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METALLURGY OF ZIRCALOY-2

PART I. THE EFFECTS OF FABRICATION VARIABLES ON THE ANISOTROPY OF MECHANICAL PROPERTIES

P. L. Rittenhouse
M. L. Picklesimer

OAK RIDGE NATIONAL LABORATORY
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P. L. Rittenhouse and M. L. Picklesimer

SUMMARY

The anisotropy of mechanical properties of Zircaloy-2 was studied as a function of fabrication variables. The variation in tensile and impact properties with specimen orientation was taken as the measure of the anisotropy of mechanical properties for each material. A qualitative separation of the effects of the fabrication variables on the resulting anisotropy of mechanical properties is possible, but it takes into consideration only the properties in the rolling plane of the plate. Therefore, since quite appreciable differences may exist between the properties in the rolling plane and those in the direction normal to the plane of the plate, care must be taken to prevent the formulation of erroneous conclusions concerning the effects of the fabrication variables on the anisotropy of mechanical properties. A contractile strain ratio, a ratio of the natural contractile strain in the rolling plane to that in the direction normal to the rolling plane, (measured on the round tensile specimen after testing) is introduced to aid in the interpretation of the tensile data.

Zircaloy-2 fabricated by the generally accepted fabrication procedure possesses a high degree of both crystallographic preferred orientation and anisotropy of mechanical properties. The commercial ORNL-HRP Metallurgy (Oak Ridge National Laboratory-Homogeneous Reactor Project) fabrication schedule (consisting of, in succession, ingot breakdown at a temperature of 1800–1900°F, major reduction at a temperature of 1800–1900°F or 1350–1450°F, a β heat treatment of 1800–1850°F for 30 min followed by either a water quench or a rapid air cool to below 1200°F, a final reduction of 25–40% at 1000°F, and an anneal at 1400–1425°F for 30 min) was found to produce a much more nearly isotropic material. Zircaloy-2 produced by this schedule was, in fact, found to be more nearly isotropic than that produced by any of the schedules investigated. Even so, this material is anisotropic in strain behavior and tensile properties in comparison to the common cubic materials.

The elimination of the intermediate β heat treatment from the ORNL-HRP Metallurgy fabrication schedule resulted in the production of a material whose tensile

properties for all directions in the plane of rolling were essentially the same, but which allowed little contractile strain to occur in the thickness direction of the plate. This indicated that a high degree of three dimensional anisotropy existed in the material.

The effect of cross rolling on the anisotropy of mechanical properties of Zircaloy-2 was found to be a function of the temperature and stage of fabrication at which it was performed, the position of the ingot axis relative to the final fabrication directions, and the type of cross rolling, whether it was unidirectional or rotational.

It was concluded that the use of other methods of examination and interpretation were necessary to satisfactorily evaluate the effects of variation of the fabrication variables on the anisotropy of Zircaloy-2. Preferred orientation determinations and a new contractile strain-axial strain analysis were used in later examinations of the specimens to permit a more complete evaluation.

INTRODUCTION

Interest in Zircaloy-2 as a structural material is at the present time centered in the nuclear reactor field. The two properties which make it attractive for nuclear use are its low thermal-neutron-absorption cross section and its excellent corrosion resistance to most environments. The principal application of Zircaloy-2 has been as cladding in the fabrication of fuel elements and as pressure tubing for water cooling in reactors. Only limited use of this alloy has been made for other engineering applications, one of these being the Zircaloy-2 core tank, or fuel containment vessel, of the Aqueous Homogeneous Reactor. In a study of the relative economics of using Zircaloy-2 or stainless steel as fuel cladding and as a structural material in five power producing thermal reactors, it was found that the use of Zircaloy-2 enables considerable savings to be made through the use of uranium of lower enrichment or reduction in the critical mass.[1] Therefore, it may be

[1] Manson Benedict, "An Economic Appraisal of Stainless Steel and Zirconium in Nuclear Power Reactors," Metal Progress 75(2), 76–81 (February, 1959).

desirable in the future to use Zircaloy-2 pressure vessels and structural members in many nuclear reactors.

For close-packed hexagonal metals and alloys, which include Zircaloy-2, it is known that there is a particularly marked influence of any preferred grain orientation on the directionality of mechanical properties. Directional properties are also known to arise from factors other than crystallographic preferred orientation. These factors may be referred to as mechanical fibering and include grain elongation and the stringering of voids, inclusions, and intermetallic compounds.

The directionality of mechanical properties of plate and sheet material is usually shown by determining the mechanical properties for a number of specimen axis orientations in the plane of the plate. Even if the properties determined are identical for all orientations, this is proof only of isotropy in the plane of the plate. A complete analysis of the state of anisotropy demands examination of the properties in the direction normal to the plane of the plate. Since it is ordinarily impossible to obtain mechanical property specimens for the normal direction from plate and sheet material of the usual range of thicknesses, another measure of directionality of properties is necessary. It was observed[2] in the testing of irradiated and unirradiated materials that Zircaloy-2 round tensile specimens became elliptical when strained, as shown in Fig. 1, and that the ellipticity varied with specimen orientation and fabrication schedule. The ratio of the contractile strains (or the ratio of the major to minor axis of the ellipse of cross section) at the fracture may then be used as a measure of anisotropy in the normal direction. An awareness and understanding of such behavior is quite important in the design of Zircaloy-2 structural members.

At room temperature, Zircaloy-2 is thought to consist of a mixture of α zirconium containing tin and oxygen in solid solution and an intermetallic compound called θ phase[3] composed of zirconium, tin, iron, nickel, and chromium.

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[2] P. L. Rittenhouse and M. L. Picklesimer, Metallurgy of Zircaloy-2 Part II The Effects of Fabrication Variables on the Preferred Orientation and Anisotropy of Strain Behavior, ORNL-2948 (to be published).

[3] L. E. Tanner and D. W. Levinson, The System Zirconium-Iron-Tin, Am. Soc. Metals Preprint No. 166 (1959).

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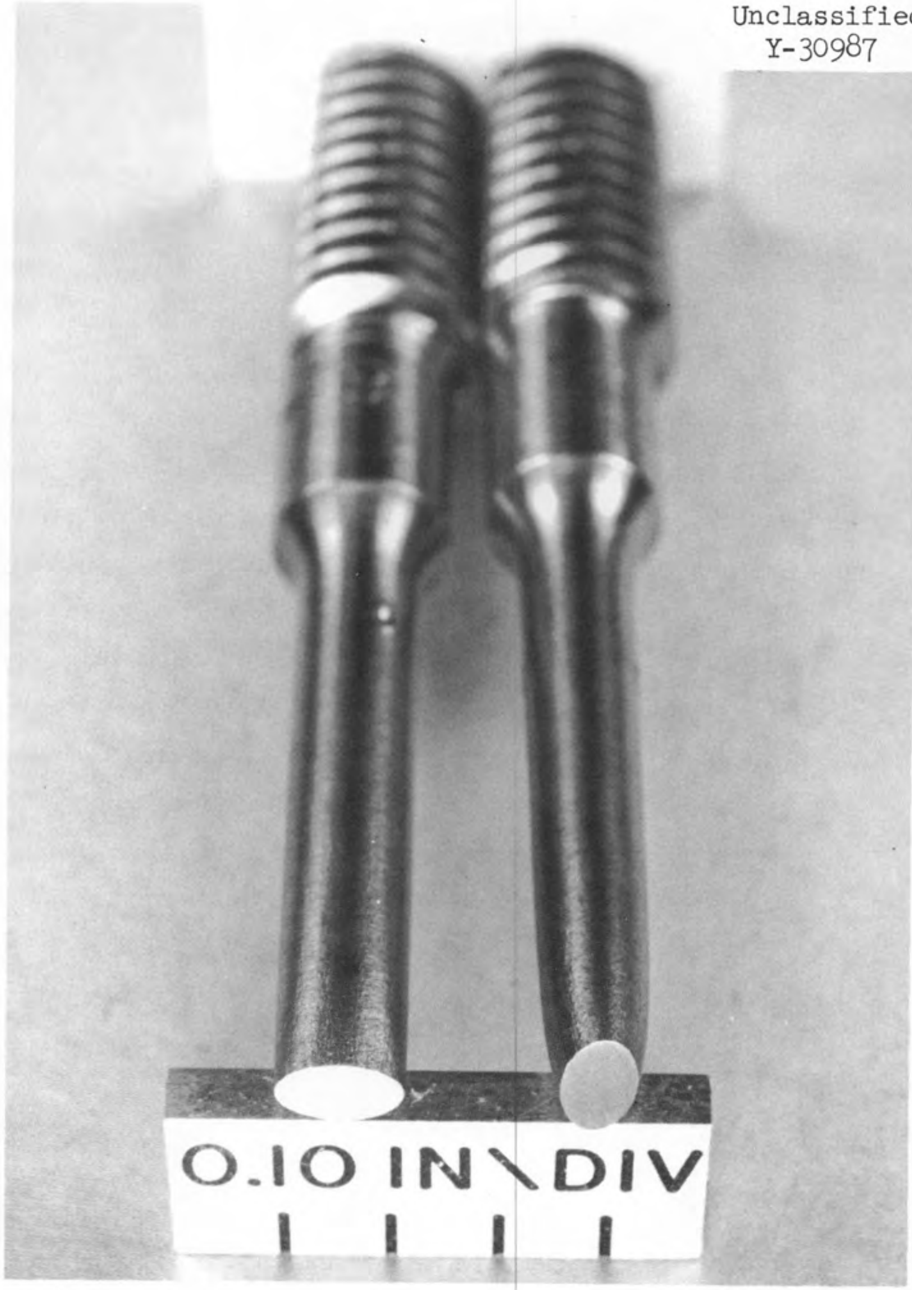

Fig. 1 Photograph of the Ellipticity of Cross Section Developed on Straining a Zircaloy-2 Round Tensile Specimen – Both Ends of the Same Specimen are Shown. One end is rotated 90° to show that the ellipticity is not the result of photography.

Because of the alloying additions, the transformation of the low-temperature close-packed hexagonal α phase to the high-temperature body-centered cubic β phase which occurs in pure zirconium at about 1590°F takes place over the temperature range from 1490 to 1780–1795°F.[4,5,6] Zircaloy-2 exists as a mixture of α and β phases between these temperatures.

The procedure which is generally followed in the commercial fabrication of Zircaloy-2 plate from ingot consists of three major working steps. The ingot is forged to billet after 1-1/2 to 3 hr at 1775°F ± 25°F. Hot rolling of the billet to slab is done at 1675°F ± 25°F after a 1–2 hr preheat. Final hot rolling to plate and annealing are done at 1550°F ± 15°F.[7,8]

The mechanical properties (usually determined on sheet-type specimens) of Zircaloy-2 fabricated by this procedure may be found in a number of reports.[9–16]

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[4] M. L. Picklesimer and G. M. Adamson, Development of a Fabrication Procedure for Zircaloy-2, ORNL-CF-56-11-115 (Nov. 21, 1956).

[5] G. M. Adamson, "Homogeneous Reactor Metallurgy," Fluid Fuel Reactors, pp. 262–279, Addison-Wesley Publishing Company, Inc., 1958.

[6] G. M. Adamson et al., Recent Advances in the Metallurgy of Zirconium and Titanium Alloys of Special Interest in Reactor Technology, Reprint from 2nd UN Geneva Conference, P/1993 USA, Pergamon Press, London, 1959.

[7] W. H. Friske, Standard Zirconium Fabrication Procedures, A paper presented at the Third Zirconium Technology Conference, Westinghouse Bettis Plant, May 1, 1957.

[8] Manufacturing Specifications for Annealed Zircaloy-2 Strip, Bar, and Forging, Carborundum Metals Company, CME-7 (Dec. 29, 1958).

[9] W. L. Mudge and F. Forscher, Mechanical Properties of Zircaloy-2, WAPD-101 (July, 1954).

[10] B. Lustman and F. Kerze, Jr., Metallurgy of Zirconium, p. 742, McGraw-Hill, New York, 1955.

[11] J. G. Goodwin, The Effects of Heat Treatment on the Mechanical and Corrosion Properties of Zircaloy-2, WAPD-NCE-7563 (Feb. 12, 1958).

[12] J. G. Goodwin, Further Studies on the Effect of Heat Treatment on the Tensile and Corrosion Properties of Zircaloy-2, WAPD-ZH-8 (June, 1958).

[13] J. G. Weinberg, Summary of Mechanical Property Data on Vacuum-Melted Zircaloy-2, WAPD-ZH-12 (Nov., 1958).

[14] J. G. Goodwin and J. Grubessich, Tensile Properties of Zircaloy-2, WAPD-ZH-15 (March, 1959).

[15] F. R. Shober et al., The Mechanical Properties of Zirconium and Zircaloy-2, BMI-1168 (Feb., 1957).

[16] G. M. Adamson et al., HRP Quar. Prog. Rep. for Periods Ending April 30 and July 31, 1958, ORNL-2561, pp. 248–250.

Although the actual values for the tensile and yield strengths vary from report to report (which is not surprising in the light of variations in ingot composition, minor differences in fabrication procedure, and differences in specimen design), the transverse direction yield strengths are, in most instances, 10,000–20,000 psi higher than the longitudinal direction yield strengths. Room temperature tensile and yield strengths from three sources are presented in Table I.

