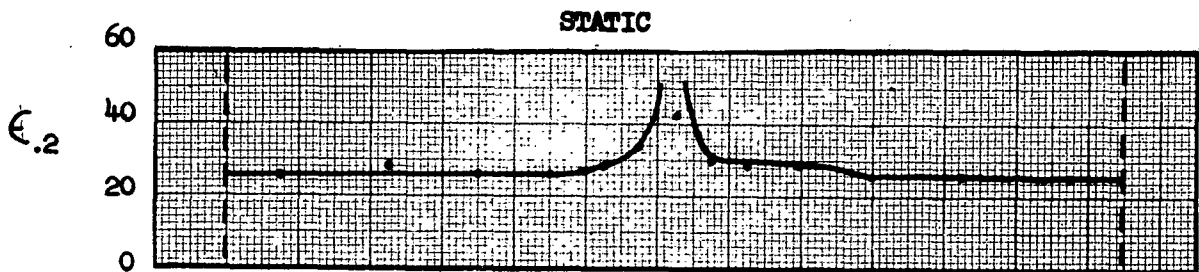


Position (Typical)

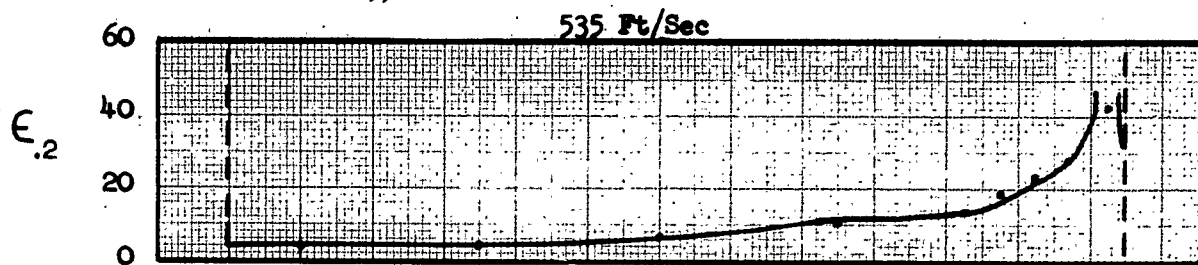
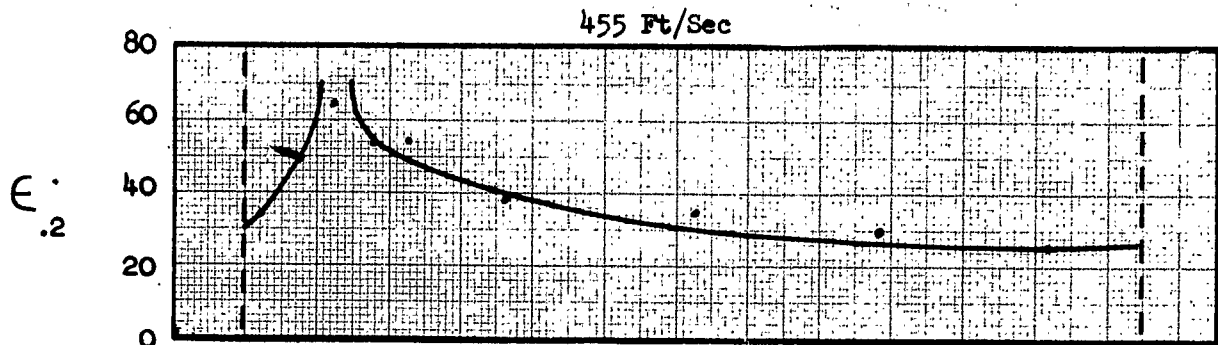
GRAPH 2 (Continued)



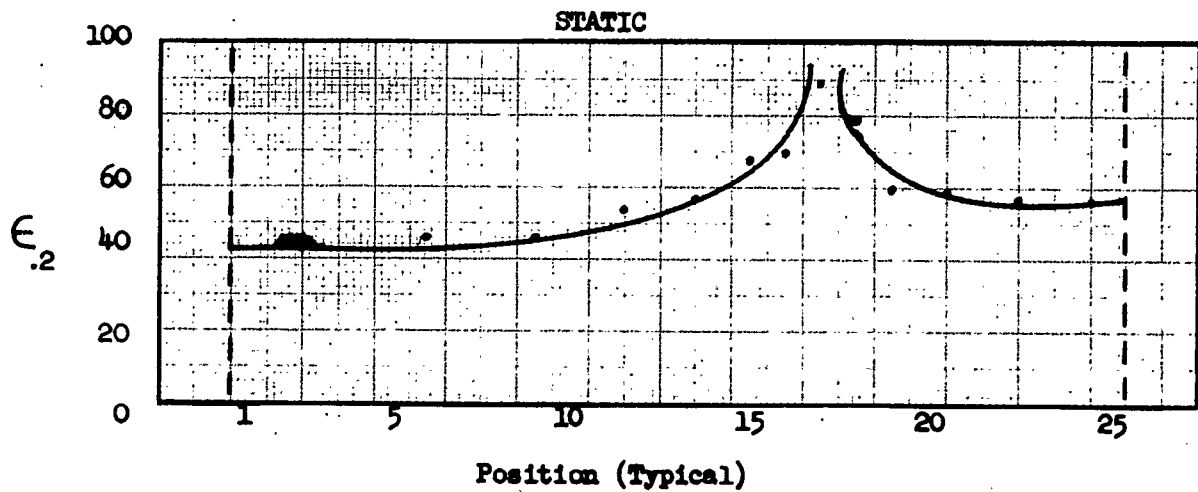
500°F - .020 GAGE



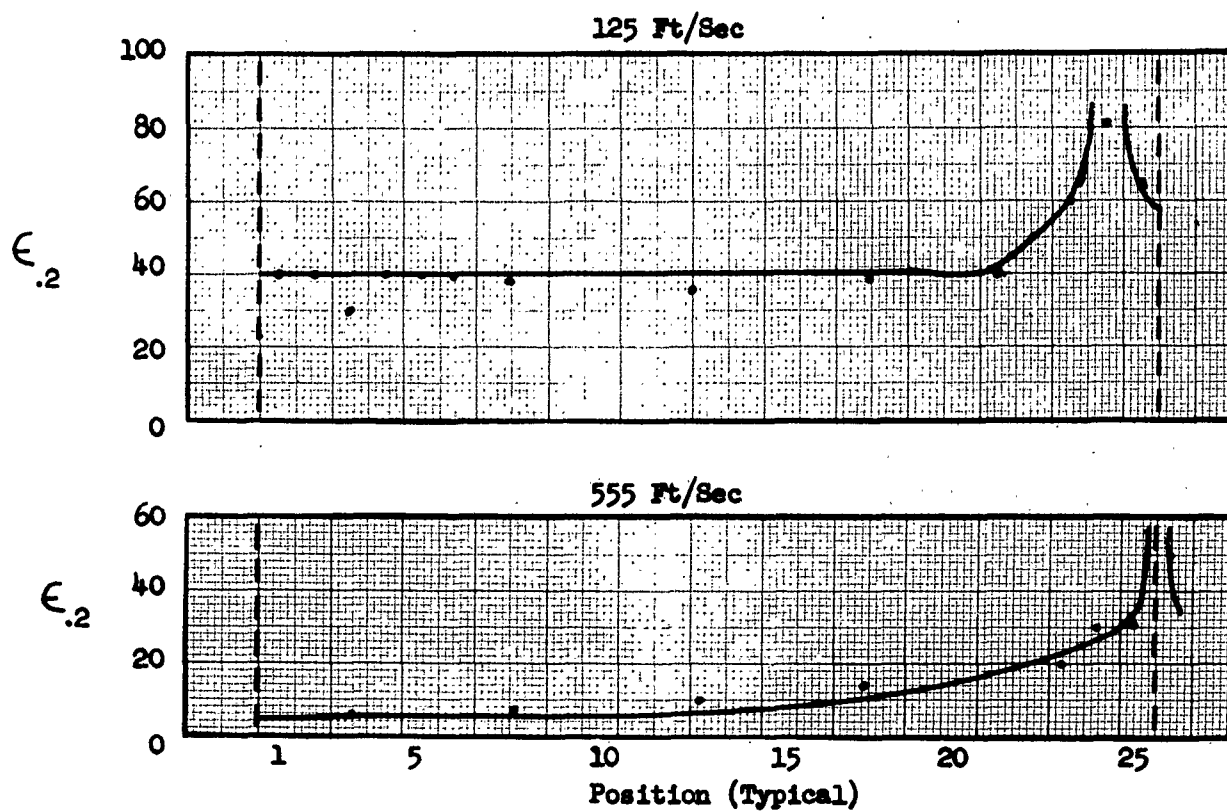
GRAPH 2 (Continued)



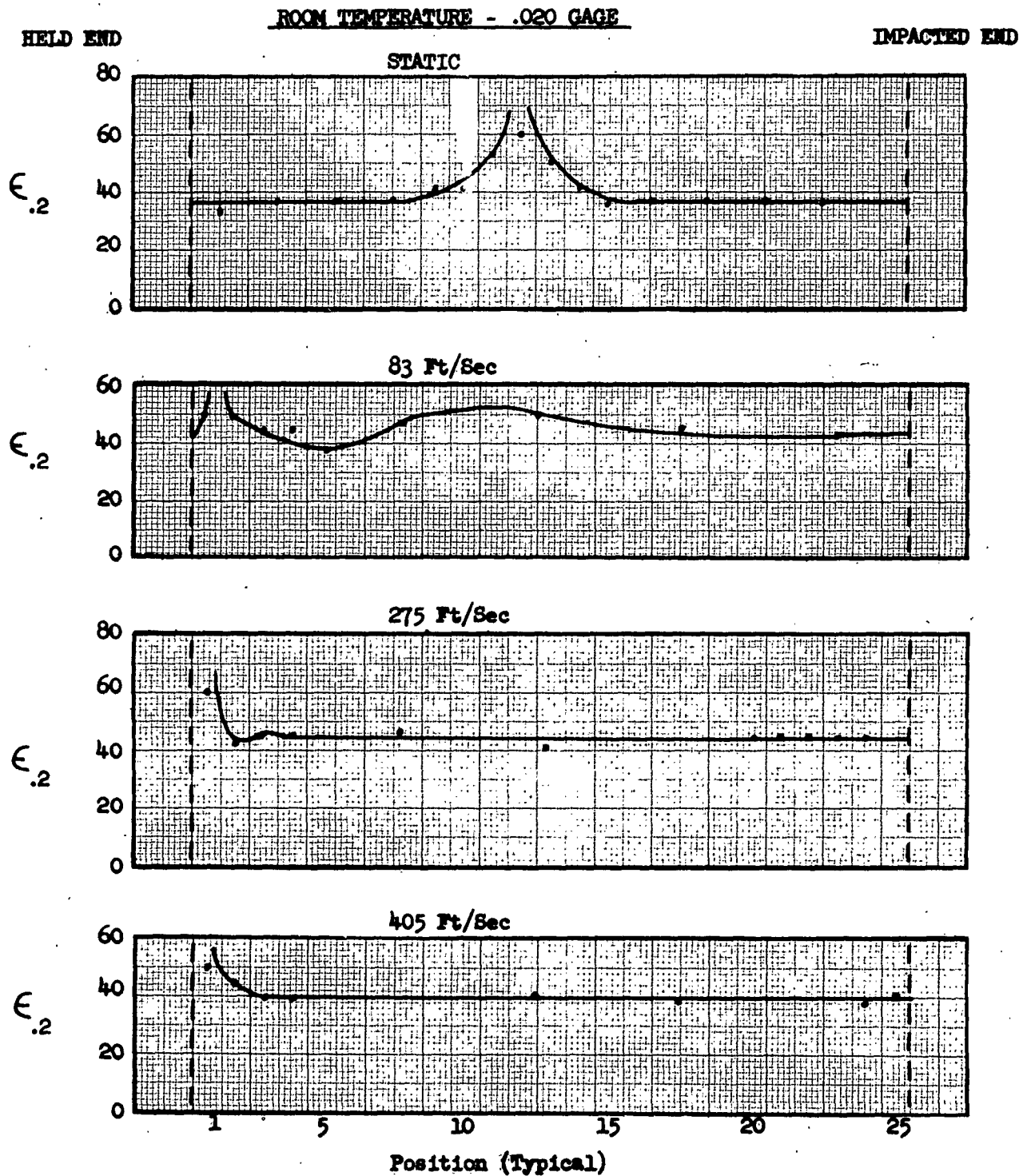
1000°F - .020 GAGE



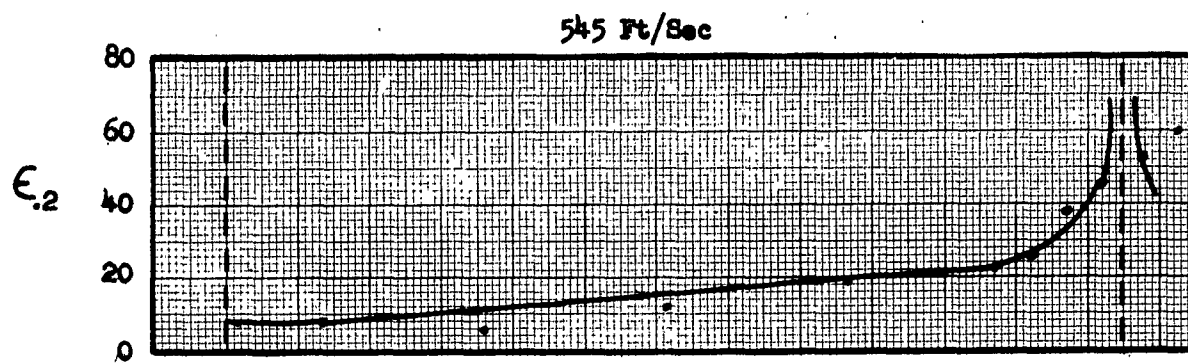
GRAPH 2 (Concluded)



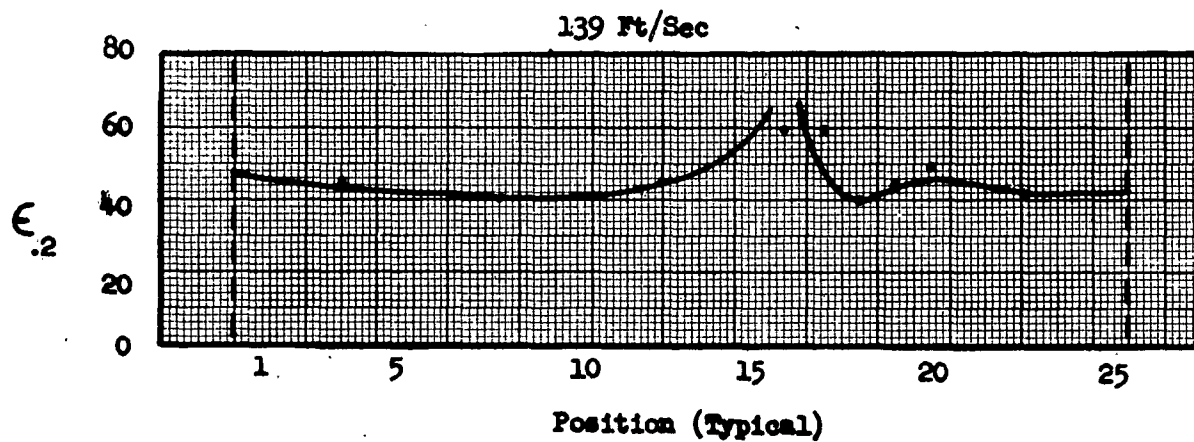
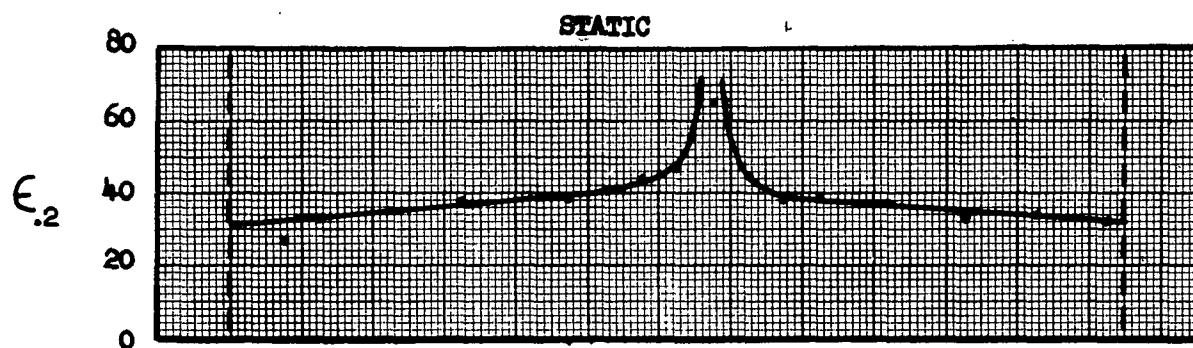
GRAPH 3
LONGITUDINAL TENSILE SPECIMENS
ELONGATION VS POSITION OF .2 INCH GAGE LENGTH
AT VARIOUS TEST TEMPERATURES AND VELOCITIES
RENE'41 - 5" GAGE LENGTH



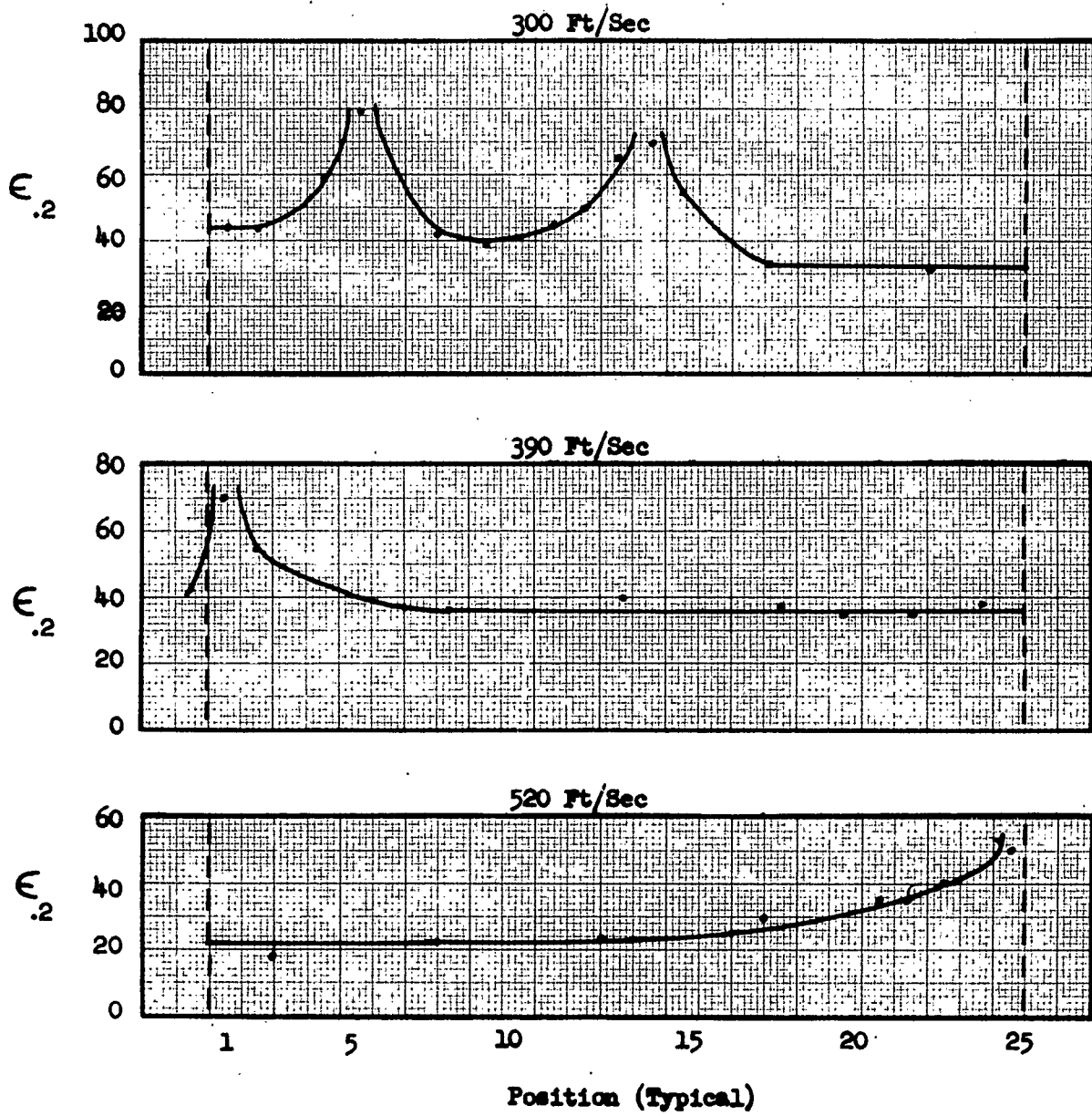
GRAPH 3 (Continued)



ROOM TEMPERATURE - .063 GAGE

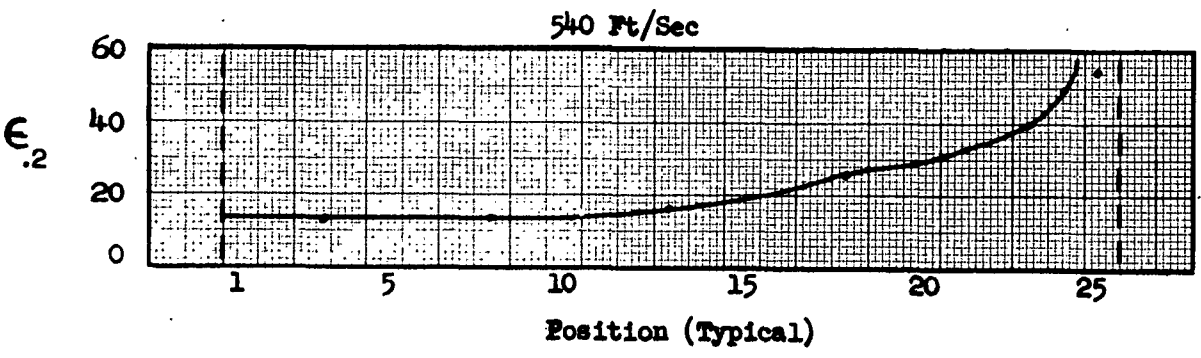
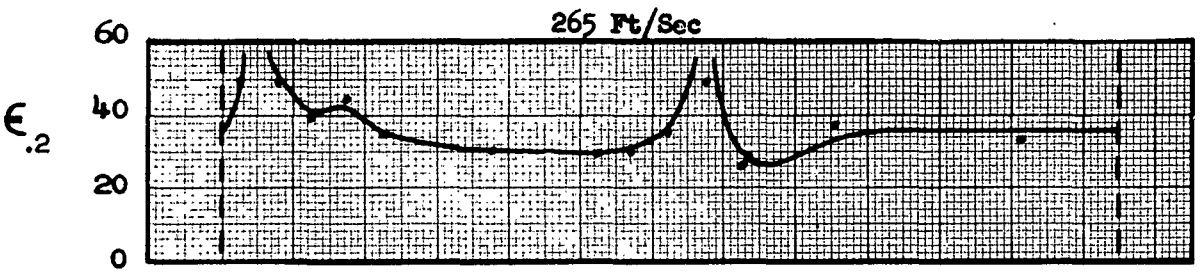
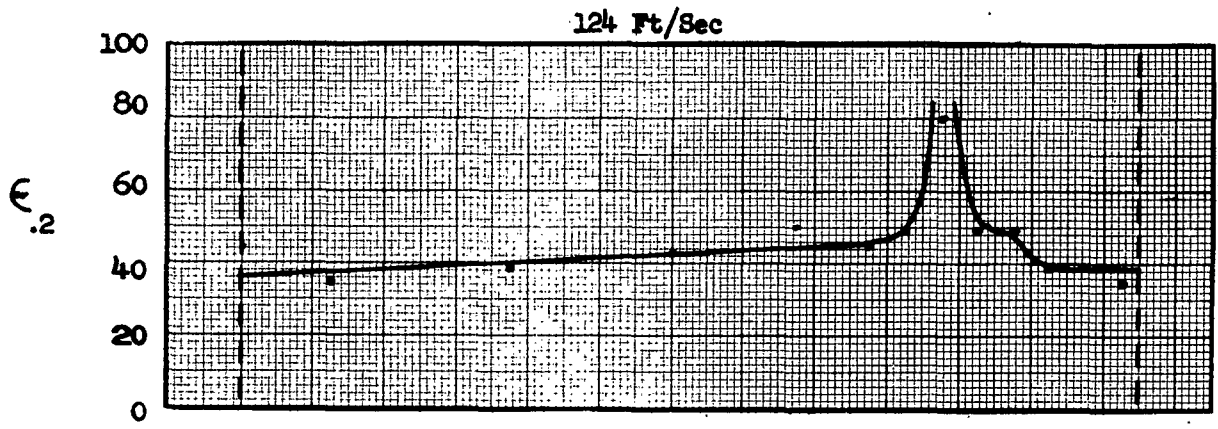
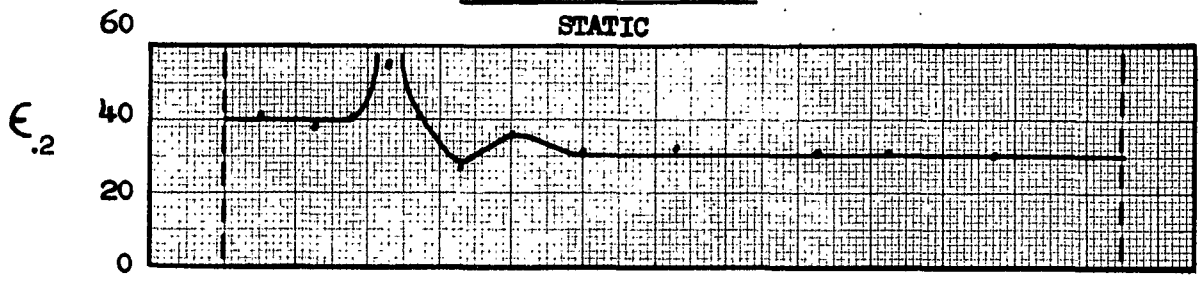


GRAPH 3 (Continued)



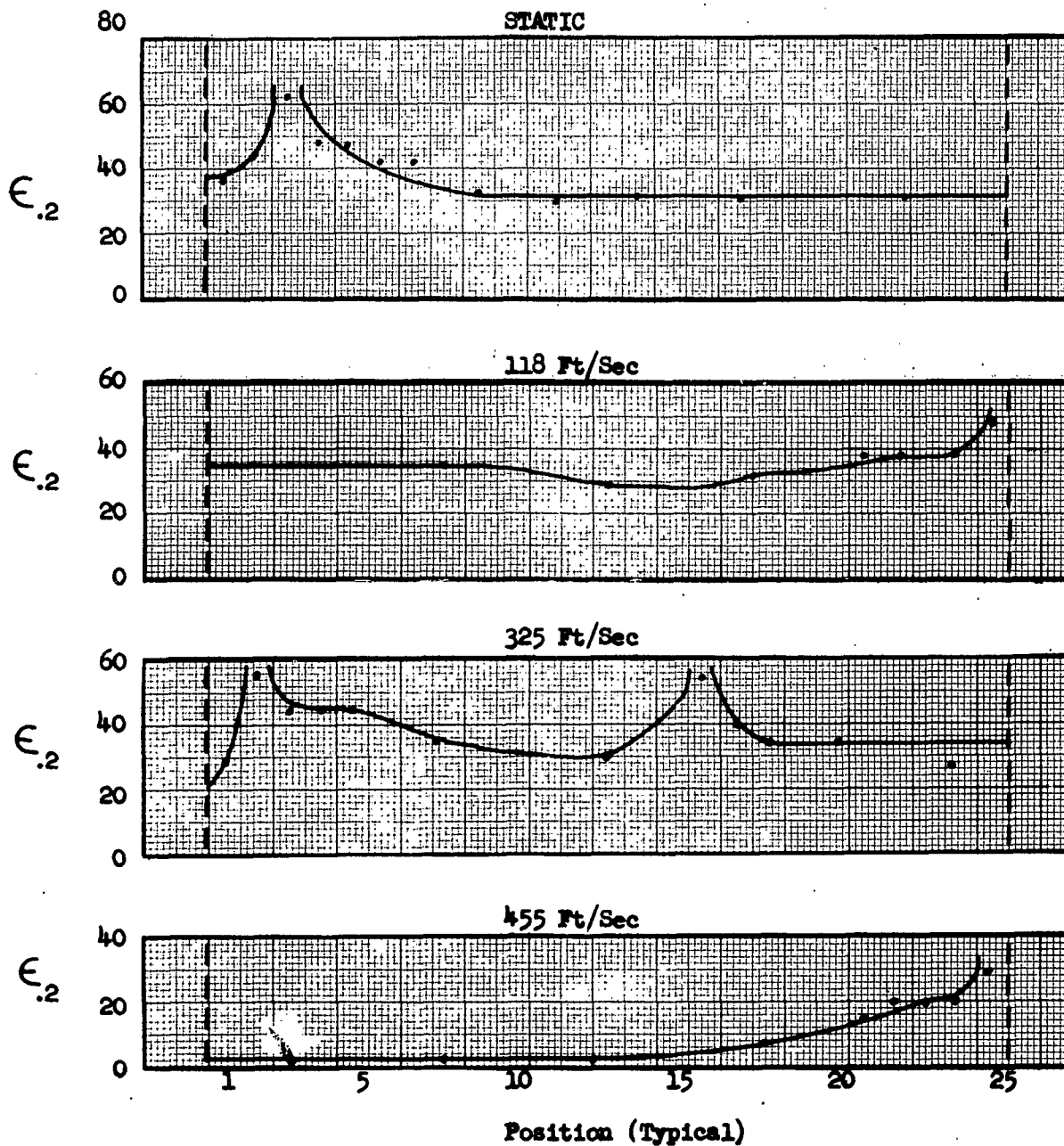
GRAPH 3 (Continued)

500°F - .020 GAGE

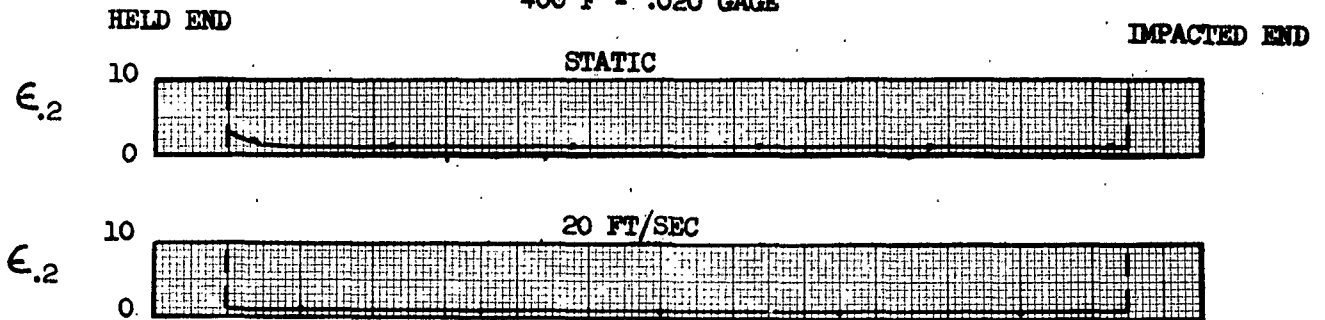


GRAPH 3 (Concluded)

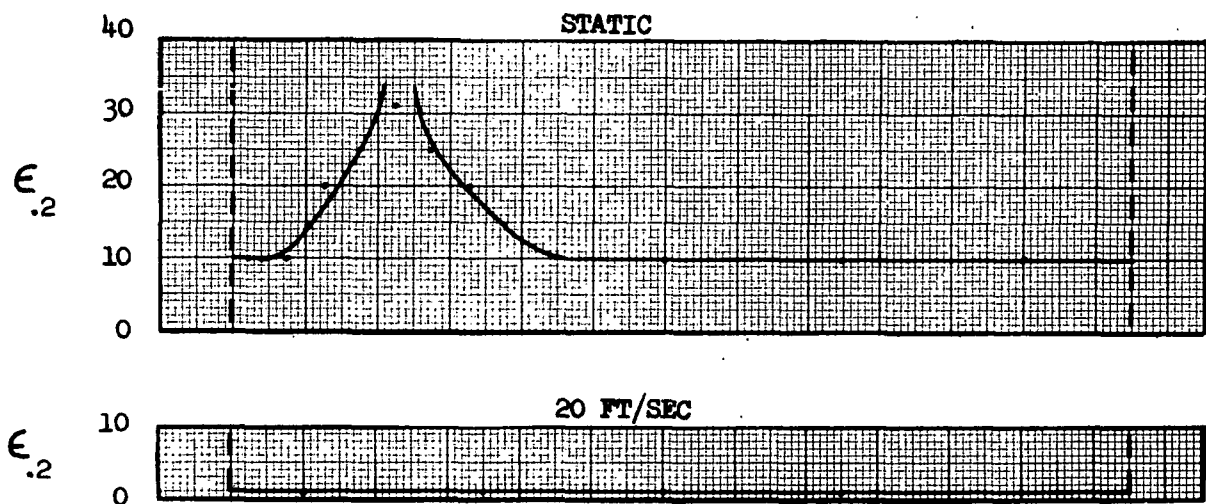
1000°F - .020 GAGE



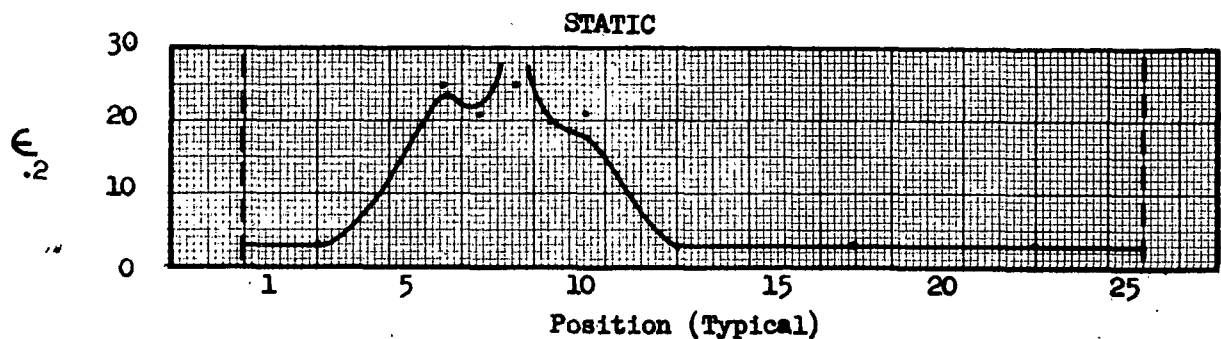
GRAPH 4
 LONGITUDINAL TENSILE SPECIMENS
 ELONGATION VS POSITION OF .2 INCH GAGE LENGTH
 AT VARIOUS TEST TEMPERATURES AND VELOCITIES
 BERYLLIUM - 5" GAGE LENGTH
 400°F - .020 GAGE



