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EVALUATION TEST METHODS FOR BERYLLIUM

MATERIALS ADVISORY BOARD

National Academy of Sciences—
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Report of the

TEST METHODS SUBCOMMITTEE

COMMITTEE ON BERYLLIUM METALLURGY

EVALUATION TEST METHODS

FOR

BERYLLIUM

Prepared By The

MATERIALS ADVISORY BOARD

Division of Engineering

as a service of

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SECTION 1

Introduction

1.1 General

This report was prepared by the Test Methods Subcommittee of the Committee on Beryllium Metallurgy to establish standardized methods and procedures for conducting mechanical property tests on beryllium. Such methods are required in view of the characteristics of beryllium, which make conventional test procedures difficult to apply. The data presented are restricted to information which is well established and accepted, but the report also identifies areas of testing controversy and highlights current technical needs in the testing area.

The report attempts to document recommended methods, based on a review of the procedures used in a number of organizations. For various reasons, many will want to deviate from these methods. To permit reliable inter-comparisons between laboratories, standardized methods are needed; and it is hoped that for this reason these methods will be adopted.

1.2 Application of Beryllium

As is now well known, beryllium has a number of very attractive properties for structural applications. These include a high stiffness to density ratio, in combination with low density, a good strength to density ratio, useful mechanical properties to moderately high temperatures, and high heat capacity. The material thus offers considerable weight benefits, when compared with more conventional materials, for structural applications where stiffness is important, for structures which are lightly loaded and carrying primarily compressive loads, for structures operating up to 1200°F, and for structures exposed to rapidly changing heating conditions.

Despite these many advantages, beryllium has not seen extensive structural use for two principal reasons: high cost, and extreme plastic anisotropy. The latter results in the lack of three dimensional ductility in sheet, extrusions, and forgings when these products have highly preferred textures. Neither of these problems has been completely solved, nor is there promise of any immediate solution. Nevertheless, interest in beryllium for structural applications is increasing rapidly. This results partly from the large number of potential space applications, where the cost can be completely justified by the weight saved, and as the result of continuing improvements in the material manufacturing processes with more compatible designs. The latter has resulted in higher strength levels, but more importantly, in a more uniform and reliable product. Mechanical properties are more consistent and reproducible, and there is no danger that some sheets or some areas in a sheet will exhibit zero tensile ductility.

1.3 Beryllium Characteristics

The low ductility of beryllium can lead to premature and catastrophic failures if it is not recognized and accommodated in the design. The inability of beryllium to accommodate large amounts of plastic strain is due in part to its crystal structure, in part to the preferred orientation that is developed in the fabrication of rolled sheet, extrusions and forgings, and in part to the presence of impurities. Another very important factor contributing to premature failure is surface condition -- surface defects and irregularities which may have little effect on more ductile materials are known to exert a pronounced influence on beryllium.

The brittle behavior of polycrystalline beryllium can be directly attributed to the small number of deformation mechanisms that it exhibits at low temperatures. For general deformation of a randomly oriented polycrystalline aggregate, it is generally agreed that each grain must exhibit at least five independent modes of deformation to permit accommodation of strain from grain to grain. Slip on the basal planes can occur in three directions, but only two of these are independent. The same holds true for the $(10\bar{1}0)$ prism planes -- there are only two independent deformation modes. Twinning would provide a fifth mode, but the amount of deformation attainable by twinning is small, and moreover, twinning leads to the formation of cracks. Extensive slip on the basal planes eventually leads to the formation of cleavage cracks, but basal slip in conjunction with prism slip is necessary if three dimensional ductility is to be achieved. The real need is for an additional slip mode, such as pyramidal slip. Although pyramidal slip has recently been observed at room temperature in single crystals, its role in the ductility of polycrystalline material remains to be assessed.

When preferred orientations are present, significant amounts of deformation can be achieved on a particular set of planes, usually the $(10\bar{1}0)$ prism planes. However, in such cases, strain is accommodated in only one or two directions. With commercial sheet material in particular, a preferred orientation with the basal planes parallel to the plane of the sheet is readily formed and zero or near zero ductility in the thickness direction results. Such a material will show good elongation in a standard tensile test but in a more complex stress state where thickness direction flow is needed to satisfy constancy of volume, the material exhibits relatively brittle behavior. Furthermore, the thickness direction strength is relatively low, so that limiting stress values in this direction are generally reached before the full axial strength can be developed. Such is the case, for example, with wide sheets in tension or bending. Contrary to the behavior of most structural materials, therefore, the response of beryllium is dependent not only on the applied stresses, but on the stress state and on the previous deformation history. Consequently, local stress raisers, such as poor surface finish, notches or cracks at corners and edges, rivet and bolt holes, etc., became very important and may control the strength of the component.

1.4 Status and Application of Mechanical Property Tests

In view of these characteristics of beryllium, the designer and fabricator find the standard mechanical property test data insufficient, since these do not completely describe material behavior. Furthermore, the test results vary depending on how the tests are conducted, how the specimens are finished, etc. Since a completely satisfactory mechanical property test is not available for beryllium, recourse is made to either the standard tensile test such as is used for other metallic materials, or to other simple tests which attempt to produce more complex stress states. Typical of the latter is the bend test by a three- or four-point loading system, in which a known bending moment is imposed on a strip cut from beryllium sheet. Data from both types of tests must be used with caution, however, when designing structural components in beryllium.

In general, mechanical property tests other than the standard tensile test produce only comparative data, unless the application happens to be identical with the test. The resulting data are, therefore, of most value for checking the effects of changes in purity, alloying, process variables, etc., during material development. Although the data may be useful in establishing material acceptance specifications, they cannot be used for structural design. For instance, the bend test is sometimes used to determine stress-strain relationships for the material and also to deduce elongation in the thickness direction. It must be understood, however, that data obtained in such a test are peculiar to the particular stress system of the test, and cannot necessarily be extrapolated to other conditions.

The standard tensile test, on the other hand, will produce quantitative data that can be used for design under certain circumstances. Yield strength and tensile strength values and the stress-strain data are directly applicable, using standard design practices, to any structure where the material is in simple uniaxial tension, provided only that the surface finish in the application is at least as good as that of the test coupons.

1.5 MAB Action

It was considered appropriate by the MAB that some attempt be made to establish testing standards for beryllium which would recognize the peculiarities of the material, and which would be generally acceptable. Such action would provide useful guidance to those entering the field of beryllium design, fabrication and use. It would also make test data from many sources directly comparable, and would provide the basis for standardizing improved methods as they become available.

To accomplish this end, a subcommittee of the Committee on Beryllium Metallurgy was formed. A list of subcommittee members is included in the front of the report. The necessary information was obtained either directly from subcommittee members, from presentations by invited guests, or by correspondence with active groups.

It was determined during the first meeting of the subcommittee that virtually no experience exists in the performance of many mechanical property tests with beryllium. In most cases it is not known whether the standard types of tests are suitable for beryllium, nor in most cases, have alternative tests specifically for beryllium been devised. The tensile test is an exception since considerable experience exists, although opinions on the usefulness of conventional tensile test procedures, and views on the manner in which such tests should be conducted, vary widely. One of the consequences of the recognition of the limitations of the tensile test has been interest in the bend test; but again, opinions on how this test should be conducted, and on its value, vary widely.

Despite this situation there is, at this time, considerable agreement on many general aspects of beryllium testing technique, such as the measures that must be taken with respect to specimen preparation, certain aspects of specimen geometry, requirements with respect to eccentricity of loading, etc. It was, therefore, decided by the subcommittee that it could most usefully attempt: a) to agree upon common aspects of beryllium testing technique, b) to "standardize" only the most basic tests where some measure of acceptance and agreement has been reached, and c) to present information explaining, for the designer, fabricator, and quality inspector, the unusual characteristics of beryllium and the usefulness and limitations of the various tests.

This report is organized in accordance with this approach and a brief discussion of the characteristics of beryllium has been presented in this introduction. Section 2 presents recommended methods of preparing flat sheet and bar-type specimens. The information is presented in specification form, permitting direct reference, since this was believed to be of most value to potential users. Some aspects of the tests were defined arbitrarily. No attempt is made to justify the methods or to present and compare alternatives, although the selections were made and reviewed by individuals who have had considerable experience with beryllium and with testing procedures in general.

Section 3 gives some general testing techniques and practices which have been found necessary with beryllium while Section 4 gives details of specific tests. The latter are again in specification form, for the reasons given above. Section 4 also discusses the use and limitations of each test.

SECTION 2

Specimen Preparation

2.1 General

When beryllium is machined, particularly wrought products, surface damage is introduced in the form of twins, cracks and residual stresses. Experience shows that this damage has a detrimental effect on mechanical properties and can result in considerable variability of properties. However, careful machining, combined with removal of damaged surface layers by etching, can result in test specimens which give consistent results. Accordingly, if test data from various sources are to be compared or used interchangeably, consistency in specimen preparation is essential. This section, therefore, describes general procedures recommended for use in the preparation of any type of specimen from flat sheet or round bar.

Details of machining practice, such as tool shapes and speeds, and details of the procedures to be followed with respect to toxicity of the material, will not be given here since they do not affect the specimen performance. An exception is the statement of the need to use sharp, carbide tipped tools. Other details can be obtained from the beryllium suppliers. Appendix A, however, does summarize some safety precautions that should be followed in handling beryllium.

2.2 Preparation of Sheet-Type Specimens

2.2.1 Cut blanks from sheet with band saw, abrasive cut-off wheel, electrospark machining, or chemical milling. Deburr and round off rough edges by sanding with 240 to 400 grit emery paper. Electrospark machining shall be used only for rough cutting, since it has been found to cause machining damage.

2.2.2 Where necessary, parallel the edges of the specimens using a milling machine, Tensile-Kut machine, or surface grinder. Specimens may be stacked to a thickness not to exceed 1/4 in. for these operations. Final cuts for paralleling should be in the sequence 0.010", 0.005", 0.003", 0.002".