TABLE I

ROOM TEMPERATURE TENSILE PROPERTIES OF ZIRCALOY-2

Property	Longitudinal	Transverse
0.2% YS[(a)] - 10^3 psi	49.4 ± 5.5	70.0 ± 4.8
TS[(a)] - 10^3 psi	75.6 ± 3.2	77.5 ± 5.1
0.2% YS[(b)] - 10^3 psi	41.3 ± 5.5	58.6 ± 3.5
TS[(b)] - 10^3 psi	67.8 ± 5.5	68.4 ± 2.5
0.2% YS[(c)] - 10^3 psi	52.3	59.0
TS[(c)] - 10^3 psi	61.4	63.3

(a) W. Mudge and F. Forscher, Mechanical Properties of Zircaloy-2, WAPD-101 (July, 1954).
(b) J. G. Goodwin and J. Grubessich, Tensile Properties of Zircaloy-2, WAPD-ZH-15 (March, 1959).
(c) G. M. Adamson, "Homogeneous Reactor Metallurgy," Fluid Fuel Reactors, Addison-Wesley, pp. 262–279, 1958.

It is easily seen from the directionality of the yield strengths that commercially fabricated Zircaloy-2 is quite anisotropic. Contributions to this anisotropy are made both by the high degree of preferred orientation[5,6,17] and by mechanical fibering. Mechanical fibering is due, in this case, to the formation of stringers of the Sn-Fe-Ni-Cr intermetallic compound (θ phase), the

[17] C. J. McHargue, "Preferred Orientation in Zircaloy-2 Plate," Inter-Company Correspondence with M. L. Picklesimer, Dec. 13, 1955.

stringering of gas voids, and the elongation of grains during fabrication.[4,18,19] The stringers of intermetallic compound are objectionable for a number of reasons. First, they have been shown to be associated with the stringer-type corrosion observed in Zircaloy-2.[20] Secondly, stringers add to the directionality of mechanical properties, especially those which exist as sheets or plates parallel to the rolling plane.[4,21] It is not surprising that the stringers of intermetallic compound should exist as sheets since they are formed from a grain-boundary film of β phase during hot fabrication.[4] Another objection, which has been little considered in the past, is that stringers in the heat-affected zone in weldments of Zircaloy-2 have been observed to open up into voids, probably because of the rapid heating and cooling rates and the high local stresses present during welding.[22] The effect of the gas stringers on the mechanical properties is not quite so great in that they exist as rods or as strings of voids.[23]

During the course of an investigation of the morphology of Zircaloy-2 at the Oak Ridge National Laboratory, it was found that the stringers of intermetallic compound formed during the commercial fabrication of Zircaloy-2 could be eliminated by heating into the β phase field (above 1780°F).[4,5,6] This led to an investigation of fabrication procedures with the objective of the elimination of the stringers. Commercially prepared Zircaloy-2 plate was refabricated by first β heat treating (heat treating in the β phase field for approx 30 min) to dissolve the intermetallic stringers and then quenching and annealing or quenching, warm working, and annealing. The refabrication showed that by β treating, quenching, warm rolling a minimum of 20%, and annealing at 1470°F, a very fine-grained structure with much less preferred orientation[6,17]

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[18] J. D. Grozier, Evolution of Stringers in Zircaloy-2, WAPD-ZH-4 (Feb., 1958).

[19] Studies of Zirconium-Iron-Tin Alloys, ARF-2068-6 (April 30, 1959).

[20] J. G. Goodwin et al., A Summary of the Work Associated with the Solution and Understanding of Stringer-Type Corrosion in Zircaloy-2 and -3, WAPD-212 (April, 1959).

[21] G. M. Adamson et al., HRP Quar. Prog. Rep. Oct. 31, 1956, ORNL-2222, pp. 116–117.

[22] G. M. Adamson et al., HRP Quar. Prog. Rep. July 31, 1956, ORNL-2148, pp. 105–106.

[23] J. D. Grozier, Some Metallographic Observations of Stringers in Zircaloy-2, WAPD-NCE-7562 (Feb. 11, 1958).

was obtained and that the stringers of intermetallic compound present in the parent material were eliminated. As a result of this study, it was recommended that all fabrication be done above 1780°F or below 1490°F to eliminate the presence of an α plus β phase structure during fabrication. It was also recommended that, after the major reduction, the material should be heated to above 1780°F for approx 30 min and quenched rapidly to below 1300°F. The β heat treatment was to be followed by a warm reduction at 950°F of not less than 20% and an anneal of 15–30 min at 1425–1470°F. All sheet, plate, and rod prepared for ORNL by commercial fabricators since this study[4] have been processed by this procedure.

Although a fabrication procedure for Zircaloy-2 was available which eliminated the problem of stringers of intermetallic compound and greatly reduced the preferred orientation, this procedure was not known to yield a material with optimum mechanical properties. This, coupled with the fact that little or nothing was known concerning the effect of fabrication variables on the final state of anisotropy of Zircaloy-2, led to an investigation of a variety of fabrication procedures. The fabrication procedures were designed to show the effect of the variables on the preferred orientation and anisotropy of mechanical properties and to yield the information necessary for the prediction and control of texture. Control of texture was thought to be of equal importance, if not of greater importance, than true randomization, since anisotropy may in some cases actually be beneficial (in certain forming operations, in spherical and cylindrical pressure vessels, and in pipe and tubing).

Studies on the effect of fabrication variables in cubic metals have shown that directionality is a function of, and increases with, increasing cold work during final reduction, an increase in the final annealing temperature, and a decrease in the penultimate annealing temperature.[24,25,26] The degree of

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[24] L. J. Klingler and G. Sachs, J. Aeronaut. Sci., p. 599 (Oct., 1948).
[25] E. W. Palmer and C. S. Smith, Trans. Met. Soc. AIME 147, 164 (1942).
[26] H. L. Burghoff and E. C. Bohlen, Trans. Met. Soc. AIME 147, 144 (1942).

directionality is not believed to be significantly affected by the type or speed of the rolling mill, the roll diameter, the reduction per pass, or whether the rolling is unidirectional or is done with reversed passes through the rolls.[25,27] Although rolling temperature, per se, was not mentioned in the studies, it is obviously related to the degree of cold work. Cross rolling has also been shown to be quite important in the development of texture in both cubic and hexagonal metals.[28-32]

At the onset of the present investigation, the variables which were selected for study were annealing temperature, the number of β heat treatments, working temperatures, and percent final reduction. Cross rolling was introduced as a variable at a later stage of the study. Tensile and impact energy tests and x-ray diffraction preferred orientation determinations were planned for evaluation of the test results.

Early in the testing program, it was realized that the standard mechanical property tests would not yield data by which a comprehensive evaluation of the effects of fabrication variables on the anisotropy could be made. An analysis based on preferred orientation and the axial and contractile strains observed on tensile specimens after testing was found to be superior in most respects for purposes of evaluation, and no complete evaluation of the present work is possible without the use of such an analysis. The detailed mechanical property data are presented, however, as a source of information for the design engineer. This compilation of data should not be used without the full realization that, with respect to the anisotropy of the material, it is incomplete and oftentimes misleading. As a guide to, or reminder of, this fact, a ratio of the contractile strains at fracture has been included as part of the listing of the usual tensile properties.

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[27] W. A. Sisson, Metals and Alloys 4, 193 (1933).

[28] C. J. Smithells and C. E. Ransley, J. Inst. Metals 60, 172 (1937).

[29] C. E. Ransley and H. P. Rooksby, J. Inst. Metals 62, 195 (1938).

[30] R. M. Brick and M. A. Williamson, Trans. Met. Soc. AIME 143, 84 (1941).

[31] R. K. McGeary and B. Lustman, J. Metals 3, 994 (1951).

[32] C. J. McHargue and L. K. Jetter, Progress in Nuclear Energy, Series V Vol. 2, p. 454, Pergamon Press, London, New York, 1959.

EXPERIMENTAL DETAILS AND PROCEDURES

The selection of the fabrication variables was based in part on what was known from cubic materials and in part from information obtained in preliminary studies which led to the present ORNL-HRP Metallurgy fabrication procedure.[4] Working temperatures were selected to give a comparison of the effects of working primarily at high α temperatures (1350–1475°F), and at temperatures in the β field (above 1775°F) plus low (less than 1100°F) and high (1350–1475°F) α temperatures. If the initial breakdown was by forging, the breakdown temperature was 1950°F. If it was by rolling, the temperature was 1900°F. The major reduction was done at 1825–1850°F or at 1475°F. In no case was working in the α plus β phase field permitted. All final reductions were at 1000°F and were 25, 40, 50, or 70%. Also considered as a variable was the number of β heat treatments (1825–1850°F for 30 min followed by a water or rapid air quench) the material received during fabrication.

Since wide sheet and plate are needed in the construction of containment and pressure vessels, it was necessary to introduce cross rolling as another fabrication variable. Cross rolling (final rolling direction was along, perpendicular to, or across the ingot axis) was performed during ingot breakdown, during the major reduction at 1475°F, or in the final reduction at 1000°F. In some cases the material was rotated 90° after each pass, and in others the material was rolled in only one direction after cross rolling was started.

The effect of annealing temperatures, both final and penultimate, was also studied. The penultimate annealing temperatures were 1825–1850°F or 1475°F. Because of the large number of fabrication procedures investigated, it would have been exceedingly difficult to test material annealed at a number of temperatures and times for each fabrication schedule. Instead, a final annealing temperature and time was selected which produced an equiaxed structure and approximately the same grain size in material for all fabrication procedures. The final annealing temperature-time combination selected was 1425°F for 45 min. Step by step details of the experimental fabrication procedures are presented in Table II.

TABLE II

ZIRCALOY-2 FABRICATION SCHEDULE DETAILS

Experimental Schedules[a]

Schedule 1 - Two Intermediate β Heat Treatments, Air Cooled

1. Forged from 4-in. dia to 1-in. plate from 1950°F
2. Annealed 30 min at 1832°F, air cooled
3. Rolled to 1/2 in. at 1000°F
4. As (2)
5. Rolled to 11/32 in. at 1000°F
6. As (2)
7. Rolled to 1/4 in. at 1000°F
8. Annealed 30 min at 1425°F, air cooled

Schedule 2 - Two Intermediate β Heat Treatments, Water Quenched

1. Forged from 4-in. dia to 1-in. plate from 1950°F
2. Annealed 30 min at 1832°F, water quenched
3. Rolled to 1/2 in. at 1000°F
4. As (2)
5. Rolled to 11/32 in. at 1000°F
6. As (2)
7. Rolled to 1/4 in. at 1000°F
8. Annealed 30 min at 1425°F, air cooled

Schedule 3 - One Intermediate β Heat Treatment

1. Forged from 4-in. dia to 1-in. plate from 1950°F
2. Annealed 30 min at 1832°F, air cooled
3. Rolled to 11/32 in. at 1000°F
4. As (2)
5. Rolled to 1/4 in. at 1000°F
6. Annealed 30 min at 1425°F, air cooled

TABLE II (Cont'd)

Schedule 4 - β Reduction Plus 25% Low α Reduction

1. Forged from 4-in. dia to 1-3/4-in. plate from 1950°F
2. Forged to 1 in. at 1475°F
3. Annealed 30 min at 1832°F, air cooled
4. Rolled to 11/32 in. at 1832°F
5. As (2)
6. Rolled to 1/4 in. at 1000°F
7. Annealed 30 min at 1425°F, air cooled

Schedule 5 - β Reduction Plus 50% Low α Reduction

1. Forged from 4-in. dia to 1-in. plate from 1950°F
2. Rolled to 1/2 in. at 1832°F
3. Annealed 30 min at 1832°F, air cooled
4. Rolled to 1/4 in. at 1000°F
5. Annealed 30 min at 1425°F, air cooled

Schedule 6 - β Reduction Plus 70% Low α Reduction

1. Forged from 4-in. dia to 1-in. plate from 1950°F
2. Annealed 30 min at 1832°F, air cooled
3. Rolled to 1/4 in. at 1000°F
4. Annealed 30 min at 1425°F, air cooled

Schedule 7 - β Reduction Plus High α Reduction

1. Forged from 4-in. dia to 1-in. plate from 1950°F
2. Annealed 30 min at 1832°F, air cooled
3. Rolled to 1/4 in. at 1475°F
4. Annealed 30 min at 1425°F, air cooled

Schedule 8 - α Worked, 70% Low α

1. Forged from 4-in. dia to 1-3/4-in. plate from 1950°F
2. Forged to 1 in. at 1475°F
3. Annealed 30 min at 1475°F, air cooled
4. Rolled to 1/4 in. at 1000°F
5. Annealed 30 min at 1425°F, air cooled

TABLE II (Cont'd)

Schedule 9 - α Worked, 50% Low α

1. Forged from 4-in. dia to 1-3/4-in. plate from 1950°F
2. Forged to 1 in. at 1475°F
3. Rolled to 1/2 in. at 1475°F
4. Annealed 30 min at 1475°F, air cooled
5. Rolled to 1/4 in. at 1000°F
6. Annealed 30 min at 1425°F, air cooled

Schedule 10 - Cross Rolled After β Heat Treatment

1. Forged from 4-in. dia to 1-3/4-in. plate from 1950°F
2. Forged to 1 in. at 1475°F
3. Annealed 45 min at 1832°F, water quenched
4. Rolled to 1/2 in. at 1400°F
5. Annealed 30 min at 1832°F, water quenched
6. Cross rolled to 9/32 in. at 1000°F
7. Annealed 30 min at 1425°F, air cooled

Schedule 11 - HRP Commercial Fabrication Procedure, 25% Final Reduction

1. Rolled from 1-1/2-in. ingot slice to 3/4 in. from 1900°F
2. Rolled to 3/8 in. at 1450°F
3. Annealed 30 min at 1850°F, air cooled
4. Rolled to 9/32 in. at 1000°F
5. Annealed 30 min at 1425°F, air cooled

Schedule 12 - Modified HRP Commercial Fabrication Procedure, 40% Final Reduction

1. Rolled from 1-1/2-in. ingot slice to 3/4 in. from 1900°F
2. Rolled to 15/32 in. at 1450°F
3. Annealed 30 min at 1850°F, air cooled
4. Rolled to 9/32 in. at 1000°F
5. Annealed 30 min at 1425°F

Schedule 13 - Cross Rolled After β Heat Treatment

1. Rolled from 1-1/2-in. ingot slice to 3/4 in. from 1900°F
2. Rolled to 15/32 in. at 1450°F

TABLE II (Cont'd)

Schedule 13 (continued)

3. Annealed 30 min at 1850°F, air cooled
4. Rolled to 9/32 in at 1000°F turning plate 90° after each pass (first and last passes in cross-rolling direction)
5. Annealed 30 min at 1425°F, air cooled

Schedule 14 - Cross Rolled During High α Reduction

1. Rolled from 1-1/2-in. ingot slice to 3/4 in. from 1900°F
2. Rolled to 3/8 in. at 1450°F turning plate 90° after each pass
3. Annealed 30 min at 1850°F, air cooled
4. Rolled to 9/32 in. at 1000°F in original rolling direction
5. Annealed 30 min at 1425°F, air cooled

Schedule 15 - Straight-Rolled β Reduction

1. Rolled from 1-1/2-in. ingot slice to 3/8 in. from 1900°F
2. Annealed 30 min at 1850°F, air cooled
3. Rolled to 9/32 in. at 1000°F
4. Annealed 30 min at 1425°F, air cooled

Schedule 16 - Cross-Rolled β Reduction

1. Rolled from 1-1/2-in. ingot slice to 3/8 in. from 1900°F turning plate 90° after each pass
2. Annealed 30 min at 1850°F, air cooled
3. Rolled to 9/32 in. at 1000°F in original direction of rolling
4. Annealed 30 min at 1425°F, air cooled

Commercially Fabricated Schedules

Schedule 17 - HRP Commercial Fabrication Procedure (Jessop Steel Co.)