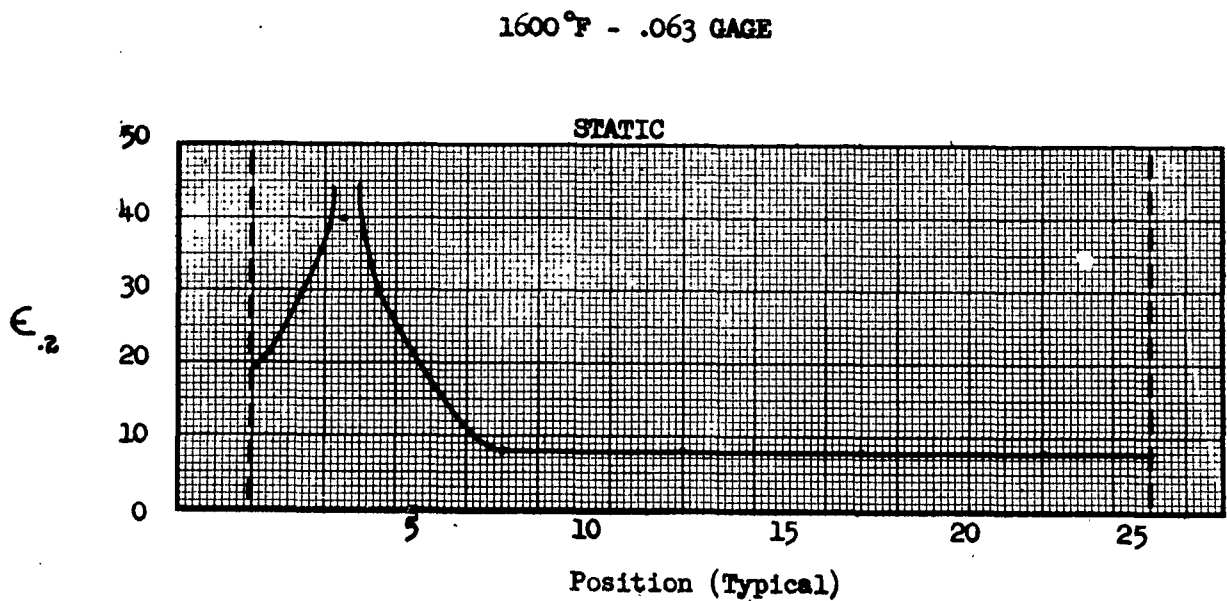
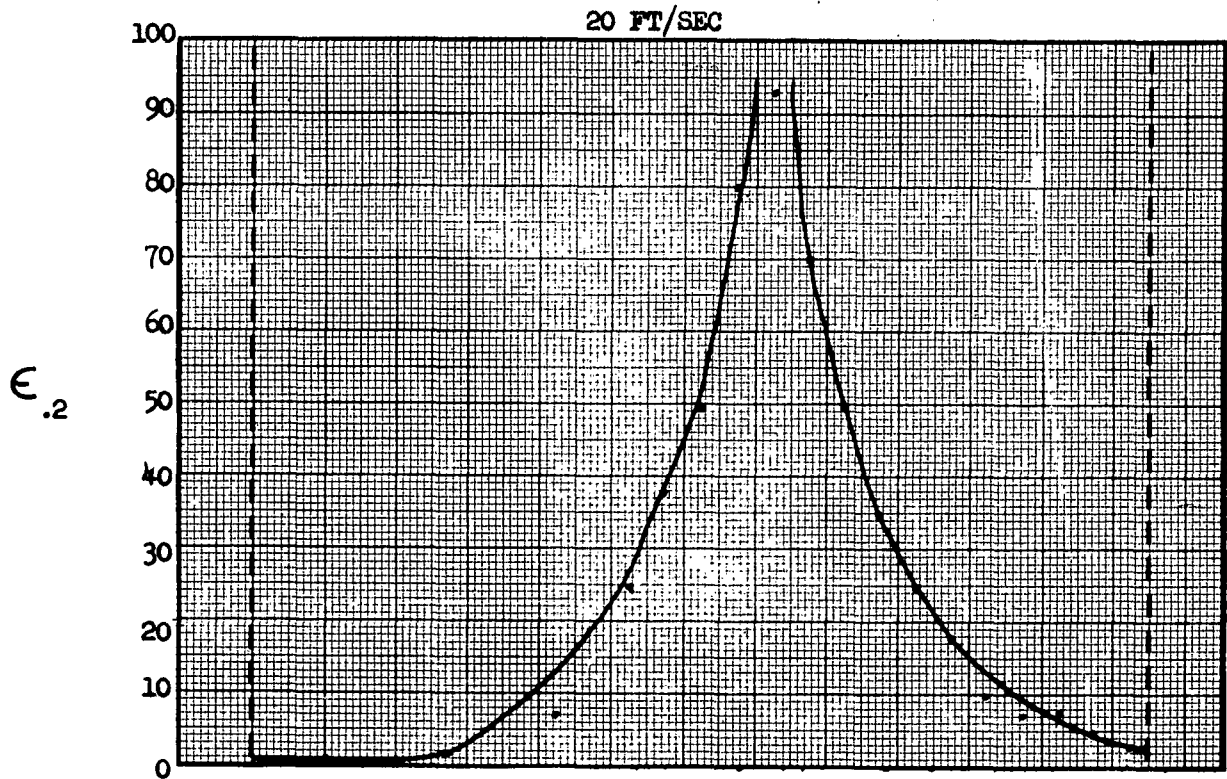
800°F - .063 GAGE



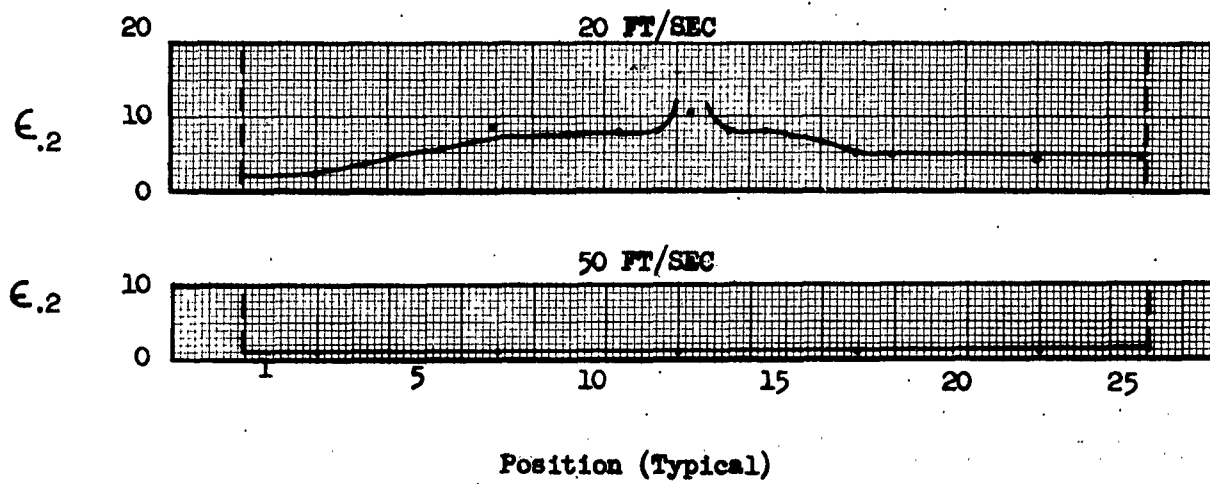
1200°F - .063 GAGE



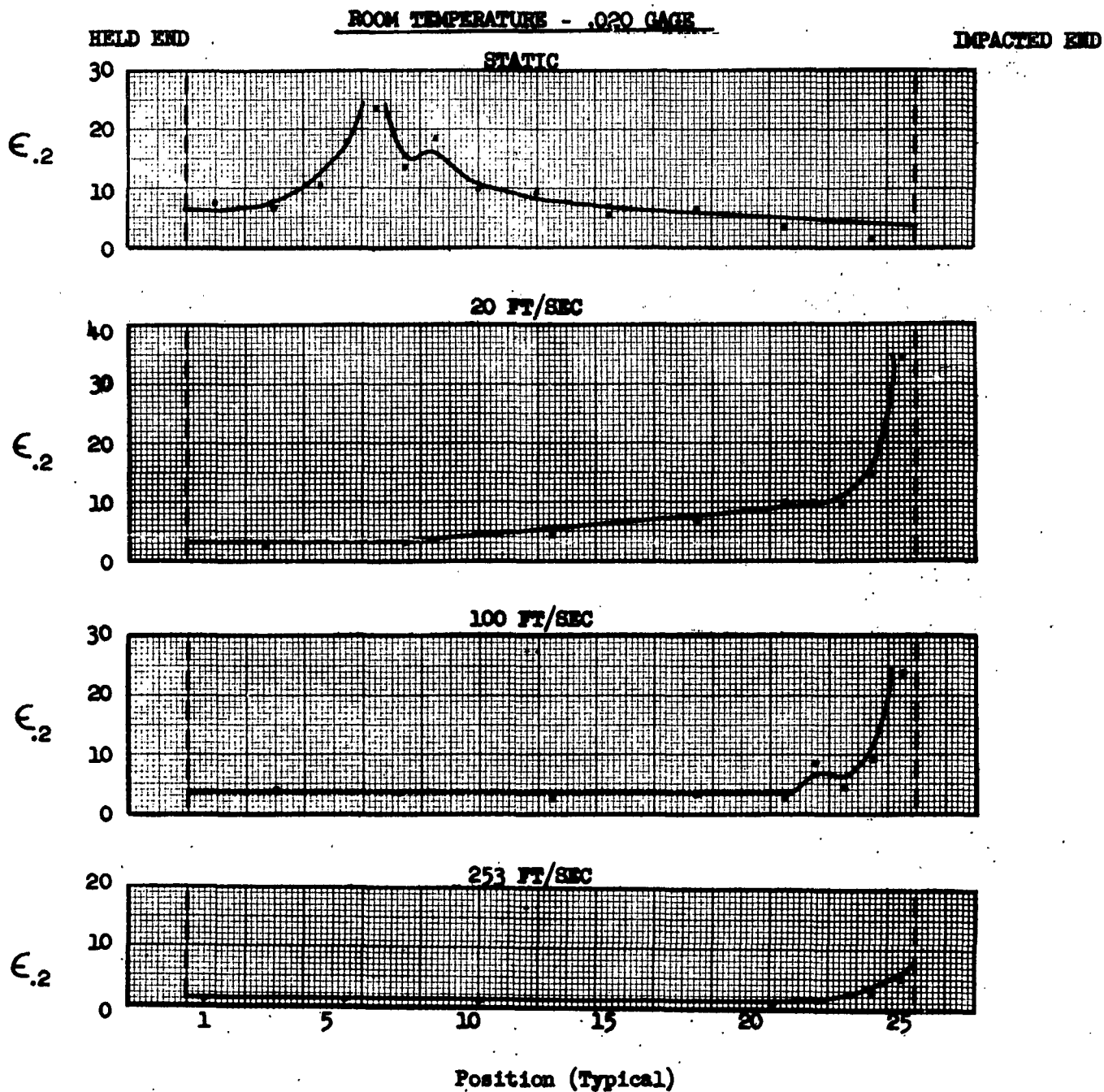
GRAPH 4 (Continued)



GRAPH 4 (Concluded)

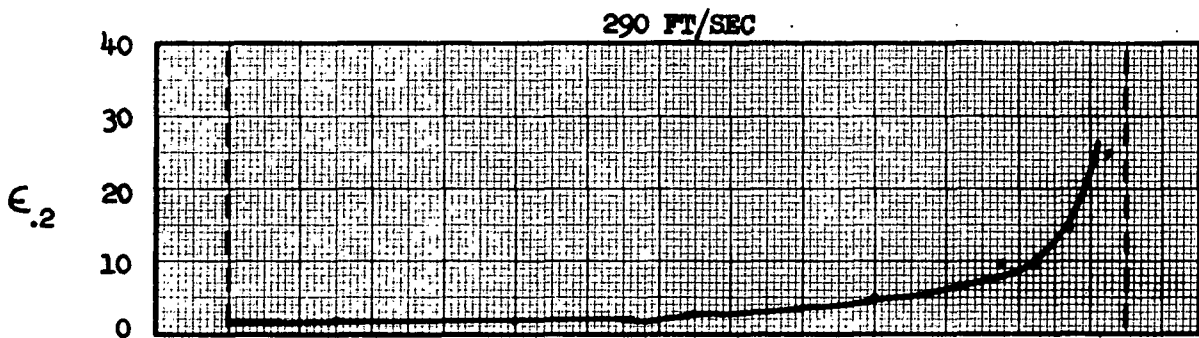
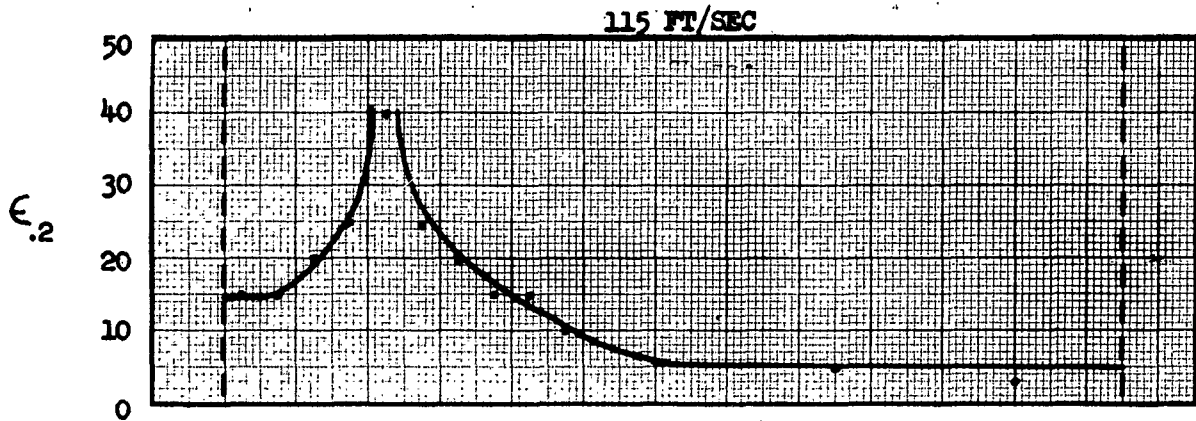
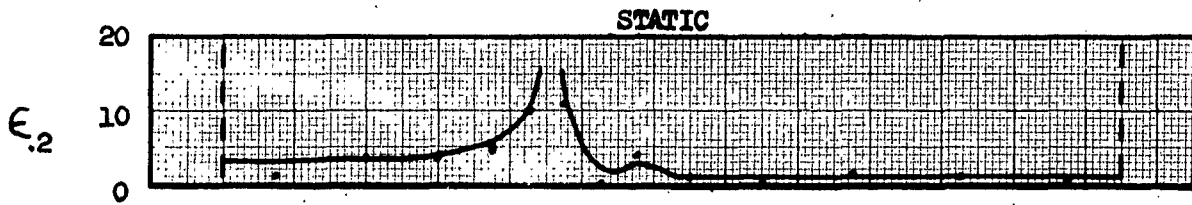


GRAPH 5
LONGITUDINAL TENSILE SPECIMENS
ELONGATION VS POSITION OF .2 INCH GAGE LENGTH
AT VARIOUS TEST TEMPERATURES AND VELOCITIES
MOLYBDENUM (.5% Ti) - $\frac{1}{2}$ " GAGE LENGTH

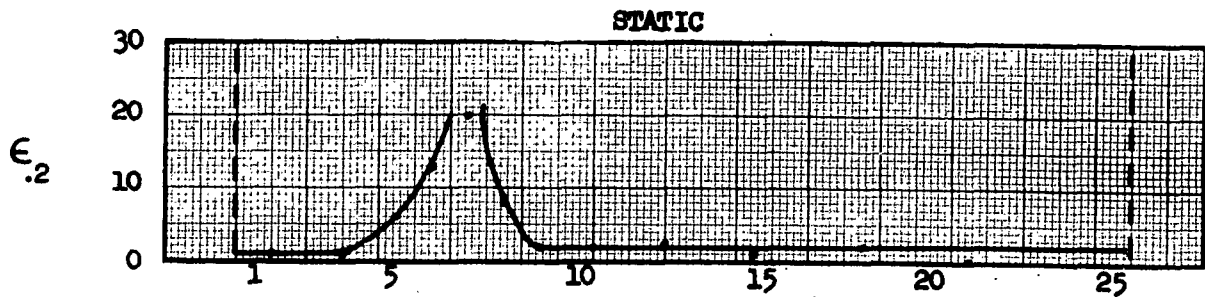


GRAPH 5 (Continued)

1000°F - .020 GAGE

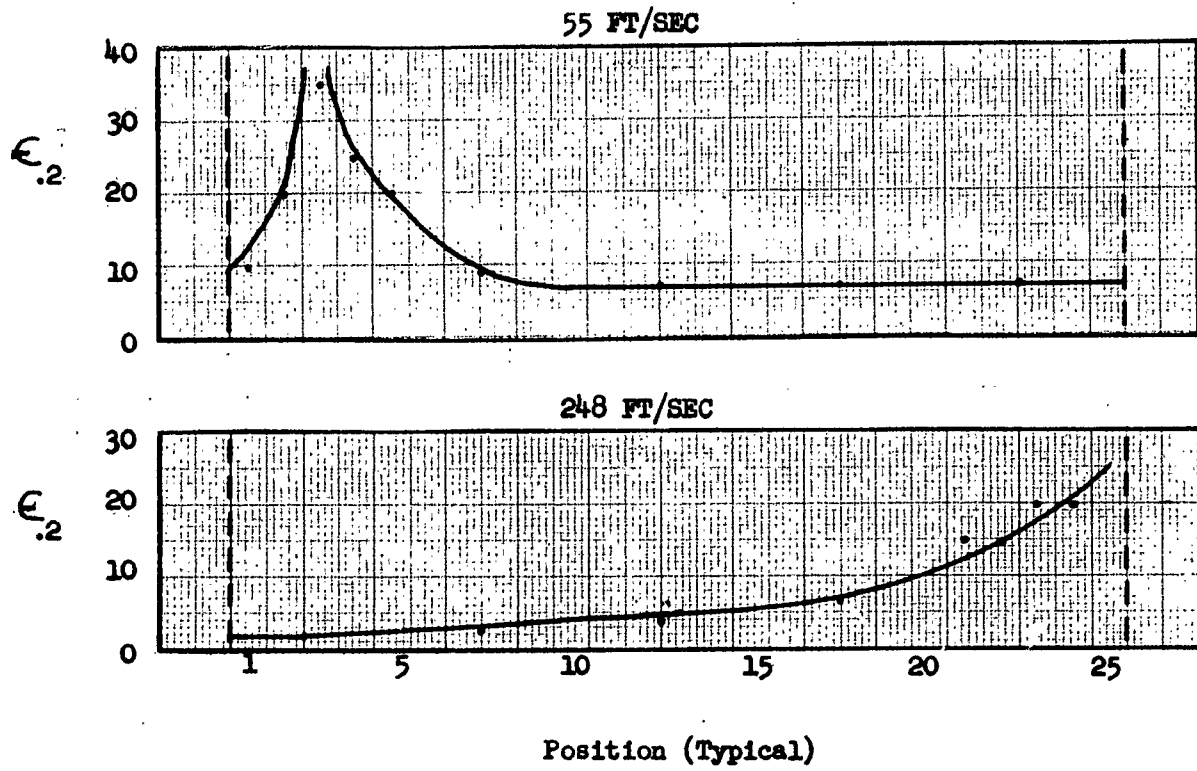


2000°F - .020 GAGE

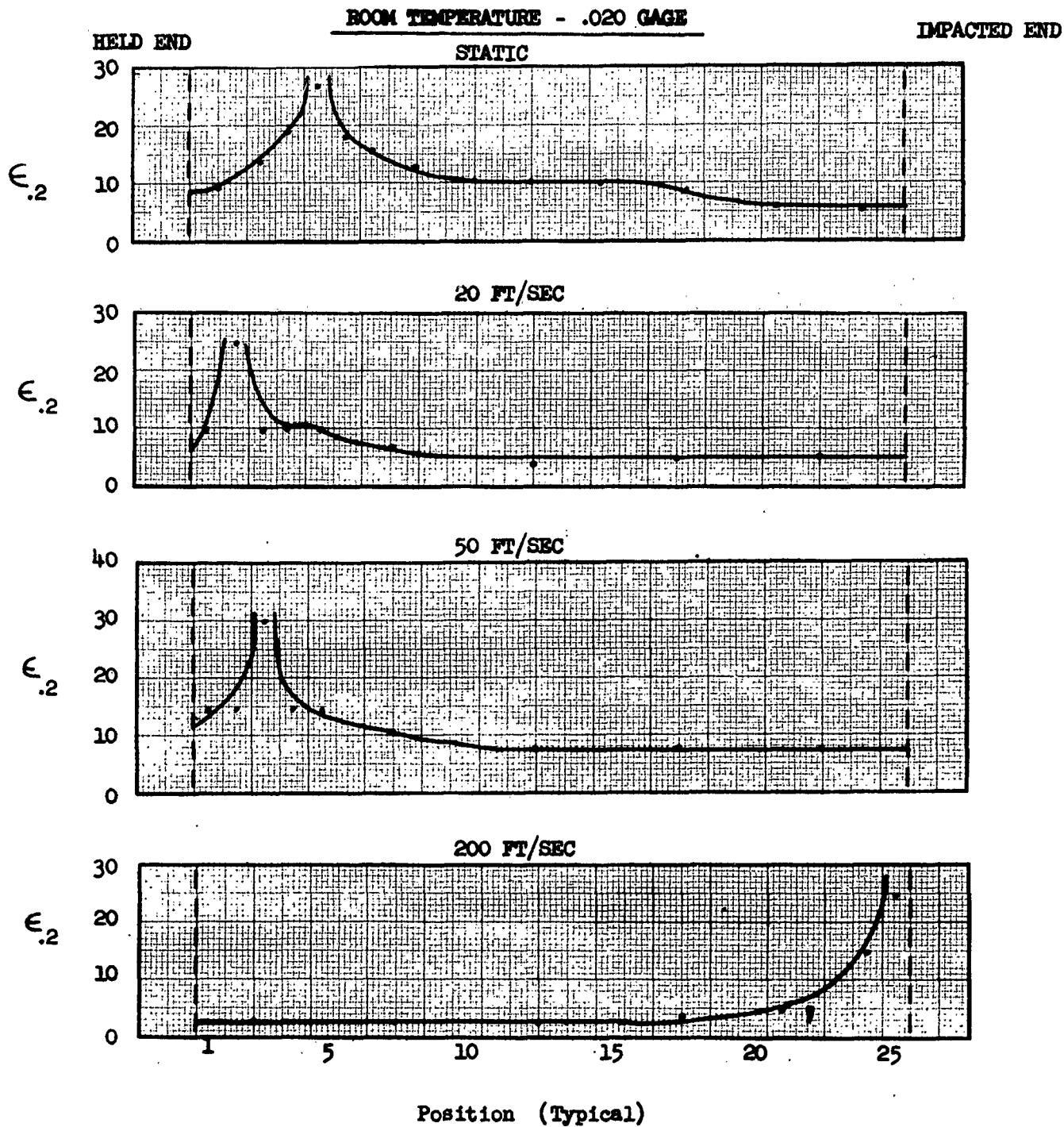


Position (Typical)

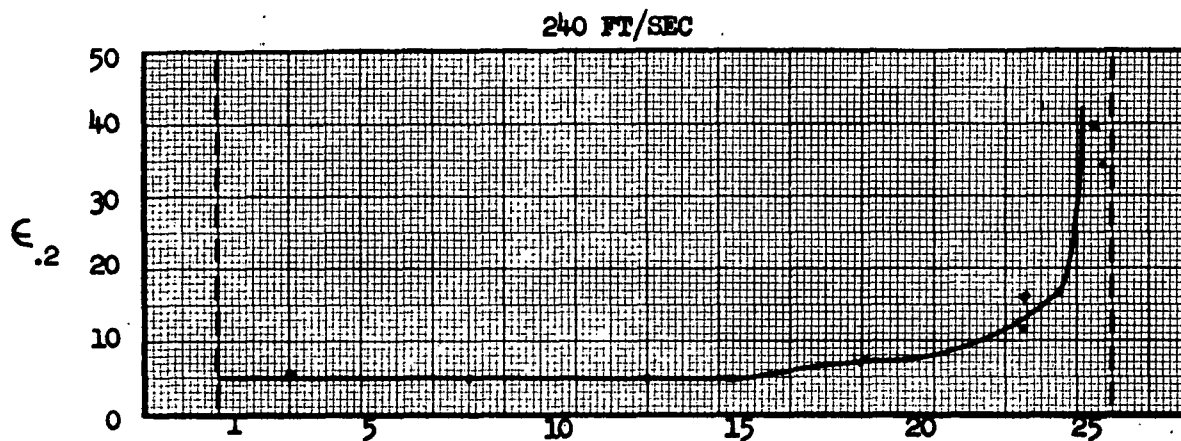
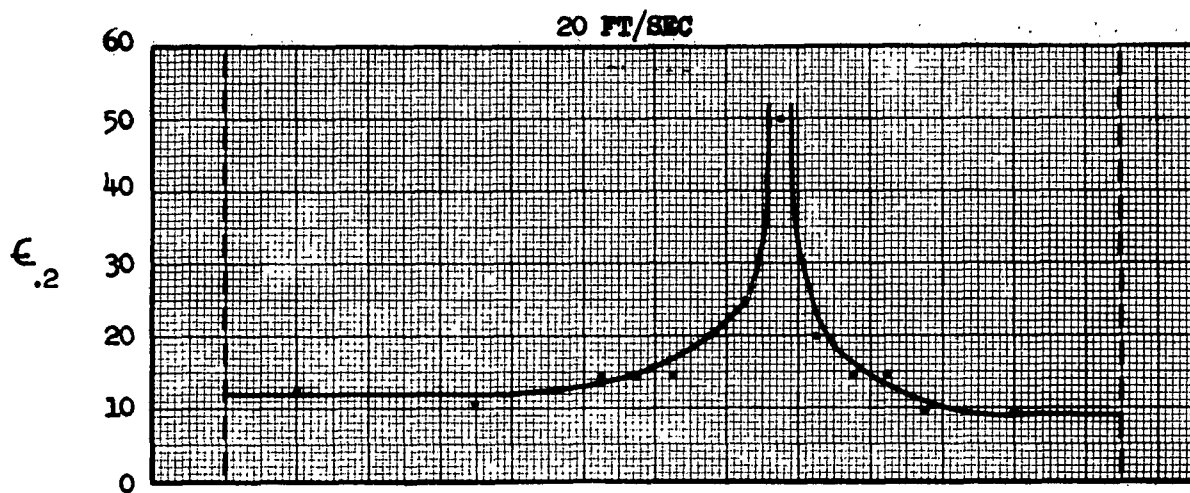
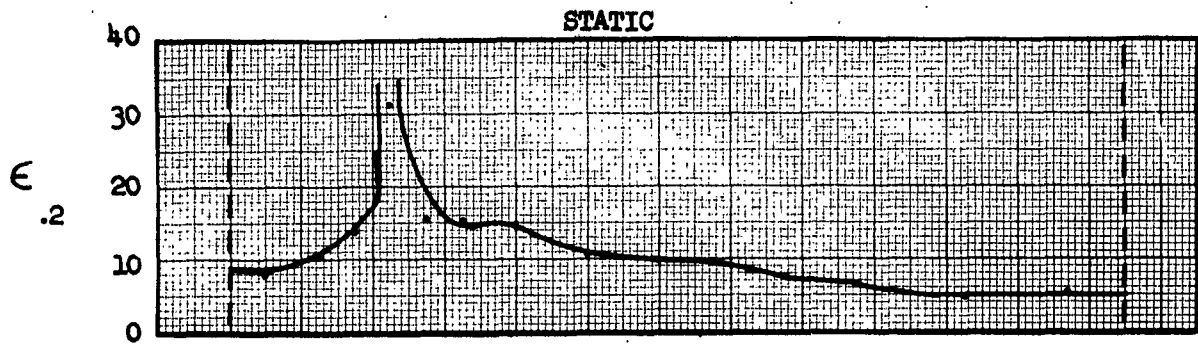
GRAPH 5 (Concluded)



GRAPH 6
 LONGITUDINAL TENSILE SPECIMENS
 ELONGATION VS POSITION OF .2 INCH GAGE LENGTH
 AT VARIOUS TEST TEMPERATURES AND VELOCITIES
 COLUMBIUM (10 Mo-10 Ti) - 5% GAGE LENGTH



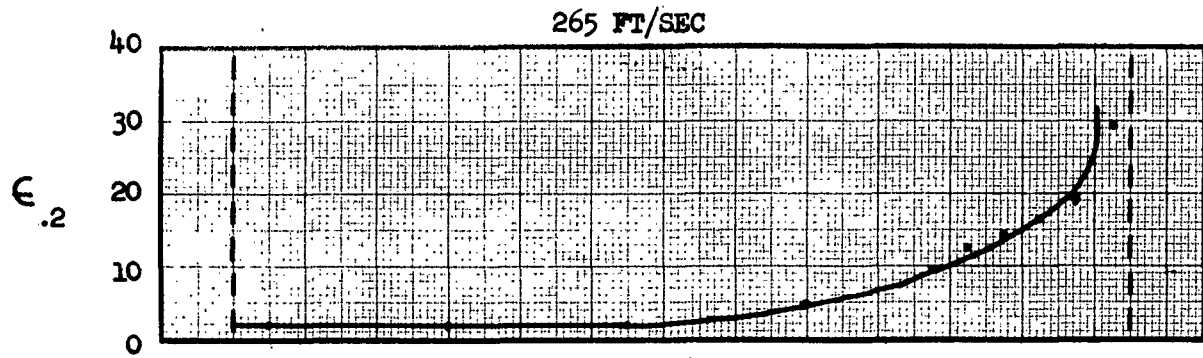
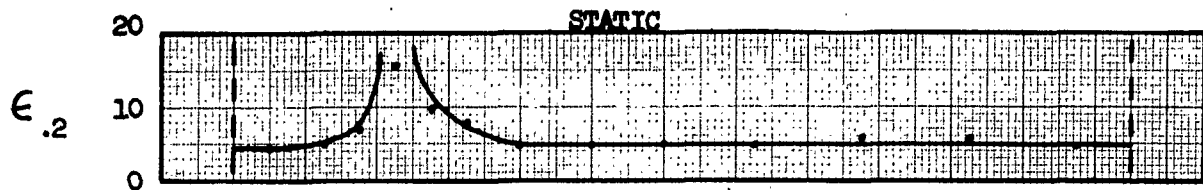
GRAPH 6 (Continued)
ROOM TEMPERATURE - .063 GAGE



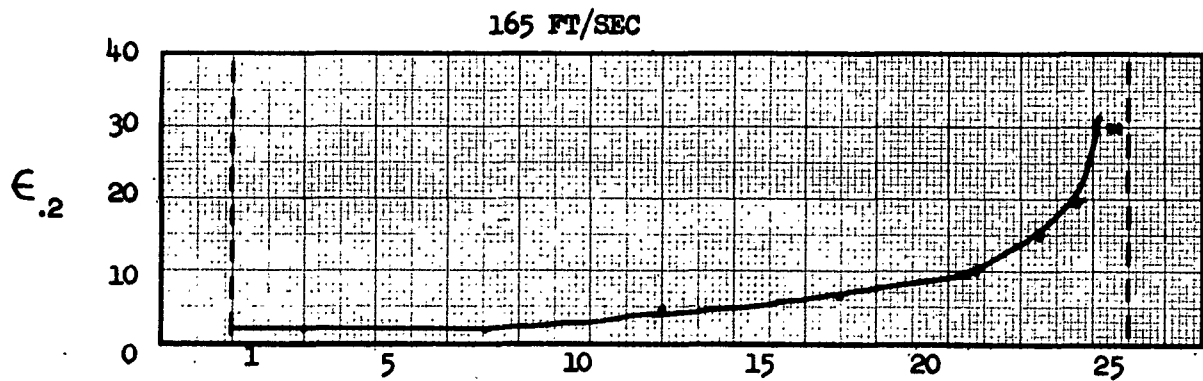
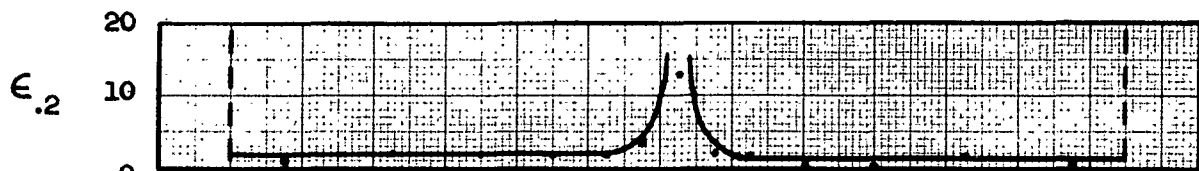
Position (Typical)