If pin-loaded or pin-located specimens are to be used, holes shall be drilled and reamed at this time. Specimens need not be fixtured individually for drilling, but precautions should be taken to prevent breakout at the exit side of the hole.

2.2.3 Cut the reduced section on a milling machine, Tensile-Kut machine, or router. Specimens should be stacked to a depth of 1/4 in. or less.

The finishing sequence after 0.015" cuts should be 0.010", 0.005", 0.002", 0.002", 0.001". Deeper cuts are not recommended, but if made, should be followed by the sequence given above.

2.2.4 Edges of the gage section shall be deburred and sanded with 240-400 grit paper. The direction of sanding should be parallel to the loading axis.

2.2.5 Etch the specimens in one of the following solutions:

2.2.5.1 20% nitric acid by volume
1% sulfuric or hydrofluoric acid by volume
Balance - deionized water
Temperature - 80 to 90°F

2.2.5.2 50 g. chromic oxide*
25 ml H_2SO_4
450 ml orthophosphoric acid
Temperature - 100 to 212°F

At least 0.002", but no more than 0.004", should be removed from each machined surface of the specimen. Ends should be masked before etching. The etchant should be circulated. After removal from the etching bath, the specimen should be rinsed in warm deionized water and immediately dried with acetone or alcohol.

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* [illegible] chromic oxide and orthophosphoric acid at 250°F. For safety, cool to 200°F before adding H_2SO_4. For use, the solution may be maintained at 212°F by a double boiler arrangement.

2.2.6 Penetrant inspection and visual examination for cracks or other defects are to be made with a binocular microscope with a minimum magnification of 15X. Depending on the severity of the defect, attempts at repair can be made, but if necessary metal removal lowers specification dimensions below permitted tolerances, the specimen should be scrapped.

2.3 Preparation of Round Bar Specimens

2.3.1 Saw-cut or abrasive-cut specimen blanks.

2.3.2 Place blanks in lathe chuck and remove excess material from half the length. Turn to a diameter approximately 0.010" greater than the largest diameter of the finished specimen. Depth of cut shall not exceed 0.100" and the final roughing cut shall not exceed 0.030". Remove blank from chuck, insert turned portion in collet, and remove excess stock from other half. Face to length and center drill both ends (drill 1/8" deep max.).

2.3.3 Mount between centers and rough in shoulders and gage section. Final roughing cut on shoulders can be as high as 0.030". On gage section, final roughing cut should not exceed 0.010".

2.3.4 Finish machine all diameters using the following sequence: 0.005", 0.002", 0.002", 0.001".

2.3.5 Etch in previously described solution to remove 0.004" to 0.008" from specimen diameter and examine for defects in accordance with 2.2.6.

SECTION 3

General Test Techniques

3.1 Specimen Size

In order to conserve material, test specimens of beryllium are commonly made in relatively small sizes in comparison to those used in other materials. Since there does appear to be an effect of size of specimen on the measured properties of beryllium, specimens having the dimensions recommended in this report should be used for acceptance testing and for gathering basic engineering data.

3.2 Strain Rate

3.2.1 At room temperature the testing rate should be adjusted to produce an initial strain rate of 0.005 ± 0.002 in/in/min. If the ductility of the sample exceeds 5 per cent for the type of test being performed, the strain rate on subsequent tests of similar material may be gradually increased to 0.05 in/in/min ±.01 after either 0.6 per cent offset or 1.0 per cent total strain is reached. Data obtained from tests in which failure occurs during the change in strain rate should not be averaged.

3.2.2 For elevated temperature testing the initial strain rate should be 0.005 ± 0.002 in/in/min until a total strain of 0.01 in/in (1%) is reached and should then be changed to 0.05 ± 0.01 in/in/min. Data obtained from tests in which failure occurs during the change in strain rate should not be averaged.

3.3 Methods of Strain Measurement

3.3.1 When materials properties involving the strain in the specimen are required, the preferred strain measurement technique involves one of the following:

3.3.1.1 Resistance-type strain gages which have been bonded to the specimen, using the gage manufacturers' recommended procedures, except that surface preparation should not include roughing or scratching the specimen (see Section 2 for correct surface preparation).

3.3.1.1.1 Prior to testing, verification of a good bond between strain gage and specimen should be made in the following manner: with the specimen in position for testing, slowly apply a load until the strain gage (or gages) in the maximum strain direction reads approximately 100 (25 in the case of precision elastic limit specimens) micro-inches per inch of strain. Note the applied load. Reduce the load until the gage reads 10 to 20 micro-inches per inch and again note the load. Cycle the loading between these points just determined three times. The strain gages can be considered properly bonded if the following three conditions are met: a) the strain interval measured by the gage under test is reproducible to within ± 2-1/2 μ in/in for at least three additional load cycles, b) the strain readings are reproducible at the upper and lower load points to within ± 2 μ in/in, and c) the strain readings remain constant to within $\pm$ 2 μ in/in at both the upper and lower load points when the load is held constant at least 60 seconds.

3.3.1.2 Extensometers attached to the gage length of the specimen, provided data obtained from tests in which failure occurs at the point of attachment are ruled invalid.

3.3.1.2.1 For modulus determination, ASTM Type A extensometer should be used. For routine testing, ASTM Type B-1 or B-2 will suffice.

3.3.1.2.2 Extensometers which attach to the shoulders of the specimen or measure only test machine head travel or in other ways average strains outside the specimen gage length should not be used.

3.3.1.3 Optical or capacitance strain measuring devices which attach to the specimen gage length, provided data obtained from tests in which failure occurs at the point of attachment are ruled invalid.

3.3.2 Deflection measurements for the purpose of calculating average strains in the 4-point bend test should be made on only the portion of the sample being subjected to a uniform bending moment and in areas sufficiently removed from points of load application to prevent localized effects from influencing the data.

3.3.2.1 For thin bend specimens (less than 0.050 inches) deflection readings should be taken in areas a minimum of 4 times specimen thickness away from loading points, or by using the recommended deflectometer (Figure 6).

3.3.2.2 Verification of strains calculated from deflection readings should be made periodically using a bend specimen instrumented with strain gages on both the tensile and compressive surfaces.

3.3.3 Recommended procedure for making gage marks or scribe lines on flat sheet material involves first applying a marking ink to the specimen and then removing the ink at appropriate locations using a 0.001-in. radius scribe and the lightest pressure which will make a clear mark. The gage mark should cover no more than the central one-half of the sheet width. Scribe lines on round samples shall be made so that their axes correspond to the axis of the specimen. Measurements, in this case, are from end of scribe line to end of scribe line. Data obtained from test in which failure occurs at a scribe line should be ruled invalid.

3.4 Alignment Procedure

In testing beryllium it is necessary to be especially careful to provide a uniform and well-defined strain distribution. Because of beryllium's high modulus of elasticity, even a relatively small misalignment can result in the development of large stresses. In addition, stress redistribution at the expense of plastic flow may exhaust an appreciable fraction of the available ductility. Universal joints or other self-aligning devices are useful but are not adequate substitutes for carefully machined grips and specimens.

While it is recognized that a measure of the misalignment of each and every specimen--through the use of strain gages or other strain measuring devices--would be most desirable (especially in tension testing), the practical result of such a recommendation would be that the cost of routine testing would become prohibitively high. Instead, it is recommended that the alignment of the specimen and the associated load transmitting devices (grips, pull rods, etc.) be periodically checked by one of the techniques which will be described. The number of such periodic inspections will depend on the ultimate use of the data and the control of specimen and fixture dimensions, but will certainly include an alignment check when changes in machining practice or new grips or fixtures are introduced.

3.4.1 The preferred method of checking machine alignment shall involve the use of an instrumented specimen using strain gages or optical strain measuring devices capable of measuring the small strain differences due to misalignment. The maximum permissible deviation of a single gage reading should be less than 5 per cent of the average strain at a nominal stress level of at least 4,000 psi.

3.4.1.1 Round specimens shall be aligned using at least three strain gages located at equal distances around the gage section periphery. Gages may be staggered in the axial direction if necessary.

3.4.1.2 Flat sheet specimens shall be aligned front to back by measurements on both faces and side to side by measurements on both edges. Side to side strain measurements may be omitted provided accurately positioned guide pins are used in the gripping system. In this case, tolerances on guide pin location shall be at least as good as $\pm$ 1 per cent of specimen gage section width.

3.4.1.3 In lieu of alignment measurements, bend specimens shall conform to the following specifications for flatness and twist. Maximum allowable bowing of the specimen in a uniform arc shall be less than the specimen thickness in 3-inches length. Maximum allowable twist from edge to edge is one half the specimen thickness in 3 inches of length. Provision shall be made in the test fixture, or with an auxiliary jig, to position the longitudinal axis of the specimen to within $\pm$ 0.025 inches of the longitudinal axis of the test fixture.

3.4.2 Alignment procedure shall consist of obtaining strain measurements from samples instrumented as described above from some small initial load up to a stress level not less than 4000 psi using either incremental loading or at a load rate compatible with good strain measurements. Alignment shall be considered satisfactory if the maximum deviation of the individual strains from the average strain throughout the selected stress interval is less than $\pm$ 5 per cent. A specimen which has been loaded as described above will not be suitable for subsequent measurement of precision elastic limit. If both an alignment check and P.E.L. determination on the same specimen is desired, the preliminary loading should be limited to 10 per cent of the expected load at the precision elastic limit (if known), or to 500 psi.