1. Rolled from 12-in.-dia ingot to 4-in. slab from 1850°F
2. Rolled to 3/4 in. at 1800°F
3. Rolled to 27/64 in. at 1450°F
4. Annealed 45 min at 1850°F, water spray quench
5. Rolled to 9/32 in. at 1100°F
6. Annealed 30 min at 1425°F, air cooled

TABLE II (Cont'd)

Schedule 18 - HRP Commercial Fabrication Procedure for Wide Plate (Jessop Steel Co.)

1. Rolled from 12-in.-dia ingot to 4-in. slab at 1850°F
2. Slab turned and rolled to 7/8 in. at 1800°F (ingot axis in transverse direction)
3. Rolled to 25/32 in. at 1450°F
4. Annealed 45 min at 1850°F, water spray quench
5. Rolled to 1/2 in. at 1100°F
6. Annealed 30 min at 1425°F, air cooled

Schedule 62 - HRP Commercial Fabrication Procedure (Item 62 - Allegheny-Ludlum Steel Co.)

1. Rolled from 12-in.-dia ingot to 1-in. plate at 1900°F
2. Rolled to 5/16 in. at 1450°F
3. Annealed 30 min at 1832°F, air cooled
4. Rolled to 1/4 in. at 1000°F
5. Annealed 30 min at 1425°F, air cooled

Schedule J - HRP Commercial Fabrication Procedure for Wide Plate (Jessop Steel Co.)

1. Rolled from 12-in.-dia by 38-in. long ingot to 52 in. long at 1850°F
2. Slab turned and rolled to 3/4 in. at 1850°F (ingot axis in transverse direction)
3. Rolled to 7/16 in. at 1450°F
4. Annealed 30 min at 1832°F, water spray quench
5. Rolled to 5/16 in. at 1000°F
6. Annealed 30 min at 1425°F, air cooled

(a) Schedules 1–10: All 1-in. plate machined on both surfaces to 13/16 in. before further fabrication to remove forging defects and oxygen-contaminated surface layer.

Material for the experimental fabrication schedules was obtained from two sources. Most of the material (for schedules 1 through 10) came from two 4-in.-dia Zircaloy-2 ingots, inert-atmosphere melted by Armour Research Foundation from scrap sheet supplied by ORNL. Ingot No. 1 was forged to 1-in. plate at 1950°F. Ingot No. 2 was forged to 1-3/4-in. plate at 1950°F and then forged to 1 in. at 1475°F. All of the 1-in. plate was machined to 13/16 in. before further fabrication. The starting material for the other experimental fabrication schedules was a 1-3/8-in.-thick slice from the top of a 1000-lb inert-atmosphere-melted Zircaloy-2 ingot (Ingot HZC-1013-22VS30). In addition to the experimentally fabricated Zircaloy-2 materials, specimens were obtained from four lots of Zircaloy-2 produced by commercial fabricators from 1000-lb ingots to ORNL-HRP Metallurgy specifications

All rolling of the experimental schedules was done at ORNL by the Metallurgy Division Fabrication Group using a two-high 20-in.-dia roll Mesta mill. The mill was programmed for 10% reduction per pass at all rolling temperatures. For a few of the schedules, however, the reduction per pass at 1832°F was 20%. Rolling preheats and reheats were done in an electric box-type furnace equipped with a ceramic-lined (Al_2O_3) Inconel muffle, continuously flushed with argon. The preheat time for rolling at 1825–1850°F was 30 min; for rolling at 1475 and 1000°F, it was 15–30 min. Material rolled at any temperature was reheated for 5–10 min after each pass. Beta heat treatments (1825–1850°F) and intermediate α anneals (1475°F) were for 30 min, followed by a water or rapid air quench. Final annealing (1425°F, 30 min, air cool) was done in a small laboratory muffle furnace with an argon atmosphere after the material was cut into specimen blanks.

The annealed specimen blanks were machined into tensile specimens (1/8-in.-dia, 1-in.-long gage section) and 0.2-in.-square subsize Izod impact specimens. Detailed drawings of the tensile and impact specimens are shown in Fig. 2. Tensile testing was performed on a 12,000-lb Baldwin Hydraulic machine at a constant head rate of 0.05 in./min. Load-elongation records were made for all of the specimens up to conventional strains of 0.01, and for some specimens, to fracture. Duplicate longitudinal and transverse direction specimens were tested for all schedules and, where material was available, at 22-1/2°

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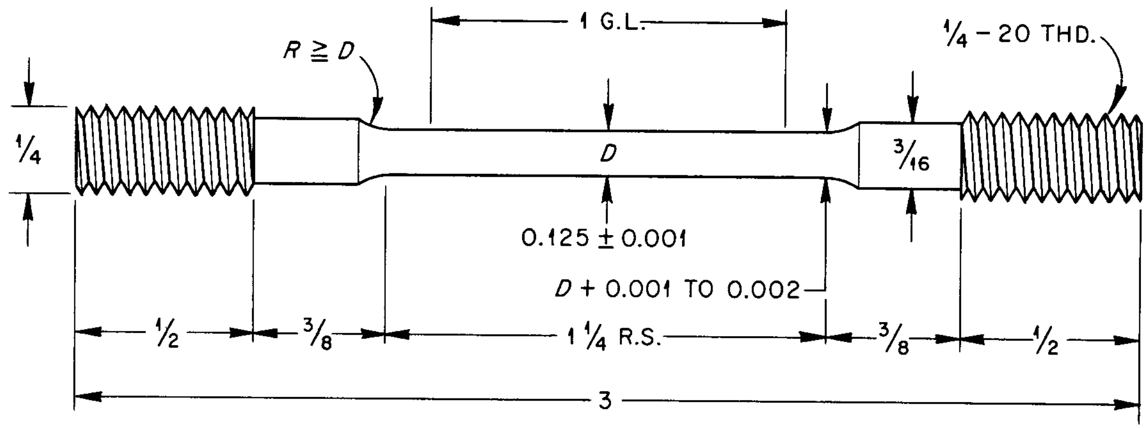
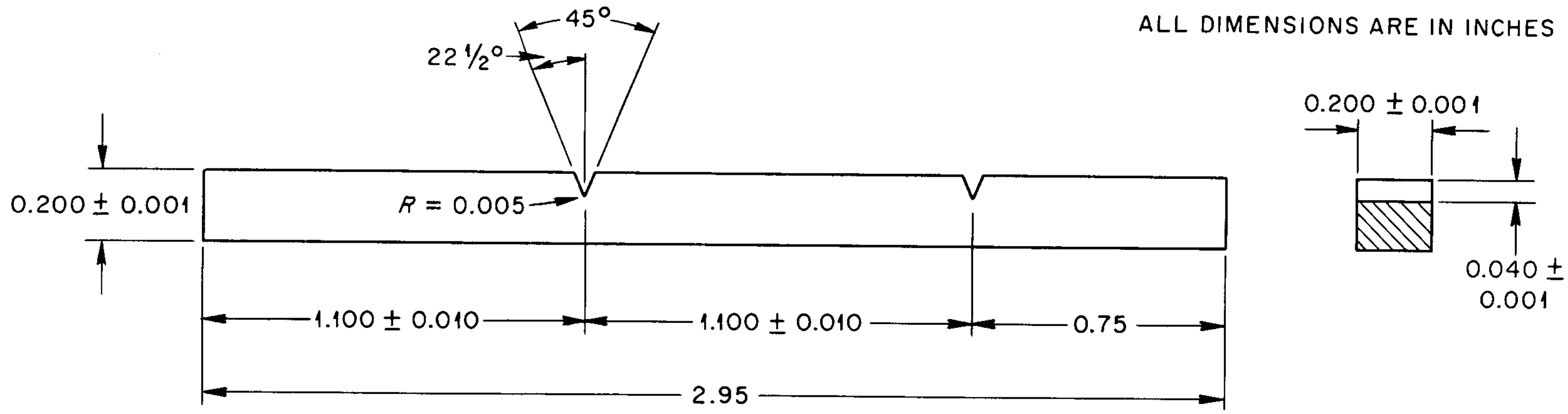


(a) TENSILE SPECIMEN

ALL DIMENSIONS ARE IN INCHES



(b) SUBSIZE DOUBLE-BREAK IZOD IMPACT SPECIMEN

Fig. 2. Detailed Drawings of the Tensile and Impact Specimens.

increments from the longitudinal toward the transverse direction. Specimens were tested at 75 (room temperature), 302, and 572°F, but specimens of all orientations were not pulled at the higher temperatures. A few sheet-type tensile specimens of Zircaloy-2 fabricated to ORNL-HRP Metallurgy specifications by Allegheny-Ludlum Steel Company (1/2-in. plate fabricated as schedule 62) and Jessop Steel Company (schedules 17 and 18) were also tested. Data obtained in the tensile tests for all specimens were ultimate tensile strength, 0.2% offset yield strength, percent extension in 1 in., reduction in area, an approximate value for the modulus of elasticity, and the ratio of the normal to the planar natural contractile strain at the fracture.

The results obtained on impact testing of zirconium and Zircaloy-2 have been found to vary markedly with specimen and notch orientation.[33–36] Therefore, the impact energy curves obtained by testing specimens of a number of orientations may be used as a measure of anisotropy. The subsize Izod impact specimens tested in this study were generally of the four orientations shown in Fig. 3. A few vertically notched specimens with specimen axes at angles between the rolling and transverse directions were also broken.

The Izod impact test machine used was of standard design (Tinius-Olson) except that the specimen vise was modified to allow contact-resistance heating of the specimens to the test temperature. Temperatures below room temperature were obtained by cooling the specimens in liquid nitrogen and then allowing them to warm to the desired test temperature in the vise. Test temperatures ranged from -320°F to 572°F.

A factor which must be considered in the impact testing of Zircaloy-2 is the effect of hydrogen on the impact energy. In zirconium, hydrogen levels as low as 10 ppm can cause an appreciable reduction in impact strength.[34] Hydrogen in Zircaloy-2 both raises the transition temperature and lowers the impact

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[33] G. M. Adamson _et al._, _HRP Quar. Prog. Rep. for Periods Ending April 30 and July 31, 1958_, ORNL-2561, pp. 248–250.

[34] W. L. Mudge, Jr., "Effect of Hydrogen on the Embrittlement of Zirconium and Zirconium-Tin Alloys," _Zirconium and Zirconium Alloys_, p. 146, American Society of Metals, Cleveland, Ohio, 1953.

[35] G. M. Adamson _et al._, _HRP Quar. Prog. Rep._, _April 30, 1957_, ORNL-2331, pp. 132–133.

[36] G. M. Adamson _et al._, _HRP Quar. Prog. Rep._, _Jan. 31, 1958_, ORNL-2493, pp. 145–146.