GRAPH 6 (Continued)

1000°F - .020 GAGE

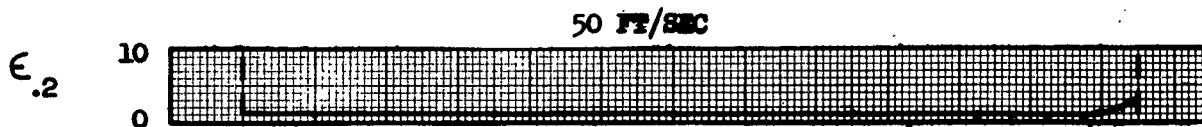
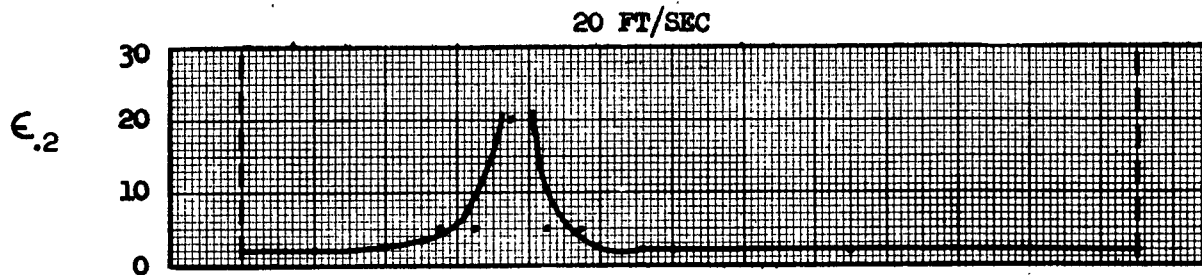


2000°F - .020 GAGE

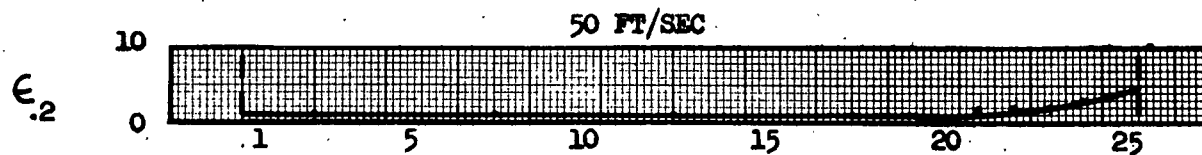
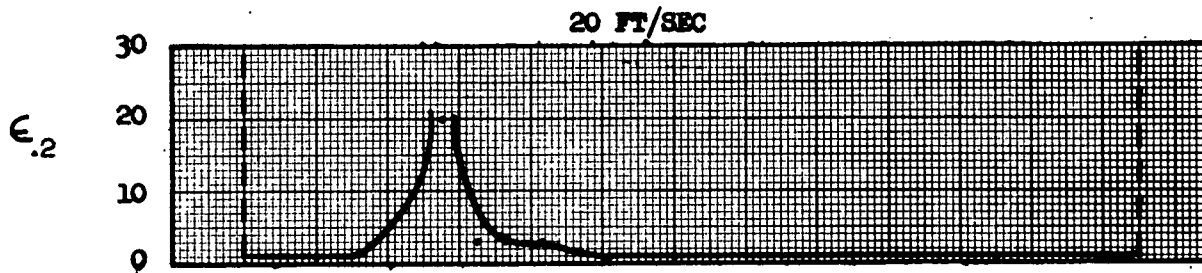
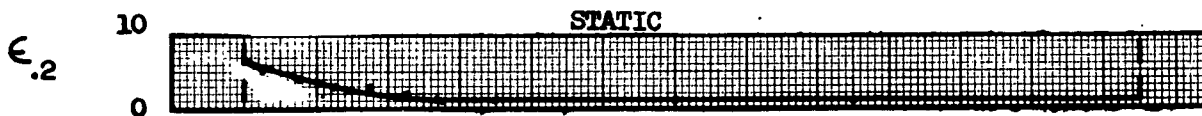


Position (Typical)

GRAPH 7
LONGITUDINAL TENSILE SPECIMENS
ELONGATION VS POSITION OF .2 INCH GAGE LENGTH
AT VARIOUS TEST TEMPERATURES AND VELOCITIES
TUNGSTEN - 5" GAGE LENGTH
1000°F - .020 GAGE

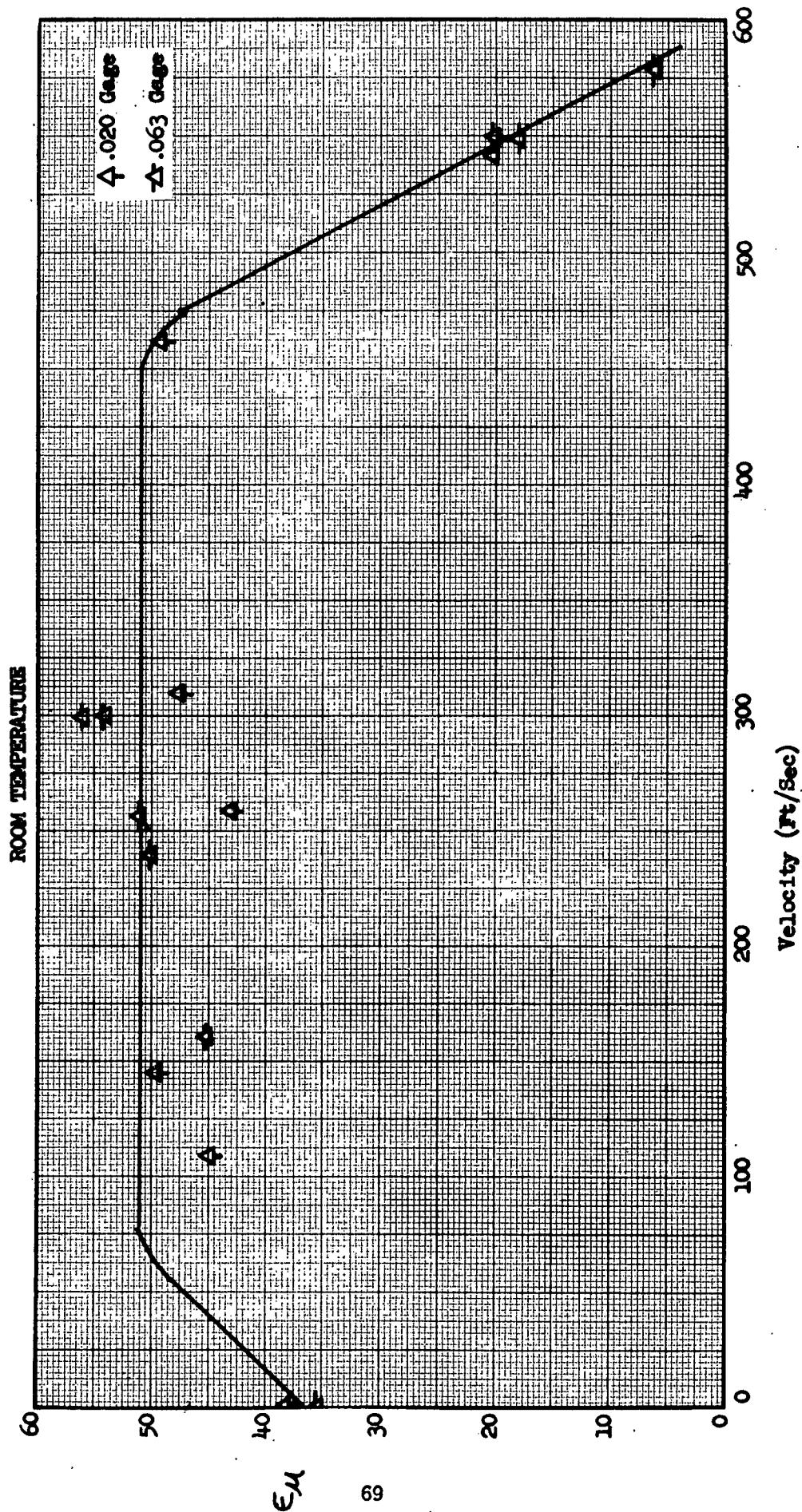


2000°F - .020 GAGE

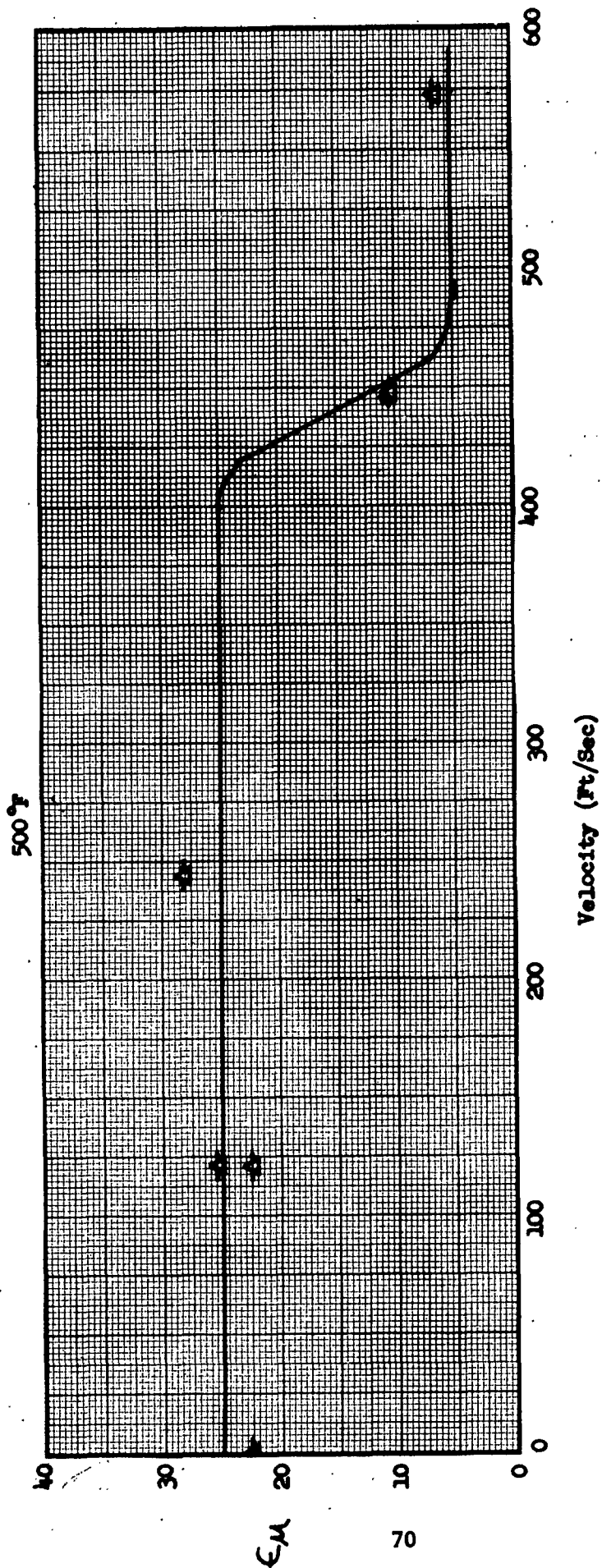


Position (Typical)

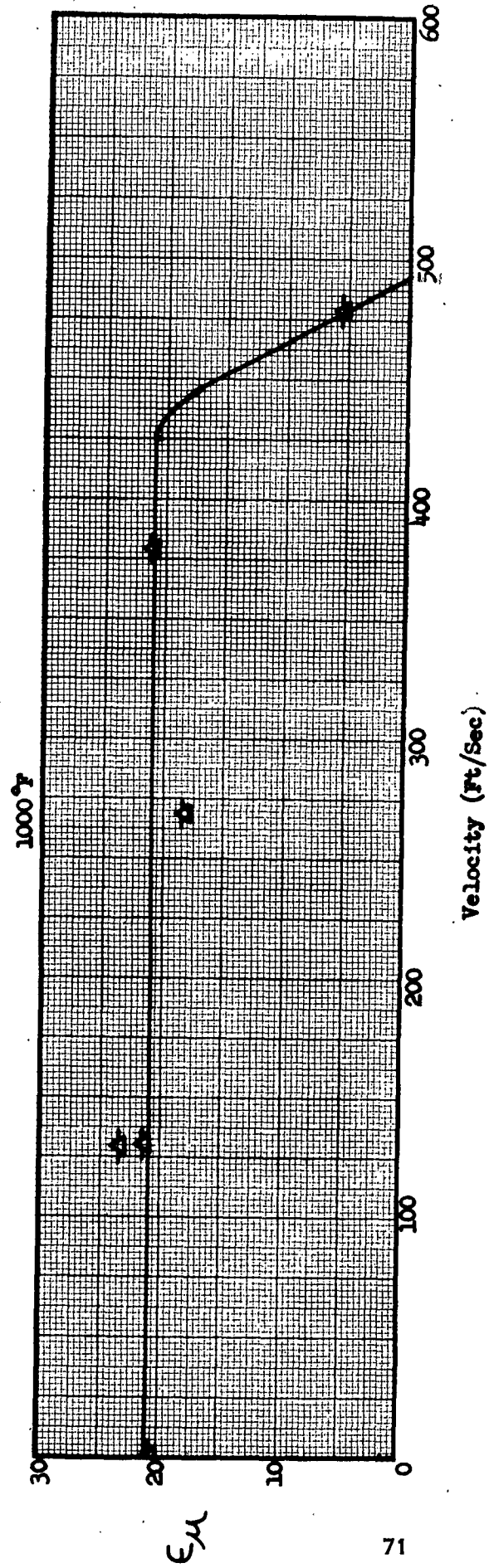
GRAPH 8
UNIFORM ELONGATION VS FORMING VELOCITY
FOR LONGITUDINAL TENSILE SPECIMENS
AT VARIOUS TEMPERATURES
17-7 PH - 5" GAGE LENGTH



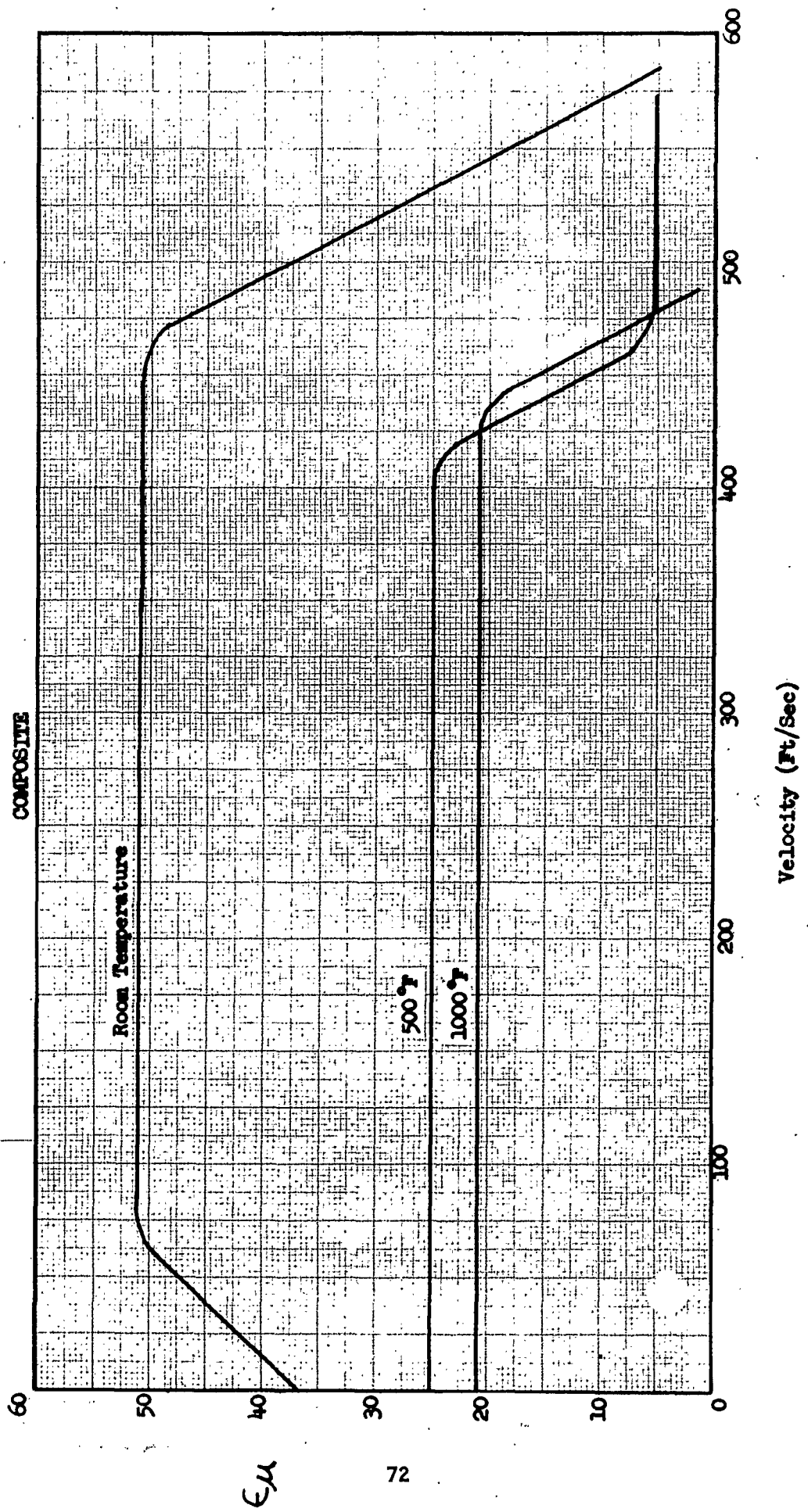
GRAPH 8 (Continued)



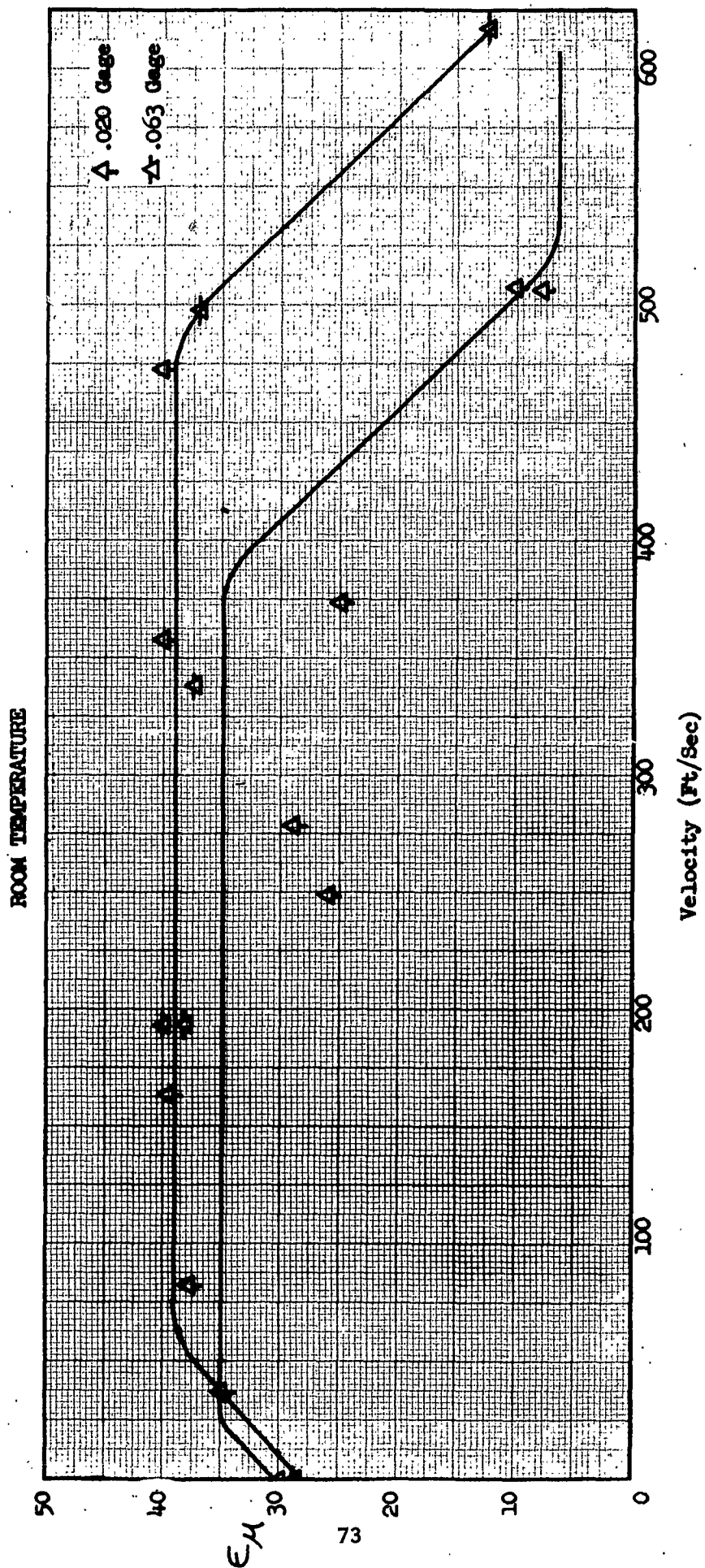
GRAPH 8 (Continued)



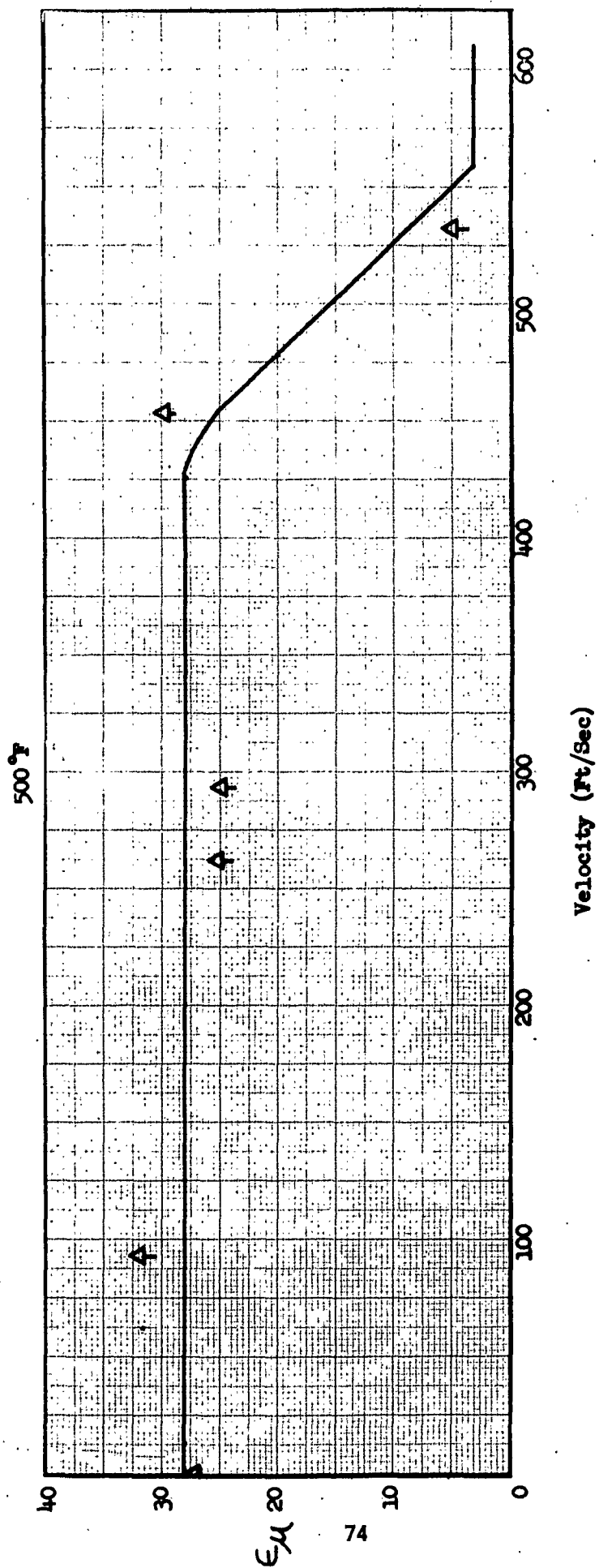
GRAPH 8 (Concluded)



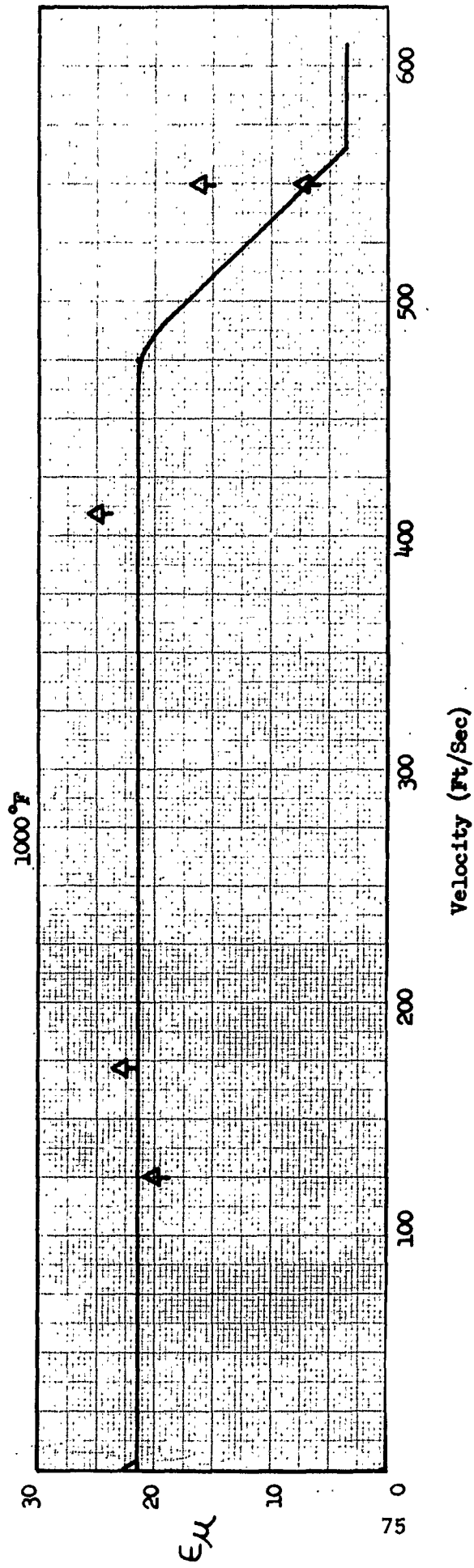
GRAPH 9
 UNIFORM ELONGATION VS FORMING VELOCITY
 FOR LONGITUDINAL TENSILE SPECIMENS
 AT VARIOUS TEMPERATURES
 A-286 - 5" GAGE LENGTH



GRAPH 9 (Continued)

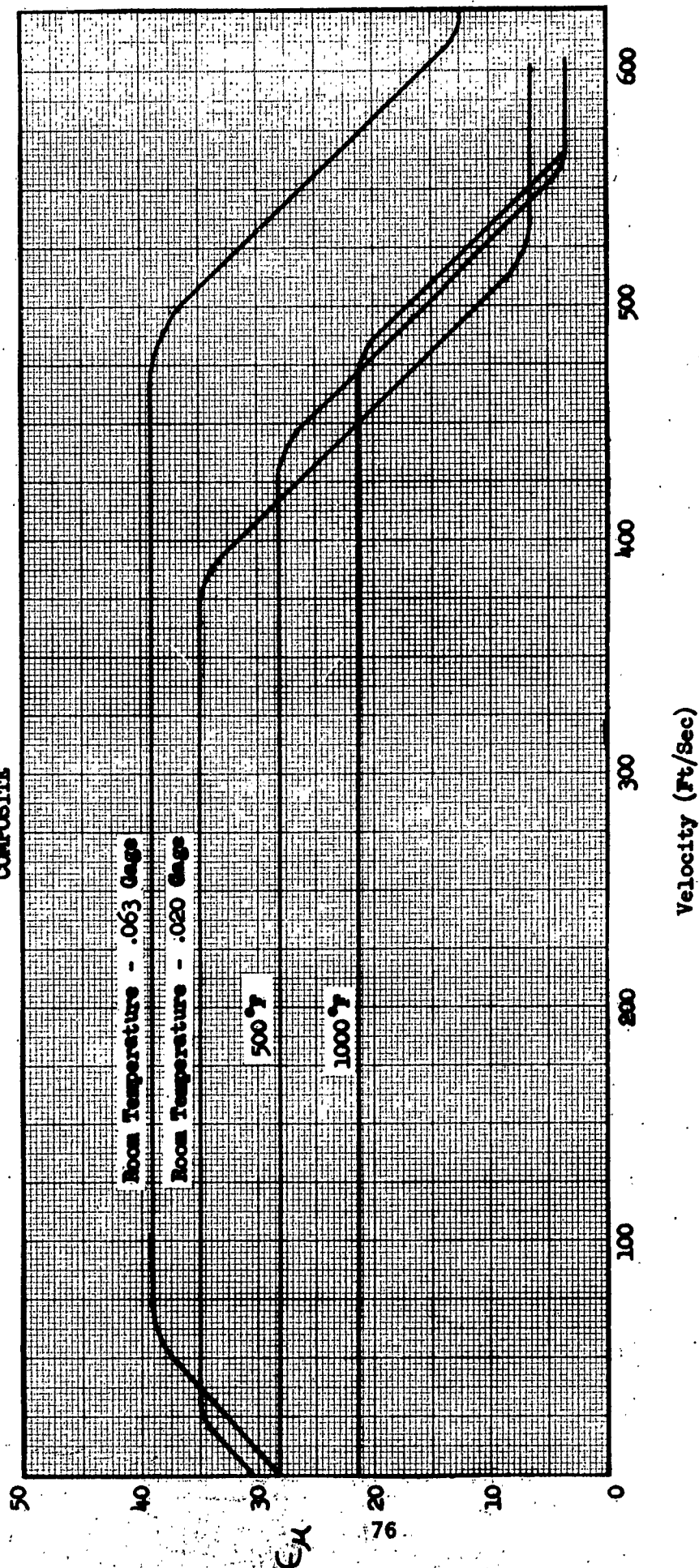


GRAPH 9 (Continued)

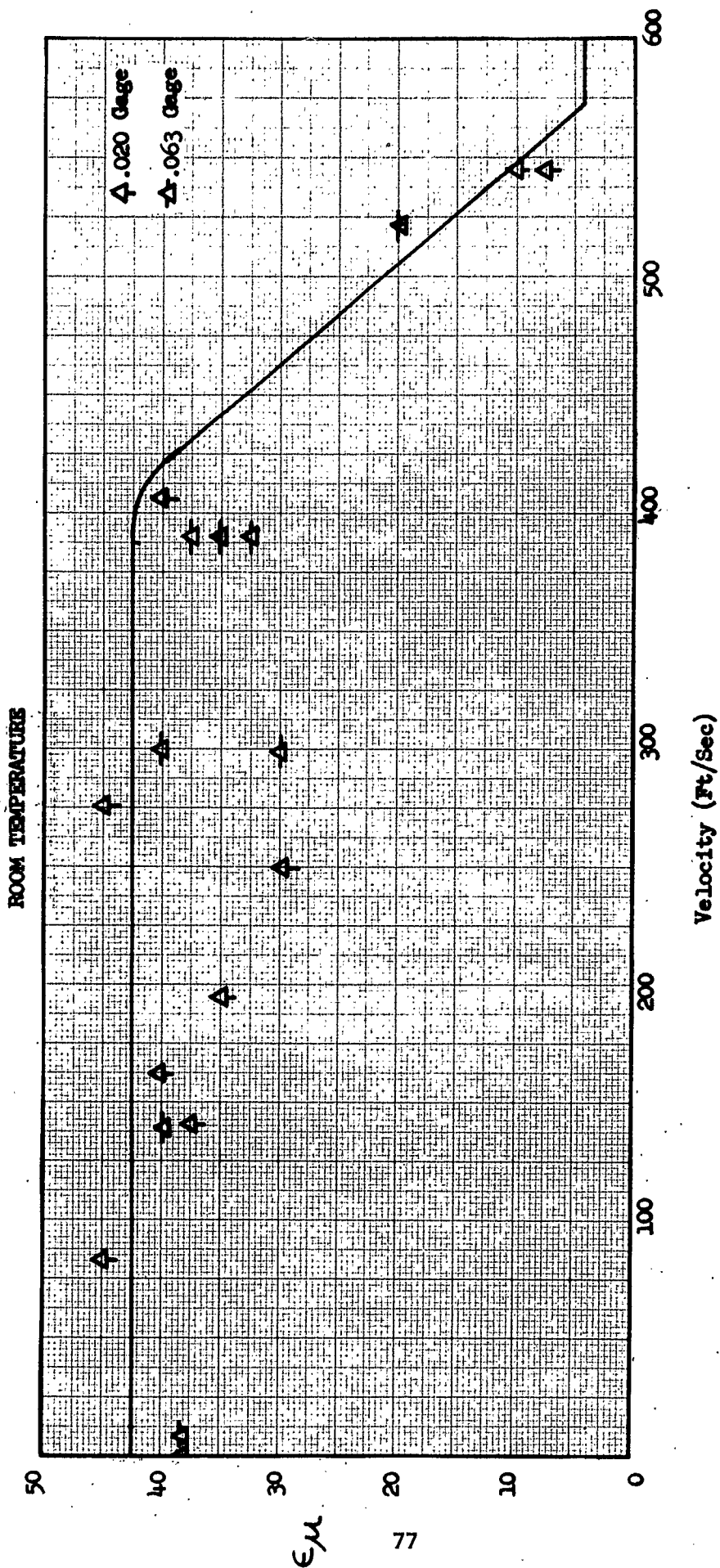


GRAPH 9 (Concluded)