3.5 Gripping of Specimens in Tension

Although the method of gripping the specimen is optional, it may be helpful to describe several techniques which have been used. On round specimens, threaded ends, button-head ends, and tapered ends have been used with the tapered specimen being the most popular. While a thread-ended specimen may be used, it does require a large-diameter thread with carefully rounded roots and a small-gage diameter to minimize grip failures. By aligning on the shoulders of the specimen, the button-head specimens give excellent concentricity of load. Careful machining of the diameters to maintain parallelism and axiality will assure alignment in the grips. The tapered head specimen can be made on a tracer lathe at minimum cost. Again, accurate machining of the ends is required to maintain alignment with the fixtures, but this is done readily, and satisfactory concentricity can be achieved.

On flat specimens, the serrated faces of the Templin-type or the Instron designed flat grips will satisfactorily hold the specimen. Even with high strength material, the number of grip failures will be small provided a fairly wide tab (2-1/2 times the gage width) is used at the grip ends. Accurately machined pin holes in the grips should be used to assure good alignment of the specimen.

Drawings of recommended tensile specimens are shown in Figures 1 to 3, and a drawing of types of specimen grips is shown in Figure 4.

3.6 <u>Test Reports</u>

The test report form on page 27 is recommended. This form requires information on materials history and test method essential to a realistic evaluation of the test data. The presentation of complete material and test information should help to prevent erroneous conclusions or avoid invalid comparisons of data. Deviations from recommended procedures should be stated.

SECTION 4

Standard Tests

Tensile (including modulus), Bend (3- & 4-point) & Precision Elastic Limit

4.1 General

This section presents recommended test specimen details and test procedures for those beryllium mechanical property tests where some agreement on both the test procedure and the usefulness of the test data has been found. In order that they will be of immediate and practical use, the procedures are given in specification form, and alternatives or possible variations have been deliberately avoided except in the case of test facilities where considerable capital expense would be involved unnecessarily if only one type of equipment were mentioned.

The tensile test is essentially standard except for the special precautions which are necessary with respect to specimen finish and tolerances and specimen alignment in the test machine.

The bend test recognizes that the tension test has limitations when complex stress states exist and the bend test is an attempt to include complex stress conditions in a test which is simple and relatively cheap to conduct. This test, however, represents one particular stress distribution and it is consequently only a qualitative evaluation of the performance of the material in a typical application. The bend test data are, therefore, not of direct use for design purposes, but are useful qualitatively in connection with the development of alloys and materials manufacturing procedures. The four-point bend test is recommended when accuracy is desired and the cost of the larger specimen is justifiable.

In some instances it may be desirable to perform a simpler bend test than the four-point. If for example, only a crude estimate of strength is needed, the modulus of rupture in simple three-point bending can be used. The three-point bend test is applicable in a number of sheet forming operations, and provides information which may be useful for the design of forming tools and for the establishment of forming procedures. Three-point bending may also be useful to identify limiting bend angles or minimum bend radius. It should be pointed out, however, that three-point loading causes a non-uniform bending moment and strain distribution which makes quantitative measurements difficult. The three-point bend test, as outlined, can be made with a smaller specimen and simpler equipment than the four point.

The elastic modulus test provides the value of modulus which may be used for engineering design purposes. The information will be satisfactory for the prediction of structural deformation and for the analysis of vibration problems and compression instability problems.

The Precision Elastic Limit Test provides information which is useful for the guidance instrument industry and for scientific work on materials. For most engineering design purposes, however, the 0.1 per cent or 0.2 per cent yield stress determined from data taken during tensile test is adequate.

4.2 Tensile Test (Including Engineering Modulus of Elasticity)

4.2.1 Purpose and Scope

This specification defines procedures for conducting room and elevated temperature tests on beryllium and beryllium alloys in either sheet or bar form.

4.2.2 General Procedures

ASTM Standard E8 for tension testing of metallic materials (and E-111 for modulus determinations), are general references for procedure. Other general procedures which recognize the peculiarities of beryllium are defined in Sections 2 and 3, and these also apply.

4.2.3 Test Specimens

Figures 1 through 3 give dimensions and dimensional tolerances for sheet and bar tensile specimens in two sizes. Elastic modulus determinations shall be made on the larger size specimens only (Figures 1 and 2). Procedures for fabricating these specimens and the associated surface finishing requirement are given in Section 2 of this report. For greater accuracy and convenience, the larger of the two specimens shown (1.0" gage length) should be used if possible. In view of the high cost of beryllium, however, the smallest possible specimen will often be desired particularly for routine quality control and receiving inspection type testing involving large quantities of specimens. The smaller specimen shown (0.5" gage length) will also serve in certain special cases, e.g., extrusions and forgings where the material volume is limited.

Details of the specimen ends are not shown since the gripping method is optional. Typical specimen ends are shown in Figure 4.

4.2.4 Test Fixtures

The tensile test machine shall comply with the requirements of ASTM E4. Methods used for elevated temperature testing shall conform in general with ASTM Standard E21. The method of gripping the specimen is optional. Alignment should be in accordance with 3.5.

4.2.5 Instrumentation

An autographic strain measurement system shall be used to determine strain from zero to a minimum of 0.2 per cent offset. Calibration, attachment and accuracy shall comply with the requirements of ASTM E83 and E21.

If modulus of elasticity values are desired, a class A (or class B-1 calibrated to class A accuracy) extensometer shall be used (see ASTM E83). Special aspects of extensometer attachment peculiar to beryllium and the class of extensometer required are defined in Section 3.3.

4.2.6 Test Procedure

4.2.6.1 Periodically check alignment with selected specimen gripping method by strain gaging a specimen in accordance with Section 3.5.

4.2.6.2 Inspect specimens to assure that surface is smooth, free from nicks, scratches, tool marks or other imperfections. Accurately measure the dimensions of the gage section to the nearest .0001 inch. Four to eight readings along the length of the specimen are usually required.

4.2.6.3 Install extensometer and load in accordance with Sec. 3.2.

4.2.6.4 Record 0.2 per cent offset yield strength, tensile strength, and plastic elongation at fracture. If modulus of elasticity measurements are being made, also measure the strain corresponding to convenient increments of stress.

4.3 Three-Point Bending

4.3.1 Purpose and Scope

This specification defines procedures for conducting room temperature bend tests in simple bending on beryllium and beryllium alloys.

4.3.2 Test Specimen

Figure 5 gives test specimen dimensions and tolerances. Fabrication procedures are given in Section 2 of this report. The geometry shown is intended to cover thicknesses up to 0.10 inches.

4.3.3 Test Fixture

A suggested basic test fixture is shown in Figure 6. Dimensions and tolerances are specified. Positioning of the specimen within the fixture is not critical and may be done by eye. A test machine, or, if modulus of rupture is not required, an arbor press may be used to apply the load.

4.3.4 Test Procedure

4.3.4.1 Measure test sample thickness to within ± 0.0005 inches and width to ± 0.001 inches.

4.3.4.2 Place specimen in fixture and load at a rate in accordance with Section 3.2.*

4.3.4.3 Continue to load until failure occurs and calculate modulus of rupture from:**

$$\text{Modulus of Rupture} = \frac{2.25P}{bt^2}$$

where P is the load,
b is the width,
and t is the thickness of the specimen.

Since the three-point bend test is used primarily as an index of formability, no directions are given for plotting a moment-strain diagram.

4.3.4.4 If minimum bend angle is required, use 0.187 inch radius loading pins and interrupt loading of test to measure unloaded bend angle. A standard protractor reading to 1° may be used for bend angle measurements, and measurements are made at points 0.75 inches from the center of the specimen. Continue incremental loading until failure is reached.

4.4 Four-Point Bend Test

4.4.1 Purpose and Scope

This specification defines a procedure for conducting bend tests in pure bending at room temperature on beryllium and beryllium alloy sheet specimens.

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*Omit if arbor press is used.

**This formula valid only for the recommended span of 1.5", as shown in Fig. 6. More generally, modulus of rupture $= \frac{3}{2} \frac{Pl}{bt^2}$, where l is the span.

4.4.2 Test Specimen

Figure 7 gives test specimen dimensions and dimensional tolerances. Procedures for fabricating these specimens are given in Section 2 of this report. The geometry shown is intended to cover thicknesses up to 0.10 inches. Thickness is not shown since this will depend on the material to be tested. For four-point bending, specimens shall have a width/thickness ratio of 20:1 for thicknesses of .05 to .10. Specimens thinner than .05 shall be a minimum of 1" wide.

4.4.3 Test Fixture

The test fixture must provide for positive location of the loading anvils and alignment of upper and lower pairs of anvils. General arrangement of the loading fixture is shown in Figure 8 and the dimensions and tolerances which must be controlled are specified. In addition, a separate jig or fixture or locating pins within the bend fixture itself will aid in positioning the specimen axis parallel to the fixture axis.

4.4.4 Instrumentation

Instrumentation for the four-point bend test should consist of a deflection measuring device to measure radius of curvature in the gage section. Dimensions for such a device are given in Figure 8 and the corresponding relationship for the determination of strain is given below. Strain gages may be used in the four-point bend test in place of radius of curvature measurements.

4.4.5 Test Procedure

4.4.5.1 Measure test section cross-section dimensions to within ± .0005 inches.

4.4.5.2 Assemble loading apparatus and adjust so that tolerances defined in Figure 8 are achieved.

4.4.5.3 Continuously load the specimen at a load rate or strain rate in accordance with Section 3.2* and read load and deflection at convenient intervals until failure occurs.

4.4.5.4 Plot stress-strain diagram using the formulas:**

$$\text{Stress} = 2.25P/wt^2$$

$$\text{Strain} = 4\,\Delta t, \text{ (for 1" gage length)}$$

$$\text{or, Strain} = E\,\frac{t}{t+m} \text{ (to correct for strain gage thickness)}$$

where P is the applied load,

Δ is the deflection reading,

t is the specimen thickness,

w is the specimen width,

E is the strain gage reading,

and m is the strain gage thickness.

4.5 Precision Elastic Limit (Microscopic Yield Point)

4.5.1 Purpose and Scope

This specification defines procedures for conducting room temperature measurements of the precision elastic limit of beryllium and beryllium alloys.