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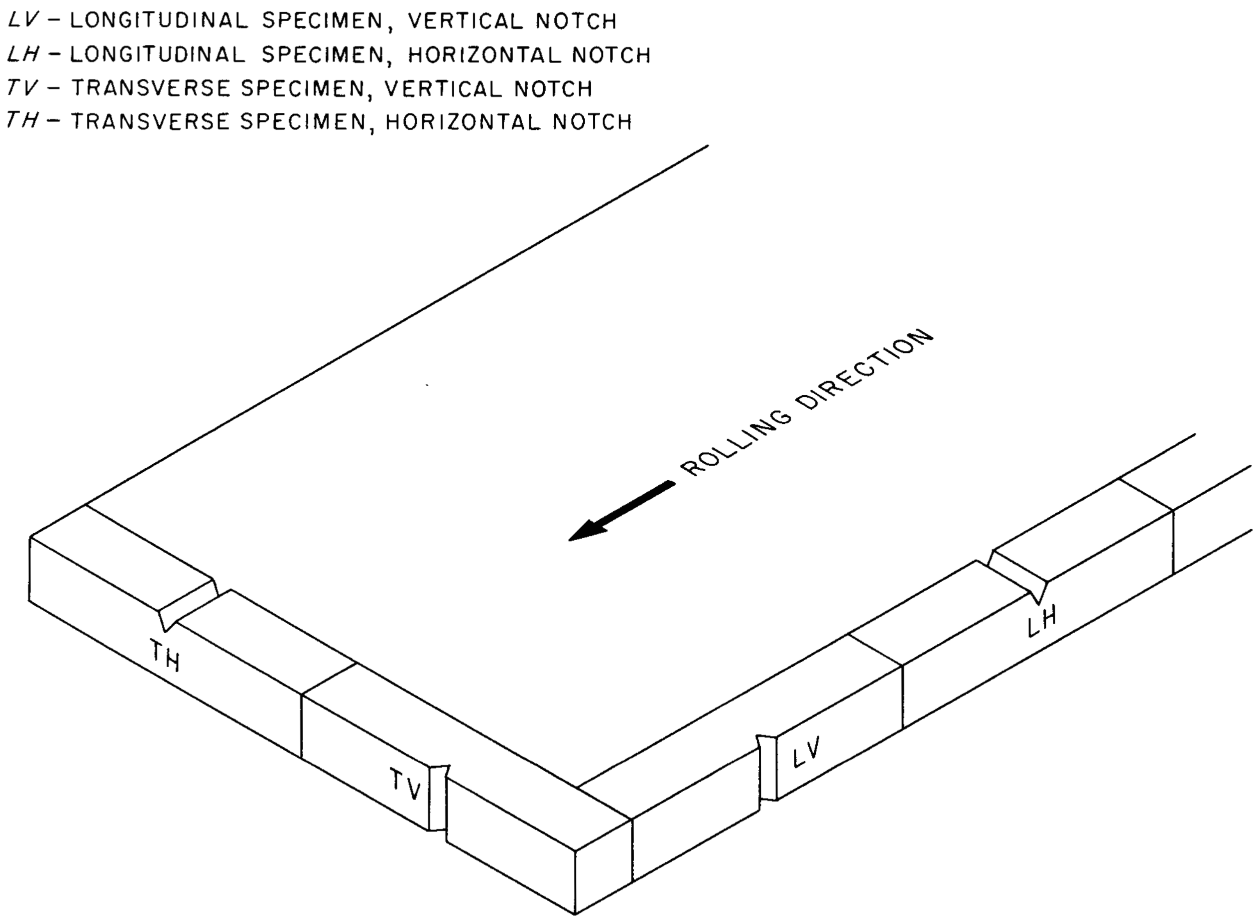

Fig. 3. Impact Specimen Notch Orientation

strength.[33] Therefore, in order to compare the impact properties of Zircaloy-2 fabricated by different procedures, it is necessary to know the hydrogen content of each material. Hydrogen contents of the test materials are reported in the section on results (Table VIII).

Details of and data from the x-ray diffraction study of the preferred orientation of the fabricated Zircaloy-2 materials are discussed in Part II of this report.[37]

RESULTS AND DISCUSSION OF RESULTS

Results of Tensile Property Tests

Tensile Property Data. Tensile and yield strengths, percent extension in 1 in., reduction in area, modulus of elasticity, and contractile strain ratio for all of the fabrication schedules are reported in Table III. The values reported are the averages of duplicate specimens. The maximum differences in yield strengths between duplicate specimens was 1800 psi except for one set for which the difference was 2400 psi. The maximum differences in tensile strength between duplicate specimens was 2800 psi except for two sets, 4000 and 4400 psi. In most sets, the differences were less than 1200 psi for both yield and tensile strengths. Load-elongation curves for specimens of a number of the schedules are shown in Appendix I.

The conventional tensile data for all of the fabrication schedules fall, with few exceptions, into a rather narrow scatter band, especially so for the tensile and yield strengths, Figs. 4-6. The tensile strengths for the two α-worked materials, schedules 8 and 9, are, however, appreciably below the scatter band of the other eighteen schedules. Reduction in area and percent extension for some orientations in schedules 4, 7, and J are also noticeably lower than the values found generally.

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[37] P. L. Rittenhouse and M. L. Picklesimer, Metallurgy of Zircaloy-2 Part II The Effects of Fabrication Variables on the Preferred Orientation and Anisotropy of Strain Behavior, ORNL-2948 (to be published).

TABLE III

TENSILE PROPERTIES OF ZIRCALOY-2[a]

Fabrication Schedule	Specimen[b] Orientation	Test Temp.[c] °F	Tensile Strength 10^3 psi	Yield Strength 10^3 psi	Percent Extension in 1 in.	Reduction in Area Percent	Modulus of Elasticity[d] 10^6 psi	$R_{c\bar{\epsilon}}$ Contractile Strain Ratio[e]
1	RD	75	77.8	58.0	24.8	46.0	13.9	0.92
Two Inter-	22-1/2°	75	75.6	56.6	26.0	47.2	14.9	0.48
mediate β Heat	45°	75	72.4	58.5	28.0	49.2	13.2	0.45
Treatments,	67-1/2°	75	74.4	64.6	22.5	48.2	16.0	0.47
Air Cooled	TD	75	73.2	62.6	22.0	52.8	16.8	0.29
	RD	302	57.2	38.2	24.5	49.3	12.6	0.87
	RD	572	36.5	23.4	26.0	63.0	11.9	0.85
2	RD	75	76.2	56.3	23.0	48.0	14.5	0.62
Two Inter-	22-1/2°	75	76.3	57.9	22.5	47.3	16.7	0.64
mediate β Heat	45°	75	74.3	59.9	22.5	44.8	13.0	0.54
Treatments,	67-1/2°	75	74.3	62.6	22.5	49.1	15.5	0.45
Water Quenched	TD	75	77.1	69.0	22.5	49.6	15.7	0.44
	RD	302	57.4	38.6	24.8	49.9	13.2	0.69
	RD	572	36.5	22.2	24.5	72.5	9.4	0.72
3	RD	75	79.4	61.9	22.5	46.1	16.2	0.43
One Inter-	22-1/2°	75	81.2	62.8	25.0	46.5	17.1	0.50
mediate β Heat	45°	75	77.5	66.1	21.0	46.7	15.1	0.47
Treatment	67-1/2°	75	77.8	67.4	21.0	44.7	15.2	0.35
	TD	75	79.6	70.2	20.0	48.8	15.0	0.40
	RD	302	60.2	43.2	22.2	48.0	11.2	0.42
	RD	572	39.0	24.5	24.0	63.7	8.8	0.48

TABLE III (Cont'd)

Fabrication Schedule	Specimen Orientation[b]	Test Temp.[c] °F	Tensile Strength 10^3 psi	Yield Strength 10^3 psi	Percent Extension in 1 in.	Reduction in Area Percent	Modulus of Elasticity[d] 10^6 psi	$R_{c\bar{\epsilon}}$ Contractile Strain Ratio[e]
4	RD	75	73.6	52.2	15.2	19.8	14.7	0.50
β Reduction	22-1/2°	75	74.5	52.9	20.0	39.5	13.2	0.41
Plus 25% Low	45°	75	72.9	57.5	18.0	40.8	13.0	0.35
α Reduction	67-1/2°	75	72.1	57.5	18.0	41.4	14.2	0.31
	TD	75	74.2	61.4	17.5	41.5	14.6	0.43
	RD	302	54.7	37.7	19.5	46.1	13.8	0.48
	RD	572	36.4	22.2	24.5	64.0	11.4	0.47
5	RD	75	80.2	62.4	19.2	42.6	15.1	0.43
β Reduction	TD	75	79.5	73.0	18.2	47.4	15.4	0.32
Plus 50% Low								
α Reduction								
6	RD	75	72.9	55.8	21.2	46.5	16.1	0.35
β Reduction	22-1/2°	75	69.9	54.8	25.0	45.6	16.0	0.27
Plus 70% Low	45°	75	66.8	56.6	25.0	48.3	16.6	0.24
α Reduction	67-1/2°	75	67.4	59.4	24.0	52.4	13.9	0.23
	TD	75	70.2	62.6	22.0	51.8	15.8	0.23
	RD	302	52.8	40.3	22.0	49.3	-	0.36
	RD	572	36.9	23.1	28.2	61.5	-	0.33
7	RD	75	82.0	56.0	20.0	30.7	14.7	0.41
β Reduction	TD	75	78.6	68.4	11.2	34.2	15.6	0.18
Plus High								
α Reduction								
8	RD	75	67.8	54.9	24.2	46.8	15.3	0.13
α Worked,	22-1/2°	75	66.5	53.7	22.5	51.1	15.3	0.13
70% Low	45°	75	66.6	56.2	25.0	48.8	14.9	0.13
α Reduction	67-1/2°	75	65.3	55.8	25.0	50.1	13.9	0.13
	TD	75	68.0	58.3	19.5	43.6	15.6	0.13
	RD	302	47.6	36.4	29.0	52.3	15.5	0.14
	RD	572	33.4	22.5	32.0	63.6	12.5	0.17

TABLE III (Cont'd)

Fabrication Schedule	Specimen Orientation(b)	Test Temp.(c) °F	Tensile Strength 10^3 psi	Yield Strength 10^3 psi	Percent Extension in 1 in.	Reduction in Area Percent	Modulus of Elasticity(d) 10^6 psi	$R_{c\bar{\epsilon}}$ Contractile Strain Ratio(e)
9	RD	75	68.3	53.5	22.5	47.7	14.7	0.17
α Worked,	TD	75	67.0	55.7	21.5	48.1	15.6	0.13
50% Low								
α Reduction								
10	RD	75	75.0	57.0	22.5	49.2	16.1	0.48
Cross Rolled	TD	75	73.5	66.6	21.7	51.8	16.0	0.28
After β Heat	RD	302	58.0	42.4	26.5	53.4	10.8	0.59
Treatment	RD	572	38.0	24.6	32.5	63.4	13.4	0.56
	TD	572	35.6	28.5	34.0	70.8	12.3	0.32
11	RD	75	72.9	52.1	23.0	44.2	15.2	0.89
HRP Commercial	45°	75	71.8	57.0	23.0	44.4	14.9	0.55
Fabrication	TD	75	72.6	62.6	26.0	49.4	16.1	0.54
Procedure, 25%	RD	302	53.6	38.2	31.5	49.9	-	0.94
Final Reduction	TD	302	51.6	43.3	37.5	54.8	15.0	0.57
	RD	572	35.4	21.0	31.0	64.7	9.3	0.88
	TD	572	33.3	24.6	31.0	65.9	13.7	0.53
12	RD	75	74.7	52.5	23.0	44.9	16.0	0.69
Modified HRP	45°	75	70.8	58.3	22.5	45.7	16.0	0.42
Commercial	TD	75	73.1	62.7	22.2	49.0	15.4	0.41
Fabrication	RD	302	54.4	35.7	32.5	53.1	13.8	0.69
Procedure, 40%	TD	302	51.9	43.3	33.0	55.6	11.2	0.41
Final Reduction	RD	572	35.7	20.8	32.0	67.2	-	0.65
	TD	572	33.8	25.3	31.0	67.6	12.6	0.38
13	RD	75	71.5	55.5	23.0	49.5	14.3	0.36
Cross Rolled	45°	75	72.9	58.8	24.5	46.8	15.7	0.36
After β Heat	TD	75	70.9	59.0	22.5	50.5	15.8	0.35
Treatment	RD	302	52.2	37.1	35.0	55.4	14.3	0.40
	TD	302	50.2	39.0	36.0	56.9	15.4	0.36
	RD	572	33.5	21.0	36.5	68.9	9.9	0.39
	TD	572	33.2	22.6	35.0	69.0	9.9	0.35

TABLE III (Cont'd)

Fabrication Schedule	Specimen Orientation(b)	Test Temp.(c) °F	Tensile Strength 10^3 psi	Yield Strength 10^3 psi	Percent Extension in 1 in.	Reduction in Area Percent	Modulus of Elasticity(d) 10^6 psi	$R_{c\bar{\epsilon}}$ Contractile Strain Ratio(e)
14	RD	75	75.7	59.3	24.0	47.4	15.8	0.84
Cross Rolled	45°	75	74.1	63.6	22.2	46.8	16.8	0.64
During High	TD	75	69.1	58.6	23.2	50.6	15.7	0.28
α Reduction	RD	302	53.9	37.2	34.5	50.3	13.9	0.95
	TD	302	49.2	39.6	41.0	57.0	12.0	0.36
	RD	572	35.0	21.8	34.5	65.4	9.3	0.94
	TD	572	33.0	24.2	36.0	69.2	10.3	0.41
15	RD	75	74.4	56.3	21.2	47.5	16.6	0.75
Straight-	45°	75	72.6	61.6	20.0	46.7	16.2	0.63
Rolled β	TD	75	73.8	65.0	23.0	46.2	15.7	0.51
Reduction	RD	302	53.4	36.8	33.0	50.2	12.4	0.89
	TD	302	52.4	44.6	34.0	56.6	13.7	0.52
	RD	572	34.8	21.8	30.5	66.9	9.5	0.86
	TD	572	33.4	25.5	33.0	68.9	10.7	0.49
16	RD	75	73.9	57.5	22.0	45.9	17.7	0.58
Cross-Rolled	45°	75	71.7	60.5	23.0	44.5	16.7	0.47
β Reduction	TD	75	71.9	59.2	23.0	50.6	16.2	0.44
	RD	302	52.6	36.8	36.0	50.0	12.0	0.64
	TD	302	49.8	40.4	39.0	56.8	12.0	0.42
	TD	572	32.3	22.4	35.0	69.4	9.2	0.40
17	RD	75	80.2	57.2	24.1	44.6	15.3	0.62
HRP Commercial	TD	75	77.4	69.8	23.7	50.4	15.6	0.38
Fabrication	RD	572	38.0	22.9	33.9	66.0	16.0	0.60
Procedure	TD	572	35.1	27.1	37.6	70.6	11.6	0.34
(Jessop Steel								
Company)								
18	RD	75	77.6	54.7	24.5	43.0	13.9	0.88
HRP Fabrication	TD	75	74.9	69.4	22.5	49.8	14.9	0.43
Procedure for	RD	302	57.6	37.2	30.0	49.9	-	0.89
Wide Plate	TD	302	51.4	47.6	36.5	57.3	-	0.46
(Jessop Steel	RD	572	37.4	22.5	37.2	64.6	9.6	0.86
Company)	TD	572	33.8	27.2	37.0	69.3	-	0.42