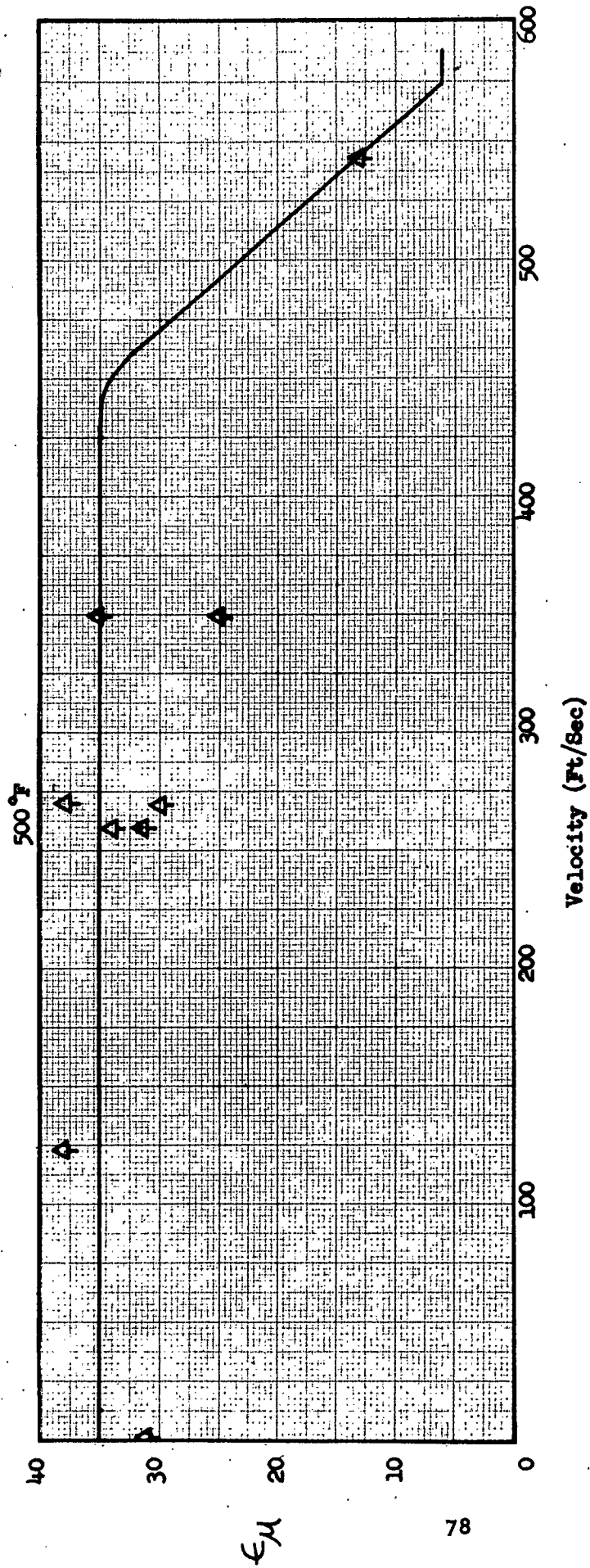
COMPOSITE



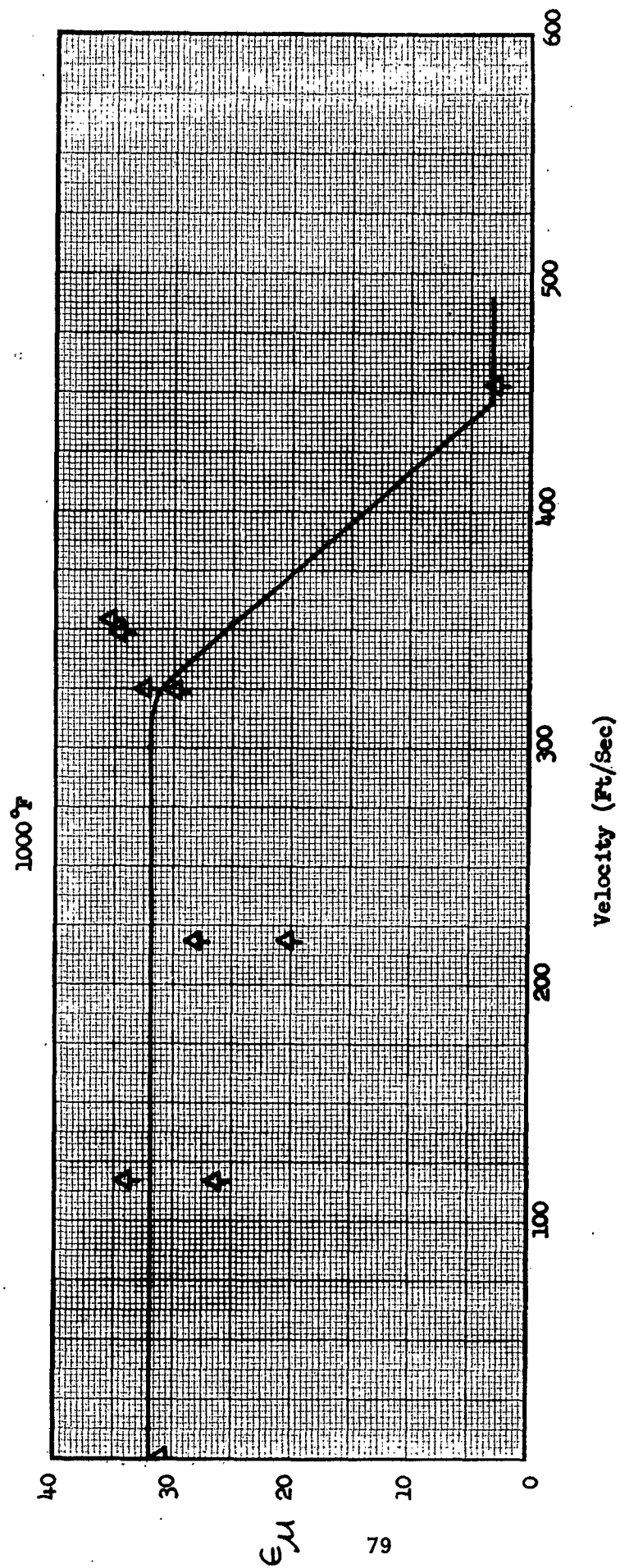
GRAPH 10
 UNIFORM ELONGATION TENSILE SPECIMENS
 FOR LONGITUDINAL TENSILE SPECIMENS
 AT VARIOUS TEMPERATURES
 REE-41 - 5" GAGE LENGTH



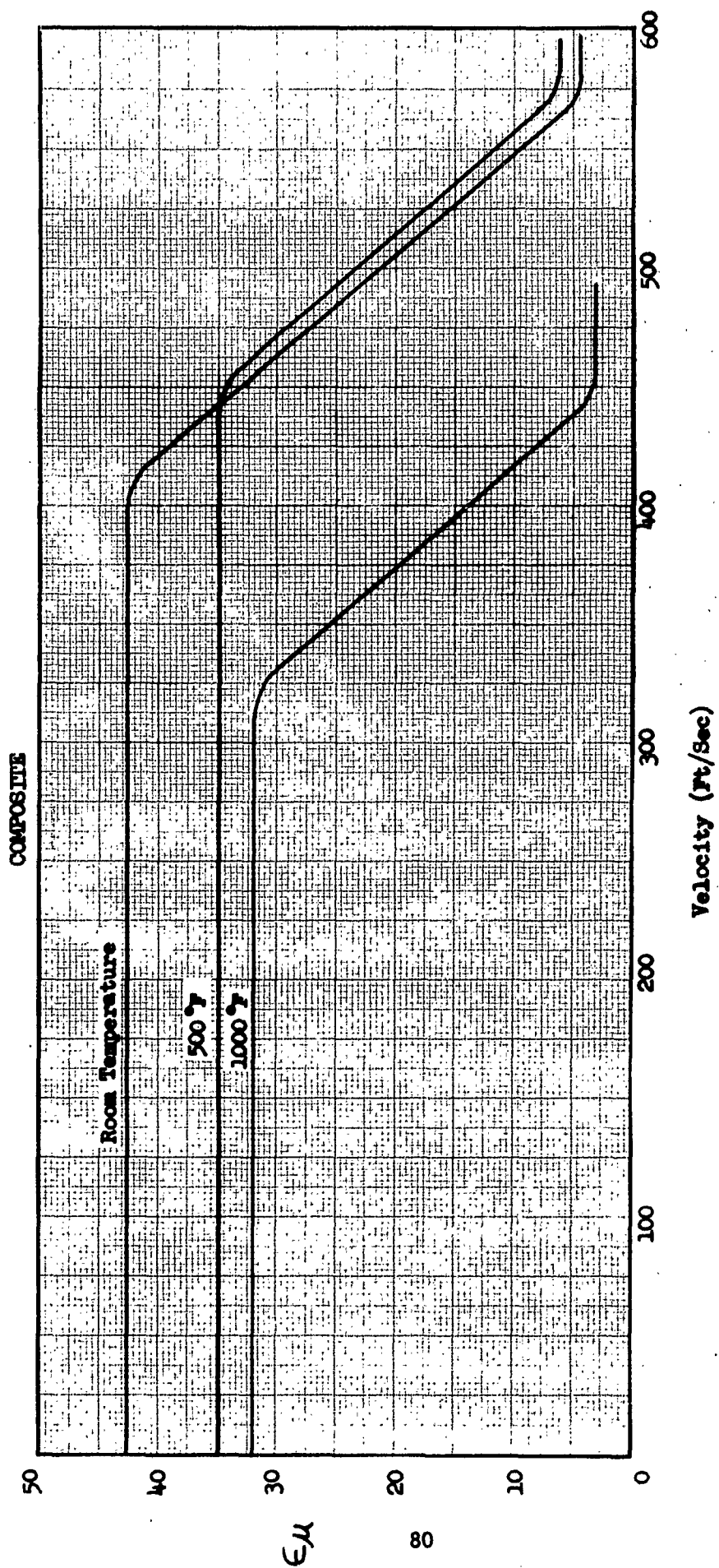
GRAPH 10 (Continued)



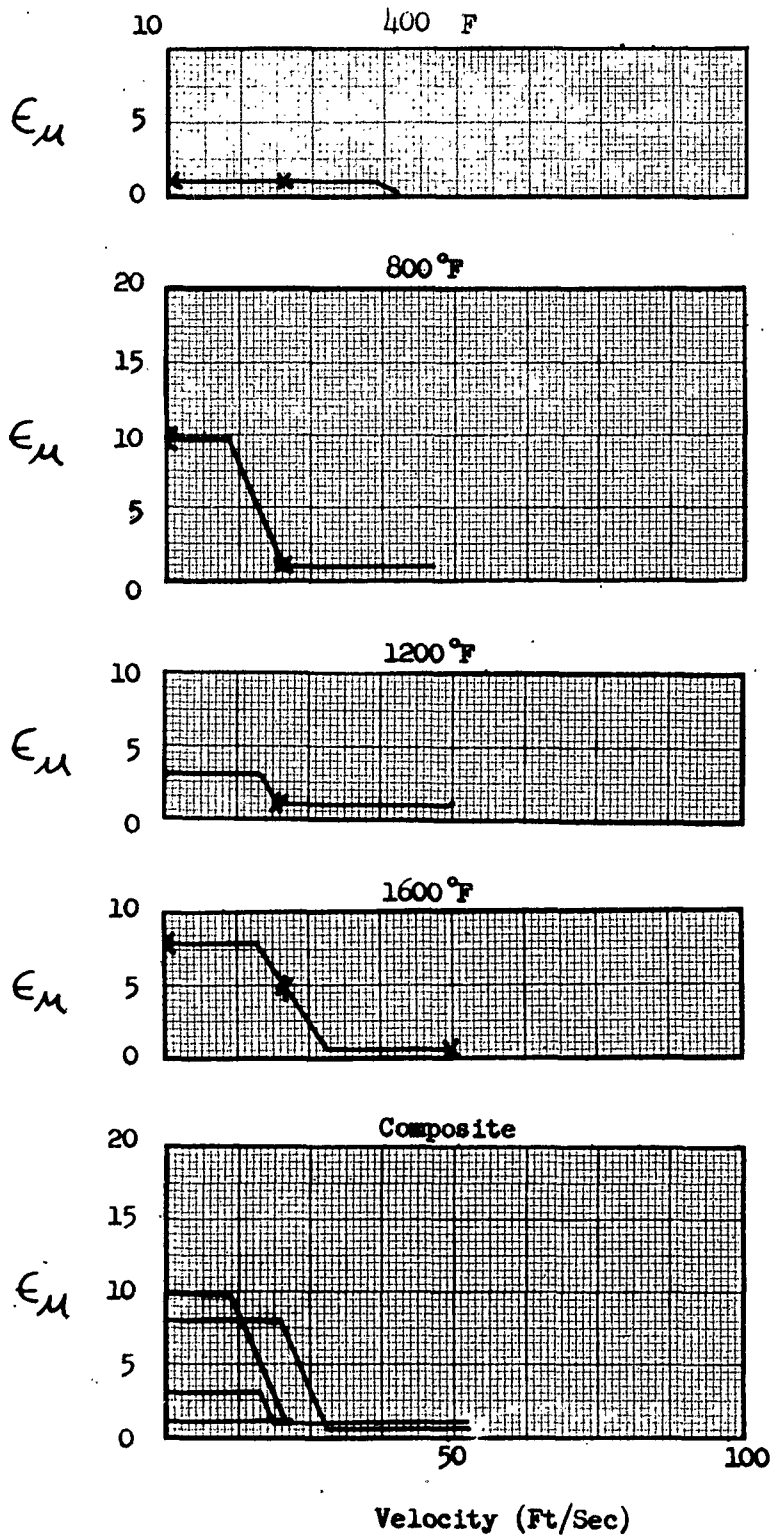
GRAPH 10 (Continued)



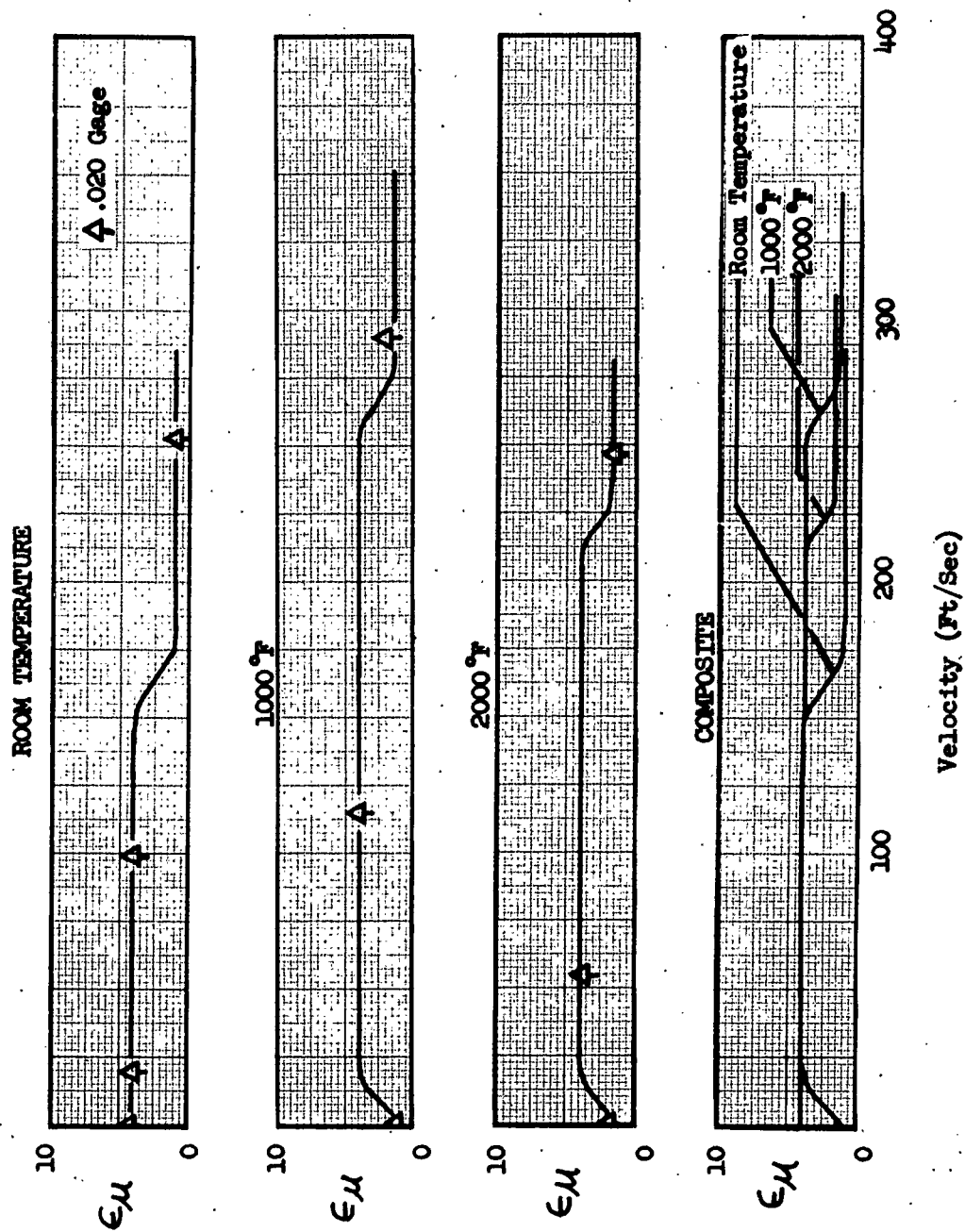
GRAPH 10 (Concluded)



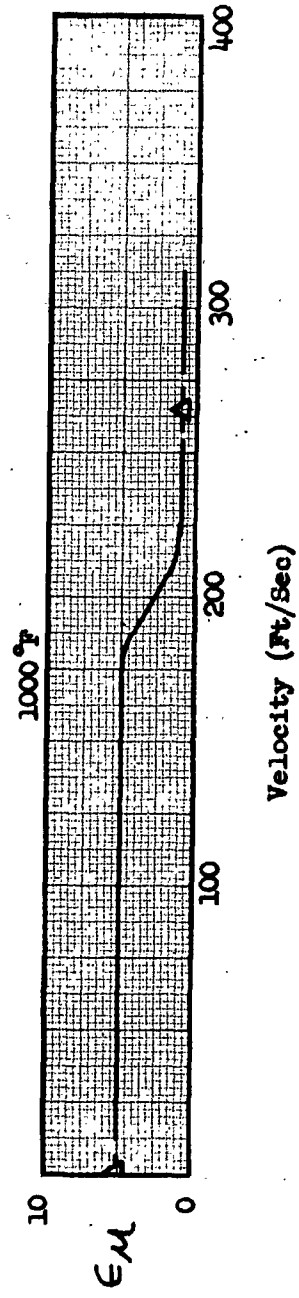
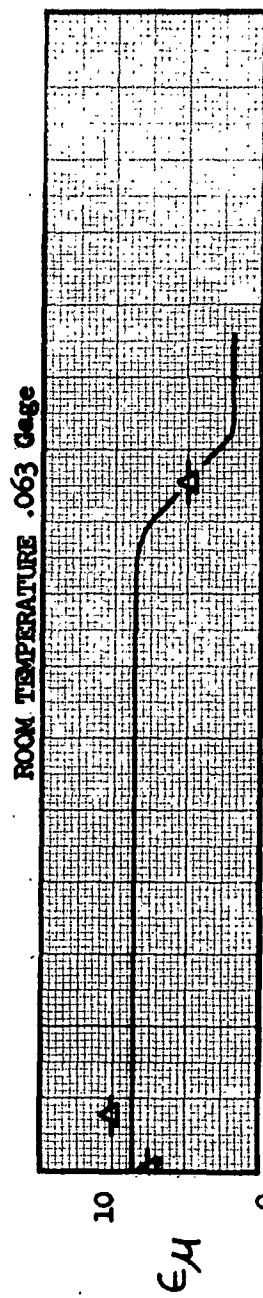
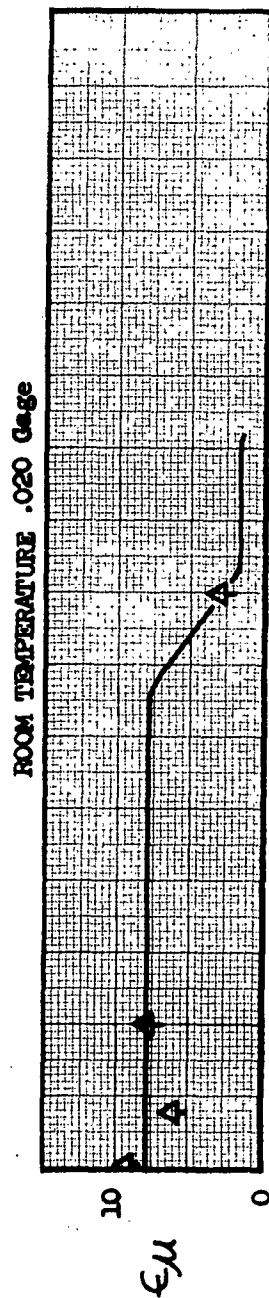
GRAPH 11
 UNIFORM ELONGATION VS FORMING VELOCITY
 FOR LONGITUDINAL TENSILE SPECIMENS
 AT VARIOUS TEMPERATURES
 BERYLLIUM - .5" GAGE LENGTH
 .063 Gage



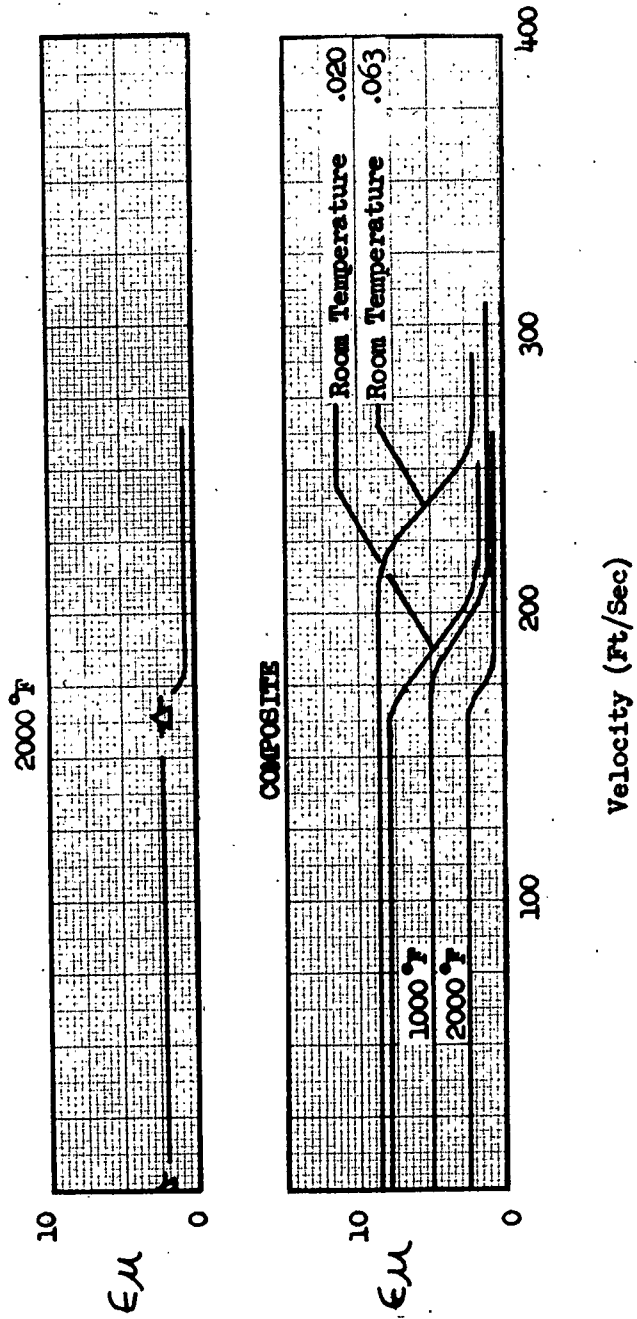
GRAPH 12
 UNIFORM ELONGATION VS FORMING VELOCITY
 FOR LONGITUDINAL TENSILE SPECIMENS
 AT VARIOUS TEMPERATURES
 MOLYBDENUM (.5% Ti)



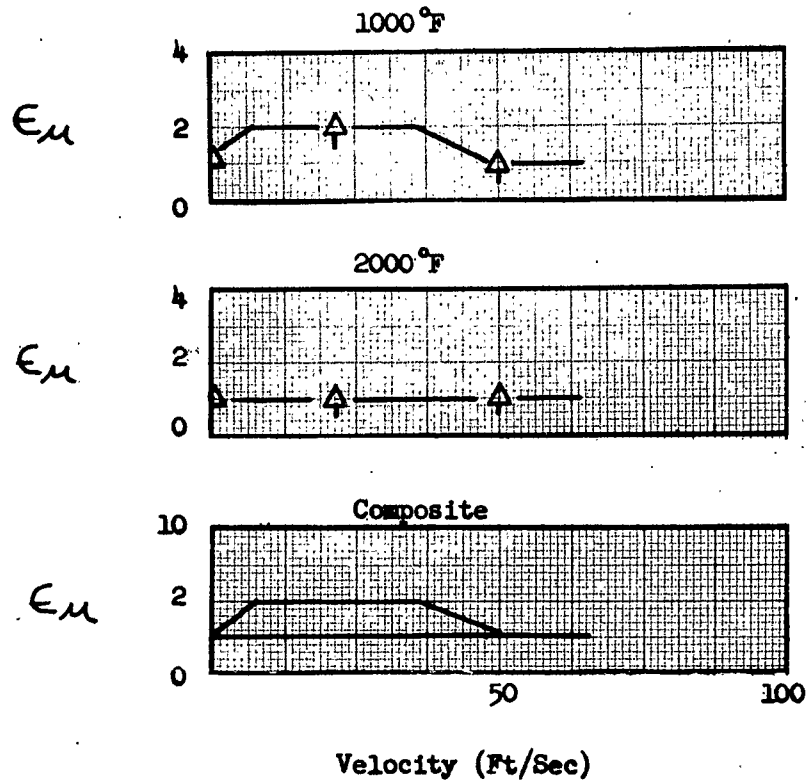
GRAPH 13
UNIFORM ELONGATION VS FORMING VELOCITY
FOR LONGITUDINAL TENSILE SPECIMENS
AT VARIOUS TEMPERATURES
COLUMBIUM (10M6-10T1)



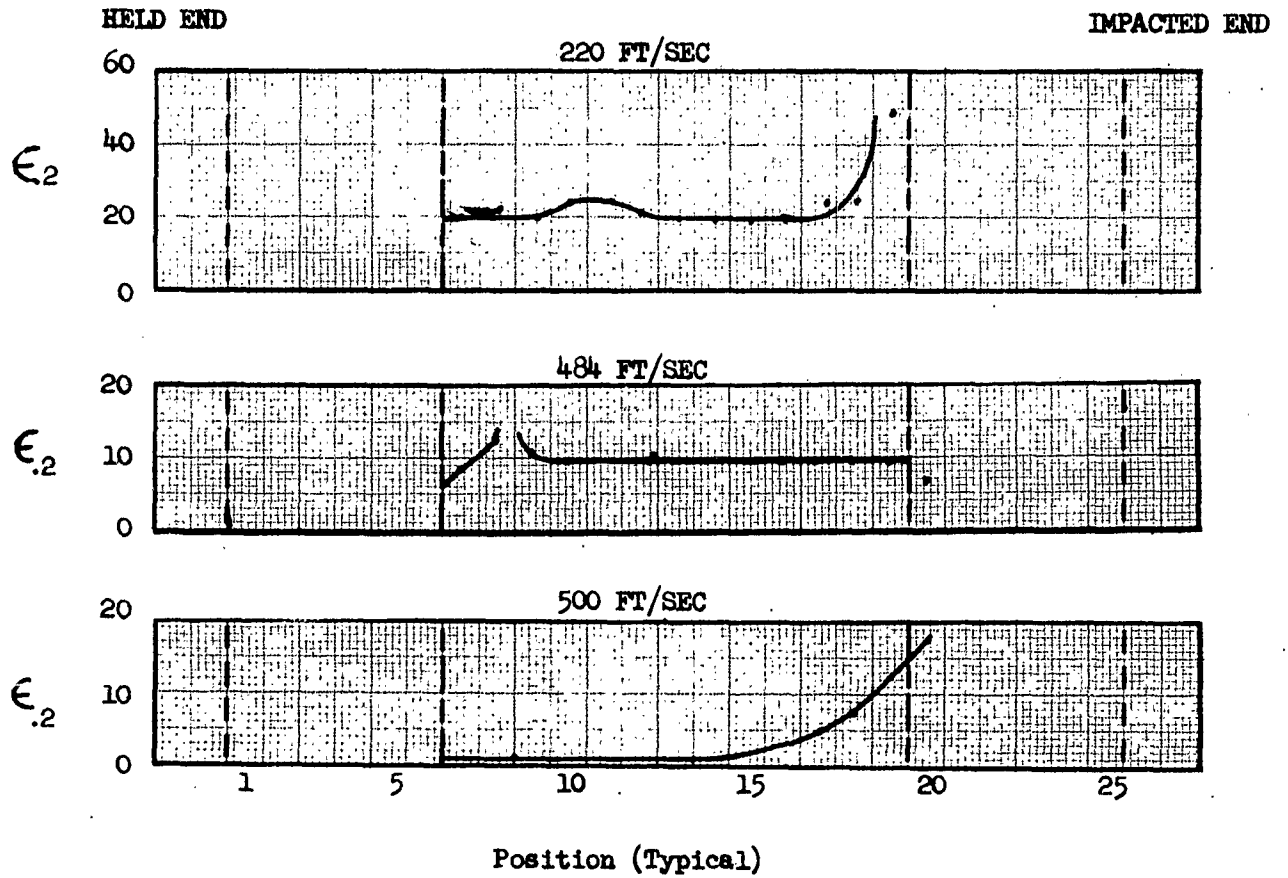
GRAPH 13 (Concluded)



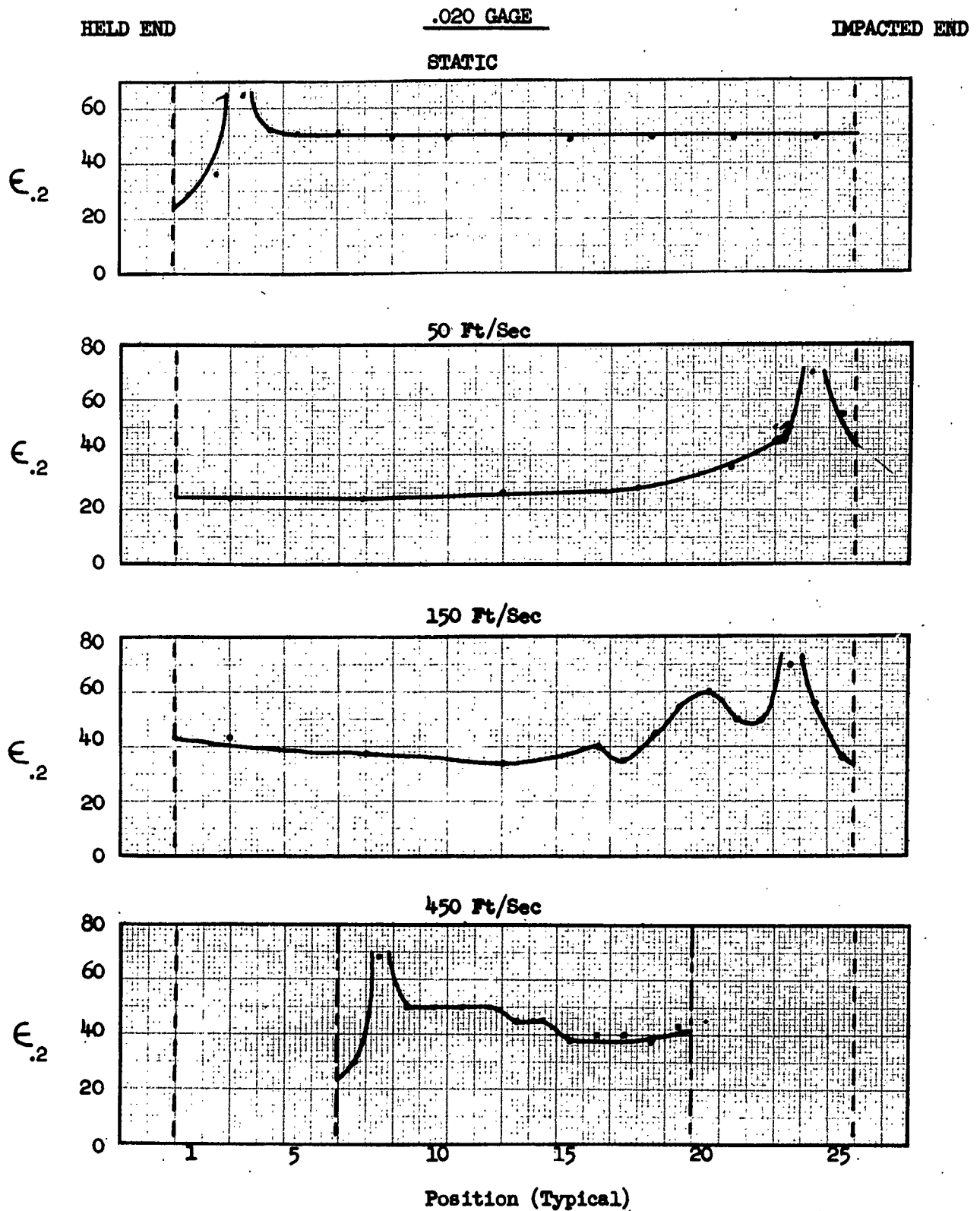
GRAPH 14
 UNIFORM ELONGATION VS FORMING VELOCITY
 FOR LONGITUDINAL TENSILE SPECIMENS
 AT VARIOUS TEMPERATURES
 TUNGSTEN - .5" GAGE LENGTH
 .020 GAGE