4.5.2 General Procedures

ASTM Standard E8 for tension testing of metallic materials is a general reference for procedure. Other general procedures which recognize the peculiarities of beryllium are defined in Sections 2& 3, and these also apply. All other procedures are defined below.

4.5.3 Test Specimens

Figures 1 and 2 give dimensions and dimensional tolerances for the precision elastic limit specimens. For greater accuracy, the

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*If it is necessary to use test machine head rate as an indication of strain rate, the head rate should be adjusted to be $\left(\frac{0.0075}{t}\right)$ inches/min., where t is specimen thickness.

**Valid only if span of upper anvil is 1.5" (See note, page 21) gage length may be increased by 2 inches. Diameter or width should be constant along the gage length. Procedures for fabricating these specimens and the associated surface finishing requirements are given in Section 2 of this report. Details of the specimen ends are not shown since the gripping method is optional. Typical ends for round specimens are shown in Figure 4.

4.5.4 Test Fixtures

The tensile test machine shall comply with the requirements of ASTM E4. The method of gripping the specimen and of obtaining the necessary alignment is optional providing that the alignment requirements of Section 3.4.1 are met. If difficulty is encountered in consistently obtaining maximum deviations of individual strains from the average strain of under 5 per cent, the checking of alignment at each specimen would be a preferred procedure.

4.5.5 Instrumentation

Calibration and accuracy shall comply with the requirements of ASTM E83, Class A. Strain gages or optical strain measuring devices shall be used for strain measurements when determining the precision elastic limit. Three or more resistance strain gages are attached at equal intervals around the circumference of round bar test specimens, or one strain gage on either side of flat sheet specimens.

4.5.6 Test Procedure

4.5.6.1 Accurately measure the dimensions of the gage section to the nearest 0.0001 inch.

4.5.6.2 Install strain and temperature measuring devices. Refer to Section 3.3.1.1.1 for details on verification of strain gage bond.

4.5.6.3 Install specimen in testing machine. Check and adjust alignment in accordance with Section 3.4 in accordance with Section 3.5. A waiting period may be needed for the equalizing of temperature so as to be able to maintain a temperature range of no more than 1/4^{o}C during the test.

4.5.6.4 Apply the load in increments which may be as low as 100-200 psi for soft alloys but which will more usually be about 500 psi. Unload to zero and repeat cycle to detect the onset of the microscopic yield point of one microinch residual strain. The application of additional increments of load will permit an extrapolation of the load-deflection curve back to confirm the load corresponding to one micro-inch strain.

TEST REPORT FORM

MATERIAL | **HEAT OR MELT NO.**

PRODUCER | **THICKNESS**

CHEMICAL ANALYSIS (Include C, O, N)

Pre test (Material sample)

Post test* (Specimen)

METALLOGRAPHIC ANALYSIS* (Include hardness data and notes on surface effects)

Pre test -

Post test -

SPECIMEN PREPARATION (Methods, Finish, Dimensions, Tolerance, etc.)

TEST DESCRIPTION

Specimen | Orientation (with respect to fabrication method)

Test Temp. | Heating Method

Soak Time | Temp. Control

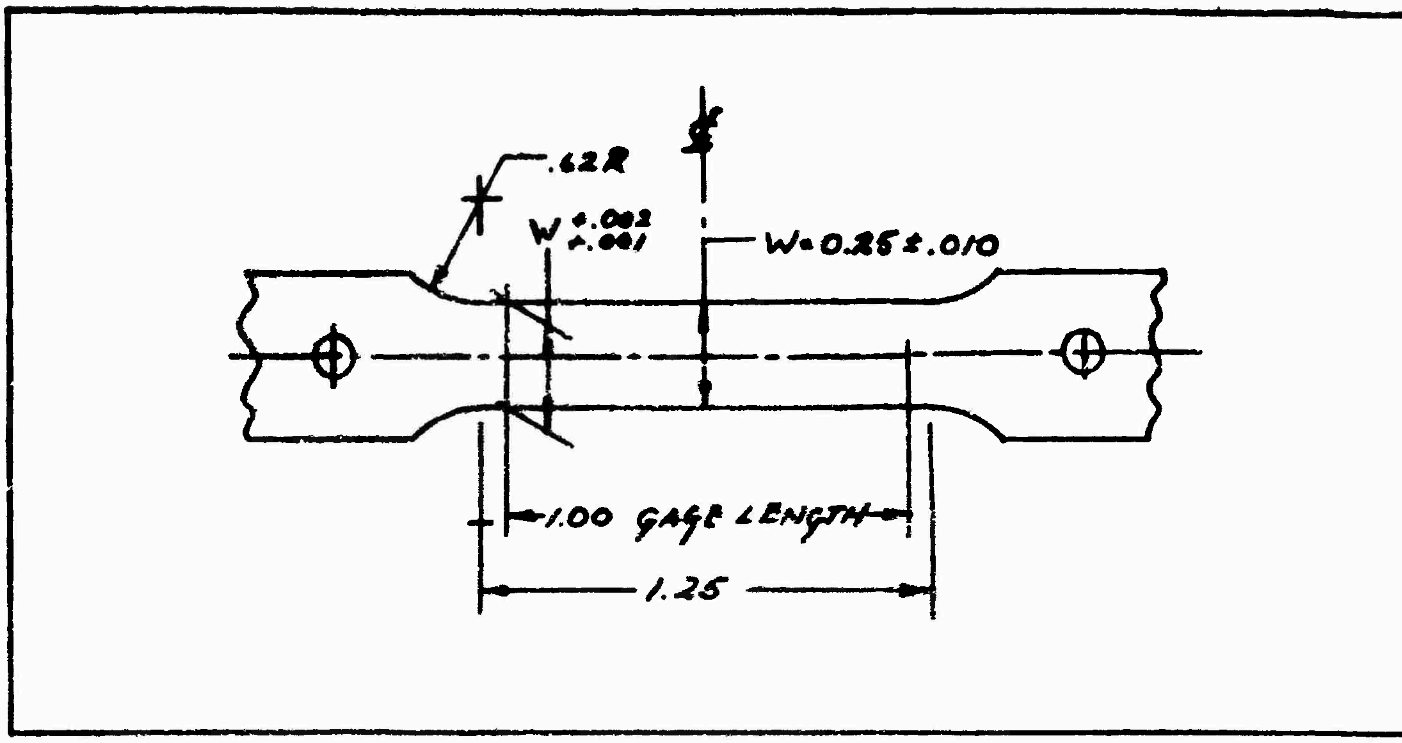
Test Machine | Test Environment

TEST PROCEDURE (Details on actual strain rates, strain measurement techniques, temperatures, control, etc., as applicable, pertinent information on calibration of instruments, limits of accuracy, test environment, and all other information which may contribute to a more useful evaluation of the data. Any deviations from standard procedures should be indicated.)

TEST RESULTS

Ultimate Tensile Strength
0.1% or 0.2% Offset Yield Strength
Elongation, % in gage length
Reduction in Area
Young's modulus
Precision Elastic Limit

*Optional



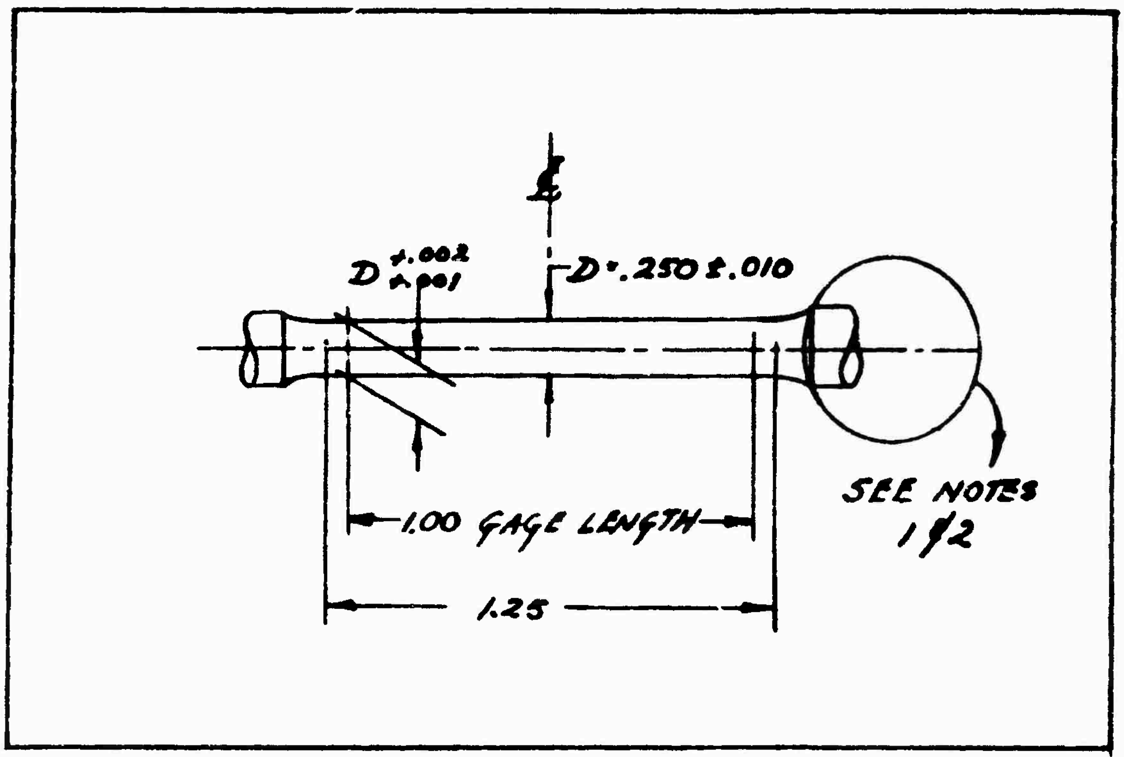
NOTES:

1. Line through centerline of holes and longitudinal centerline through gage section shall coincide within .001 inches.

2. Specimen surface finish shall be in accordance with Section 2.

3. Dimensions shown are prior to etching. Etching shall be in accordance with Section 2.2.5.

FIGURE 1 TENSION TEST-SHEET SPECIMEN
1-INCH GAGE LENGTH



NOTES:

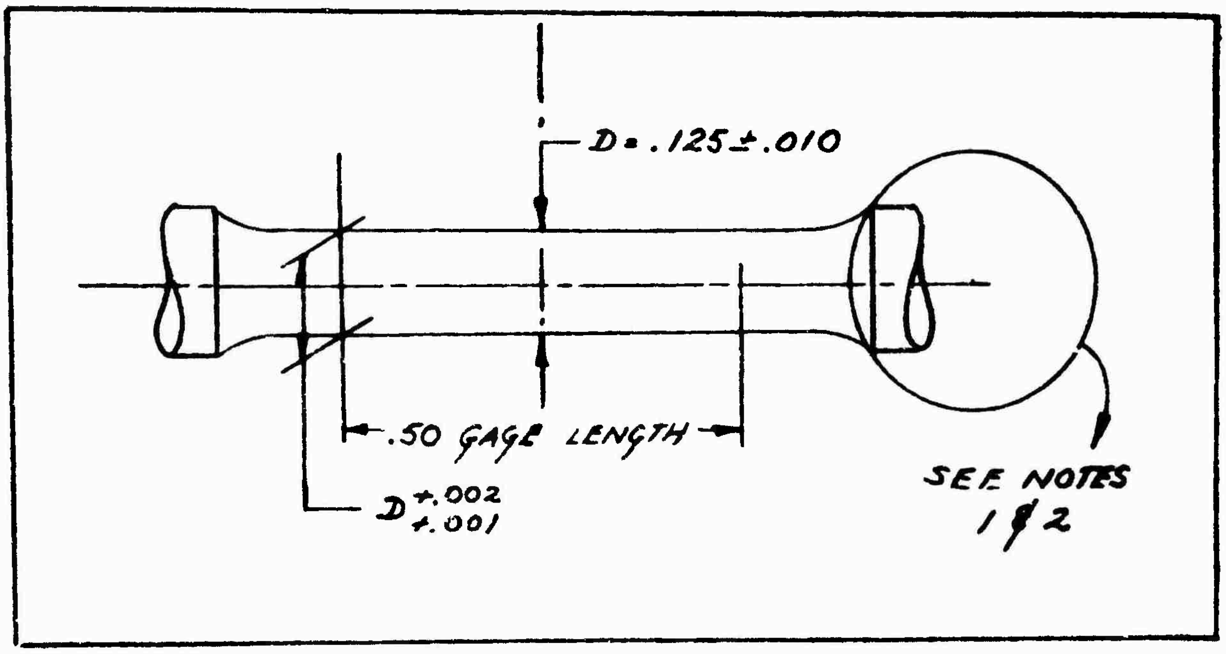
1. The gripping ends of the specimen shall be in accordance with Section 3.5.

2. The ends of the specimens shall be symmetrical with the centerline of the reduced specimen within .001 inches.

3. Specimen surface finish shall be in accordance with Section 2.

4. Dimensions shown are prior to etching. Etching shall be in accordance with Section 2.2.5.

FIGURE 2 TENSION TEST-BAR SPECIMEN
1-INCH GAGE LENGTH



NOTES:

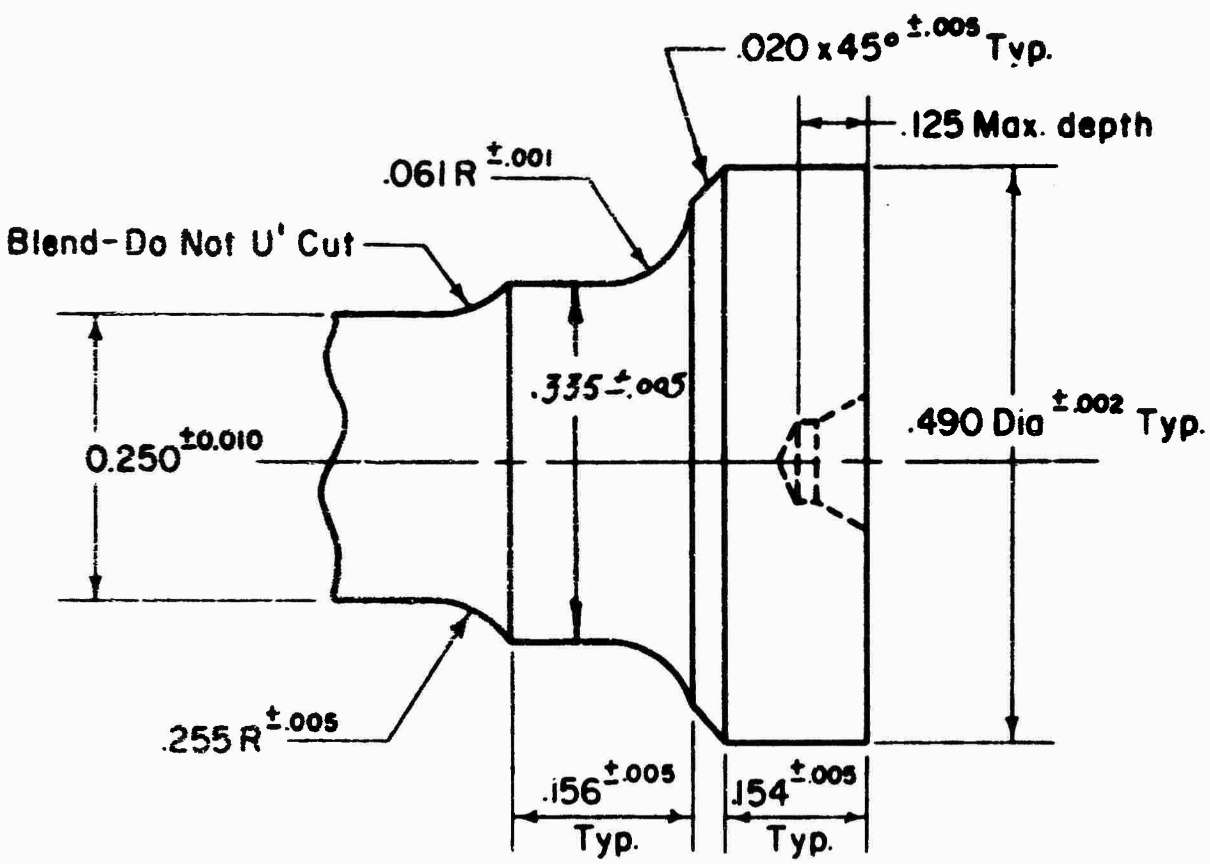
1. The gripping ends of the specimen shall be in accordance with Section 2.5.

2. The ends of the specimen shall be symmetrical with the centerline of the reduced section within .0005 inches.

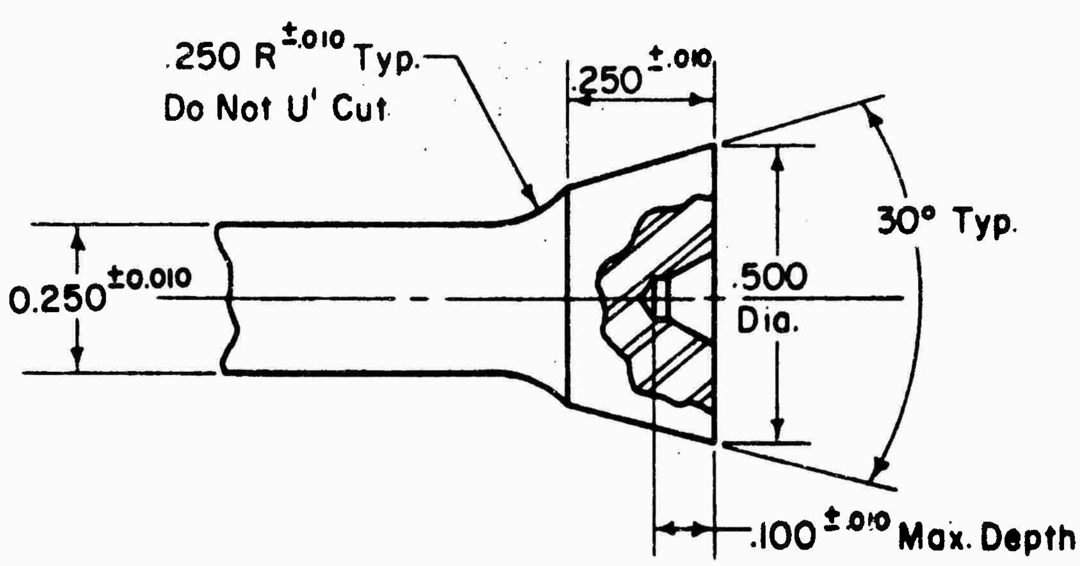
3. Specimen surface finish shall be in accordance with Section 2.