TABLE III (Cont'd)

Fabrication Schedule	Specimen Orientation[b]	Test Temp.[c] °F	Tensile Strength 10^3 psi	Yield Strength 10^3 psi	Percent Extension in 1 in.	Reduction in Area Percent	Modulus of Elasticity[d] 10^6 psi	$R_{c\bar{\epsilon}}$ Contractile Strain Ratio[e]
62	RD	75	75.8	55.8	22.5	44.6	16.8	0.71
HRP Commercial	TD	75	74.2	63.2	22.2	43.6	16.3	0.45
Fabrication	RD	302	57.2	34.8	26.0	50.4	15.5	0.73
Procedure	TD	302	52.0	43.3	23.0	-	13.6	-
(Item 62 -								
Allegheny Ludlum								
Steel Company)								
J	RD	75	74.9	52.0	22.0	33.6	15.9	2.29
HRP Commercial	22-1/2°	75	75.8	63.2	18.5	36.2	15.1	0.55
Fabrication	45°	75	74.3	66.1	18.0	41.5	17.0	0.81
Procedure for	67-1/2°	75	76.6	71.0	18.7	44.0	15.3	0.59
Wide Plate	TD	75	78.1	70.0	21.5	44.8	16.7	0.67
(Jessop Steel	RD	302	55.9	32.9	20.0	36.6	-	2.58
Company)	TD	302	56.6	48.4	23.5	51.2	-	0.87
	RD	572	36.7	25.0	26.5	56.7	9.7	2.12
	TD	572	36.3	30.9	29.0	65.6	9.9	0.65

(a) Tests were conducted in duplicate. The values reported are the averages.

(b) RD - Rolling direction
22-1/2° - 22-1/2° from rolling direction
45° - 45° from rolling direction
67-1/2° - 67-1/2° from rolling direction
TD - Transverse direction

(c) Test temperatures were recorded in °C but are presented in °F for the convenience of the reader.

(d) See discussion in text.

(e) Ratio of the natural contractile strain in the normal direction to the plate to the natural contractile strain in the plane of the plate. Strains measured at the fracture. For truly isotropic material $R_{c\bar{\epsilon}} = 1.0$ for all specimen orientations. All tests were conducted in duplicate.

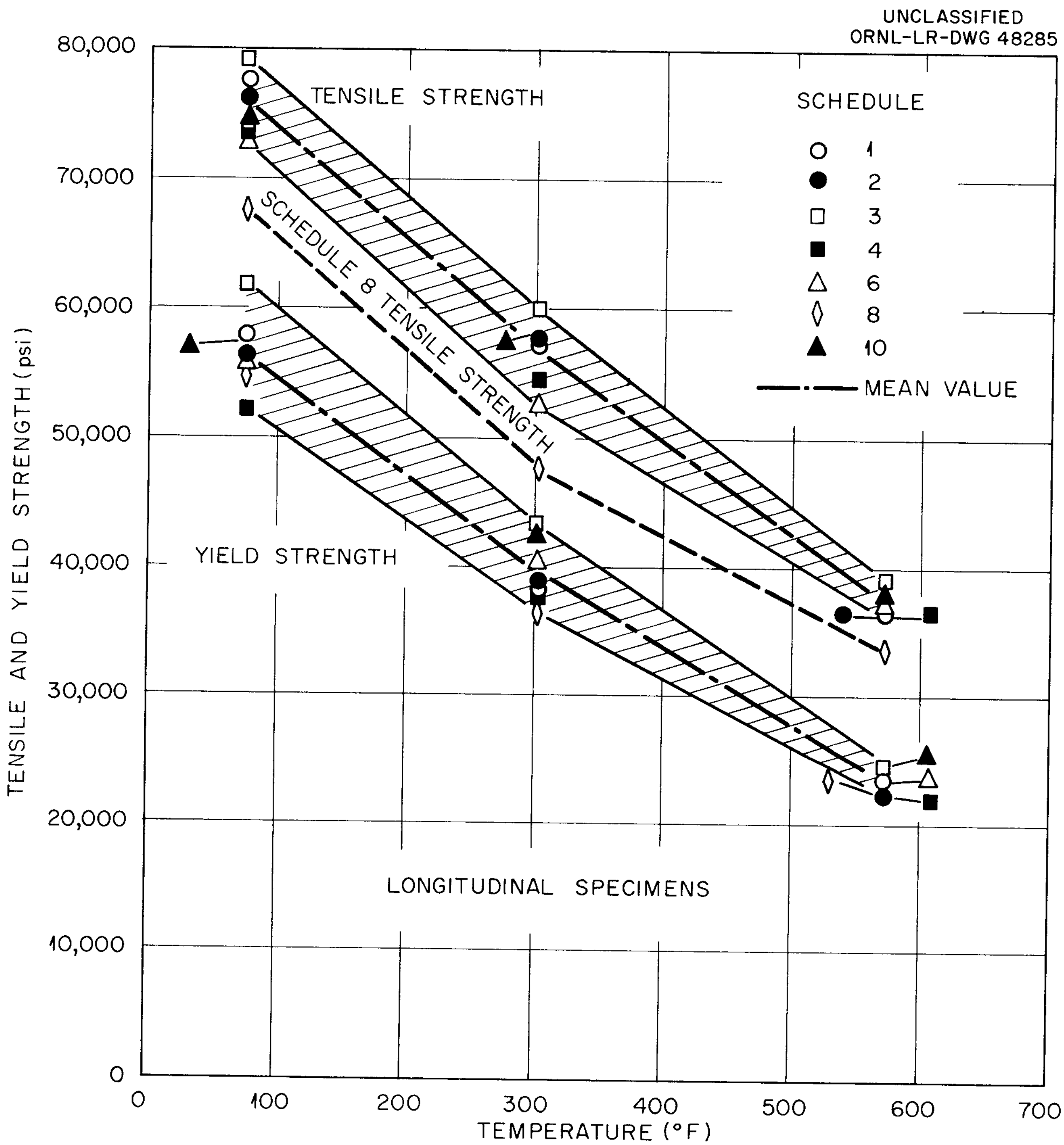

Fig. 4. Longitudinal Direction Tensile and Yield Strength as a Function of Temperature.

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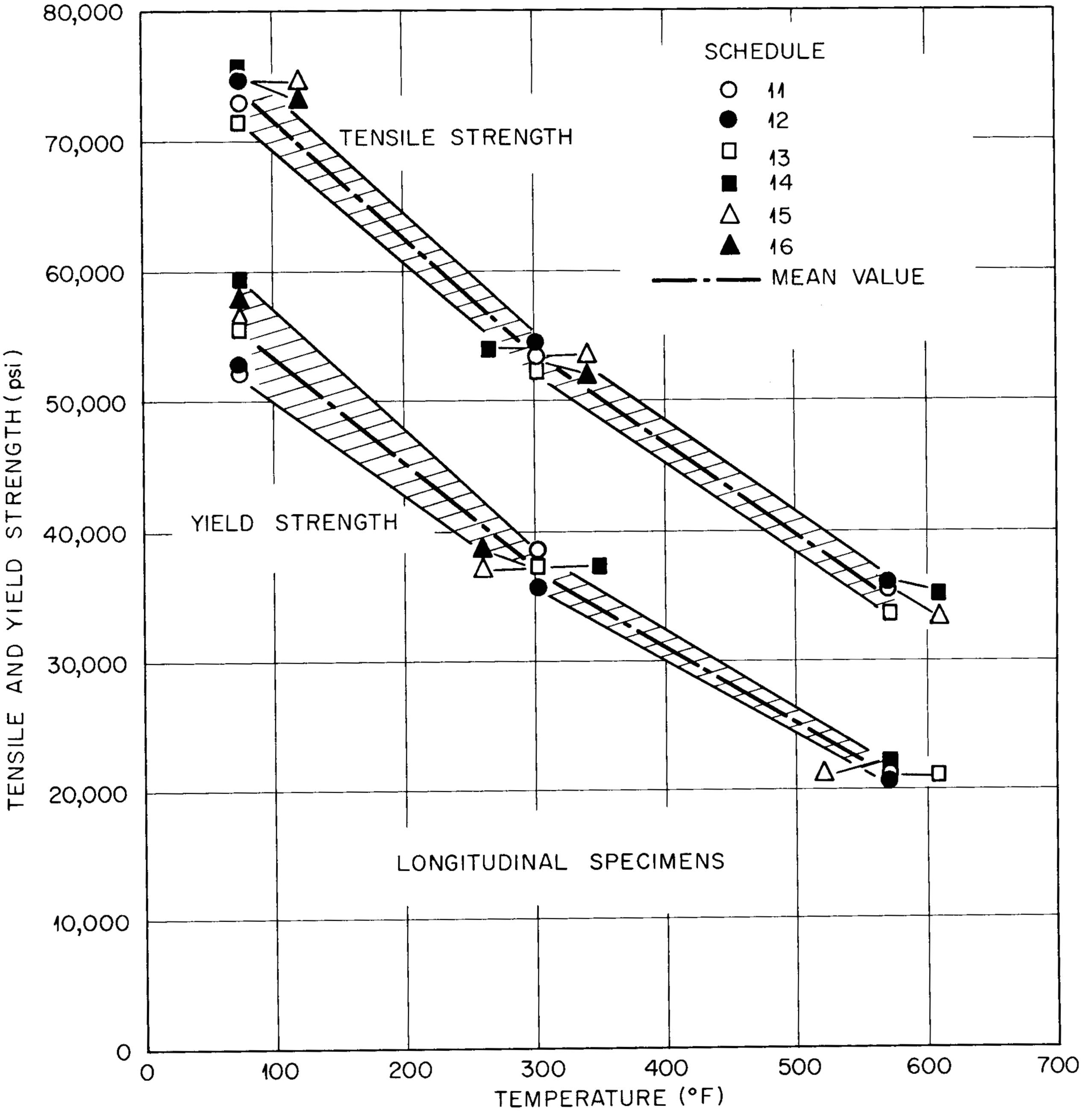

Fig. 5. Longitudinal Direction Tensile and Yield Strength as a Function of Temperature.

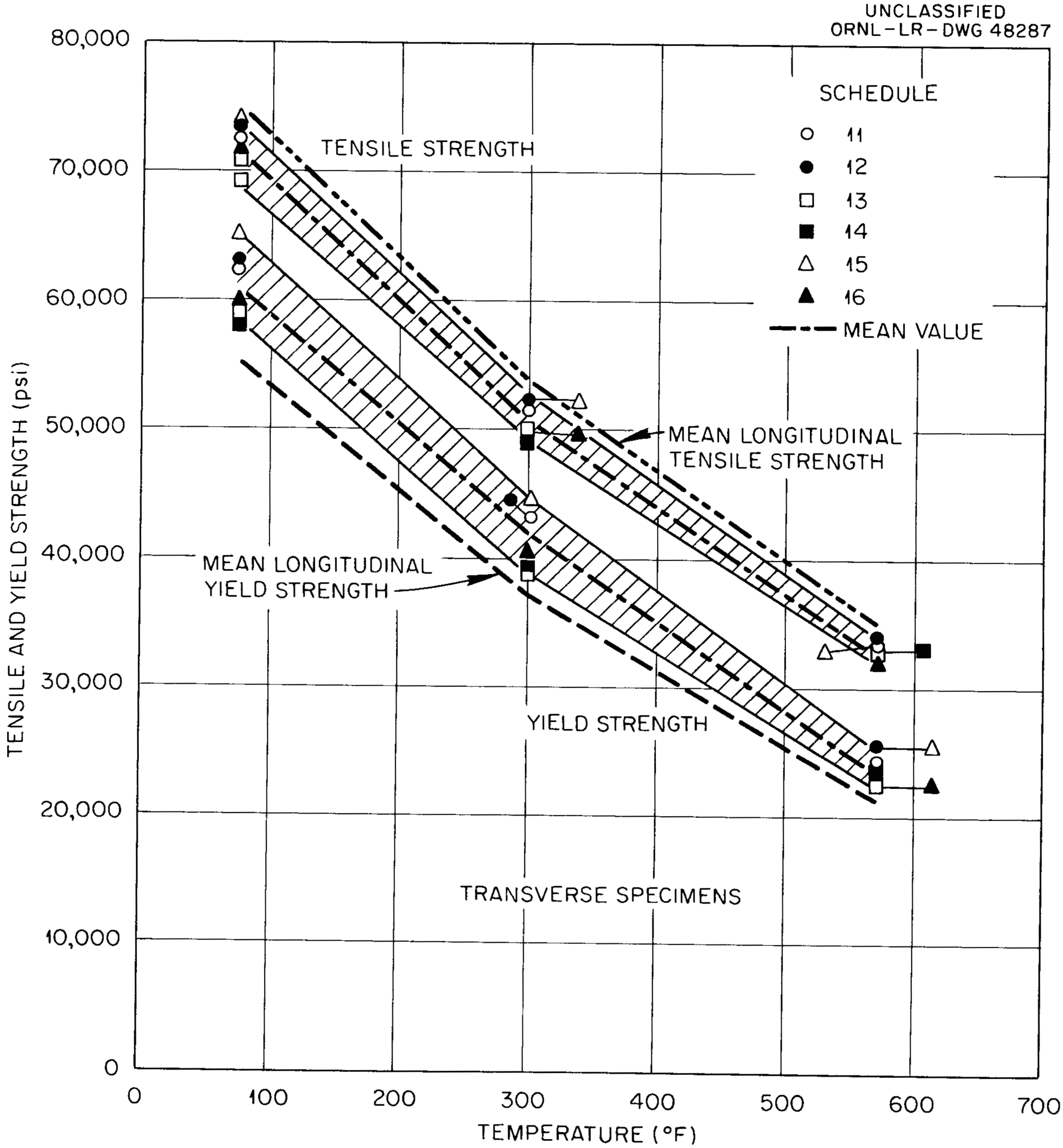

Fig. 6. Transverse Direction Tensile and Yield Strength as a Function of Temperature.