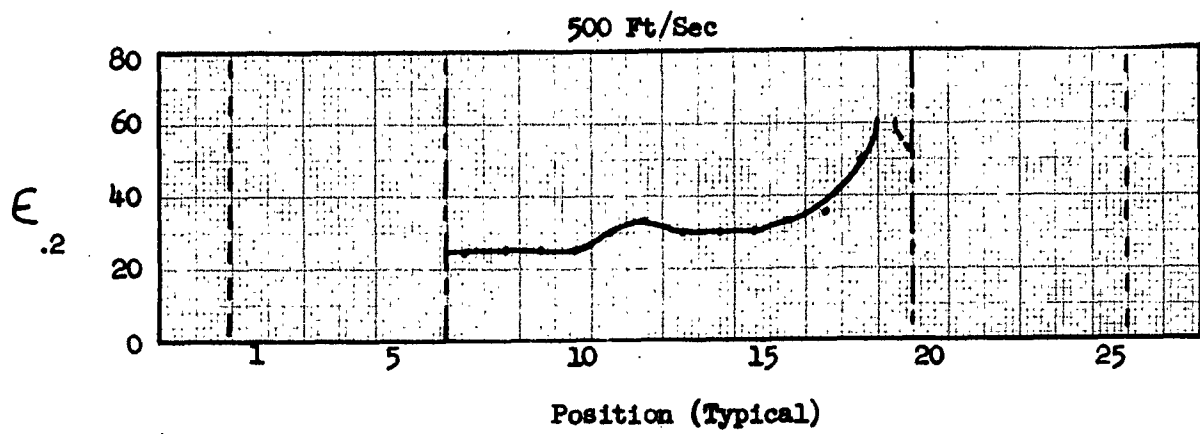
GRAPH 15
 LONGITUDINAL TENSILE SPECIMENS
 ELONGATION VS POSITION OF .2 INCH GAGE LENGTH
 AT -320°F AND VARIOUS TEST VELOCITIES
 17-7 PH - 5" GAGE LENGTH



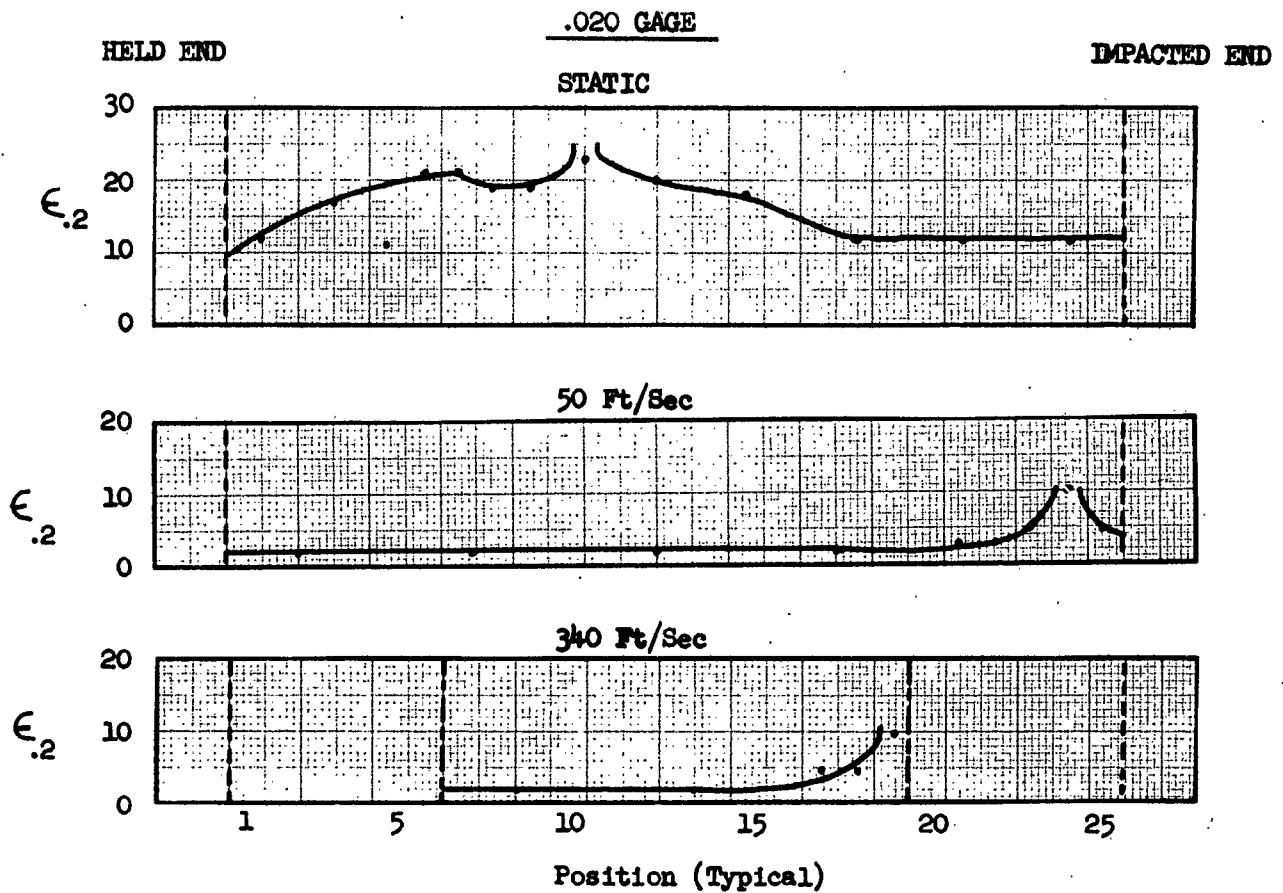
GRAPH 16
 LONGITUDINAL TENSILE SPECIMENS
 ELONGATION VS POSITION OF .2 INCH GAGE LENGTH
 AT -320°F AND VARIOUS TEST VELOCITIES
 A-286 - 5" GAGE LENGTH



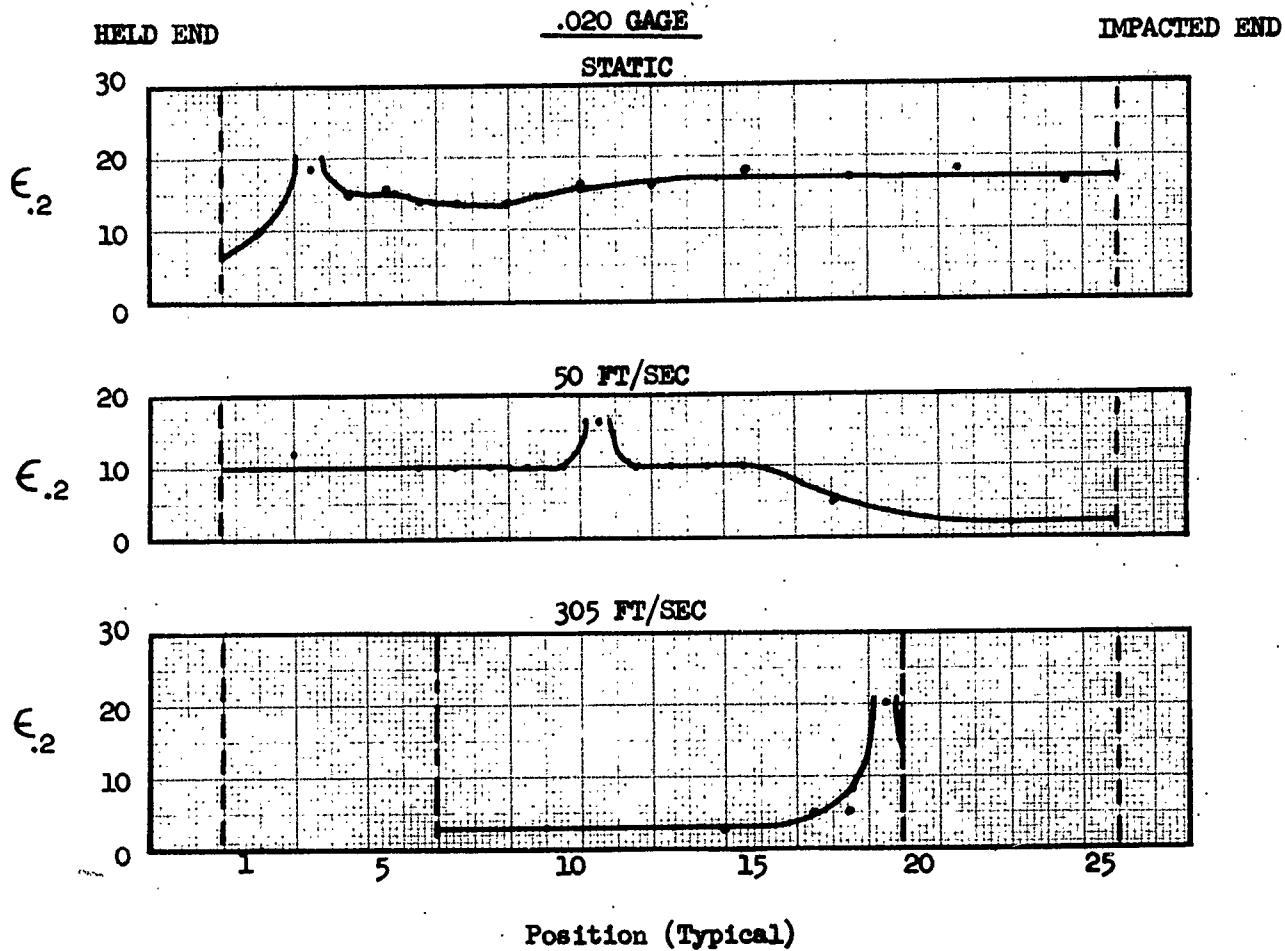
GRAPH 16 (Concluded)



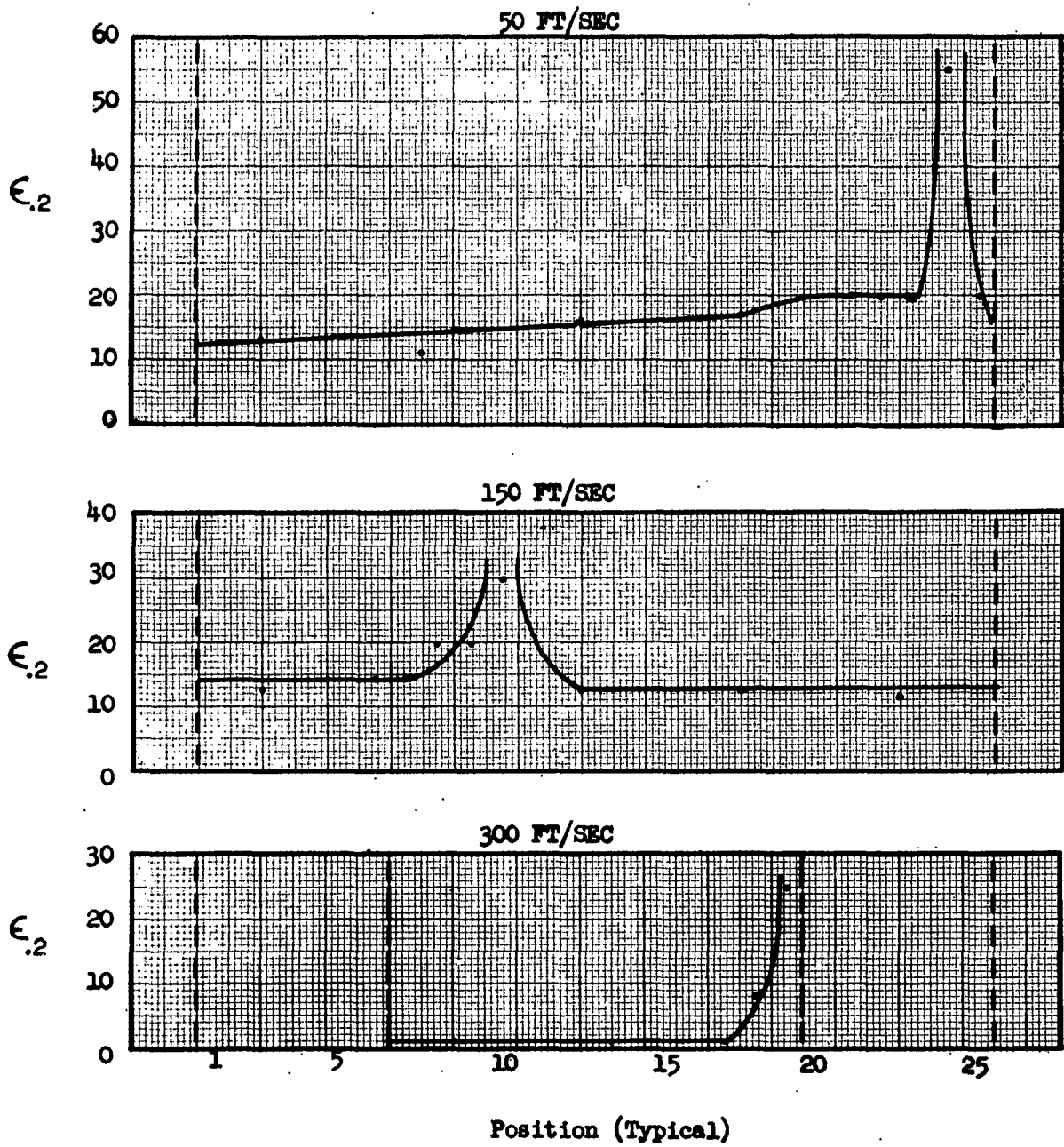
GRAPH 17
 LONGITUDINAL TENSILE SPECIMENS
 ELONGATION VS POSITION OF .2 INCH GAGE LENGTH
 AT -320°F AND VARIOUS TEST VELOCITIES
 VASCOJET 1000 - 5" GAGE LENGTH



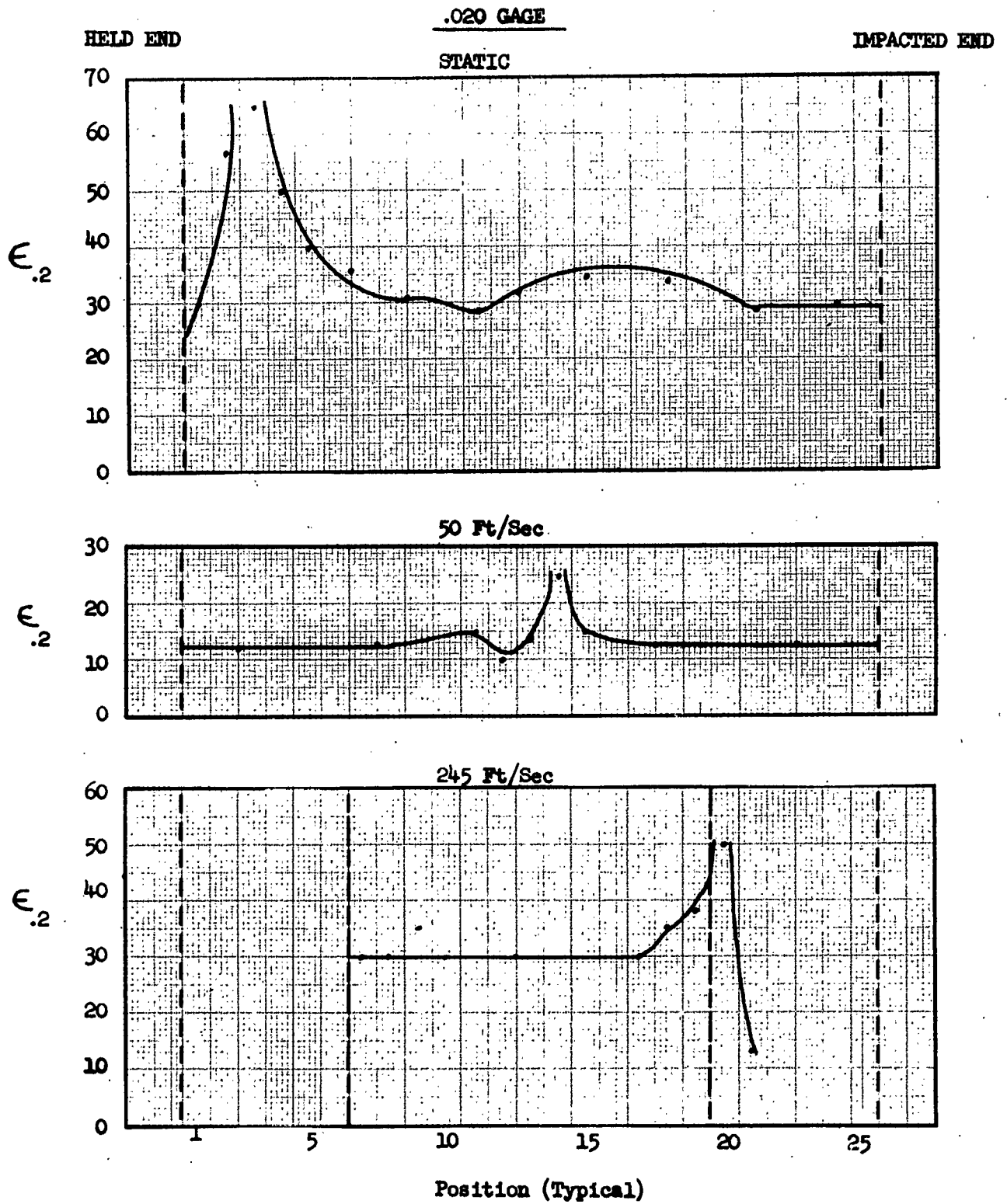
GRAPH 18
 LONGITUDINAL TENSILE SPECIMENS
 ELONGATION VS POSITION OF .2 INCH GAGE LENGTH
 AT -320°F AND VARIOUS VELOCITIES
 USS 12 MoV - 5" GAGE LENGTH



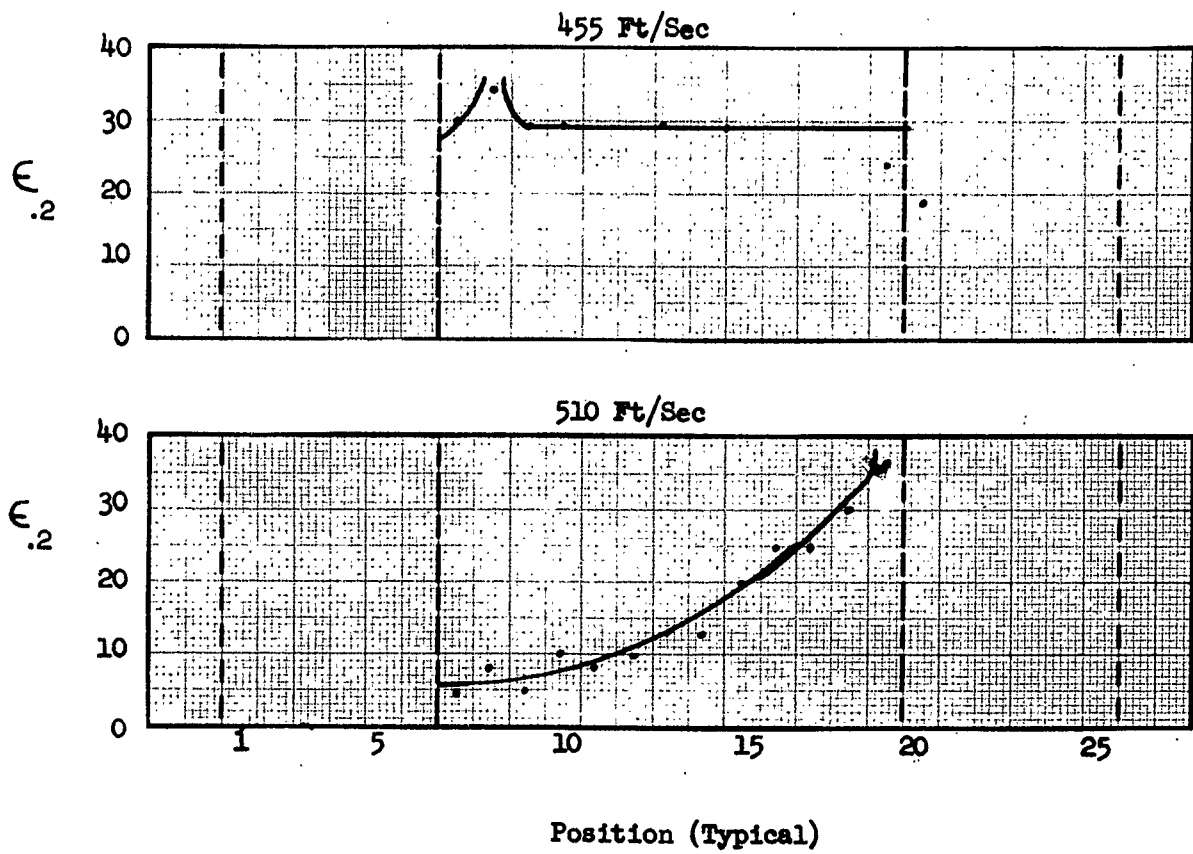
GRAPH 19
 LONGITUDINAL TENSILE SPECIMENS
 ELONGATION VS POSITION OF .2 INCH GAGE LENGTH
 AT -320°F AND VARIOUS TEST VELOCITIES
 L-605 - 5" GAGE LENGTH
 .063 GAGE



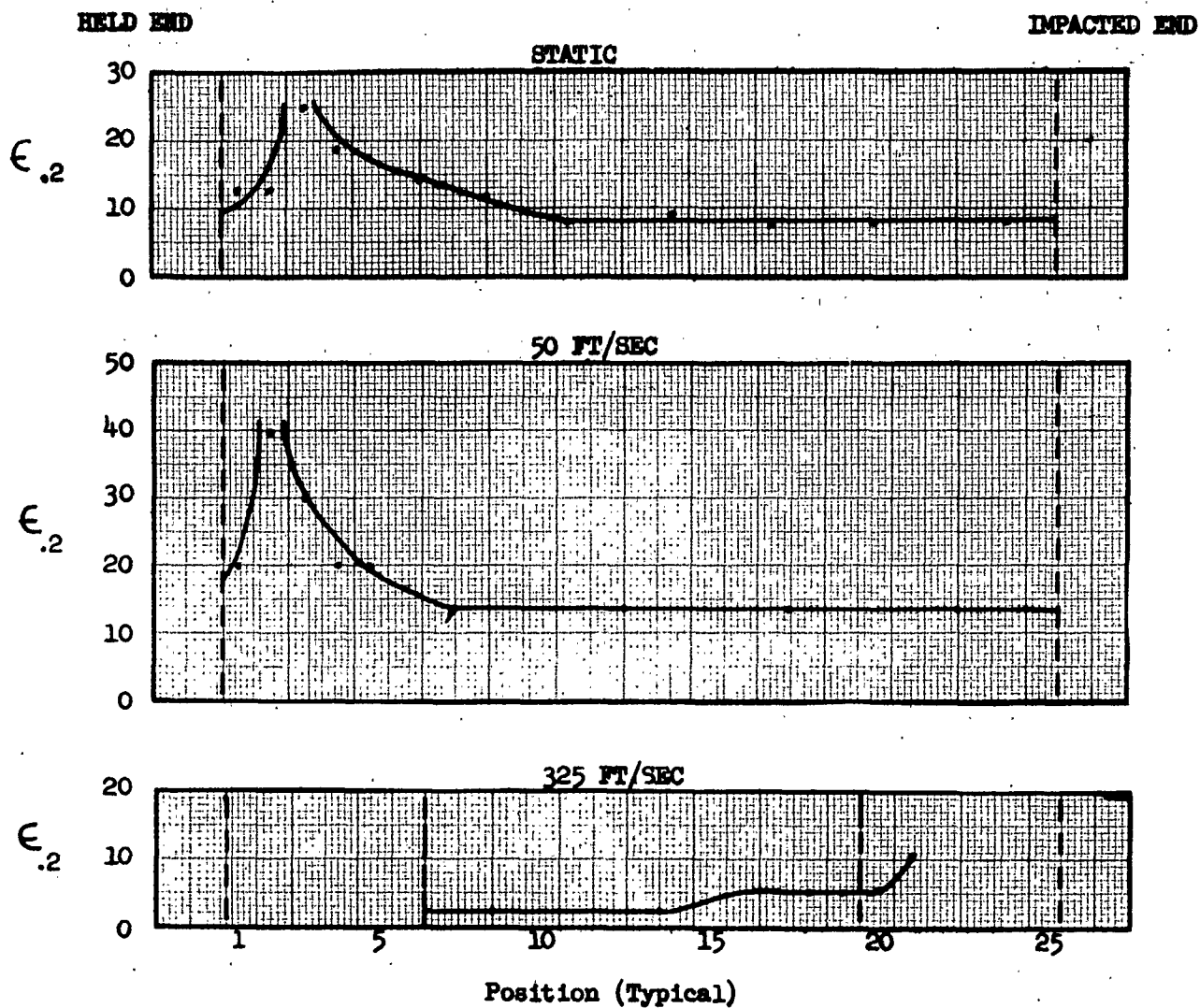
GRAPH 20
LONGITUDINAL TENSILE SPECIMENS
ELONGATION VS POSITION OF .2 INCH GAGE LENGTH
AT -320°F AND VARIOUS TEST VELOCITIES
RENE'41 - 5" GAGE LENGTH



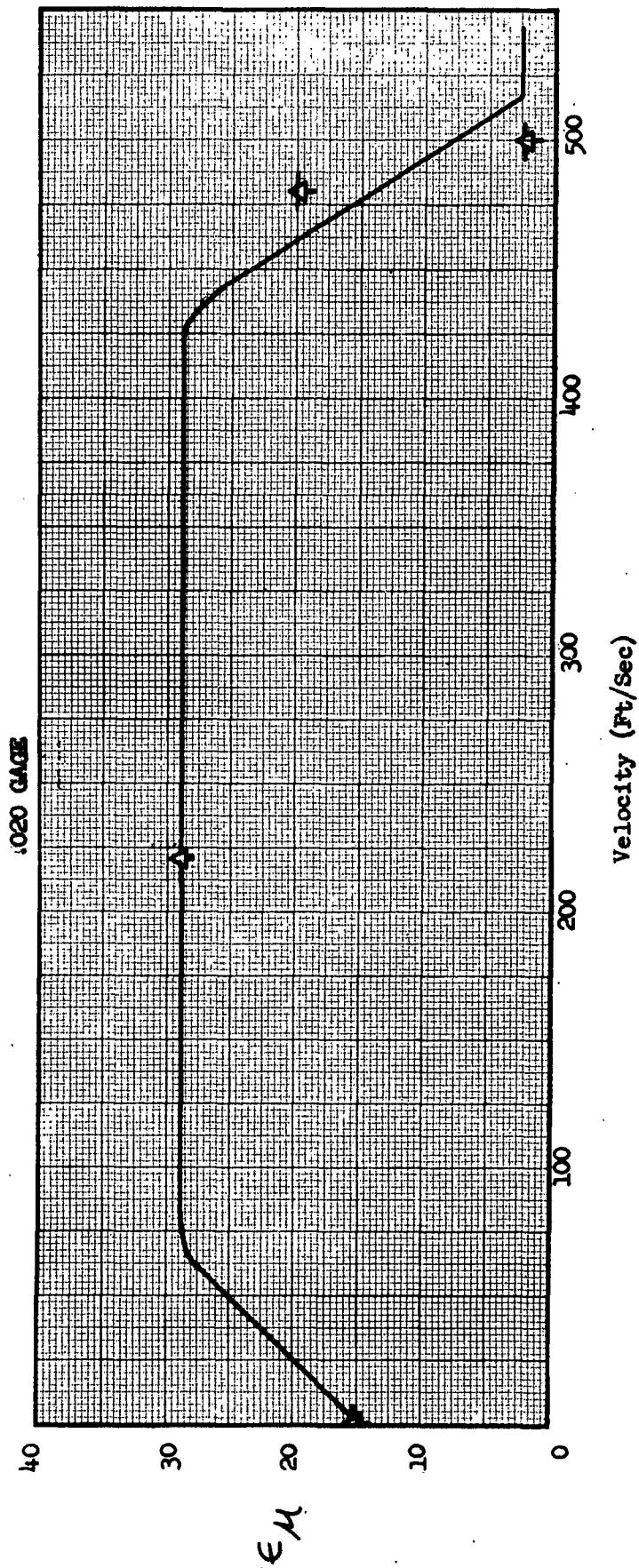
GRAPH 20 (Concluded)



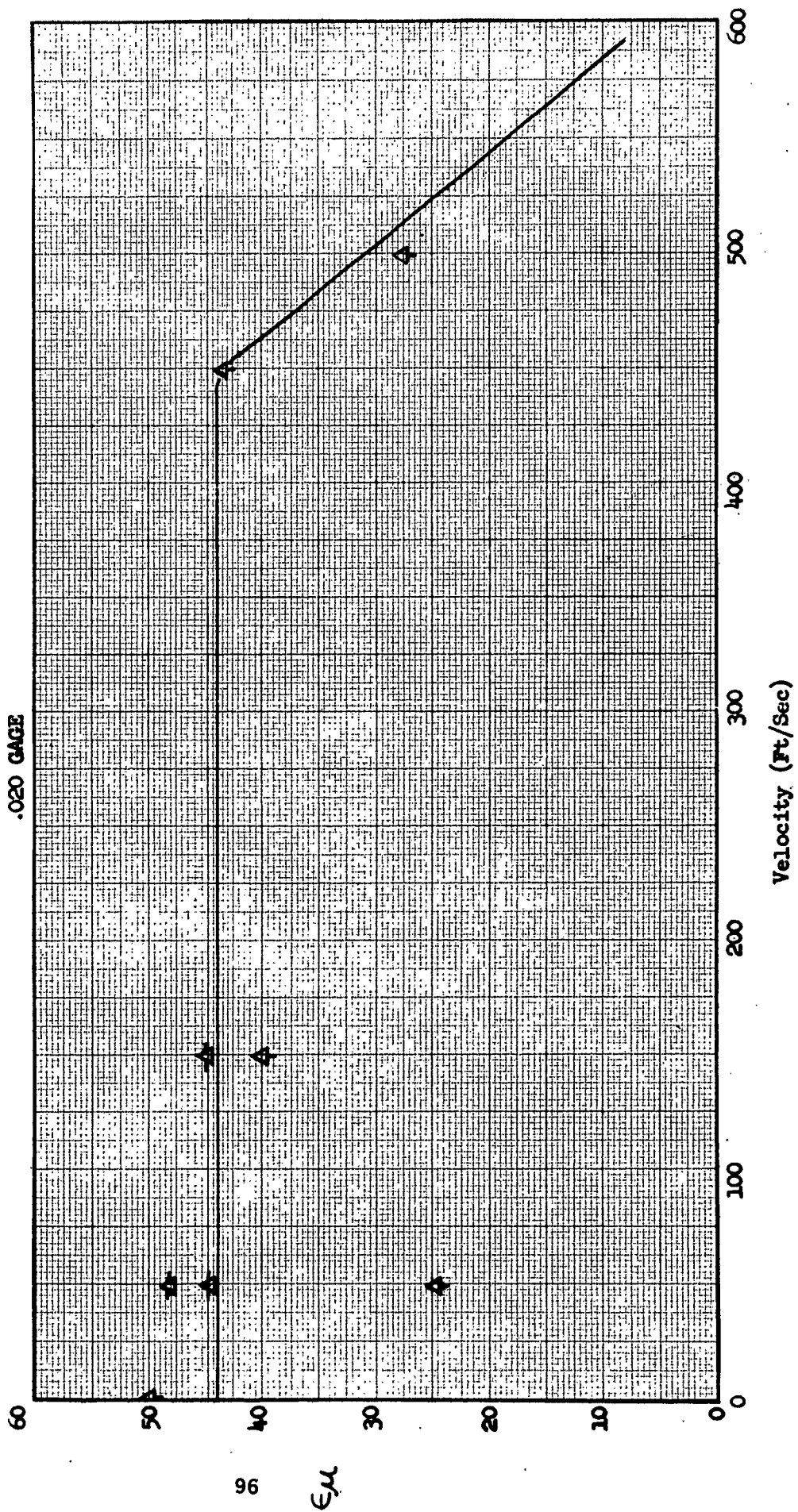
GRAPH 21
 LONGITUDINAL TENSILE SPECIMENS
 ELONGATION VS POSITION OF .2 INCH GAGE LENGTH
 AT -320°F AND VARIOUS TEST VELOCITIES
 2024-O ALUMINUM - 5" GAGE LENGTH



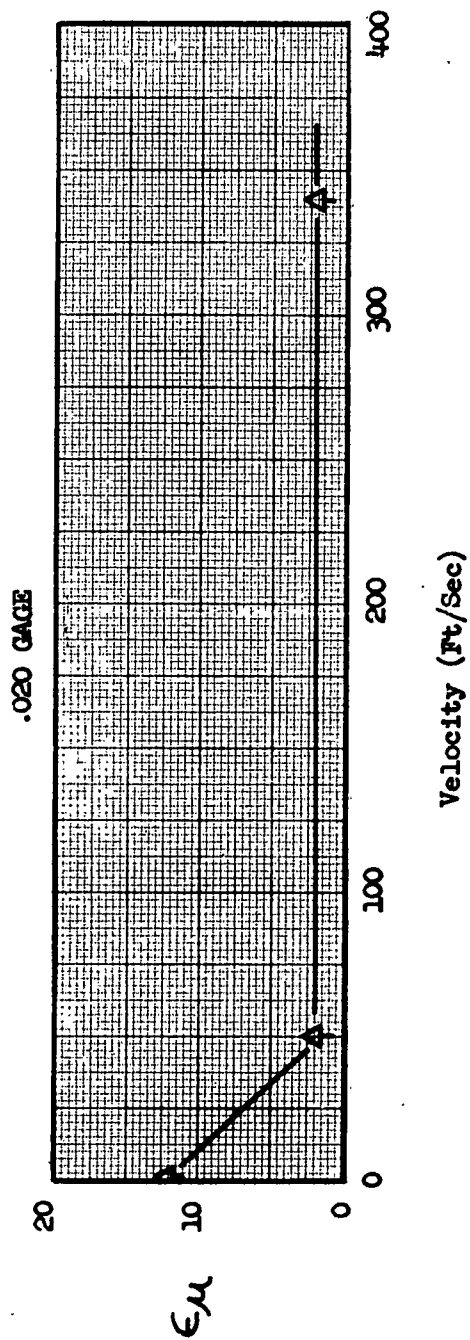
GRAPH 22
 UNIFORM ELONGATION VS FORMING VELOCITY
 FOR LONGITUDINAL TENSILE SPECIMENS
 AT -320°F
 17-7 PH - 5" GAGE LENGTH