4. Dimensions shown are prior to etching. Etching shall be in accordance with Section 2.2.5.

FIGURE 3 TENSION TEST-BAR SPECIMEN
1/2 INCH GAGE LENGTH

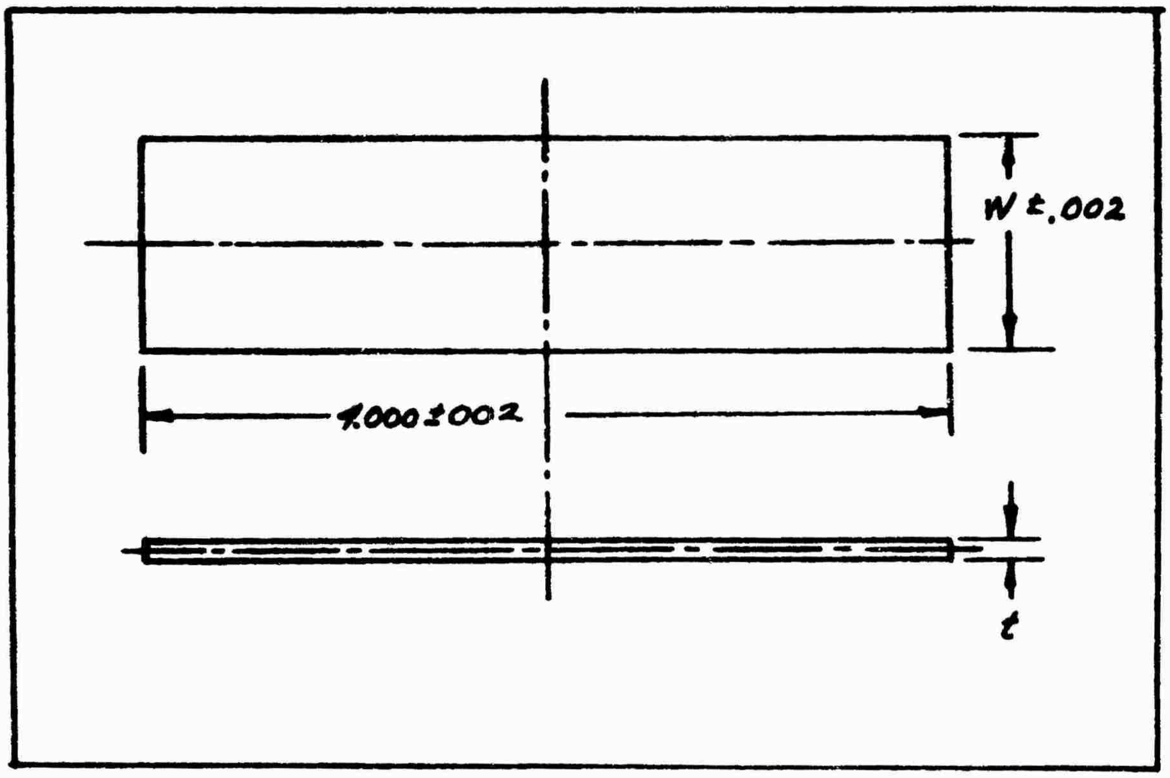


a. Button Head End Tensile Specimen



b. Tapered End Tensile Specimen

FIGURE 4. TYPICAL BUTTON-HEADED AND TAPERED-END SPECIMENS



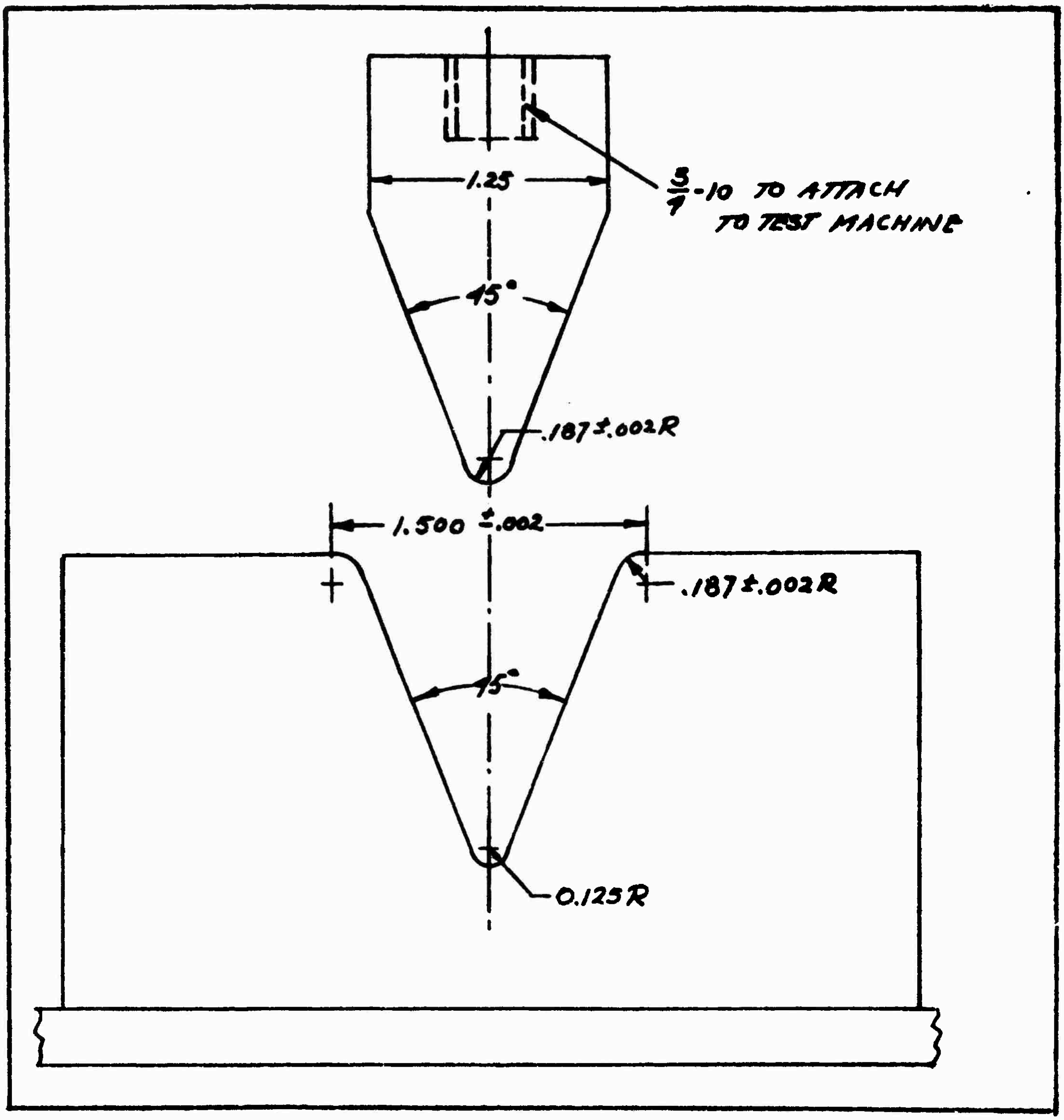
NOTES:

1. Test specimens shall have a width-to-thickness ratio of 10 for specimens 0.05 in. to 0.10 in. thick, but shall be 0.5 inches wide for material thickness less than 0.05 in.

2. Maximum specimen thickness is 0.10 inches.

3. Specimen finish shall be in accordance with Section 2.0.

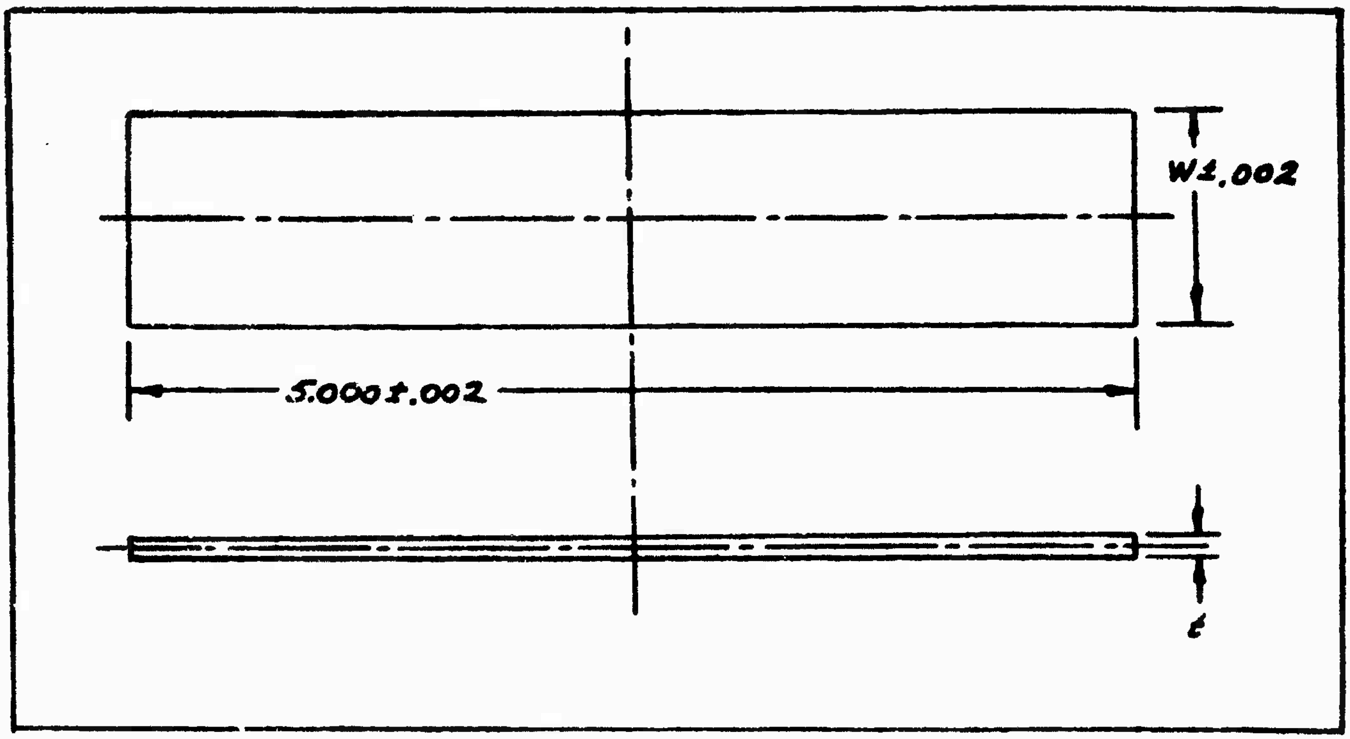
FIGURE 5 BEND TEST SPECIMEN
(THREE-POINT BENDING)