Evaluation of the Reproducibility of Tensile Data. As a check on the reproducibility of the tensile data, twelve longitudinal and twelve transverse direction specimens of schedule 17 were tested, half at room temperature and half at 572°F. The results of these tests are presented in Table IV.

Although the strengths show excellent reproducibility, except those for the yield strengths of the rolling direction specimens tested at 572°F, this set of data is not thought to be strictly characteristic of the behavior of all of the tensile specimens. Examination of the tensile and yield strengths for all of the schedules shows that a realistic estimate of the standard deviation is ± 500 to ± 750 psi. The standard deviation of the percent extension in 1 in. is within reason. The percent reduction in area, determined by optical comparator measurements, has a standard deviation of ± 1% for the rolling direction and ± 2% for the transverse direction specimens. The difference in the standard deviation between the two directions is probably significant and is thought to be due to the configuration of the fractures. The propagation of the crack during fracture causes a distortion or flare in the shape of the irregular surface of fracture, necessitating an estimate of the location of the minimum elliptical cross section which is undistorted. The standard deviation of the contractile strain ratio, $R_{c\bar{\epsilon}}$, varied from ± 0.02 to ± 0.04. As in the case of the reduction in area, the reproducibility of the strain ratio is a function of the fracture configuration and will vary from schedule to schedule.

The values of the modulus of elasticity presented in Table III are subject to considerable error. Differences found between duplicate specimens were oftentimes greater than the differences between specimen orientations. The difficulty in determining an accurate value of the modulus of elasticity arises from the small specimen size and the use of the load-elongation curves for the calculation of the modulus. Prevention of misalignment and slipping of strain gages is difficult, especially at elevated temperatures where the specimen is enclosed in a furnace.

Size Effects for Tensile Specimens. The size of the tensile and impact specimens used in this study was dictated by the limited amount of material which was available. As a cursory check of size effects, longitudinal and

TABLE IV

REPRODUCIBILITY OF ZIRCALOY-2 TENSILE DATA - SCHEDULE 17

Specimen Orientation(a)	Test Temp. °F	Tensile Strength 10^3 psi	Yield Strength 10^3 psi	Percent Extension in 1 in.	Reduction in Area Percent	$R_{c\bar{\epsilon}}$ Contractile Strain Ratio(b)
RD	75	80.2	57.9	22.0	45.2	0.63
		80.0	57.9	24.0	45.6	0.58
		80.0	56.2	27.0	45.0	0.62
		80.7	56.7	20.0	43.9	0.58
		80.2	57.0	27.0	44.6	0.64
		80.4	57.4	25.0	43.2	0.64
		Av. = 80.2	Av. = 57.2	Av. = 24.2	Av. = 44.6	Av. = 0.62
		σ(c) = 0.2	σ = 0.6	σ = 2.5	σ = 0.9	σ = 0.03
TD	75	77.6	69.3	21.0	48.0	0.37
		76.6	70.7	25.0	49.3	0.40
		77.1	69.8	20.0	50.9	0.39
		77.4	70.1	30.0	49.8	0.35
		77.8	69.1	23.0	51.9	0.42
		77.9	69.7	25.0	52.3	0.36
		Av. = 77.4	Av. = 69.8	Av. = 23.7	Av. = 50.4	Av. = 0.38
		σ = 0.4	σ = 0.5	σ = 3.2	σ = 2.0	σ = 0.02
RD	572	37.6	22.0	34.0	65.9	0.60
		38.3	24.6	38.0	65.5	0.62
		37.9	21.4	33.0	65.3	0.62
		38.4	25.7	32.0	66.3	0.64
		37.5	20.9	33.5	66.9	0.64
		38.2	22.8	33.0	65.9	0.62
		Av. = 38.0	Av. = 22.9	Av. = 33.9	Av. = 66.0	Av. = 0.62
		σ = 0.3	σ = 1.7	σ = 1.9	σ = 1.0	σ = 0.02
TD	572	34.8	26.4	36.0	70.6	0.40
		35.0	27.1	35.5	74.3	0.43
		35.3	27.1	40.0	70.4	0.36
		35.0	27.1	36.0	69.2	0.32
		35.3	26.9	43.0	71.0	0.32
		35.1	28.1	35.0	68.1	0.32
		Av. = 35.1	Av. = 27.1	Av. = 37.6	Av. = 70.6	Av. = 0.36
		σ = 0.2	σ = 0.5	σ = 2.8	σ = 2.1	σ = 0.04

(a) RD - Rolling (or longitudinal) direction.
TD - Transverse direction.

(b) Ratio of the natural contractile strain in the normal direction to the plate to the natural contractile strain in the plane of the plate. Strains measured at the fracture.

(c) Standard deviation - $\sigma = \sqrt{\frac{\Sigma fd^2}{r}}$.

transverse tensile specimens with 1/4-in. and 1/8-in.-dia, 1-in.-long gage sections were machined from 1/2-in. schedule 18 Zircaloy-2 plate. Two longitudinal and two transverse 1/8-in.-dia gage section specimens and three 1/4-in.-dia gage section specimens of each of the two orientations were tested at room temperature. Tensile data for each of the specimens are shown in Table V.

Tensile strengths for the 1/8-in.- and 1/4-in.-dia gage section specimens agree exceptionally well. The transverse direction yield strength for the 1/8-in.-dia specimens falls within the standard deviation of the 1/4-in.-dia specimens, but the longitudinal yield strength of the 1/8-in.-dia specimens is about 5000 psi higher than the longitudinal yield strength of the 1/4-in.-dia specimens. The effect of specimen diameter on the percent extension is seen to be quite large, the percent extension for the 1/4-in.-dia specimens being about 150% of that for the 1/8-in.-dia specimens. The reductions in area for the two sets of specimens seem to be equivalent, with the exception of one high value for a 1/4-in.-dia transverse direction specimen. The contractile strain ratio for the 1/4-in.-dia transverse direction tensile specimens averages 0.06 greater than that for the 1/8-in.-dia specimens, but is identical for the rolling direction specimens of both gage sizes.

Comparison of Tensile Data of Round and Sheet-Type Tensile Specimens. Sheet-type tensile specimens of three schedules of Zircaloy-2 were tested. The design and orientations of the specimens are shown in Fig. 7. The tensile data (tensile and yield strengths and percent extension in 1, 2, and 3 in.) are presented in Table VI.

Comparison of the yield strengths determined on round and sheet-type specimens of schedules 17 and 18 materials show that the values of the yield strengths of the sheet-type specimens were 2500–4500 psi lower than those for the round specimens. The tensile strengths were also from 1100–3200 psi lower. The percent extension in 1 in. was, however, 20–50% greater for the sheet-type specimens. The percent extension measured in 2 in. for the sheet specimens was comparable to the extension in 1 in. for the rounds. Commercially fabricated Zircaloy-2 schedule A1, which had a fabrication procedure approximately that of schedule 17, showed very low values for both tensile and yield strengths, 11,000–19,000 psi lower than for schedule 17 material. The lower strengths determined on sheet-type specimens for schedule A1 in comparison to those for schedule 17 may be due to differences in preferred orientation produced by relatively small deviations in fabrication procedure.

TABLE V

COMPARISON OF THE ROOM TEMPERATURE TENSILE PROPERTIES OF 1/4-in. AND 1/8-in. DIAMETER GAGE SECTION SPECIMENS OF ZIRCALOY-2 - SCHEDULE 18

Specimen[a] Orientation	Tensile Strength 10^3 psi 1/4 in.	Tensile Strength 10^3 psi 1/8 in.	Yield Strength 10^3 psi 1/4 in.	Yield Strength 10^3 psi 1/8 in.	Percent Extension in 1 in. 1/4 in.	Percent Extension in 1 in. 1/8 in.	Reduction in Area Percent 1/4 in.	Reduction in Area Percent 1/8 in.	$R_{c\bar{\epsilon}}$ Contractile Strain Ratio 1/4 in.	$R_{c\bar{\epsilon}}$ Contractile Strain Ratio 1/8 in.
RD	74.2	76.9	48.5	55.4	35.0	24.0	43.2	43.8	-	0.87
	77.8	78.3	50.9	54.0	28.0	25.0	39.2	42.2	0.88	0.88
	77.2		47.9		32.5		39.8		0.85	
TD	74.7	74.7	67.0	69.7	35.0	20.0	57.6	48.9	0.53	0.43
	75.3	75.1	70.5	69.2	31.0	25.0	47.8	50.7	0.47	0.43
	75.1		65.2		32.0		47.6		0.48	

(a) RD - Rolling direction
TD - Transverse direction.

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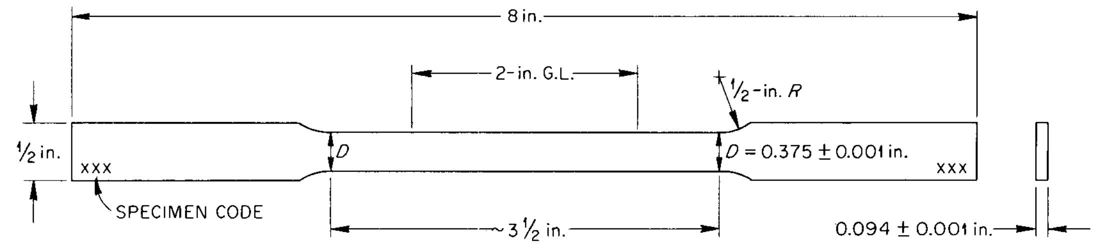
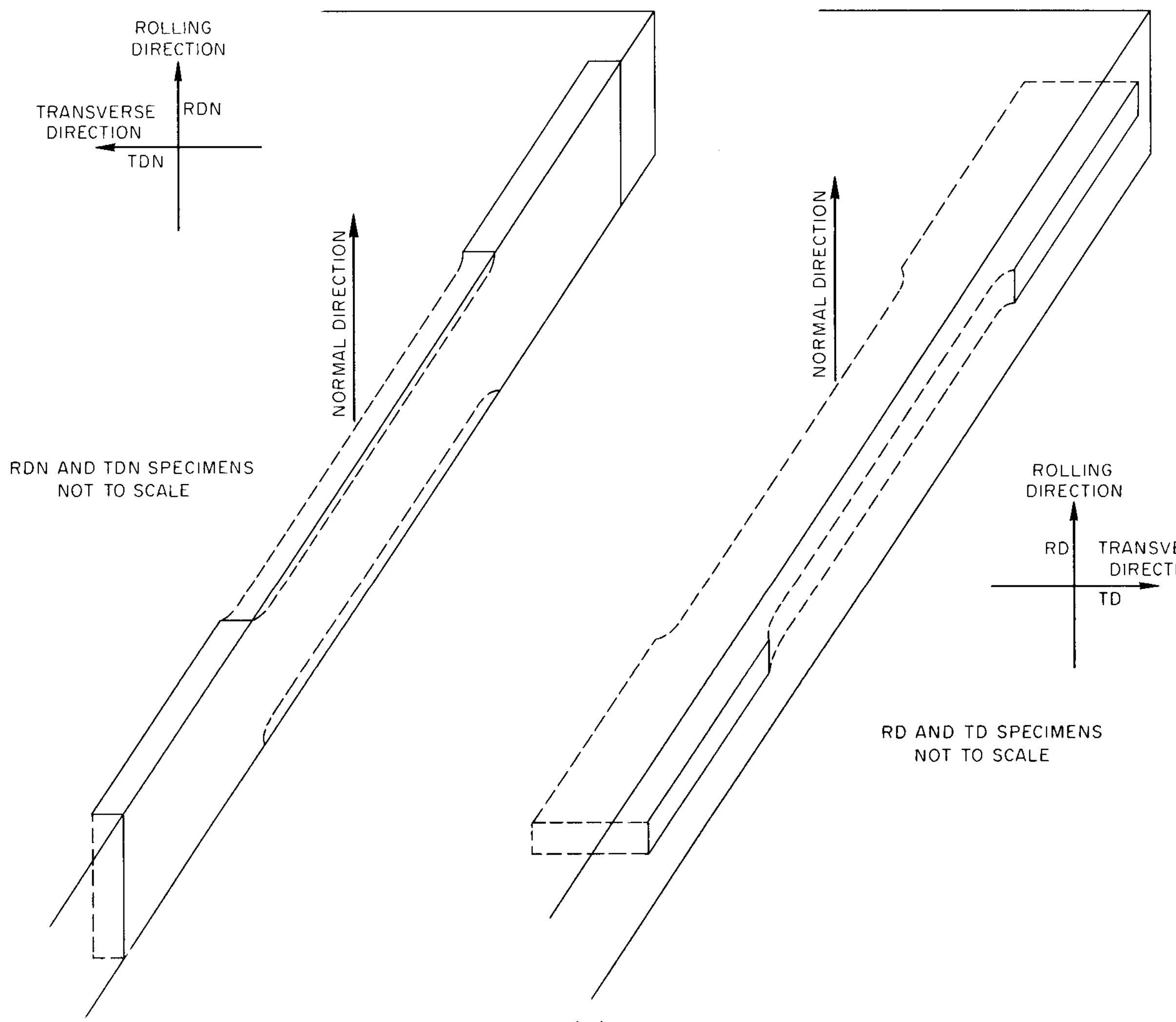


(a)



(b)

Fig. 7. Sheet Type Tensile Specimen Design and Orientation.