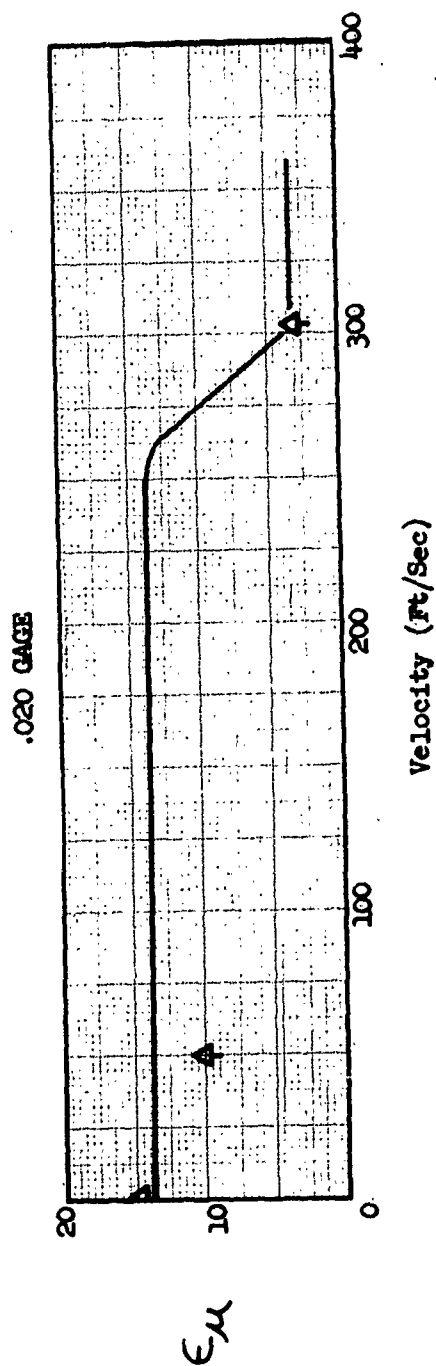
GRAPH 23
 UNIFORM ELONGATION VS FORMING VELOCITY
 FOR LONGITUDINAL TENSILE SPECIMENS
 AT -320°F
 A-286 - 5" GAGE LENGTH



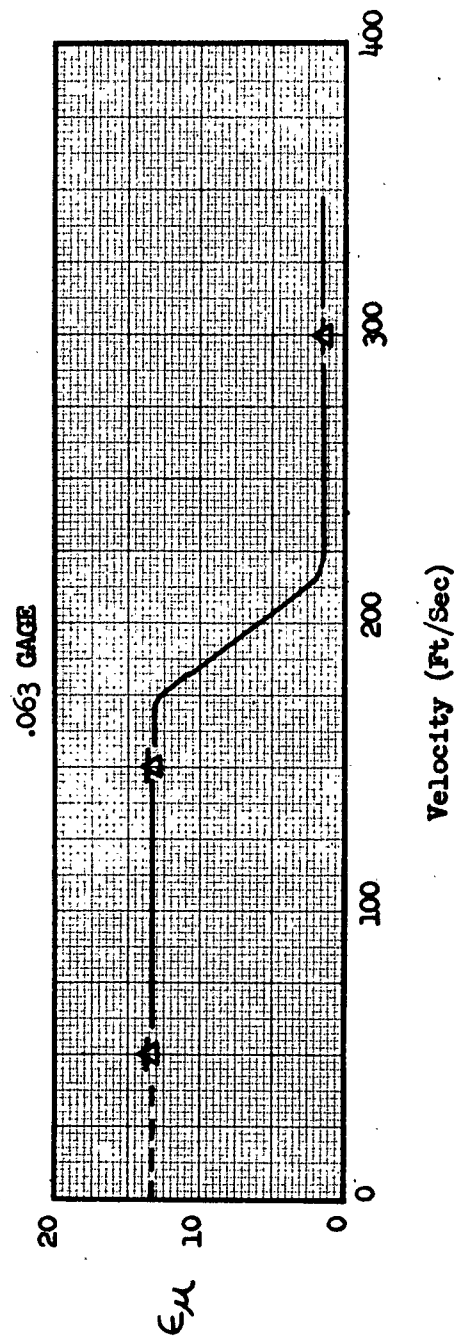
GRAPH 24
 UNIFORM ELONGATION VS FORMING VELOCITY
 FOR LONGITUDINAL TENSILE SPECIMENS
 AT -320°F
 VASCOJET 1000 - 5" GAGE LENGTH



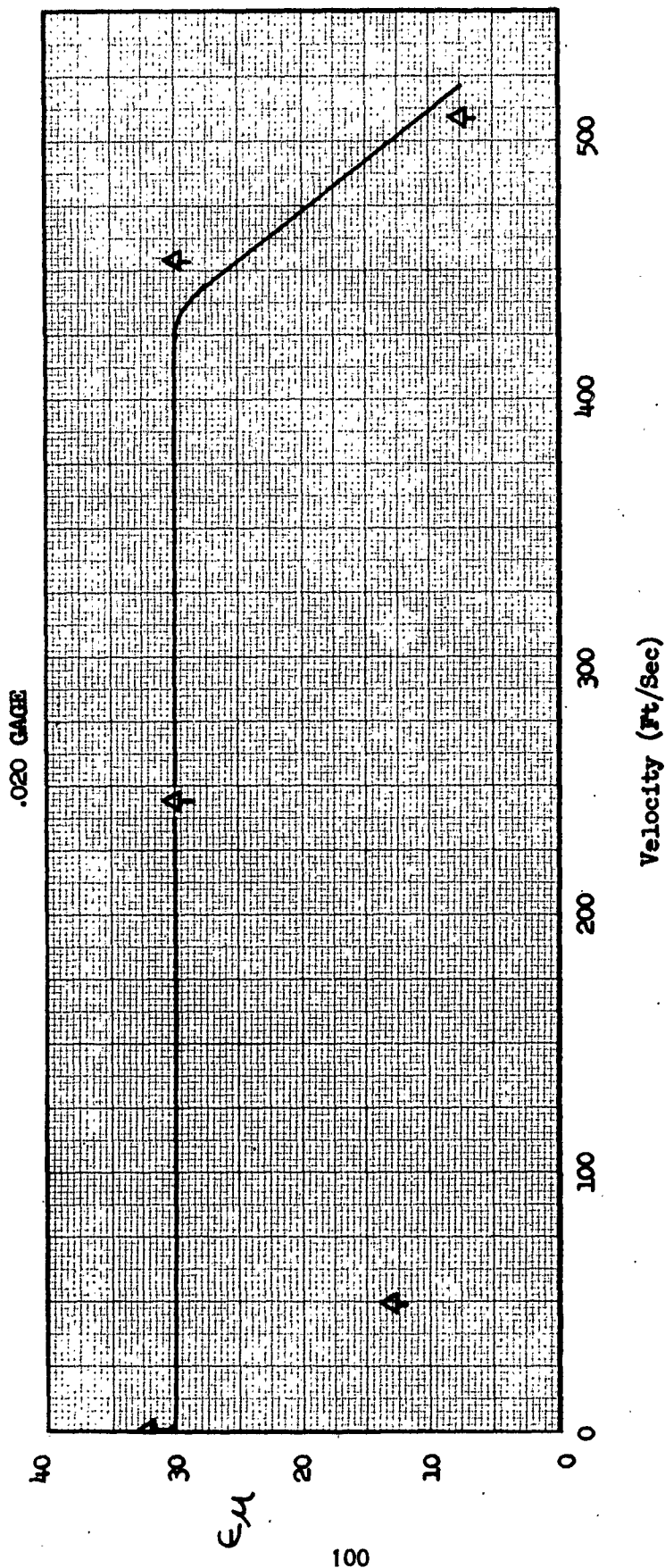
GRAPH 25
 UNIFORM ELONGATION VS FORMING VELOCITY
 FOR LONGITUDINAL TENSILE SPECIMENS
 AT -320°F
 USS 12 MoV - 5" GAGE LENGTH



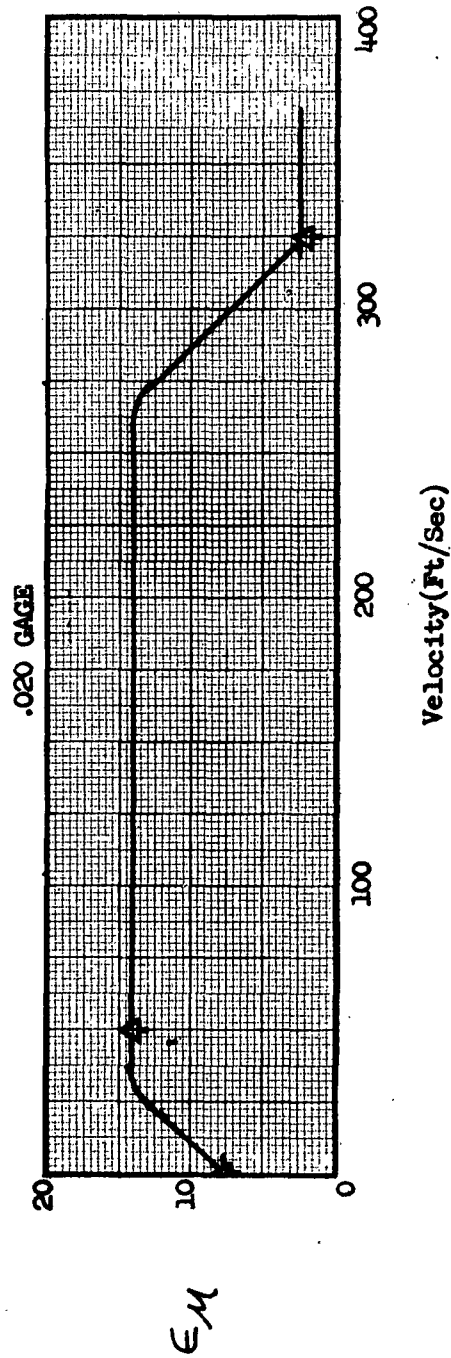
GRAPH 26
 UNIFORM ELONGATION VS FORMING VELOCITY
 FOR LONGITUDINAL TENSILE SPECIMENS
 AT -320°F
 L-605 - 5" GAGE LENGTH



GRAPH 27
 UNIFORM ELONGATION VS FORMING VELOCITY
 FOR LONGITUDINAL TENSILE SPECIMENS
 AT -320°F
 RENE'41 - 5" GAGE LENGTH



GRAPH 28
 UNIFORM ELONGATION VS FORMING VELOCITY
 FOR LONGITUDINAL TENSILE SPECIMENS
 AT -320°F
 2024-O ALUMINUM - 5" GAGE LENGTH



APPENDIX B

TABLE 1
FREE BULGE DOME
LOW EXPLOSIVE HIGH TEMPERATURE
TENSILE TESTING DATA

Material	Part No.	Charge-Grains (Bullseye Powder)	* Velocity fps	Temp. °F	Average Strain %
17-7 PH	01101811	60	245	500	27.5
	01101812	70	250	500	27.5
	01101813	80	260	500	21.5
	01101814	60	245	1000	19.0
	01101815	70	250	1000	28.0
	01101816	80	260	1000	26.0
A-286	02102031	65	256	500	23.0
	02102032	70	209	500	26.5
	02102033	75	240	500	25.5
	02102034	65	256	1000	29.0
	02102035	70	209	1000	24.0
	02102036	75	240	1000	30.5
Vascojet 1000	03101126	75	259	500	18.5
	03101127	80	232	500	14.0
	03101128	70	212	500	17.5
	03101129	70	212	1000	26.0
	03101130	75	232	1000	8.5
	03101131	80	260	1000	16.0
USS 12 MoV	04103009	75	283	500	21.0
	04103010	70	261	500	25.0
	04103011	65	190	1000	20.0
	04103012	65	190	500	18.5
	04103013	70	261	1000	21.0
	04103014	75	283	1000	21.0
Titanium (6Al-4V)	05102017	65	95	500	16.0
	05102018	70	158	500	13.0
	05102019	75	312	500	15.5
	05102020	65	95	1200	10.0
	05102022	70	158	1200	12.5
	05102023	75	312	1200	19.0
Titanium (All Beta)	06102019	65	93	500	8.5
	06102020	70	124	500	20.0
	06102021	75	249	500	14.5
	06102022	65	93	1200	17.5
	06102023	70	124	1200	18.0
	06102024	75	249	1200	4.0
L-605	07101019	60	192	500	27.5
	07101020	70	212	500	29.0
	07101021	80	260	500	24.5

TABLE 1 (Continued)
FREE BULGE DOME
LOW EXPLOSIVE HIGH TEMPERATURE
TENSILE TESTING DATA

Material	Part No.	Charge-Grains (Bullseye Powder)	* Velocity fps	Temp. °F	Average Strain-%
L-605 (Continued)	07101022	60	192	1000	32.0
	07101023	70	212	1000	28.0
	07101024	80	260	1000	30.5
Rene '41	08103050	75	222	500	21.5
	08103051	70	221	500	21.5
	08103052	80	261	500	21.5
	08103053	70	222	1000	19.0
	08103054	75	221	1000	25.0
	08103055	80	261	1000	23.0
Molybdenum (.5% Ti)	10101080	85	462	R.T.	0.25
	10101081	75	390	R.T.	0.25
	10101082	50	272	R.T.	0.25
	10101083	75	390	600	20.5
	10101084	85	462	600	21.0
	10101085	85	462	300	21.5
	10101086	75	390	300	23.0
Columbium	11101080	75	288	R.T.	17.0
	11101081	65	253	R.T.	11.5
	11101082	85	342	R.T.	16.5
	11101083	85	342	1400	3.0
	11101084	85	342	500	4.5
	11101085	65	253	500	17.0
	11101086	65	253	1400	3.0
Tungsten	12105080	60	263	R.T.	0
	12105081	85	407	R.T.	0
	12105082	60	263	800	0
Aluminum 2024-O	X13101809	40	315	200	1.5
	X13101810	30	175	200	21.5
	X13101811	30	175	380	30.5
	X13101812	40	294	200	18.5
	X13101813	40	325	200	0.5

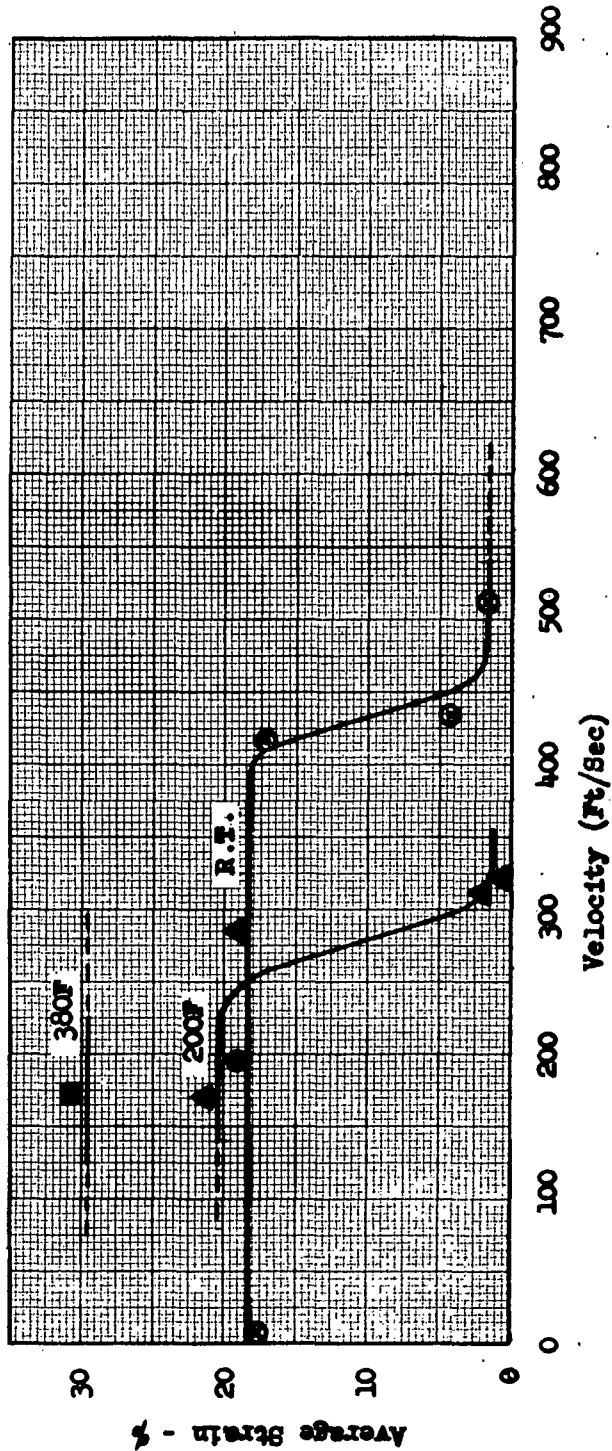
*Velocity measured 0.050" to 0.40" from dome surface.

TABLE 2
FREE BULGE TUBE
LOW EXPLOSIVE HIGH TEMPERATURE
TENSILE TESTING DATA

Material	Part No.	Charge-Grains (Bullseye Powder)	* Velocity fps	Temp. °F	Average Strain %
17-7 PH	01107004	70	227	500	25.6
	01107005	50	157	500	24.9
	01107006	45	140	1000	27.9
	01107008	60	180	1000	25.14
	01107009	70	227	1000	21.5
	01107010	40	130	500	33.3
	01107011	75	240	1000	26.8
	01107012	60	182	500	35.0
A-286	02102011	45	110	500	20.0
	02102012	55	150	500	19.3
	02102013	65	190	500	22.0
	02102014	75	225	500	19.8
	02102015	45	110	1000	21.3
	02102016	65	190	1000	19.5
	02102017	75	225	1000	19.7
	02102018	55	150	1000	24.6
Vascojet 1000	03102011	50	100	1000	19.5
	03102012	57	125	1000	19.4
	03102013	62	217	1000	21.3
	03102014	68	230	1000	18.0
	03102015	50	100	500	21.4
	03102016	57	125	500	18.6
	03102017	62	217	500	23.0
	03102018	68	230	500	22.9
Titanium (6Al-4V)	05102011	80	80	500	13.9
	05102012	70	38	500	8.5
	05102013	87	133	500	10.3
	05102014	92	220	500	12.0
	05102015	80	80	1200	17.5
	05102016	87	133	1200	14.3
	05102017	92	220	1200	15.38
	05102018	70	38	1200	18.9
Rene '41	08102004	60	130	500	23.56
	08102005	73	215	500	21.7
	08102006	65	175	500	24.3
	08102007	60	130	1000	24.95
	08102008	73	215	1000	25.4
	08102009	65	175	1000	23.4
	08102010	55	95	1000	17.0
	08102011	55	95	500	24.3

*Velocity measured 0.050" to 0.20" from outside diameter of tube.

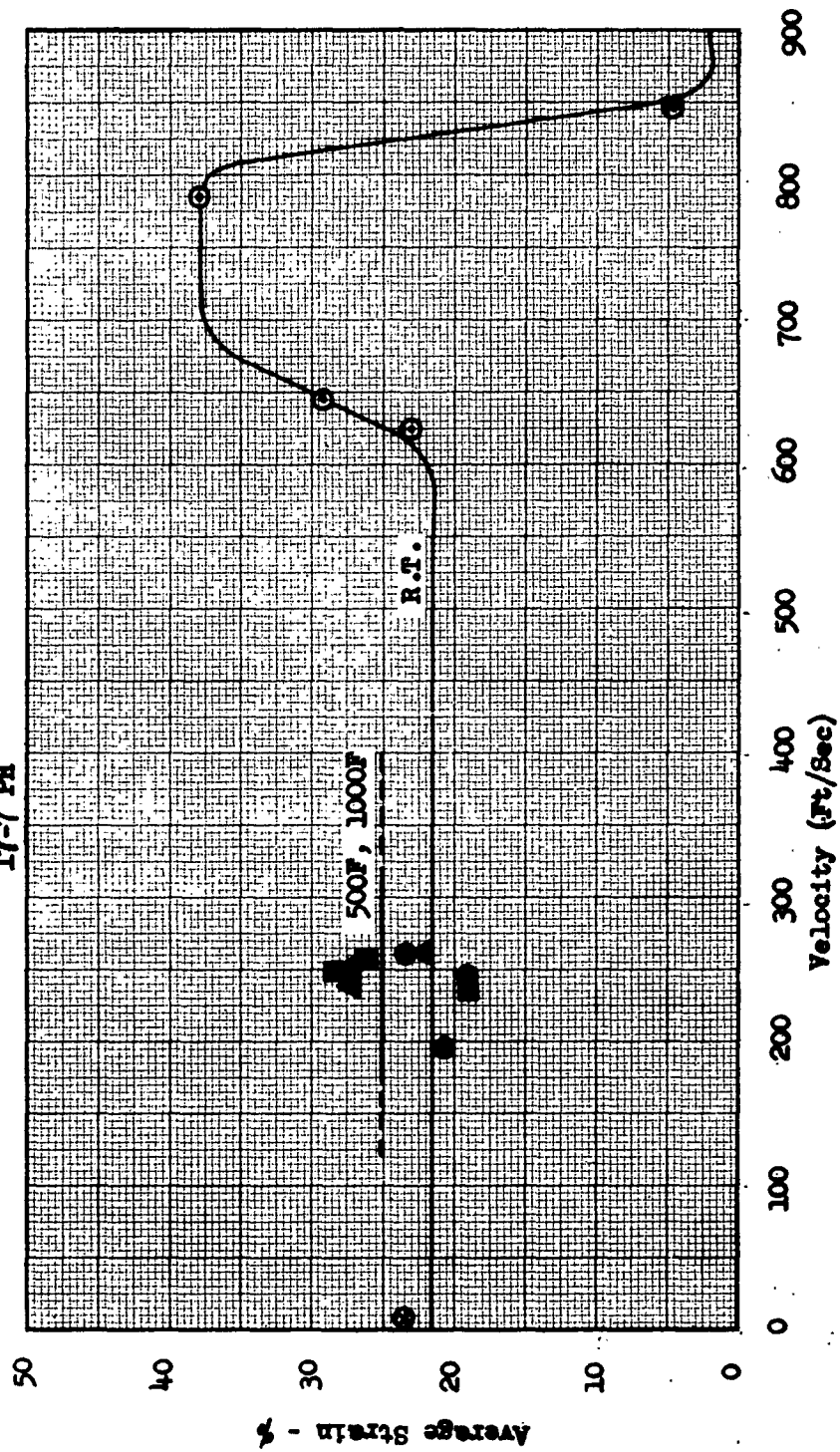
GRAPH 29
EXPLOSIVE FREE BULGE DOME
AVERAGE STRAIN VS VELOCITY
2024-O ALUMINUM



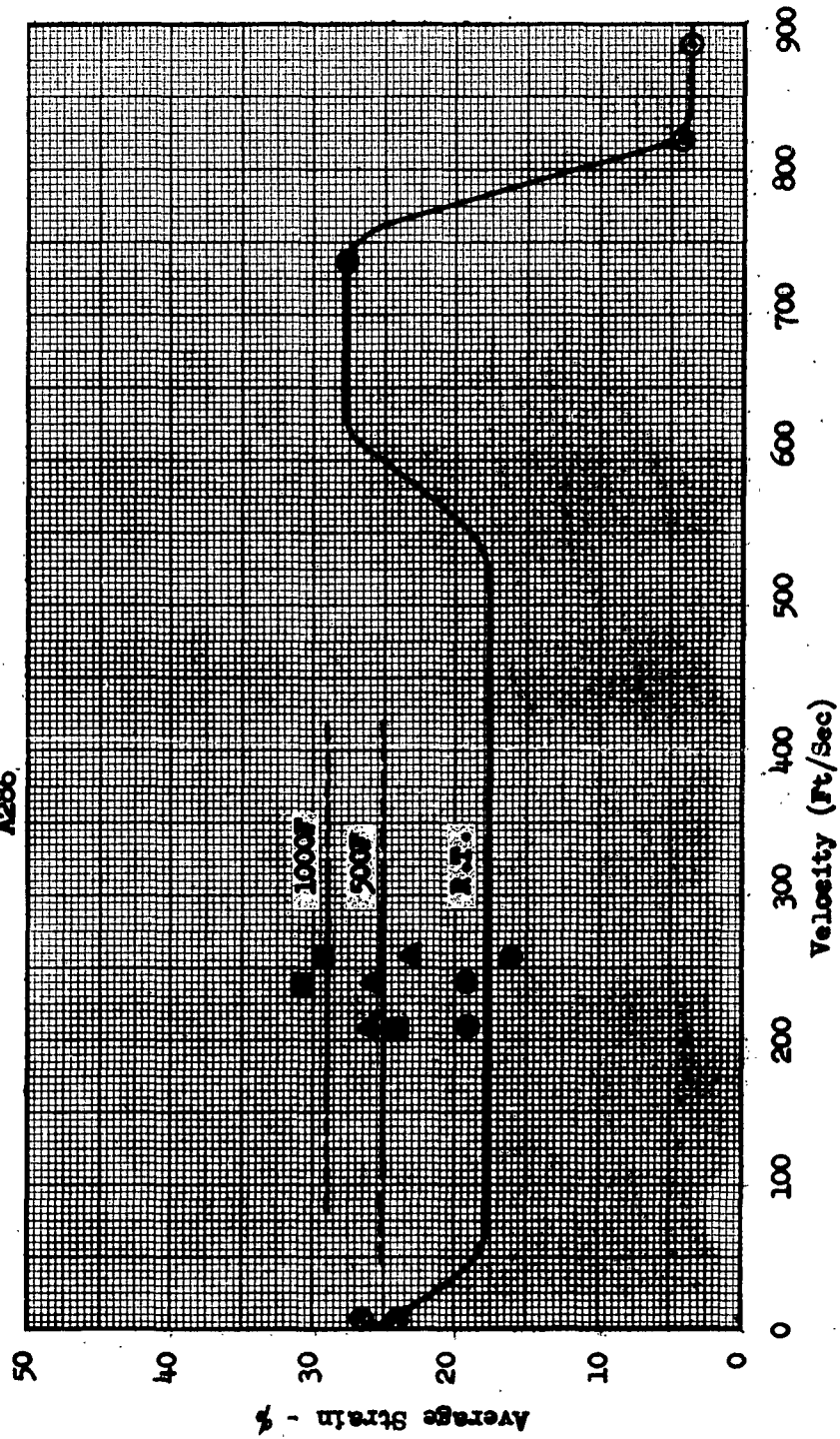
LEGEND:

- ⊗ - room temperature - static test
- - room temperature - low explosive
- ⊙ - room temperature - high explosive
- ▲ - intermediate test temperature - low explosive
- - highest test temperature - low explosive
- probable curve in region of no tests