NOTES:

1. Fixture is self aligned by bringing tapered surfaces into contact. Specimen alignment is by eye.

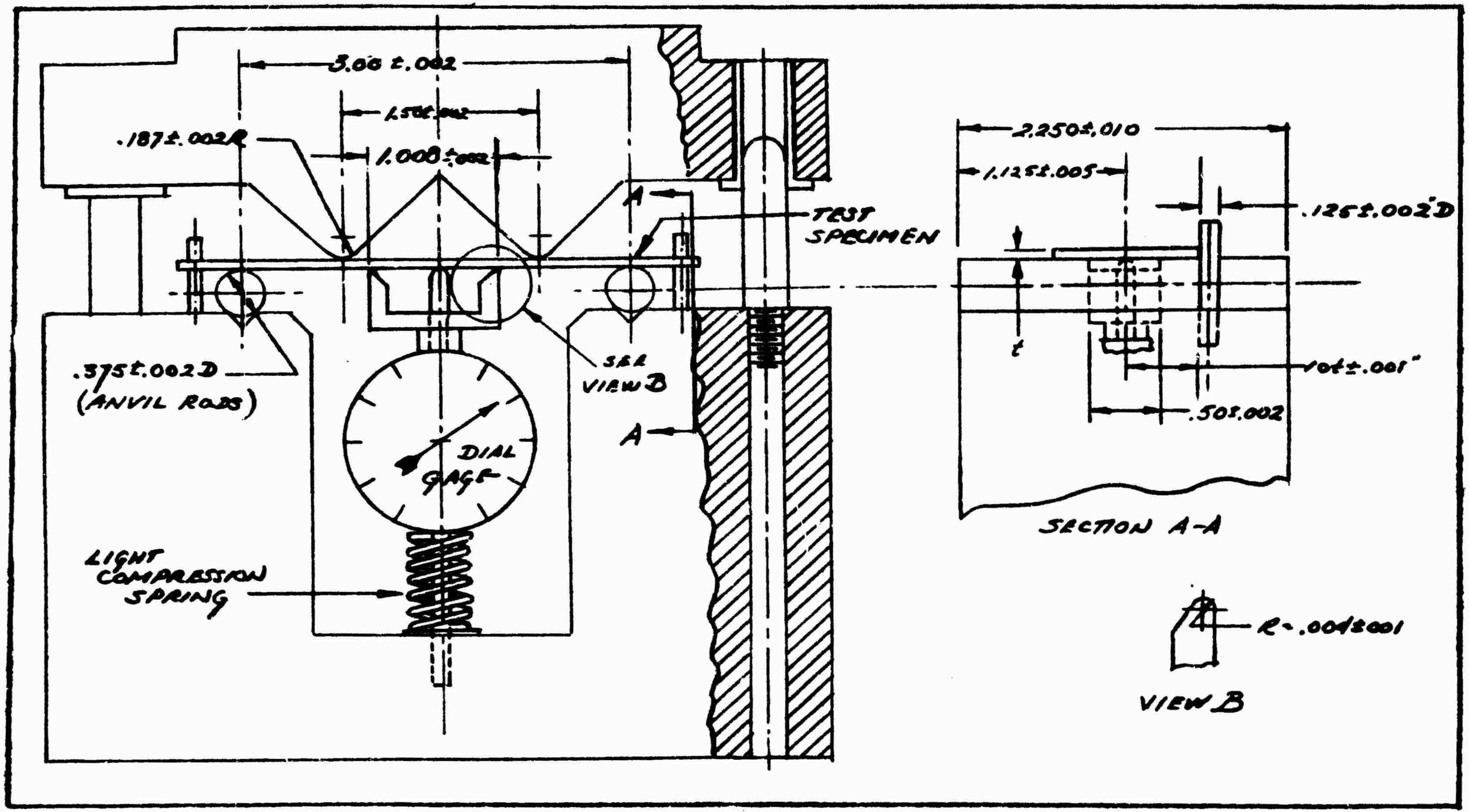
FIGURE 6 BEND-TEST FIXTURE
(THREE-POINT BENDING)



NOTES:

1. The test specimen shall have a width-to-thickness ratio **as specified in Section 4.4.2.**
2. Maximum specimen thickness is 0.10 inches.
3. Specimen surface finish shall be in accordance with Section 2.0.

FIGURE 7 BEND TEST SPECIMEN
(FOUR-POINT BENDING)



Notes: 1. The .125-inch pins shall be set in pre-drilled holes so that test specimen is symmetrical with the centerline of the test machine loading head.

FIGURE 8 BEND TEST FIXTURE
(Four Point Loading)

APPENDIX A

Safety Precautions for Handling Beryllium

Beryllium and its compounds can produce toxic effects when ingested into the lungs in sufficient quantities. Since this report describes specimen preparation procedures, which will invariably produce fine beryllium particles, it was felt necessary to include a brief description of the hazards of beryllium and some of the techniques that can be used to overcome any danger. The following standard is similar to one used by a large industrial company and is thought to be typical of the precautions that should be taken.

1. SCOPE:

This standard identifies the hazards involved and outlines the general precautions necessary in the handling of beryllium metal and its compounds. Actual specific safety and industrial hygiene requirements should be specified for individual operations only after thorough review by qualified individuals.

2. APPLICABLE REFERENCES:

2.1 U. S. Air Force, Aeronautical Systems Division, Wright-Patterson Air Force Base, Ohio, Report Number **ASD-TDR-62-7-665, TOXICITY OF** BERYLLIUM (March 1962).

2.2 American Industrial Hygiene Association: 14125 Prevost, Detroit, Michigan: Hygienic Guide -- Beryllium and Compounds (Sept. 1956).

2.3 Kehoe, R. A., ed. Workshop on Beryllium, Cincinnati, Ohio, The Kettering Laboratory, University of Cincinnati, Ohio (January 5 and 6, 1961).

2.4 Conference on Beryllium Disease and Its Control, A.M.A. Arch. Ind. Health, Vol. 19, No. 2 (February 1959).

2.5 Tepper, Hardy, & Chamberlain, Toxicity of Beryllium Compounds, Elseiner, (1962).

3. BASIC HAZARDS:

The hazards that are encountered in working with beryllium and its compounds can be broken down into three general groups:

3.1 A respiratory problem resulting from the inhalation of above tolerance concentrations of beryllium dust or fumes in the air.

3.2 Any cuts or open wounds implanted with beryllium or its compounds tend not to heal until the foreign matter is removed.

3.3 A temporary dermatitis condition can be caused by some of the soluble compounds of beryllium, but not by the pure metal or oxide.

4. CONTROL LIMITS:

In order to keep respiratory exposures within safe limits the following hygienic standards shall be met:

4.1 The average daily concentration of respirable beryllium in air in beryllium facilities shall be maintained at less than 2 micrograms per cubic meter; with no short exposure (i.e. about 20 minutes) concentration greater than 25 micrograms per cubic meter.

4.2 Emission of beryllium particulate matter into the outside air shall be limited so that the beryllium in air concentration at the property line does not exceed 0.01 micrograms per cubic meter when averaged over a one-month period.

5. ENGINEERING CONTROLS

5.1 Operations involving beryllium which are capable of producing airborne concentration of dust, mists, or fumes in excess of the above limits must be provided with special engineering controls. All or part of the following methods of contamination control may be required. Upon review of a proposed operation, a safety and industrial hygiene organization should prescribe which methods are required.

5.1.1 Identification of equipment which contains or has been contaminated with beryllium by application of labels.

5.1.2 Laboratory bench hood with an average face velocity of 150 fpm.

5.1.3 Enclosure with local exhaust which provides a velocity of 150 fpm through all openings.

5.1.4 Close-capture exhaust hoses with air flow sufficient to provide necessary control velocity at the operation.

5.1.5 Totally enclosed room, maintained at a negative pressure to the surrounding area.

5.1.6 Air cleaning equipment capable of removing beryllium contamination from exhaust air to acceptable levels.

5.1.7 Special work clothing, adjacent change room, showers, and clothes washing machine and dryer.

6. **ADDITIONAL PRECAUTIONARY MEASURES:**

6.1 When air exhaust is not available or is inoperative, individual respiratory protection shall be worn where hazardous air concentration is possible. Individual respiratory protection shall be MSA Comfo or Dustfoe respirators equipped with type H Ultrafilter cartridges or air-supplied respirators.

6.2 Only personnel approved by a physician, after special physical examination, shall be assigned to jobs involving possible beryllium dust, mist, or fume exposure. All personnel shall be oriented as to hazards and necessary safeguards involved in beryllium handling.

6.3 All cuts, abrasions or punctures of the skin received while working with beryllium or its compounds shall be treated immediately.

6.4 Traffic through areas in which beryllium is being worked shall be held to a minimum in order to reduce the possible spread of contamination.

6.5 All waste beryllium and contaminated scrap shall be placed in sealed containers.

6.6 Suitable air sampling program shall be conducted to assure that the beryllium in air concentration limits are not exceeded and to determine effectiveness of control measures.

6.7 Good housekeeping is important in all beryllium operations. Clean up shall be done by wet wiping or mopping or by vacuuming with a vacuum cleaner whose exhaust is filtered.

7. **SUMMARY**

The inhalation of beryllium dust can cause serious illness and even death however, with the application of proper controls the material can be handled safely in most any operation. This is demonstrated by the fact that since the toxicity of beryllium was first recognized in the late 1940's and effective dust control methods were put into use there has not been a single case of chronic beryllium disease traceable to exposures where dust controls were used.