TABLE VI

ROOM TEMPERATURE TENSILE PROPERTIES OF ZIRCALOY-2 SHEET-TYPE SPECIMENS

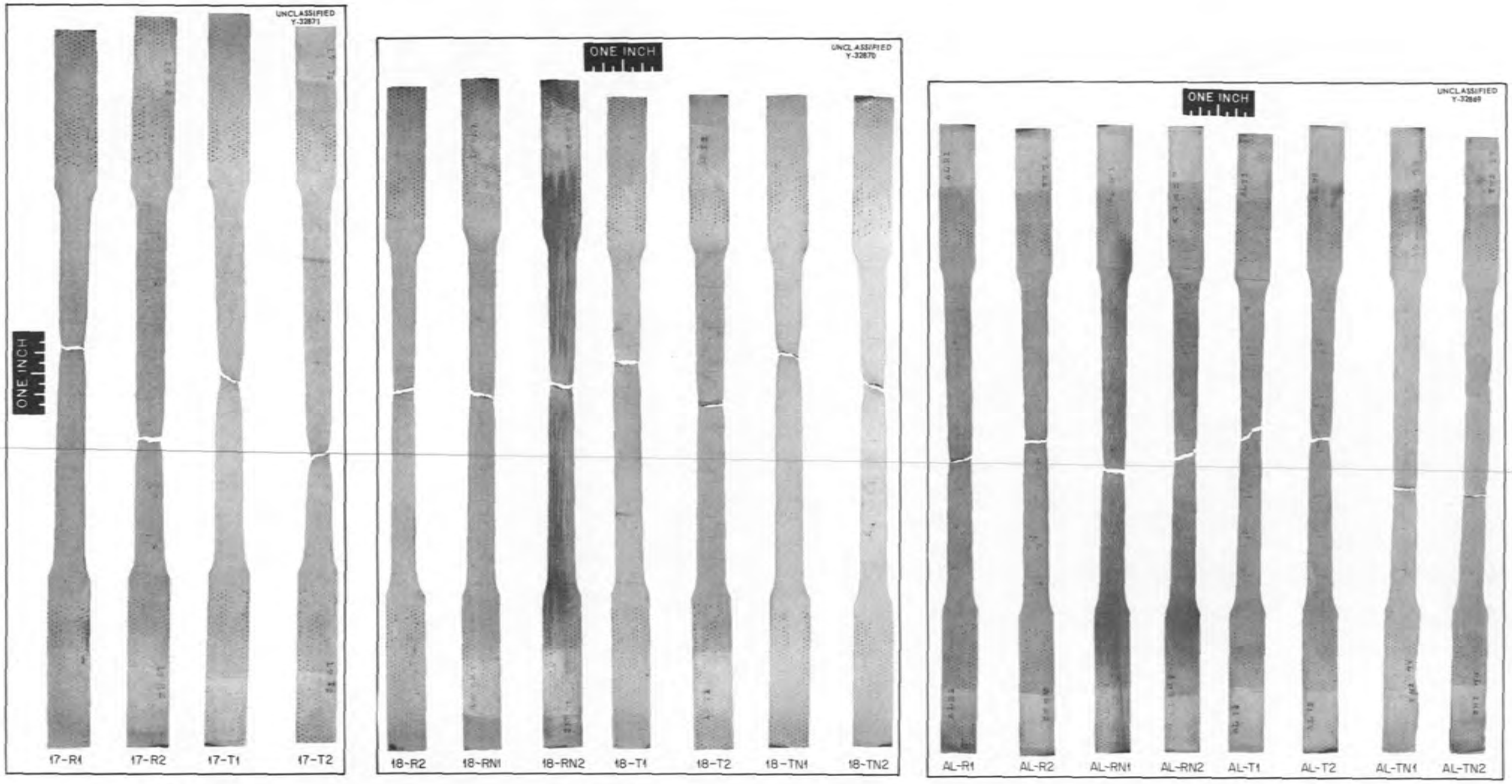
Schedule	Specimen Orientation[a]	Tensile Strength 10^3 psi	Yield Strength 10^3 psi	Percent Extension in 1 in.	2 in.	3 in.
17	RD	80.1	52.9	32	24	19
	TD	76.0	67.4	38	26	22
18	RD	74.7	50.5	27	21	16
	RDN	73.9	49.8	30	25	21
	TD	73.4	64.9	26	20	16
	TDN	74.3	64.6	30	21	18
A1[b]	RD	61.1	41.5	38	29	24
	RDN	61.9	41.3	38	29	24
	TD	63.3	52.7	36	29	24
	TDN	63.2	52.0	34	28	22

(a) See Fig. 20 for explanation of specimen orientation.
(b) Fabrication procedure similar to that for schedule 17 - 1/2 in. plate.

Because of the configurations of the cross sections at the fracture, it was impossible to obtain meaningful values of reductions in area and contractile strain ratios for the sheet specimens. Photographs of the tensile specimens showing the reduction in width (or the width direction strains) are shown in Fig. 8. The contractile strains in the thickness directions varied from edge-to-edge across the width, generally being a maximum at the center. Aside from this, the cross sections at fracture were twisted or tilted out of the plane of the specimen. Rough measurements of the tensile specimens gave reductions in area from 30–40% for schedules 18 and A1, and from 35–50% for schedule 17. The values found for the transverse direction orientations were generally higher than those for the longitudinal direction specimens. The strain behavior of the sheet-type tensile specimens was consistent with that observed for the round specimens but, because of the difficulties in measurement, values of contractile strains could not be computed.

Anisotropy of Tensile Properties as a Function of Tensile Axis in the Rolling Plane

Tensile Properties versus Tensile Axis. Mechanical properties as a function of tensile axes are presented in Figs. 9–21. The rolling (or longitudinal) direction properties are plotted at 0° on the polar co-ordinate axes. Tensile and yield strengths are shown in the 0°–90° quadrant, percent extension and reduction in area in the 270°–360° quadrant. Rolling direction properties were taken as the base-line values so that directionality of properties is seen as a displacement of values for other orientations above or below the base line. Only those schedules for which at least three orientations were tested are shown in this series of figures. The property which varied most consistently and to the greatest degree was the yield strength. It usually increased from the rolling direction to the transverse direction and was usually a maximum in this direction. Exceptions to this are seen in schedules 14 and 16 where the yield strengths at 45° were a maximum, and in schedules 1 and J where the yield strengths at 67-1/2° from the rolling direction were the highest. In the latter case the transverse direction yield strength was still considerably higher than those for the 22-1/2°, 45°, and rolling directions, but in the case of schedules 14 and 16 the longitudinal and transverse yield strengths were equal.



(*a*) SCHEDULE 17　　(*b*) SCHEDULE 18　　(*c*) SCHEDULE AL

Fig. 8. Photographs of Sheet-Type Tensile Specimens of Zircaloy-2 Showing Reductions in Width.

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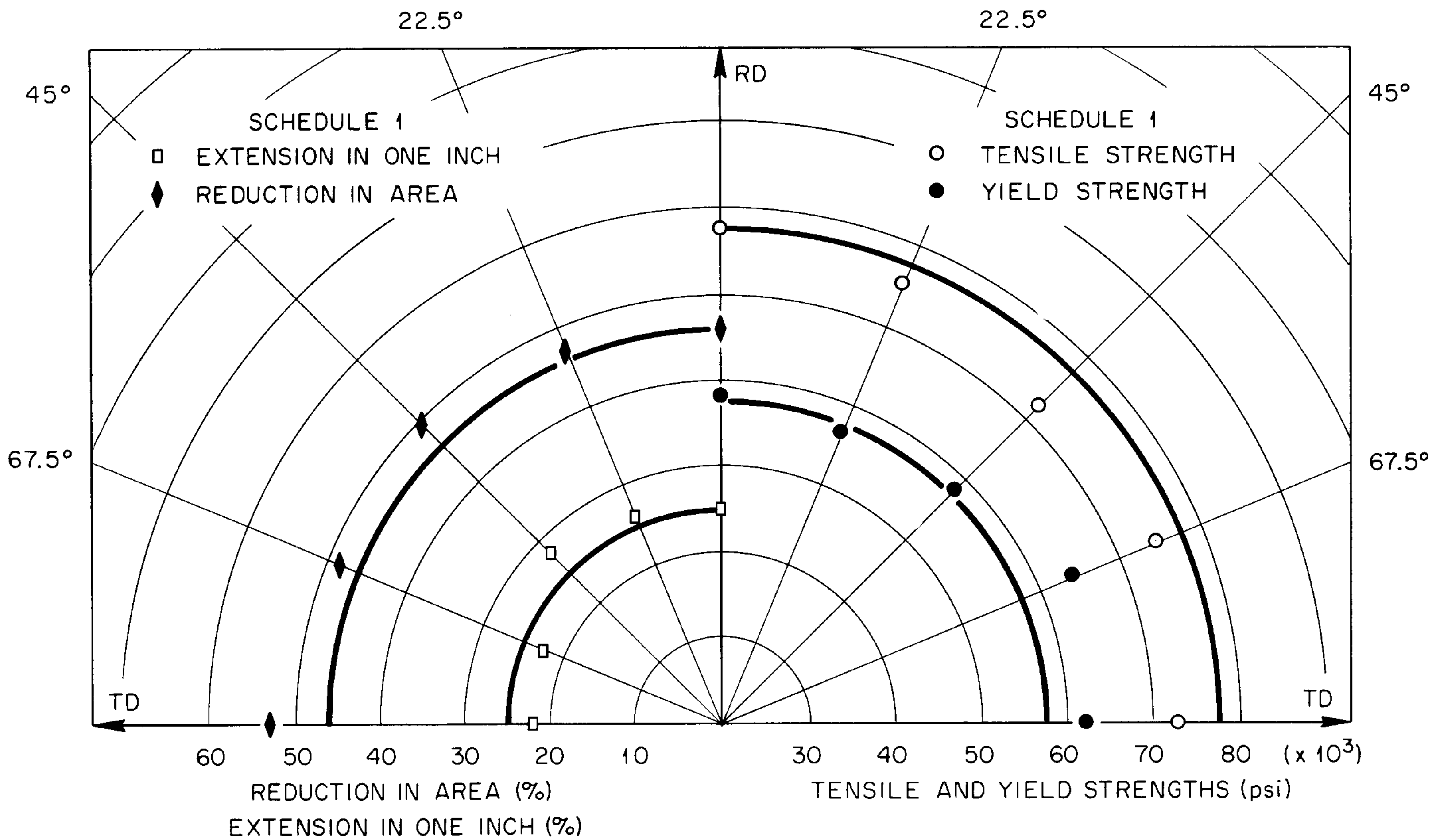

Fig. 9. Tensile Properties of Schedule 1 Zircaloy-2 as a Function of Tensile Axis in the Plane of the Plate. Schedule 1: Two Intermediate β Heat-Treatments, Air Cooled.

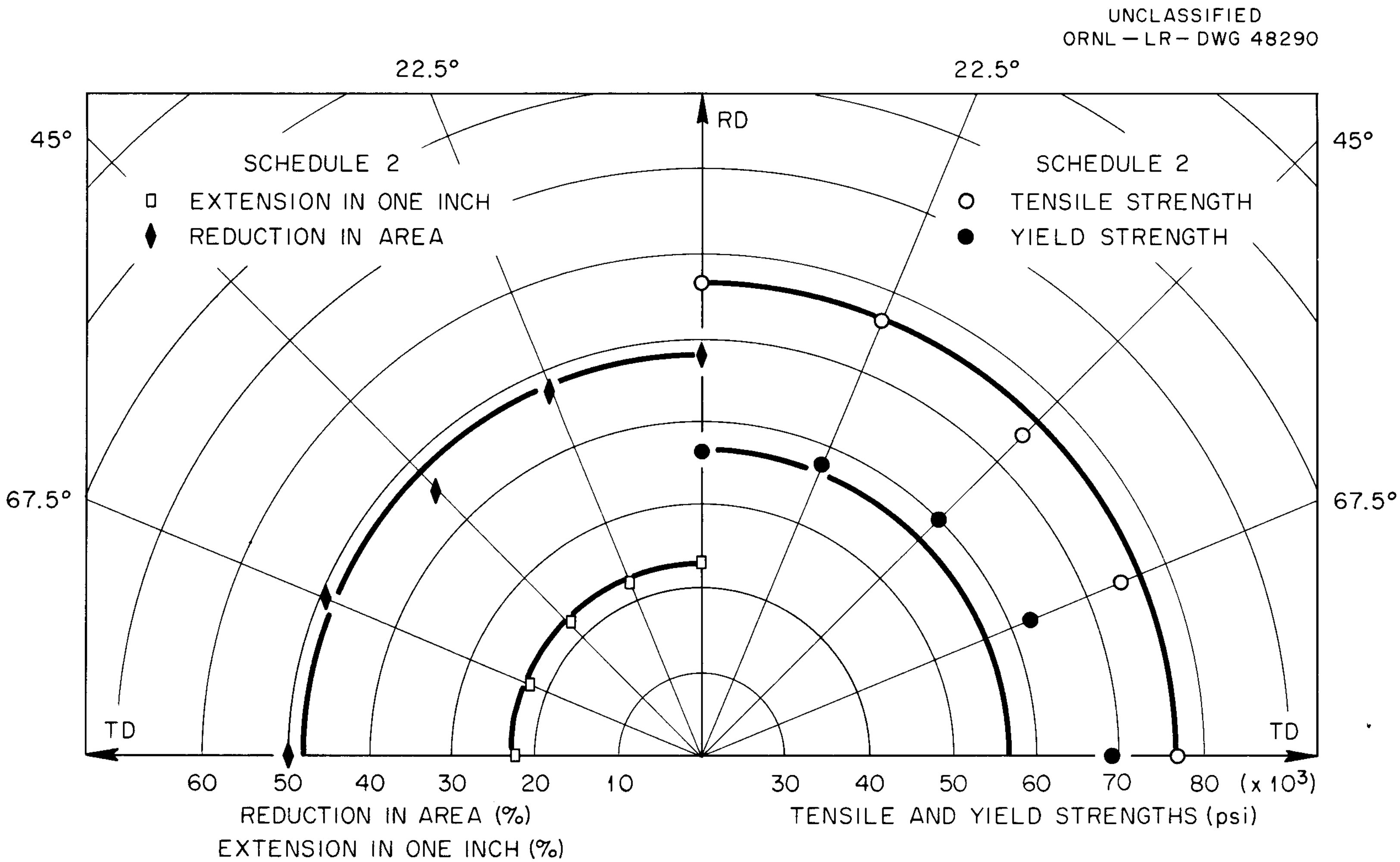

Fig. 10. Tensile Properties of Schedule 2 Zircaloy-2 as a Function of Tensile Axis in the Plane of the Plate. Schedule 2: Two Intermediate β Heat-Treatments, Air-Cooled.