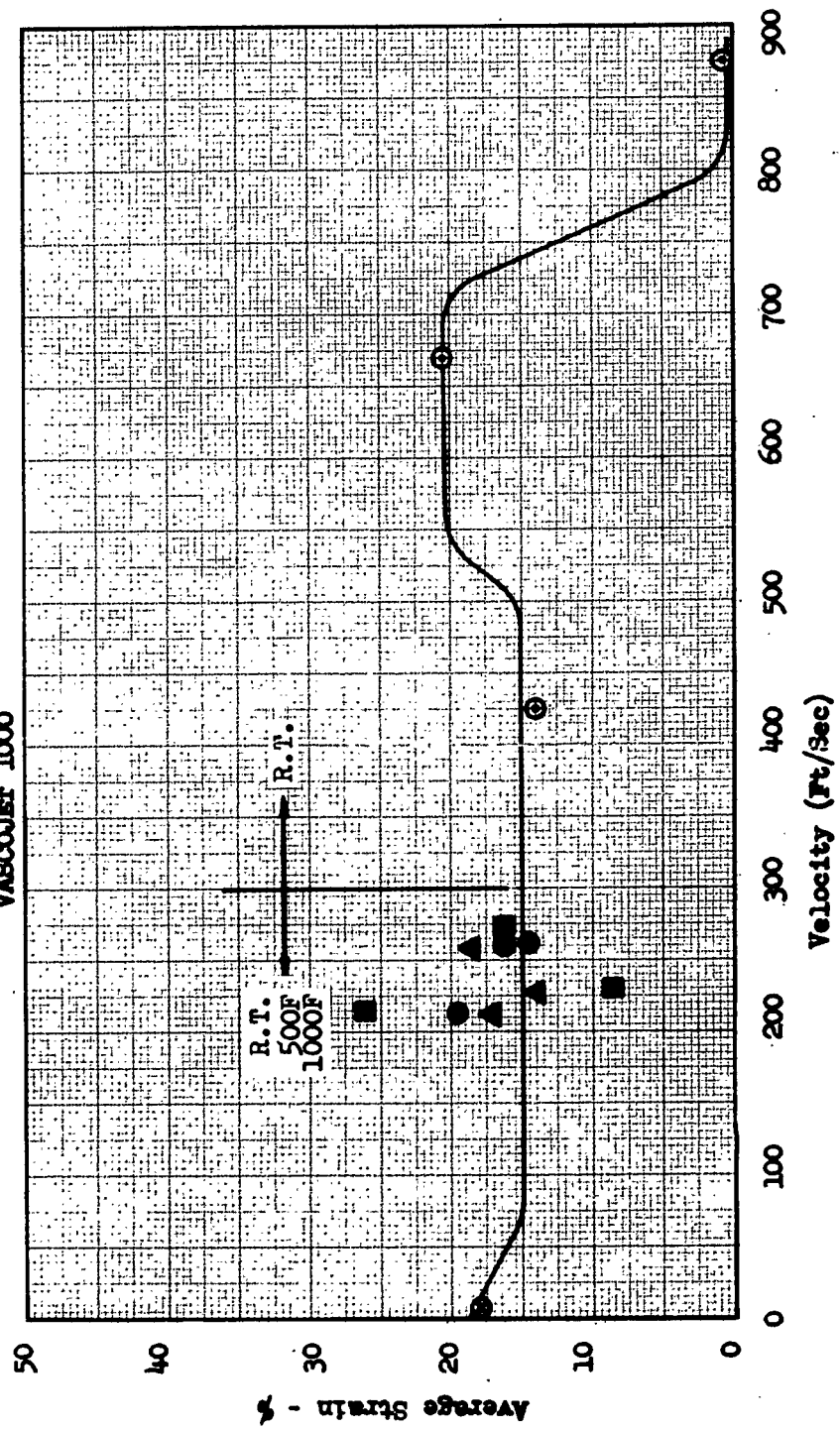
GRAPH 30
EXPLOSIVE FREE BULGE DOME
AVERAGE STRAIN VS VELOCITY
17-7 PH



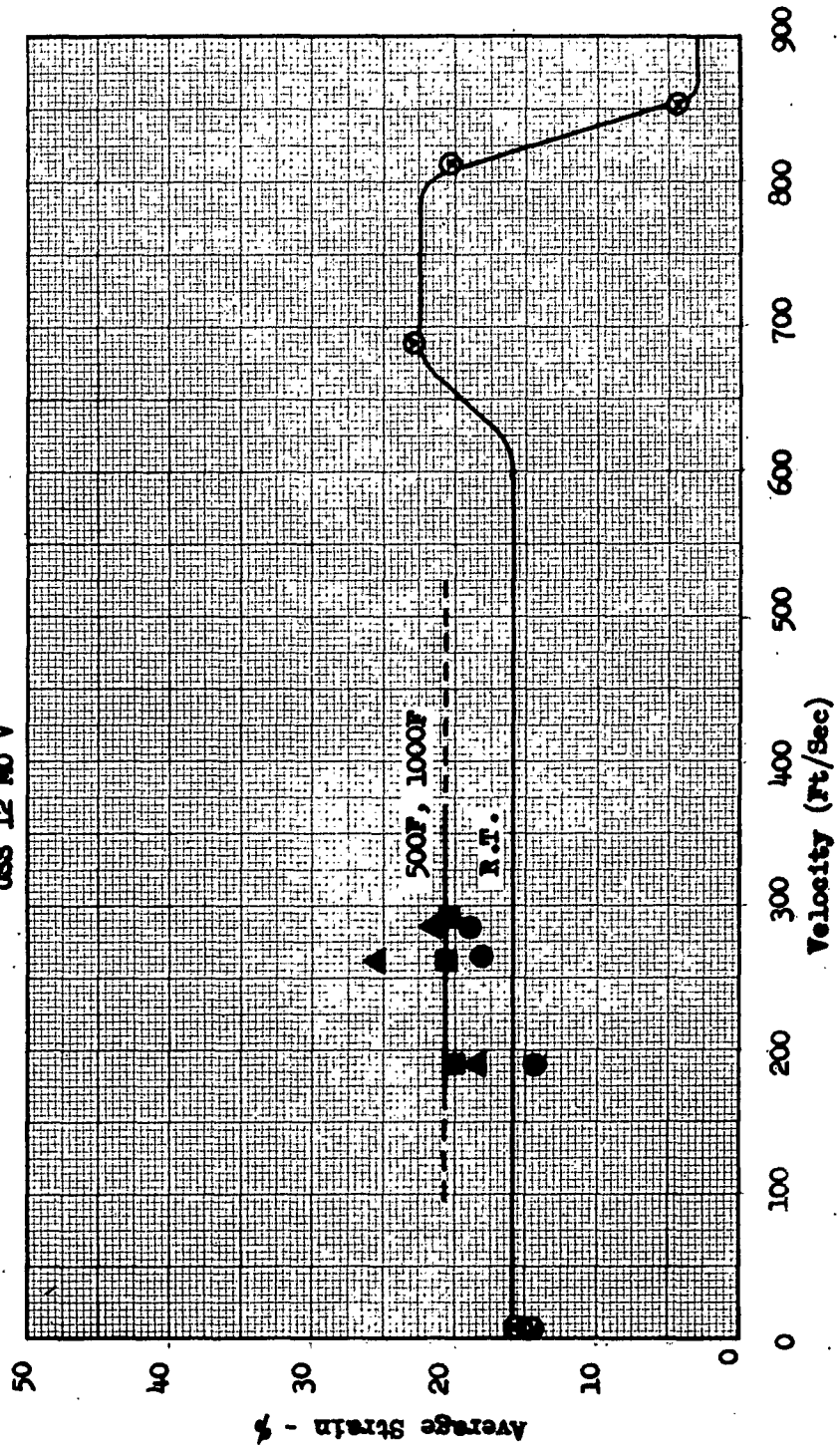
GRAPH 31
EXPLOSIVE FREE BULGE DOME
AVERAGE STRAIN VS VELOCITY
A286



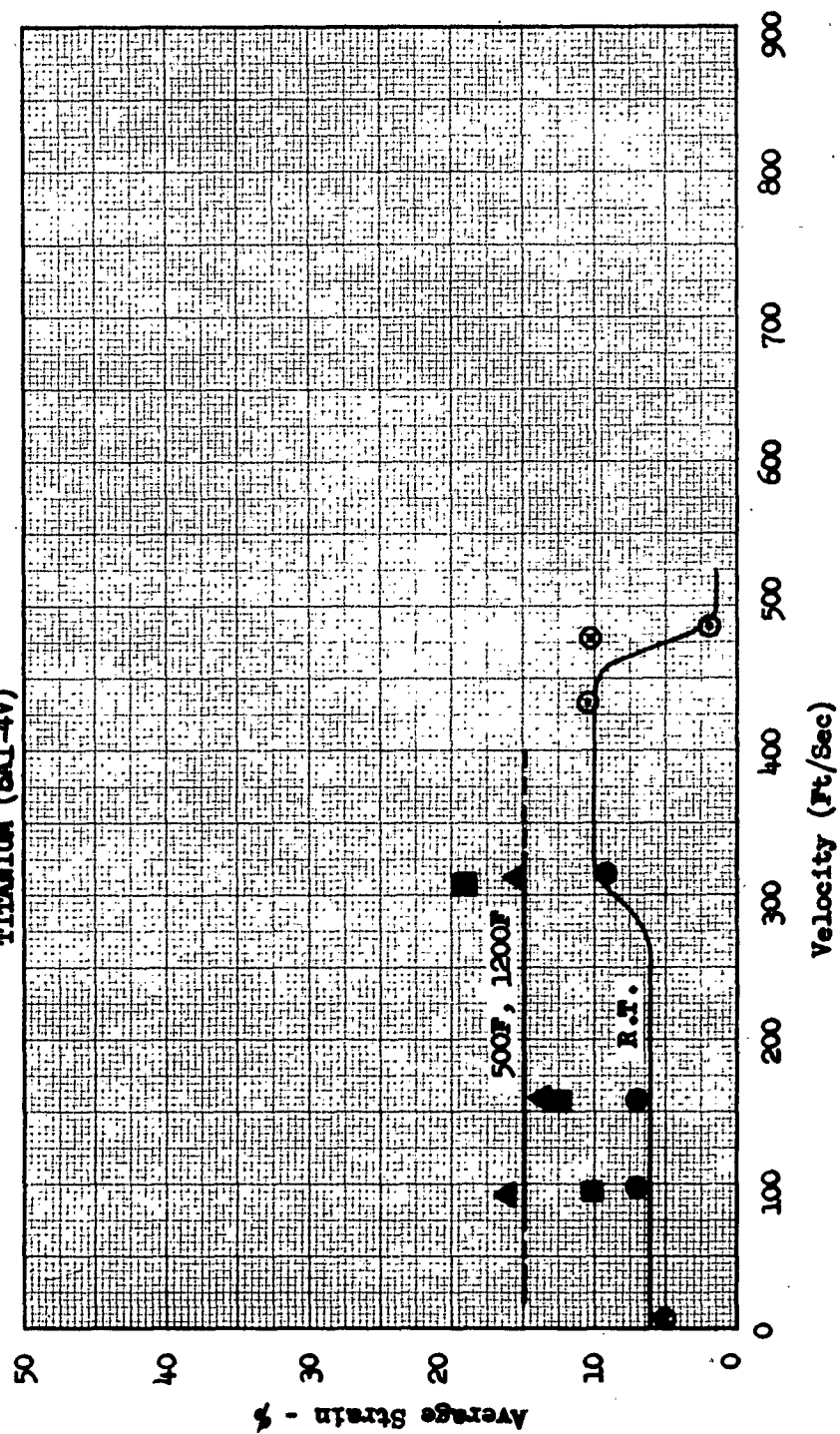
GRAPH 32
EXPLOSIVE FREE BULGE DOME
AVERAGE STRAIN VS VELOCITY
VASCOJET 1000



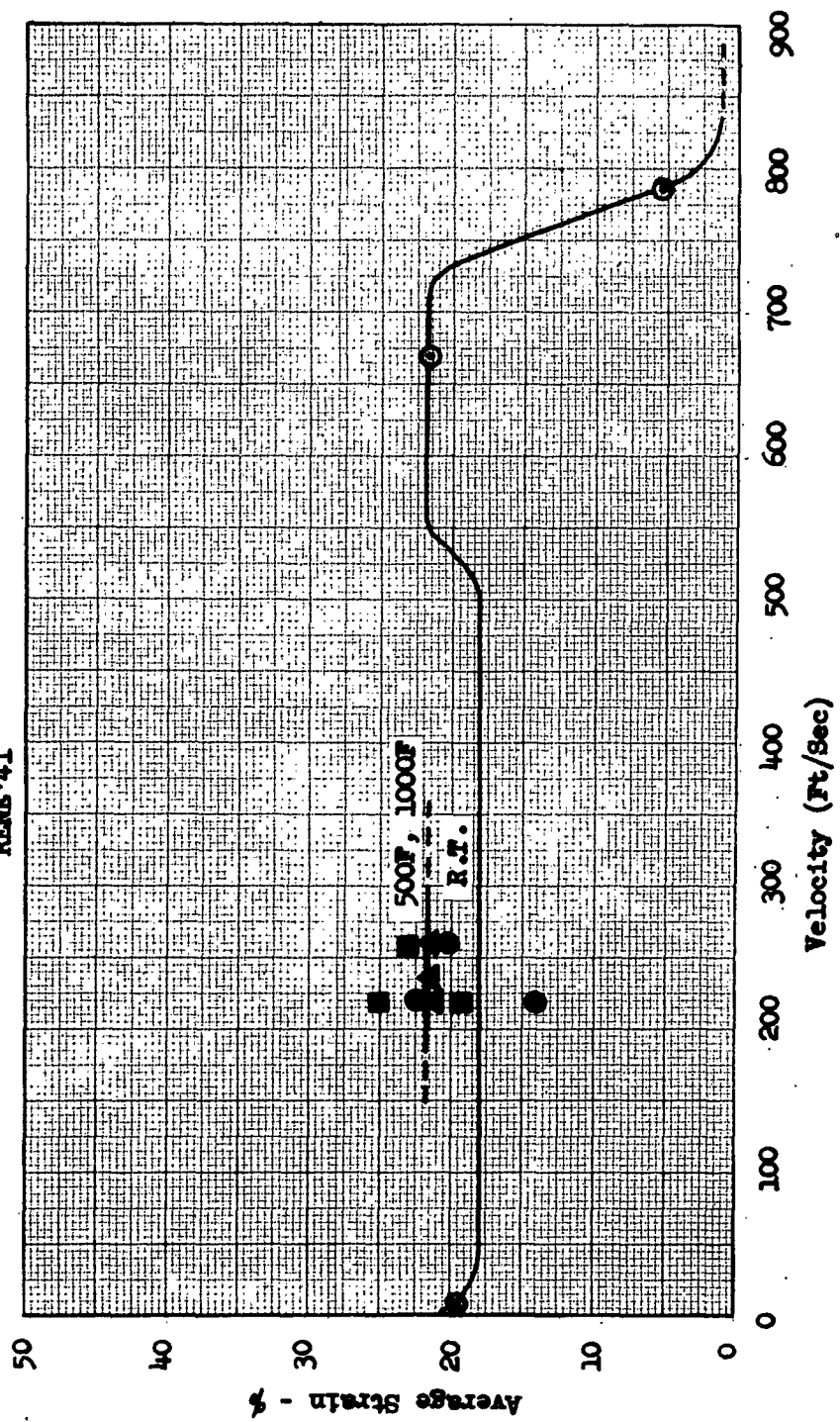
GRAPH 33
EXPLOSIVE FREE BULGE DOME
AVERAGE STRAIN VS VELOCITY
USS 12 NO V



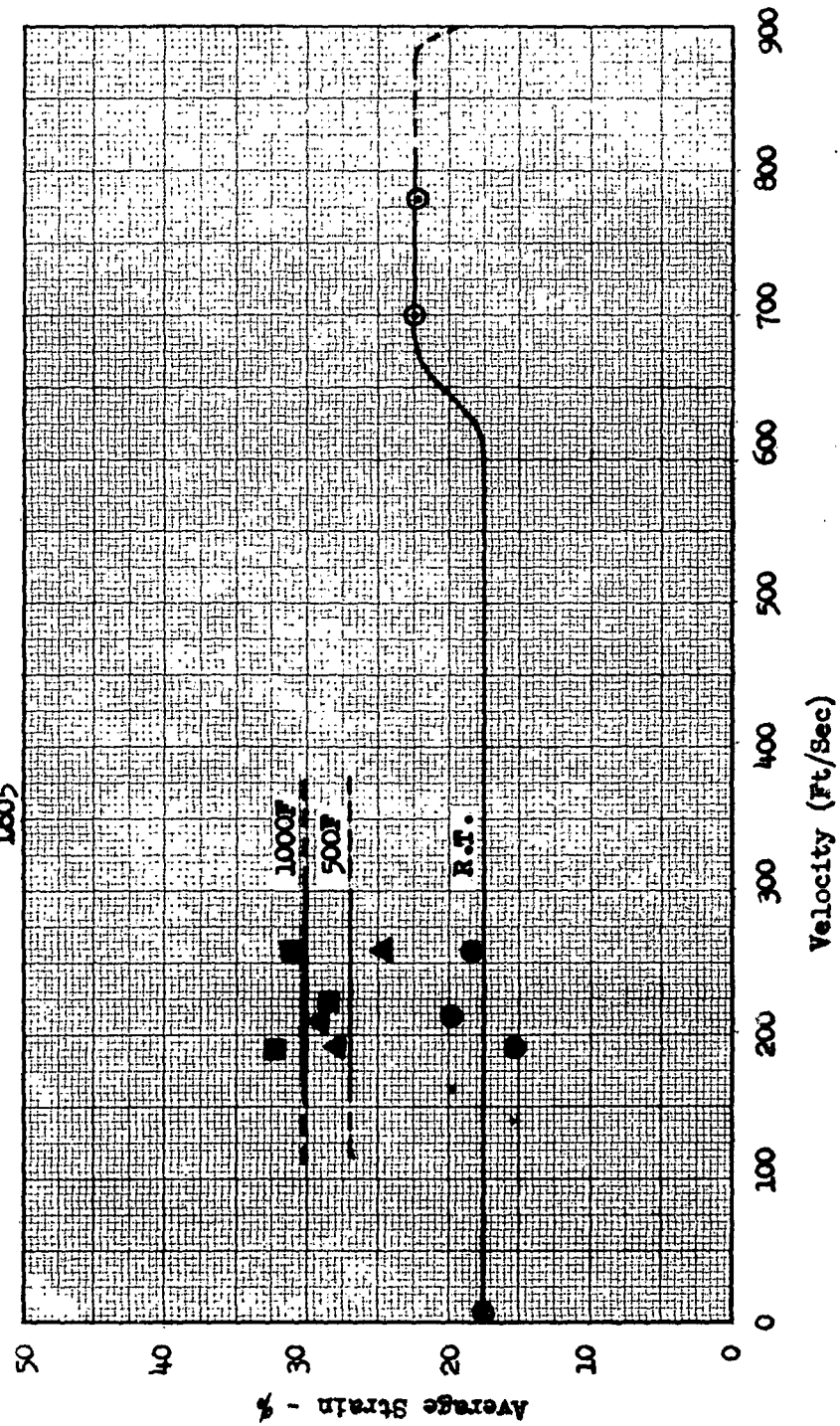
GRAPH 34
EXPLOSIVE FREE BULGE DOME
AVERAGE STRAIN VS VELOCITY
TITANIUM (6A1-4V)



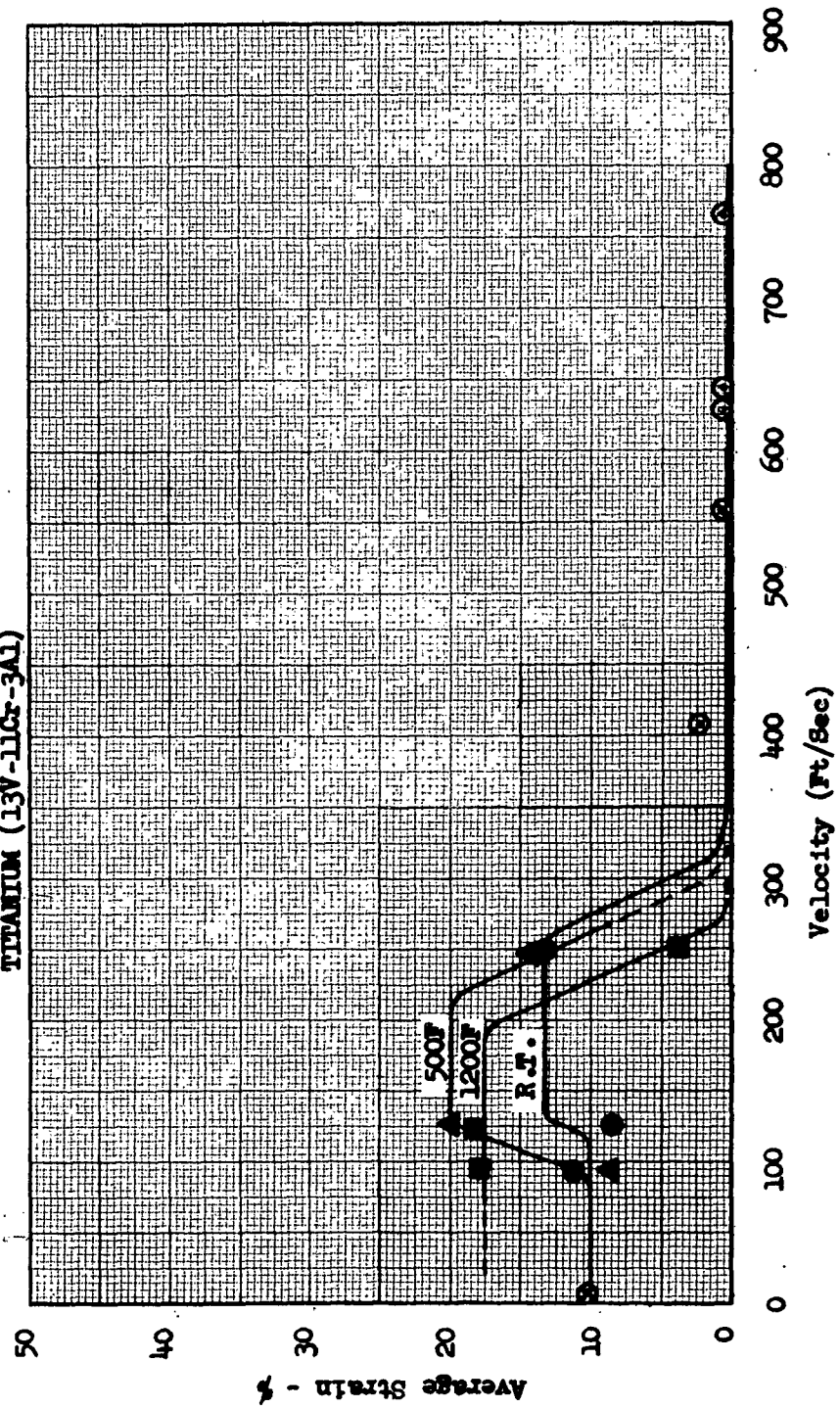
GRAPH 35
EXPLOSIVE FREE BULGE DOME
AVERAGE STRAIN VS VELOCITY
RHEE '41



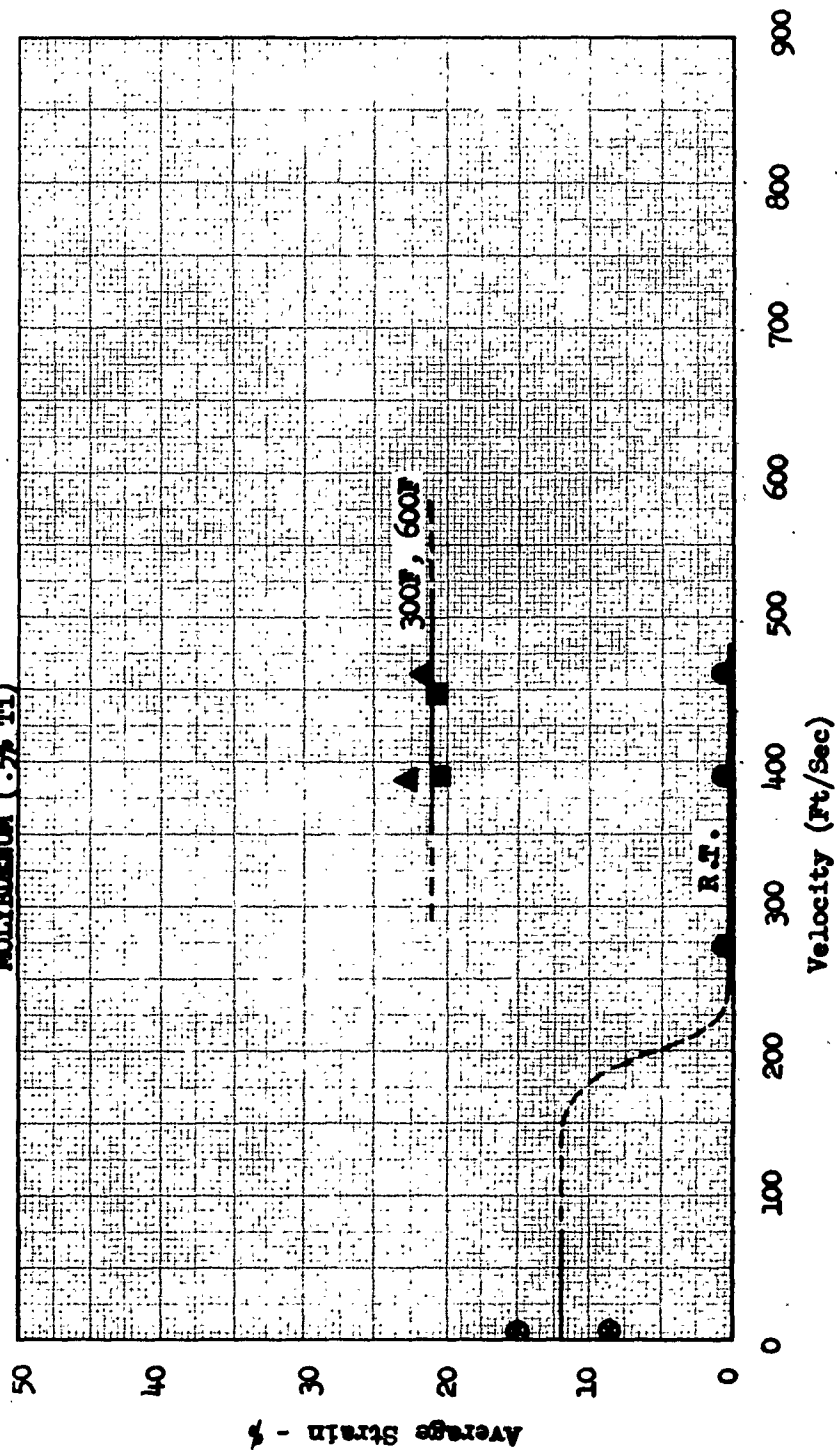
GRAPH 36
EXPLOSIVE FREE BULGE DOME
AVERAGE STRAIN VS VELOCITY
1605



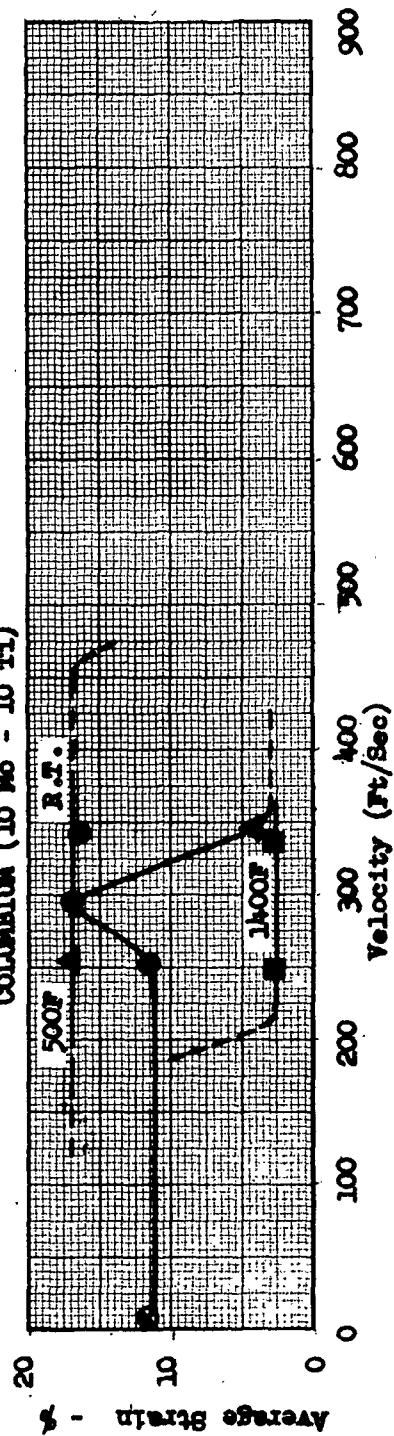
GRAPH 37
EXPLOSIVE FREE BULGE DOME
AVERAGE STRAIN VS VELOCITY
TITANIUM (13V-11Gr-3Al)



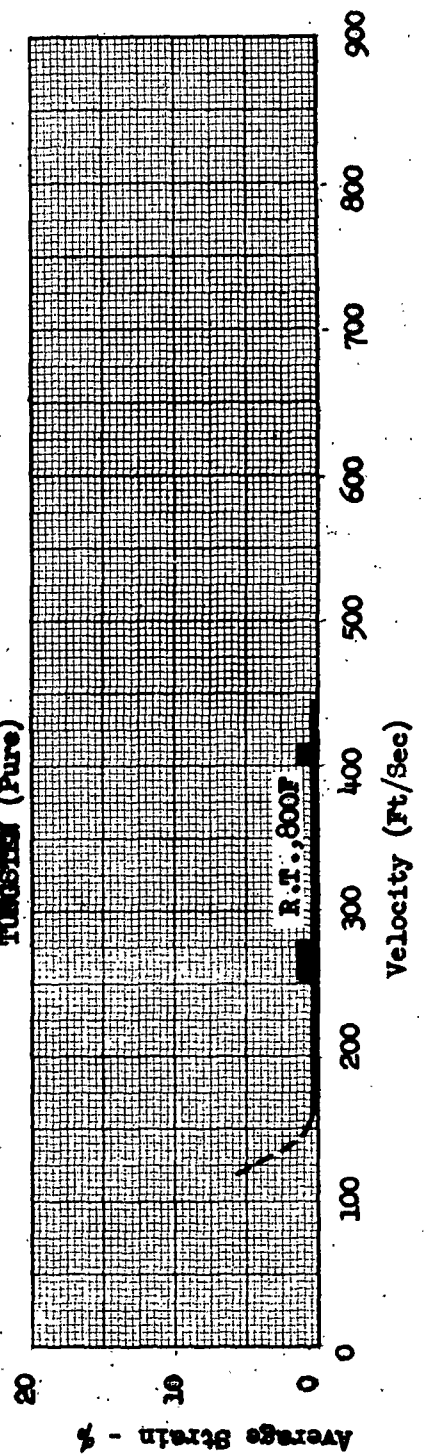
GRAPH 38
EXPLOSIVE FREE BULGE DOME
AVERAGE STRAIN VS VELOCITY
MOLYBDENUM (.5% Ti)



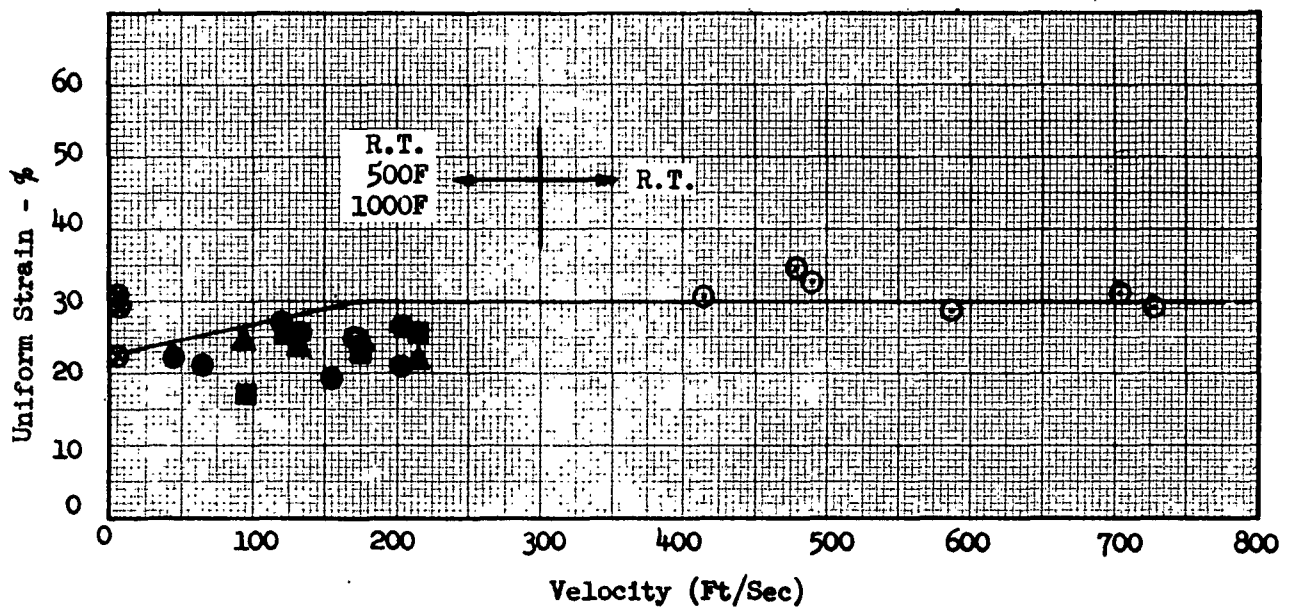
GRAPH 39
EXPLOSIVE FREE BULGE DOME
AVERAGE STRAIN VS VELOCITY
COLUMBIUM (10 Mo - 10 T1)



GRAPH 40
EXPLOSIVE FREE BULGE DOME
AVERAGE STRAIN VS VELOCITY
TUNGSTEN (Pure)



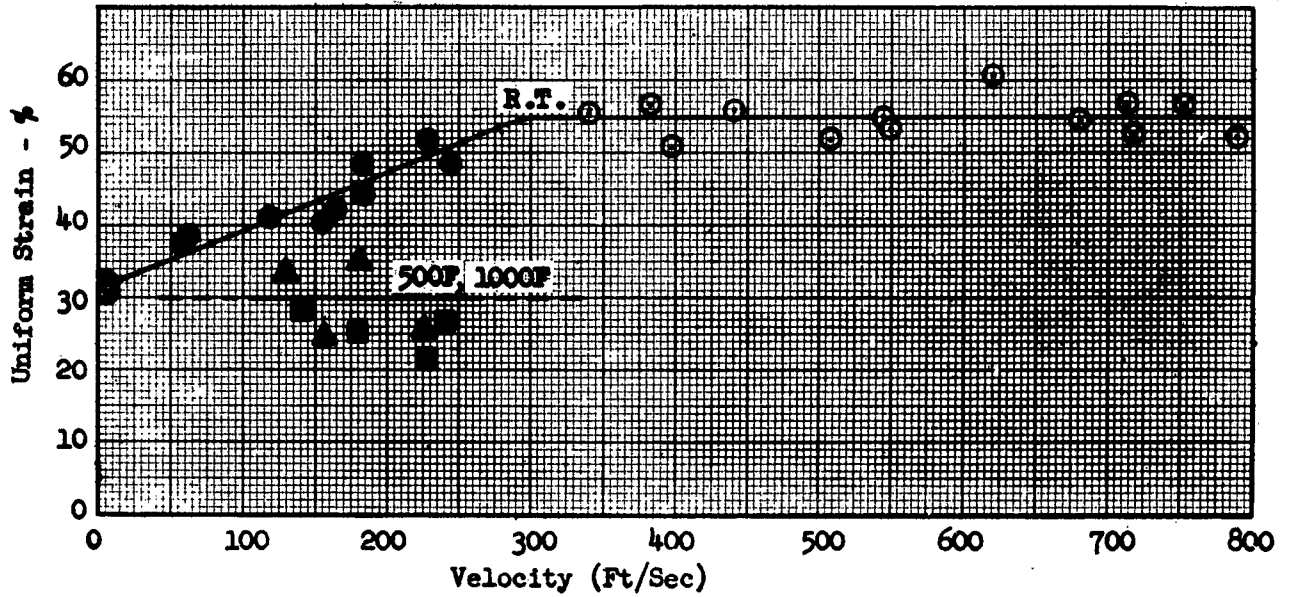
GRAPH 41
EXPLOSIVE FREE BULGE TUBE
AVERAGE STRAIN VS VELOCITY
RENE'41



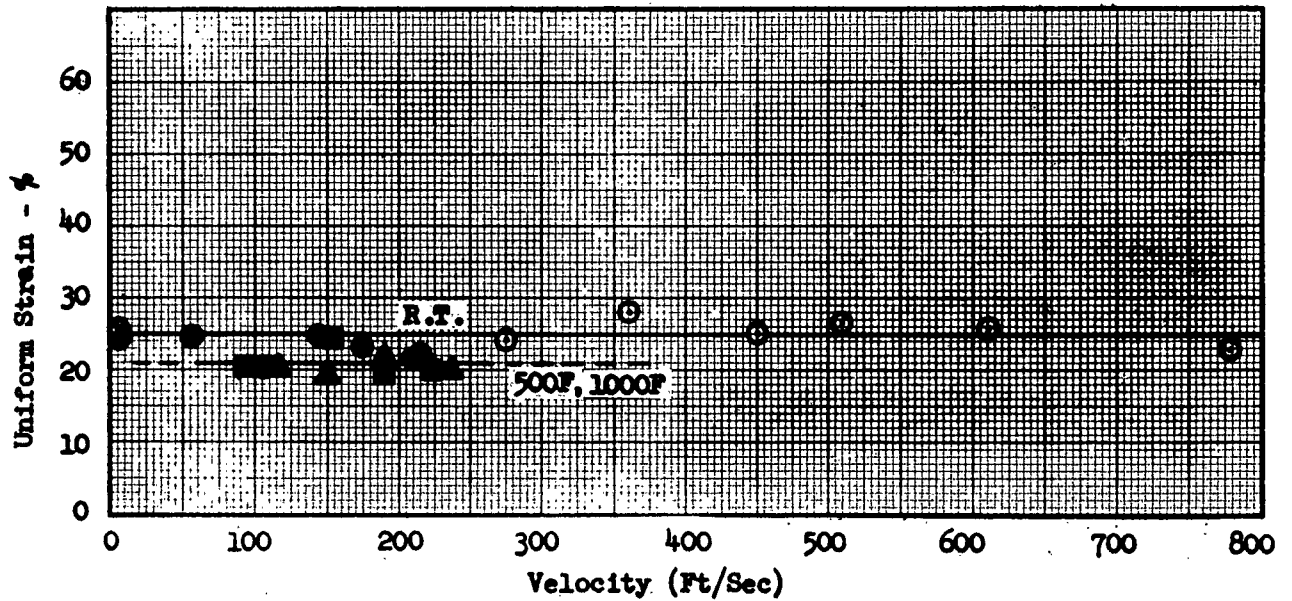
Legend:

- ⊗ - Room temperature - static test
- - Room temperature - low explosive
- ⊙ - Room temperature - high explosive
- ▲ - Intermediate test temperature - low explosive
- - Highest test temperature - low explosive
- Probable curve in region of no tests