APPENDIX B

INDUSTRIAL HYGIENE GUIDE

BERYLLIUM AND ITS COMPOUNDS*

(Revised 1964)

Significant Physical Properties

Beryllium is a silvery-white, brittle metallic element similar in appearance to magnesium.

Chemical symbol:	Be	BeO
Atomic number:	4	-
Atomic (or molecular) weight	9.01	25.01
Density:	1.85 at 25°C	3.03
Melting point:	1285°C	2550°C
Boiling point:	2970°C	3960°C (estimated)
Solubility:	Soluble in dilute acids and alkalis	Insoluble in water, acids (except hydrofluoric) and alkali (except fused). Attacked by water vapor at temperatures above 1300°C

Vapor pressure (obtained graphically)[1]:					
	mm Hg	7.6×10^{-6}	7.6×10^{-4}	7.6×10^{-2}	7.6
	°C	890	1080	1330	1810

Beryllium is an amphoteric element and its salts readily hydrolyze forming the beryllium cation, basic beryllium compounds or beryllates as the pH of the solution is increased.

The Committee wishes to acknowledge the assistance of Harry F. Schulte in the writing of this Guide and of the Industrial Hygiene and Clinical Toxicology Committee of I.M.A. in the preparation of the medical information section of this Guide.

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*Industrial Hygiene Journal, pages 614-617, November-December 1964, copied by permission.

I. HYGIENIC STANDARDS

A. **RECOMMENDED MAXIMAL ATMOSPHERIC CONCENTRATIONS (8 hours):** 0.002 mg per cubic meter.[2,3,4]

B. **SHORT EXPOSURE TOLERANCE (less than 30 minutes):** 0.025 mg per cubic meter.[3,4,5]

C. **NON-OCCUPATIONAL:** A monthly average concentration of 0.00001 mg per cubic meter has been used as a guide for the maximal atmospheric concentration outside the plant. This is based on epidemiological studies.[3,4,6,7]

II. TOXIC PROPERTIES

A. **INHALATION:** Inhalation of beryllium and its compounds may produce two types of disease--acute and chronic.

1. Acute: Acute disease may result from relatively brief exposure to high concentrations of beryllium or its compounds. The result may be a pneumonitis where exposure is to the metal, oxide or other compounds. Nasopharyngitis or tracheobronchitis is more likely from highly soluble compounds.[8] The pneumonitis may be fulminating following massive exposure or less severe with gradual onset from lesser exposure.[9,10]

2. Chronic: Chronic disease may result from varying lengths of exposure to a wide range of concentrations including quite low concentrations. In some cases there is a prompt onset of symptoms while in others there may be a delay of many months or years between the last exposure and onset of symptoms.

   Pulmonary manifestations usually include dyspnea and a chronic cough. Significant weight loss within a short period of time is a symptom in many cases as are anorexia, fatigue, weakness and malaise.[4] Although respiratory symptoms are most prominent and usually occur first, the chronic disease is considered by many to be a systemic disease which may involve other organs.[8] Chest x-rays are useful in diagnosis and treatment but only in conjunction with other clinical findings.

B. SKIN CONTACT: Skin contact with soluble salts, particularly acidic salts, may produce dermatitis of primary irritant or sensitization type.[4,10] Accidental implantation of beryllium or its compounds beneath the skin may cause necrosis of adjacent tissue with the formation of an ulcer. Implantation of comparatively insoluble compounds may produce a granuloma. Healing does not occur unless the beryllium-containing material is completely removed.

C. EYE CONTACT: Conjunctival inflammation may accompany contact dermatitis resulting from soluble beryllium compounds.

D. INGESTION: No harmful clinical effects have been reported from ingestion of beryllium-containing materials.

Wide variations in the effects produced by beryllium compounds of differing physical properties have been reported. Acute disease, skin and eye effects have been associated largely with soluble compounds, although the metal and the oxide also have been implicated. Chronic disease has been associated, although not exclusively, with the more slowly soluble compounds such as the oxide, beryllium metal, and the phosphors which were once used to coat fluorescent lamps (prior to 1949). Only the silicate mineral, beryl, has definitely not been found associated with beryllium disease. The degree of toxicity is associated in some manner with solubility and particle size as well as other factors but information is not adequate to exempt any beryllium-containing material except beryl from the rigid control requirements.

III. INDUSTRIAL HYGIENE PRACTICE

A. **INDUSTRIAL USES: Because of its low density combined with high rigidity, beryllium metal is used in the aerospace and aircraft industries as a structural material. Use of the metal powder as a rocket fuel component is under investigation. In the atomic energy industry, beryllium has a wide variety of applications, particularly as a reactor component because of its specific nuclear properties. Alloyed with copper, it produces a hard metal of high conductivity and tensile strength which is resistant to fatigue. As such, it is used for making nonsparking tools and current-carrying springs and molds. The oxide has found considerable use as a ceramic material and in neon sign manufacturing.**

B. **EVALUATION OF EXPOSURES:**

1. Air Sampling and Analysis:

   (a) Air sampling usually is done by means of filter paper or occasionally by electrostatic precipitator.[3,4,11] Various forms of beryllium monitors have been devised for recording the air concentration of beryllium continuously after a few minutes delay.[12]

   (b) Air samples collected on filter paper or by the electrostatic precipitator may be analyzed colorimetrically,[13] fluorimetrically by the morin method[14,15,16] or spectrographically.[17,18]

2. Sampling and Analysis of Biological Materials: Urine analyses of beryllium have shown little quantitative correlation with either exposure to beryllium or with clinical findings and hence are seldom done. Positive identification of beryllium in urine does indicate exposure to beryllium in some

form and is of value only in establishing this fact. Tissues may be analyzed spectrographically[17] or fluorimetrically.[15]

3. Swipe Samples: Swipe or smear samples sometimes are taken to determine the degree of cleanness of surfaces. A measured area is rubbed with a filter paper and the sample is analyzed in the same manner as an air sample. Repeated analyses of this sort can form a basis for judging whether a given surface area is in need of more frequent cleaning. A surface cleanness of less than 0.025 mg of beryllium per square foot usually can be obtained by ordinary cleaning methods and has been used as an index of cleanliness by some.[11] It has no other health significance.

C. HAZARDS AND THEIR RECOMMENDED CONTROL:

1. Inhalation: Control of inhalation hazards may be accomplished by enclosure or local exhaust ventilation or a combination of these. Small, high-velocity exhaust pickups[4,19] or semienclosure with moderate velocity exhaust[11,20] may be used on machining operations.[21] A wide variety of combinations of enclosure and ventilation has been used on other operations.[3,20]

   Where respiratory protective devices are required, the user should refer to the "Respiratory Protective Devices Manual".[22] Gloves and clothing worn while working with beryllium should not be worn home. All clothing and other personal items contaminated with beryllium should be laundered separately, using facilities designed to prevent contamination of the air with beryllium. Beryllium metal should be stored in such a way that it will not come into contact with moisture which causes the formation of a loosely adherent powder that may become airborne and produce an exposure by inhalation.[20]

2. Skin Contact: Contact with soluble compounds, especially fluorides, should be prevented. Scrupulous adherence to good housekeeping practices, plant and personal cleanliness are an obvious necessity. Lacerations and abrasions with beryllium-containing materials, especially where beryllium compounds are implanted in the tissue, are difficult to heal (see Section II. B.). Special handling may be necessary to minimize the possibility of such injuries. There is no danger in ordinary skin contact with beryllium metal, alloys or fused ceramic material.

3. Eye Contact: Eye protective devices should be worn when working with soluble beryllium compounds under conditions where splashing or mist production can occur.

4. Ingestion: No special precautions other than those used in handling most chemicals are required.

5. Fire and Explosion: Bulk pieces of beryllium metal are extremely difficult to ignite and show little oxidation up to 900°C. Like most metal powders, finely divided beryllium ignites under proper conditions and can explode if suspended in air in the presence of a strong ignition source. Its low density makes it somewhat easier to create an explosive concentration in air than is the case with other metals. Powdered beryllium metal (as in a dust collector) burns quietly if ignited.

IV. MEDICAL INFORMATION

A. EMERGENCY TREATMENT: Any person having a known exposure to a high concentration of airborne beryllium or its compounds should be given prompt medical attention and observed closely for exidence of pneumonitis. Medical management as well as signs and symptoms of overexposure simulate those of phosgene and oxides of nitrogen. (Refer to Hygienic Guide on Nitric Acid for details.) A 14- by 17-inch chest x-ray picture should be taken immediately for comparison with possible subsequent x-rays and the exposed worker put at complete rest. Follow-up observation and examination are essential for all individuals who have been exposed to hazardous levels of beryllium or its compounds.

Cuts or puncture wounds, where beryllium or its compounds may be embedded under the skin, should be thoroughly cleansed immediately by a physician. Any implanted beryllium must be excised.

B. SPECIAL PROCEDURES: X-ray pictures (14- by 17-inch) of the chest should be made on all personnel prior to job assignment. A careful history of respiratory disease should be taken. Periodic chest x-rays should be made at least annually with prompt removal from exposure at the first evidence of abnormal findings. Any dramatic unexplained weight loss should be considered as a possible first indication of beryllium disease.[4] Steroid therapy should be considered in the case of either acute or chronic beryllium disease.

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13 ABSTRACT

This report was prepared to establish standardized methods and procedures for conducting mechanical property tests on beryllium. Such methods are required in view of the characteristics of beryllium, which make conventional test procedures difficult to apply. The data presented are restricted to information which is well established and accepted, but the report also identifies areas of testing controversy and highlights current technical needs in the testing area.

The report attempts to document recommended methods, based on a review of the procedures used in a number of organizations. For various reasons, many will want to deviate from these methods. To permit reliable inter-comparisons between laboratories, standardized methods are needed; and it is hoped that for this reason these methods will be adopted. Recommended procedures for tensile, 3-point bend, 4-point bend and precision elastic limit tests are described.

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