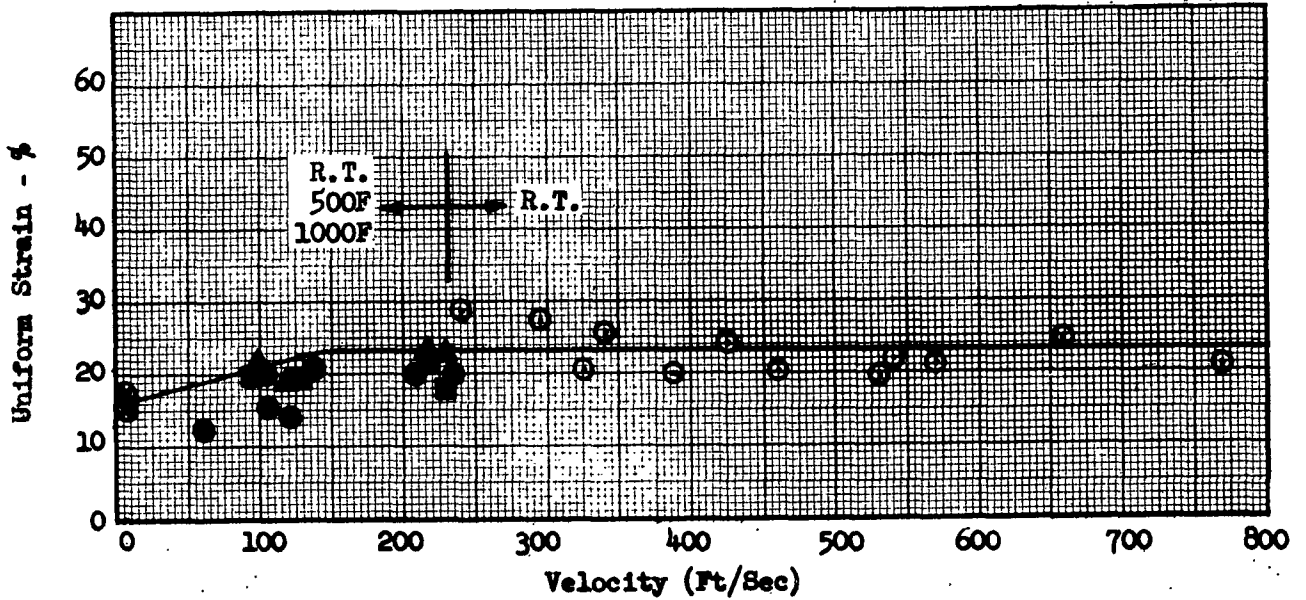
GRAPH 42
EXPLOSIVE FREE BULGE TUBE
AVERAGE STRAIN VS VELOCITY
17-7 PH



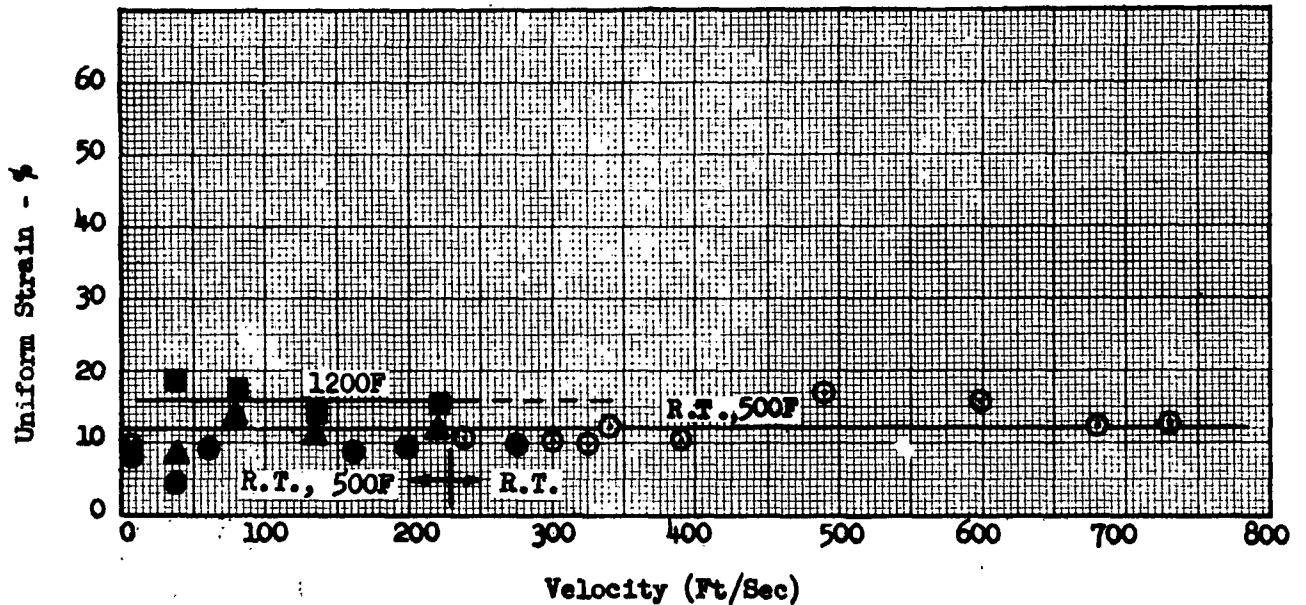
GRAPH 43
EXPLOSIVE FREE BULGE TUBE
AVERAGE STRAIN VS VELOCITY
A-286



GRAPH 44
EXPLOSIVE FREE BULGE TUBE
AVERAGE STRAIN VS VELOCITY
VASCOJET 1000



GRAPH 45
EXPLOSIVE FREE BULGE TUBE
AVERAGE STRAIN VS VELOCITY
TITANIUM (6Al-4V)



APPENDIX C

TABLE 3
DEEP RECESSING - DRAW
STATIC FORMING
(ROOM TEMPERATURE)

Material	Part Number	Gage	Approximate Depth at Fracture (Inches)	$\frac{D_o-D}{D_o}$	ϵ_T	Remarks
17-7 PH	S01203-001	.063	3.00	.200	37.0	(A)
A-286	S02101-004	.020	3.00	.200	37.0	(A)
↓	S02201-001	.063	3.00	.150	42.0	(A)
Vascojet 1000	S03201-001	.063	3.00	.175	39.5	(A)
USS 12 MoV	S04201-001	.063	3.00	.175	39.5	(A)
Ti(6Al-4V)	S05202-001	.063	1.25	.031	9.67	(B)
Ti(13V-11Cr-3Al)	S06202-004	.063	1.60	.063	16.5	(B)
L-605	S07101-004	.020	3.00	.163	40.7	(A) (B)
↓	S07202-001	.063	3.00	.163	40.7	(A)
Rene '41	S08101-004	.020	3.00	.175	39.5	(A) (K)
↓	S08203-001	.063	3.00	.155	41.5	(A)
2024-O Aluminum	S13201-004	.063	3.00	.200	37.0	(A)

TABLE 4
DEEP RECESSING - DRAW
LOW EXPLOSIVE AIR
(ROOM TEMPERATURE)

Material	Part Number	Gage	Die Number	Charge (c)	$\frac{D_o-D}{D_o}$	ϵ_T	Results
17-7 PH	LE01101-003	.020	2	350	.040	22.0	Good
↓	LE01101-004	.020	3	350	.076	49.4	Split
↓	LE01201-003	.063	2	500	.040	22.0	Good
A-286	LE01201-004	.063	3	600	.105	46.5	(D)
↓	LE02101-003	.020	2	350	.042	21.8	Good
↓	LE02101-004	.020	3	350	.062	50.8	Split
↓	LE02201-003	.063	2	500	.038	22.2	Good
Vascojet 1000	LE02201-004	.063	3	700	.105	46.5	Split
↓	LE03101-003	.020	2	350	.001	25.9	↓
↓	LE03201-003	.063	2	500	.045	21.5	↓
USS 12 MoV	LE04101-003	.020	2	250	.000	26.0	↓
↓	LE04201-003	.063	2	500	.050	21.0	↓
Ti(6Al-4V)	LE05101-002	.020	1	225	.000	6.0	↓
↓	LE05201-002	.063	1	225	.000	6.0	Split
Ti(13V-11Cr-3Al)	LE06201-002	.063	1	225	.000	6.0	Good
↓	LE06201-003	.063	2	225	.000	26.0	Split
L-605	LE07101-003	.020	2	250	.051	20.9	Good
↓	LE07101-004	.020	3	400	.105	46.5	Split
↓	LE07201-003	.063	2	550	.047	21.3	Good
↓	LE07201-004	.063	3	650	.132	43.8	(D)
Rene '41	LE08101-003	.020	2	350	.027	23.3	Good
↓	LE08101-004	.020	3	350			Split
↓	LE08201-003	.063	2	500	.048	21.2	Good
↓	LE08201-004	.063	3	650	.060	51.0	(D)

TABLE 4 (Continued)
DEEP RECESSING - DRAW
LOW EXPLOSIVE AIR
(ROOM TEMPERATURE)

Material	Part Number	Gage	Die Number	Charge (c)	$\frac{Do-D}{Do}$	ϵ_T	Results
2024-O Aluminum ↓	LE13101-003	.020	1	225	.024	3.6	Good
	LE13101-004	.020	2	350	.021	23.9	Split
	LE13201-003	.063	1	225			Good
	LE13201-004	.063	2	350			Split

TABLE 5
DEEP RECESSING - DRAW
HIGH EXPLOSIVE - WATER
(ROOM TEMPERATURE)

Material	Part Number	Gage	Die Number	Charge (E)	$\frac{Do-D}{Do}$	ϵ_T	Results
17-7 PH ↓	HEO1102-001	.020	2	7½	.053	20.7	Good
	HEO1102-002	.020	3	7½	.090	48.0	Split
A-286 ↓	HEO1203-001	.063	2	10	.043	21.7	Good
	HEO1203-002	.063	3	20	.111	45.9	Good
Vascojet 1000 ↓	HEO2102-001	.020	2	5	.053	20.7	Good
	HEO2102-002	.020	3	10	.030	54.0	Good
USS 12 MoV ↓	HEO2202-001	.063	2	10	.045	21.5	Good
	HEO2202-002	.063	3	25	.136	43.4	Good
Ti(6Al-4V) ↓	HEO3101-001	.020	2	5	.050	21.0	Good
	HEO3101-002	.020	3	7½	.101	46.9	Split
Ti(13V-11Cr-3Al) ↓	HEO3201-001	.063	2	10	.042	21.8	Good
	HEO3201-002	.063	3	27½	.145	42.5	Good
L-605 ↓	HEO4102-001	.020	2	5	.051	20.9	Good
	HEO4102-002	.020	3	12½	.119	45.1	Split
Rene '41 ↓	HEO4202-001	.063	2	10	.037	22.3	Good
	HEO4202-002	.063	3	25	.025	54.5	Good
↓	HEO5102-001	.020	2	5	.000	26.0	Split
	HEO5102-002	.020	1	2½	.024	3.6	↓
↓	HEO5201-001	.063	2	10	.000	26.0	
	HEO5201-002	.063	1	5	.057	0.3	Split
↓	HEO6102-001	.020	2	5	.000	26.0	
	HEO6102-002	.020	1	2½	.030	3.0	↓
↓	HEO6201-001	.063	2	10	.000	26.0	
	HEO6201-002	.063	1	5	.023	3.7	Split
↓	HEO7101-001	.020	2	5	.050	21.0	Good
	HEO7101-002	.020	3	10	.094	47.6	↓
↓	HEO7201-001	.063	2	10	.041	21.9	
	HEO7201-002	.063	3	30	.131	43.9	↓
↓	HEO8103-001	.020	2	5	.048	21.2	
	HEO8103-002	.020	3	10	.115	45.5	↓
↓	HEO8203-001	.063	2	10			
	HEO8203-002	.063	3	27½	.125	44.5	Good

TABLE 5 (Continued)
DEEP RECESSING - DRAW
HIGH EXPLOSIVE - WATER
(ROOM TEMPERATURE)

Material	Part Number	Gage	Die Number	Charge (c)	$\frac{Do-D}{Do}$	ϵ_T	Results
2024-0 Aluminum	HE13102-001	.020	2	$2\frac{1}{2}$	.044	21.6	Good
	HE13102-002	.020	3	$7\frac{1}{2}$	.103	46.7	Split
	HE13201-001	.063	2	$7\frac{1}{2}$	.042	21.8	Good
	HE13201-002	.063	3	20	.110	46.0	Split

TABLE 6
DEEP RECESSING - DRAW
ELECTROMAGNETIC
(ROOM TEMPERATURE)

Material	Part Number	Gage	Energy Kilo-joules	Measured Elong. in 6 Inches	ϵ_T	Results
A286	EMO2101-001	.020	18.4	8 1/16	34.4	Crack
USS 12 MoV	EMO4101-001	.020	18.4	7 3/4	29.2	Crack
Ti(6Al-4V)	EMO5101-001	.020	18.4	7	16.7	Crack
L-605	EMO7101-001	.020	18.4	7 5/16	21.9	Good
2024-0 Aluminum	EM13201-001	.063	12.8	8 1/8	35.4	Crack

TABLE 7
DEEP RECESSING - NO DRAW
STATIC FORMING
(ROOM TEMPERATURE)

Material	Part Number	Gage	Approximate Depth at Fracture (Inches)	Draw %	ϵ_T
17-7 PH	S01101-003	.020	1.95	0	23.9
A-286	S02101-003	.020	1.95	0	23.9
Vascojet 1000	S03113-003	.020	1.50	0	14.4
USS 12 MoV	S04101-003	.020	1.95	0	23.9
Ti(6Al-4V)	S05101-002	.020	0.90	0	5.2
Ti(13V-11Cr-3Al)	S06202-003	.063	1.40	0	12.3
L-605	S07101-003	.020	1.85	0	22.2
Rene '41	S08101-003	.020	1.95	0	23.9
2024-0 Aluminum	S13201-003	.063	1.65	0	17.7

TABLE 8
DEEP RECESSING - NO DRAW
STATIC FORMING
(ELEVATED TEMPERATURE)

Material	Part Number	Gage	Approx. Depth at Fracture (Inches)	Draw %	ϵ_T	Temp. °F
17-7 PH ↓ A-286 ↓ Vascojet 1000 ↓ USS 12 MoV ↓ Ti (6Al-4V) ↓ Ti (13V-11Cr-3Al) ↓ L-605 ↓ Rene '41 ↓ 2024-0 Aluminum ↓	S01101-004	.020	1.40	0	12.3	1000
	S01101-005	.020	1.30		10.8	400
	S01201-005	.063	1.40		12.3	650
	S02101-005	.020	1.50		14.4	1000
	S02101-006	.020	1.40		12.3	600
	S03101-004	.020	1.50		14.4	1000
	S03201-002	.063	1.50		14.4	1100
	S03201-003	.063	0.90		5.2	650
	S03201-004	.063	0.95		5.7	400
	S04101-004	.020	0.90		5.2	400
	S04101-005	.020	1.35		11.2	1000
	S04201-002	.063	1.20		8.9	400
	S04201-003	.063	1.25		9.7	600
	S04201-004	.063	1.95		23.9	1100
	S05101-003	.020	1.75		19.8	1200
	S05201-002	.063	1.80		21.0	1200
	S05201-003	.063	0.90		5.2	400
	S06101-001	.020	1.75		19.8	1200
	S06201-005	.063	1.30		10.8	400
	S07201-002	.063	1.90		23.5	1000
	S07201-003	.063	1.95		23.9	750
	S08101-005	.020	1.95		23.9	500
	S08101-006	.020	1.75		19.8	1000
	S13201-005	.063	1.40		12.3	200
	S13201-006	.063	1.75		19.8	400
	S13201-007	.063	1.75		19.8	500
	S13201-008	.063	1.20		8.9	300
	S13201-009	.063	1.20	0	8.9	200

TABLE 9
DEEP RECESSING - NO DRAW
LOW EXPLOSIVE AIR
(ROOM TEMPERATURE)

Material	Part Number	Gage	Die No.	Charge (c)	Draw %	ϵ_T	Results
17-7 PH ↓ A-286 ↓ Vascojet 1000 ↓	LE01101-001	.020	1	225	0	6.0	Good
	LE01101-002	.020	2	300		26.0	Split
	LE01201-001	.063	1	300		6.0	Good
	LE01201-002	.063	2	400		26.0	Split
	LE02101-001	.020	1	225		6.0	Good
	LE02101-002	.020	2	300		26.0	Split
	LE02201-001	.063	1	300		6.0	Good
	LE02201-002	.063	2	400		26.0	Split
	LE03101-001	.020	1	225		6.0	Good
	LE03101-002	.020	2	250		26.0	Split

TABLE 9 (Continued)
DEEP RECESSING - NO DRAW
LOW EXPLOSIVE AIR
(ROOM TEMPERATURE)

Material	Part Number	Gage	Die No.	Charge (c)	Draw %	ϵ_T	Results
Vascojet 1000	LE03201-001	.063	1	250	0	6.0	Good
↓	LE03201-002	.063	2	250	↓	26.0	Split
USS 12 MoV	LE04101-001	.020	1	225	↓	6.0	Good
↓	LE04101-002	.020	2	225	↓	26.0	Split
↓	LE04201-001	.063	1	250	↓	6.0	Good
↓	LE04201-002	.063	2	250	↓	26.0	Split
Ti(6Al-4V)	LE05101-001	.020	1	225	↓	6.0	Split
↓	LE05201-001	.063	1	225	↓	6.0	Split
Ti(13V-11Cr-3Al)	LE06101-001	.020	1	225	↓	6.0	Split
↓	LE06201-001	.063	1	225	↓	6.0	Split
L-605	LE07101-001	.020	1	225	↓	6.0	Good
↓	LE07101-002	.020	2	250	↓	26.0	Split
↓	LE07201-001	.063	1	300	↓	6.0	Good
↓	LE07201-002	.063	2	400	↓	26.0	Split
Rene '41	LE08101-001	.020	1	225	↓	6.0	Good
↓	LE08101-002	.020	2	250	↓	26.0	Split
↓	LE08201-001	.063	1	300	↓	6.0	Good
↓	LE08201-002	.063	2	400	↓	26.0	Split
2024-O Aluminum	LE13101-001	.020	1	100	↓	6.0	Good
↓	LE13101-002	.020	2	225	↓	26.0	Split
↓	LE13201-001	.063	1	200	↓	6.0	Good
↓	LE13201-002	.063	2	250	↓	26.0	Split

TABLE 10
DEEP RECESSING - NO DRAW
LOW EXPLOSIVE AIR
(ELEVATED TEMPERATURE)

Material	Part No.	Gage	Die No.	Charge (c)	Draw %	ϵ_T	Temp. °F	Results
17-7 Ph	LE01101-005	.020	2	200	0	26.0	1000	Split
↓	LE01201-005	.063	2	400	↓	26.0	↓	Good
↓	LE01201-006	.063	3	500	↓	57.0	↓	Split
A-286	LE02101-005	.020	2	200	↓	26.0	↓	Split
↓	LE02201-005	.063	2	400	↓	26.0	↓	Good
↓	LE02201-006	.063	3	500	↓	57.0	↓	Split
Vascojet 1000	LE03101-004	.020	2	200	↓	26.0	↓	Split
↓	LE03201-004	.063	2	400	↓	26.0	↓	Split
USS 12 MoV	LE04101-004	.020	2	200	↓	26.0	↓	Split
↓	LE04201-004	.063	2	400	↓	26.0	1000	Split
Ti(6Al-4V)	LE05101-003	.020	1	200	↓	6.0	1200	Good
↓	LE05101-004	.020	2	200	↓	26.0	↓	Split
↓	LE05201-003	.063	1	400	↓	6.0	↓	Good
↓	LE05201-004	.063	2	400	↓	26.0	↓	Split

TABLE 10 (Continued)
DEEP RECESSING - NO DRAW
(LOW EXPLOSIVE AIR)
ELEVATED TEMPERATURE

Material	Part No.	Gage	Die No.	Charge (C)	Draw %	ϵ_T	Temp. °F	Results
Ti(13V-11Cr-3Al)	LE06201-004	.063	1	200	0	6.0	1200	Good
↓	LE06201-005	.063	2	300	↓	26.0	1200	Split
L-605	LE07101-005	.020	2	200	↓	26.0	500	Good
↓	LE07101-006	.020	3	300	↓	6.0	↓	Split
↓	LE07201-005	.063	2	400	↓	26.0	↓	Split
Rene '41	LE08101-005	.020	2	200	↓	26.0	↓	Good
↓	LE08101-006	.020	3	300	↓	57.0	↓	Split
↓	LE08201-005	.063	2	400	↓	26.0	500	Split
2024-0 Aluminum	LE13101-005	.020	2	100	↓	26.0	200	Split
↓	LE13201-005	.063	2	200	0	26.0	200	Split

TABLE 11
DEEP RECESSING - NO DRAW
HIGH EXPLOSIVE - WATER
(ROOM TEMPERATURE)

Material	Part No.	Gage	Die No.	Charge (E)	$\frac{Do-D}{Do}$	ϵ_T	Results	Remarks
17-7 Ph	HE01102-003	.020	2	7½	.025	23.5	Good	(F)
↓	HE01102-004	.020	3	15	.001	56.9	Split	
↓	HE01203-003	.063	2	15	.025	23.5	Good	
A-286	HE01203-004	.063	3	20	.113	45.7	↓	
↓	HE02102-003	.020	2	7½	.014	24.6	Good	
↓	HE02102-004	.020	3	15	.113	45.7	Split	
Vascojet 1000	HE02202-003	.063	2	15	.023	23.7	Good	
↓	HE03101-003	.020	2	7½	.046	21.4	Good	
↓	HE03101-004	.020	3	10	.090	48.0	Split	
USS 12 MoV	HE03201-003	.063	2	15	.040	22.0	Good	
↓	HE04102-003	.020	2	7½	.053	20.7	Good	
↓	HE04102-004	.020	3	15	.128	44.2	Split	
Ti(6Al-4V)	HE04201-003	.063	2	15	.041	21.9	Good	
↓	HE05102-003	.020	2	5	.000	26.0	Split	
↓	HE05102-004	.020	1	2½	↓	6.0	Split	
↓	HE05201-003	.063	2	15	↓	26.0	Split	
↓	HE05201-004	.063	1	5	↓	6.0	Split	
Ti(13V-11Cr-3Al)	HE06102-003	.020	2	5	↓	26.0	Split	
↓	HE06102-004	.020	1	5	↓	6.0	Split	
↓	HE06201-003	.063	2	15	↓	26.0	Split	
↓	HE06201-004	.063	1	5	.000	6.0	Split	
L-605	HE07101-003	.020	2	7½	.031	22.9	Good	
↓	HE07101-004	.020	3	15	.054	51.6	Split	
↓	HE07201-003	.063	2	15	.028	23.2	Good	

TABLE 11 (Continued)
DEEP RECESSING - NO DRAW
HIGH EXPLOSIVE - WATER
(ROOM TEMPERATURE)

Material	Part No.	Gage	Die No.	Charge (E)	$\frac{Do-D}{Do}$	ϵ_T	Results	Remarks
Rene '41 ↓ 2024-O Aluminum ↓	HE08103-003	.020	2	5	.036	22.4	Good	
	HE08103-004	.020	3	15	.077	49.3	Split	
	HE08203-003	.063	2	15	.041	21.9	Good	
	HE13101-003	.020	1	2½	.000	6.0	Good	
	HE13101-004	.020	2	5	.006	25.4	Split	
	HE13201-003	.063	3	10	.027	54.3	Split	

TABLE 12
DEEP RECESSING - NO DRAW
ELECTRO-HYDRAULIC
(ROOM TEMPERATURE)

Material	Part No.	Gage	Die No.	Energy Kilo-joules	Draw %	ϵ_T	Results	Remarks
17-7 PH ↓ A-286 ↓ Vascojet 1000 ↓ USS 12 MoV ↓ Ti(6Al-4V) ↓ Ti(13V-11Cr-3Al) ↓ L-605 ↓ Rene '41 ↓ 2024-O Aluminum ↓	EH01101-001	.020	1	7.2	0	6.0	Good	(G)
	EH01101-002	.020	2	11.2		26.0	Split	(G)
	EH01201-001	.063	2	16.1		26.0	(D)	(G)
	EH02101-001	.020	1	16.1		6.0	Good	(G)
	EH02101-002	.020	2	19.9		26.0	Split	(G)
	EH03101-001	.020	1	11.2		6.0	Good	(G)
	EH03101-002	.020	2	14.2		26.0	Split	(G)
	EH04101-001	.020	1	7.2		6.0	Good	(G)
	EH04101-002	.020	2	19.9		26.0	Split	(G)
	EH05101-001	.020	1	5.0		6.0	Split	(G)
	EH05101-002	.020	2	12.4		26.0	Split	(G)
	EH06201-001	.063	1	14.4		6.0	Split	(D) (G)
	EH07101-001	.020	1	11.2		6.0	Good	(G)
	EH07101-002	.020	2	19.9		26.0	Split	(G)
	EH08101-001	.020	1	11.2		6.0	Good	(G)
	EH08101-002	.020	2	39.8		26.0	Split	(G) (J)
	EH13101-001	.020	1	1.8		6.0	Good	(G)
	EH13101-002	.020	2	7.2		26.0	Split	(G)
	EH13201-001	.063	2	11.2		26.0	Good	(G)

TABLE 13
SHALLOW RECESSING - NO DRAW
STATIC FORMING
(ROOM TEMPERATURE)

Material	Part No.	Gage	Die No.	Draw %	ϵ_T	Results
17-7 Ph	S01101-001	.020	2	0	15.0	Good
↓	S01101-002	.020	3	↓	30.0	Split
A-286	S02101-001	.020	1	↓	5.0	Good
↓	S02101-002	.020	2	↓	15.0	Split
Vascojet 1000	S03113-001	.020	1	↓	5.0	Good
↓	S03113-002	.020	2	↓	15.0	Split
USS 12 MoV	S04101-001	.020	1	↓	5.0	Good
↓	S04101-002	.020	2	↓	15.0	Split
Ti(6Al-4V)	S05101-001	.020	1	↓	5.0	Split
Ti(13V-11Cr-3Al)	S06201-001	.063	1	↓	5.0	Good
↓	S06201-002	.063	2	↓	15.0	Split
L-605	S07101-001	.020	2	↓	15.0	Good
↓	S07101-002	.020	3	↓	30.0	Split
Rene '41	S08101-001	.020	1	↓	5.0	Good
↓	S08101-002	.020	2	↓	15.0	Split
2024-0 Aluminum	S13101-001	.020	1	↓	5.0	Good
↓	S13101-002	.020	2	0	15.0	Split

TABLE 14
SHALLOW RECESSING - NO DRAW
LOW EXPLOSIVE AIR
(ROOM TEMPERATURE)

Material	Part No.	Gage	Die No.	Charge (c)	Draw %	ϵ_T	Results
17-7 Ph	LE01101-006	.020	1	225	0	5.0	Good
↓	LE01101-007	.020	2	225	↓	15.0	Split
A-286	LE01201-007	.063	2	400	↓	15.0	(D)
↓	LE02101-006	.020	1	225	↓	5.0	Good
↓	LE02101-007	.020	2	300	↓	15.0	Split
Vascojet 1000	LE02201-007	.063	2	500	↓	15.0	(D)
↓	LE03101-005	.020	1	300	↓	5.0	Good
↓	LE03101-006	.020	2	300	↓	15.0	Split
↓	LE03201-005	.063	1	250	↓	5.0	Good
↓	LE03201-006	.063	2	250	↓	15.0	Split
USS 12 MoV	LE04101-005	.020	1	300	↓	5.0	Good
↓	LE04101-006	.020	2	225	↓	15.0	Split
↓	LE04201-005	.063	1	350	↓	5.0	Good
↓	LE04201-006	.063	2	225	↓	15.0	Split
Ti(6Al-4V)	LE05101-005	.020	1	225	↓	5.0	Split
↓	LE05201-005	.063	1	250	↓	5.0	Split
Ti(13V-11Cr-3Al)	LE06101-002	.020	1	200	↓	5.0	Split
↓	LE06201-006	.063	1	225	↓	5.0	Split
L-605	LE07101-007	.020	1	225	↓	5.0	Good
↓	LE07101-008	.020	2	300	↓	15.0	Split
↓	LE07201-006	.063	2	500	↓	15.0	(D)

TABLE 14 (Continued)
SHALLOW RECESSING - NO DRAW
LOW EXPLOSIVE AIR
(ROOM TEMPERATURE)

Material	Part No.	Gage	Die No.	Charge (c)	Draw %	ϵ_T	Results
Rene '41 ↓ 2024 -O Aluminum ↓	LE08101-007	.020	1	225	0	5.0	Good
	LE08101-008	.020	2	300	↓	15.0	Split
	LE08201-006	.063	2	500	↓	15.0	(D)
	LE13101-006	.020	1	225	↓	5.0	Good
	LE13101-007	.020	2	225	↓	15.0	Split
	LE13201-006	.063	1	225	↓	5.0	Good
	LE13201-007	.063	2	225	0	15.0	Split

TABLE 15
SHALLOW RECESSING - NO DRAW
LOW EXPLOSIVE AIR
(ELEVATED TEMPERATURE)

Material	Part No.	Gage	Die No.	Charge (c)	Draw %	ϵ_T	Temp. °F	Results
17-7 Ph	LE01101-008	.020	2	200	0	15.0	1000	Split
	LE01201-008	.063	2	400	↓	↓	↓	Split
A-286	LE02101-008	.020	2	200	↓	↓	↓	Split
	LE02201-008	.063	2	400	↓	↓	↓	Split
Vascojet 1000	LE03101-007	.020	2	200	↓	↓	↓	Split
	LE03201-007	.063	2	400	↓	↓	↓	Split
USS 12 MoV	LE04101-007	.020	2	200	↓	↓	↓	Split
	LE04201-007	.063	2	400	↓	15.0	1000	Split
Ti(6Al-4V)	LE05101-006	.020	1	200	↓	5.0	1200	Good
	LE05101-007	.020	2	200	↓	15.0	↓	Split
	LE05201-006	.063	1	400	↓	5.0	↓	Good
	LE05201-007	.063	2	400	↓	15.0	↓	Split
Ti(13V-11Cr-3Al)	LE06201-007	.063	1	400	↓	5.0	↓	Good
	LE06201-008	.063	2	400	↓	15.0	1200	Split
L-605	LE07101-009	.020	2	200	↓	↓	500	Split
	LE07201-007	.063	2	500	↓	↓	↓	(D)
Rene '41	LE08101-009	.020	2	200	↓	↓	↓	Split
	LE08201-007	.063	2	500	↓	↓	500	(D)
2024 -O Aluminum	LE13101-006	.020	2	200	↓	↓	200	Split
	LE13201-006	.063	2	300	0	15.0	200	Split

TABLE 16
SHALLOW RECESSING - NO DRAW
HIGH EXPLOSIVE - WATER
(ROOM TEMPERATURE)

Material	Part No.	Gage	Die No.	Charge (E)	$\frac{Do-D}{Do}$	ϵT	Results
17-7 Ph	HE01102-005	.020	2	10	.000	15.0	Good
	HE01102-006	.020	3	10	.019	28.0	Split
↓	HE01203-005	.063	2	10	.012	14.3	Good
	HE01203-006	.063	3	20	.012	28.7	Split
A-286	HE02102-005	.020	2	10	.000	15.5	Good
	HE02102-006	.020	3	10	.000	29.9	Split
↓	HE02202-004	.063	2	10	.005	15.0	Good
	HE02202-005	.063	3	20	.012	28.7	Split
Vascojet 1000	HE03101-005	.020	1	5	.000	5.3	Good
	HE03101-006	.020	2	10	.000	15.5	Split
↓	HE03201-004	.063	1	10	.000	5.3	Good
	HE03201-005	.063	2	20	.007	14.8	Split
USS 12 MoV	HE04102-005	.020	1	5	.000	5.3	Good
	HE04102-006	.020	2	10	.001	15.4	Split
↓	HE04201-004	.063	1	10	.000	5.3	Good
	HE04201-005	.063	2	20	.006	14.9	Split
Ti(6Al-4V)	HE05102-005	.020	1	5	.003	5.0	Split
	HE05201-005	.063	1	5	.002	5.0	Split
↓	HE06102-005	.020	1	2 $\frac{1}{2}$	.000	5.3	Split
	HE06201-005	.063	1	5	.002	5.1	Split
Ti(13V-11Cr-3Al)	HE07101-005	.020	2	10	.008	14.7	Good
	HE07101-006	.020	3	10	.024	27.5	Split
↓	HE07201-004	.063	2	20	.007	14.8	Good
	HE07201-005	.063	3	20	.034	26.5	Split
L-605	HE08103-005	.020	2	10	.004	15.1	Good
	HE08103-006	.020	3	10	.004	29.5	Split
↓	HE08203-004	.063	2	20	.010	14.5	Good
	HE08203-005	.063	3	20	.023	27.6	Split
Rene '41	HE13101-005	.020	1	2 $\frac{1}{2}$	.000	5.3	Good
	HE13101-006	.020	2	7 $\frac{1}{2}$	.000	15.5	Split
↓	HE13201-005	.063	1	5	.000	5.3	Good
	HE13201-006	.063	2	10	.000	15.5	Split
2024-O Aluminum							

TABLE 17
SHALLOW RECESSING - NO DRAW
ELECTRO-HYDRAULIC
(ROOM TEMPERATURE)

Material	Part No.	Gage	Die No.	Energy Kilo-joules	Draw %	E T	Results	Remarks
17-7 Ph	EH01101-003	.020	2	32.2	0	15.0	Good	(G) (J)
↓	EH01101-004	.020	3	13.8	↓	30.0	Split	(H)
A-286	EH02101-003	.020	1	10.9	↓	5.0	Good	(H)
↓	EH02101-004	.020	2	16.1	↓	15.0	Split	(G)
Vascojet 1000	EH03101-003	.020	1	6.1	↓	5.0	Good	(H)
↓	EH03101-004	.020	2	11.2	↓	15.0	Split	(G)
USS 12 MoV	EH04101-003	.020	1	4.3	↓	5.0	Good	(H)
↓	EH04101-004	.020	2	16.1	↓	15.0	Split	(G)
Ti(6Al-4V)	EH05101-003	.020	1	2.7	↓	5.0	Split	(H)
↓	EH05101-004	.020	2	11.2	↓	15.0	Split	(G)
L-605	EH07101-003	.020	1	6.1	↓	5.0	Good	(H)
↓	EH07101-004	.020	2	16.1	↓	15.0	Split	(G)
Rene '41	EH08101-003	.020	2	13.8	↓	15.0	Good	(H)
↓	EH08101-004	.020	3	13.8	↓	30.0	Split	(H)
2024-O Aluminum	EH13101-003	.020	1	1.5	↓	5.0	Good	(H)
↓	EH13101-004	.020	2	4.3	0	15.0	Split	(H)

NOTES FOR TABLES 3 THRU 17.

- (A) - Forming was stopped at a depth of 3 inches.
- (B) - Part had puckers on one side.
- (C) - Grains of bullseye gunpowder.
- (D) - Part not formed down completely to die contour.
- (E) - Grams of RDX.
- (F) - Unable to prevent drawing.
- (G) - Seven capacitors.
- (H) - Six capacitors.
- (J) - Two shots.
- (K) - Pulled off to one side.

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