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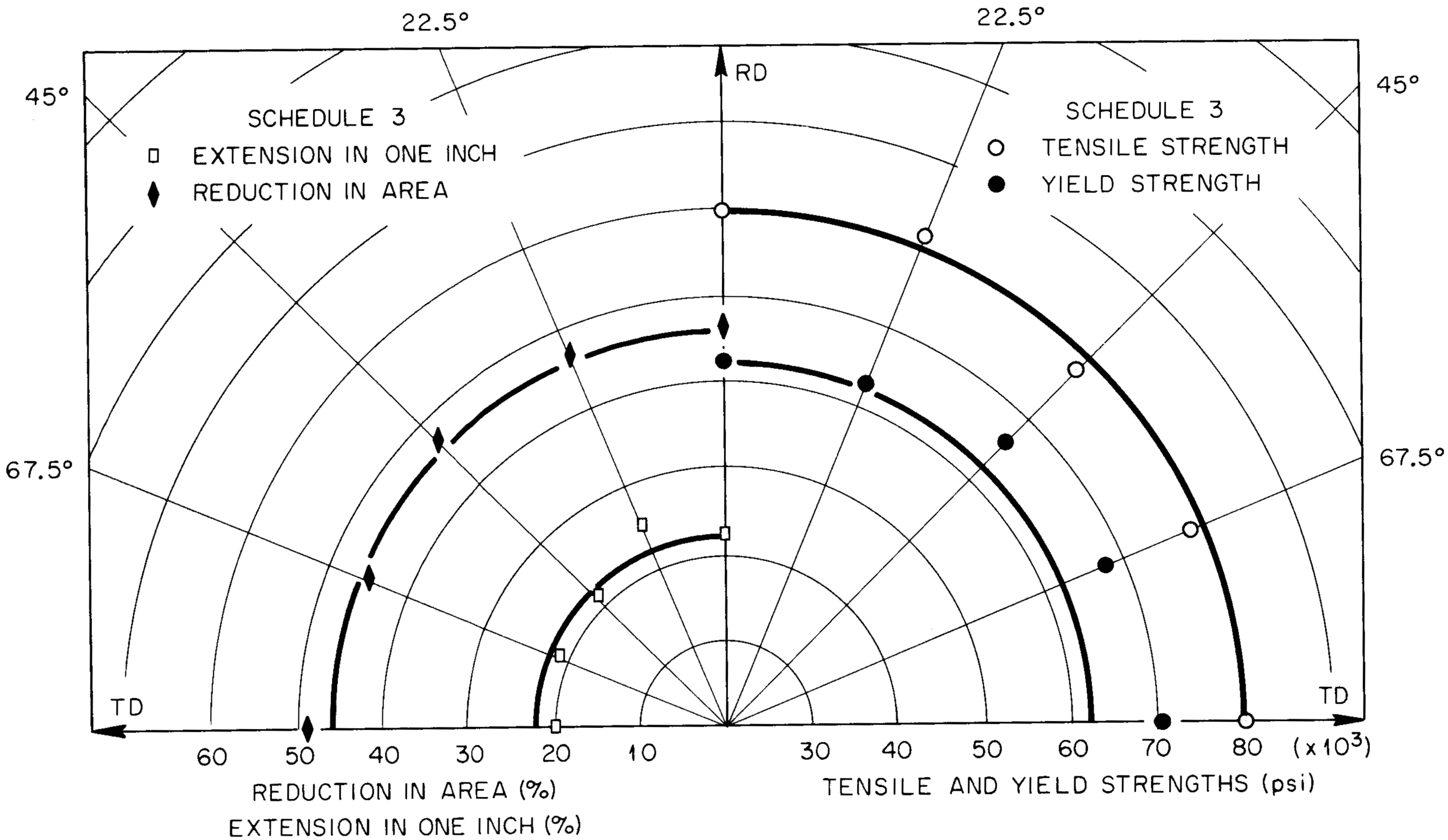

Fig. 11. Tensile Properties of Schedule 3 Zircaloy−2 as a Function of Tensile Axis in the Plane of the Plate. Schedule 3: One Intermediate β Heat−Treatment.

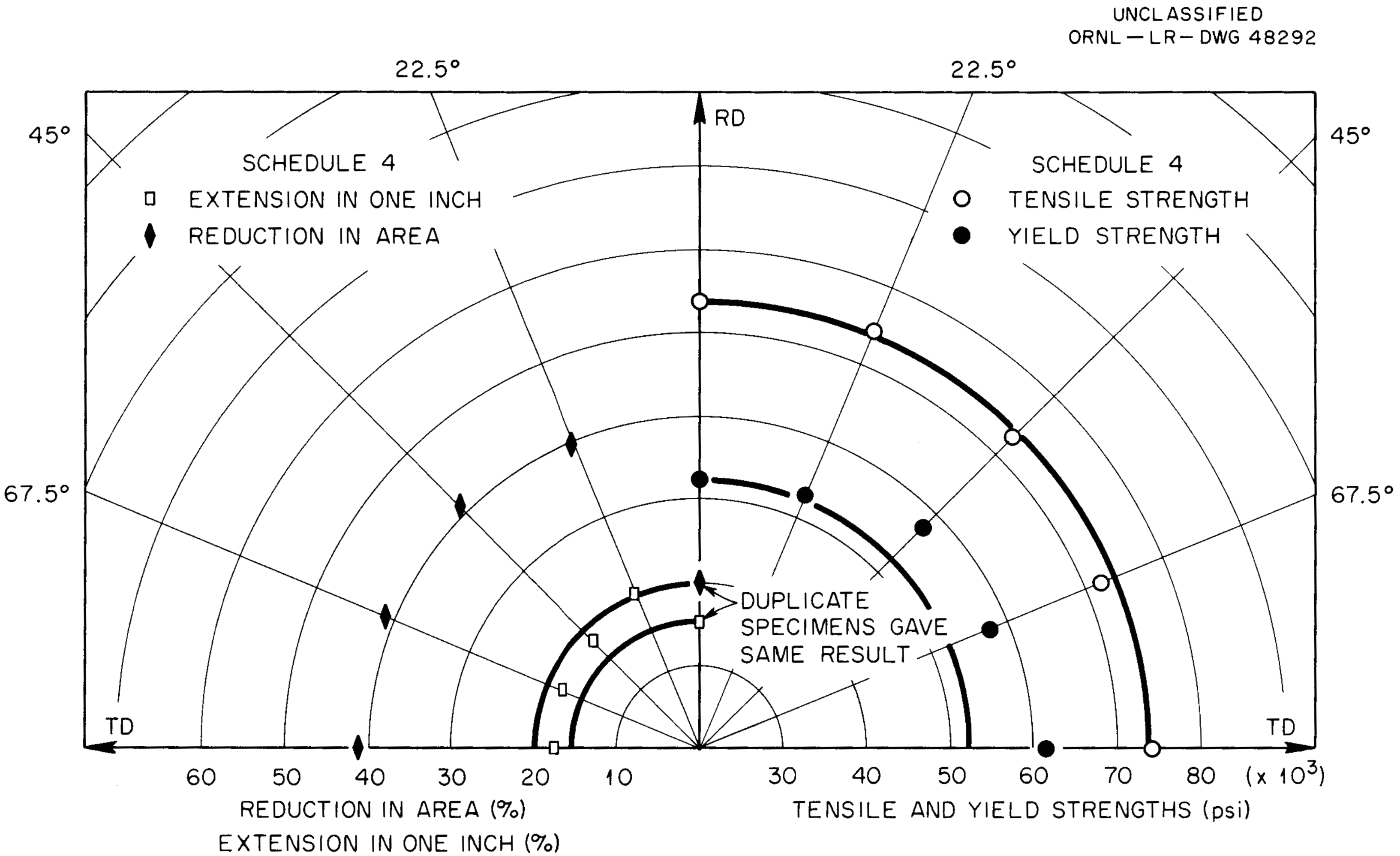

Fig. 12. Tensile Properties of Schedule 4 Zircaloy—2 as a Function of Tensile Axis in the Plane of the Plate. Schedule 4: β Reduction Plus 25 Per Cent Low α Reduction.

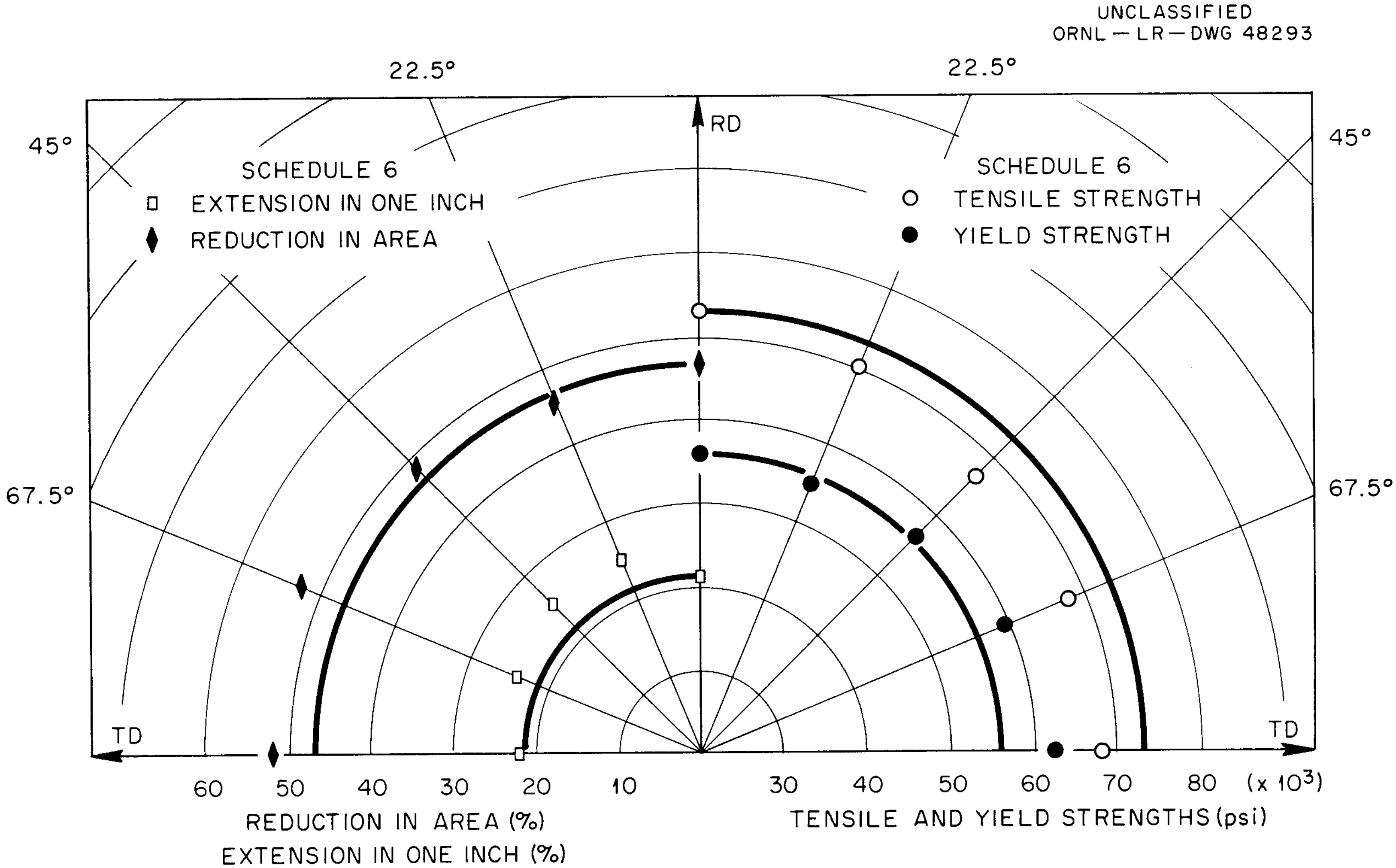

Fig. 13. Tensile Properties of Schedule 6 Zircaloy-2 as a Function of Tensile Axis in the Plane of the Plate. Schedule 6: β Reduction Plus 70 Per Cent Low α Reduction.

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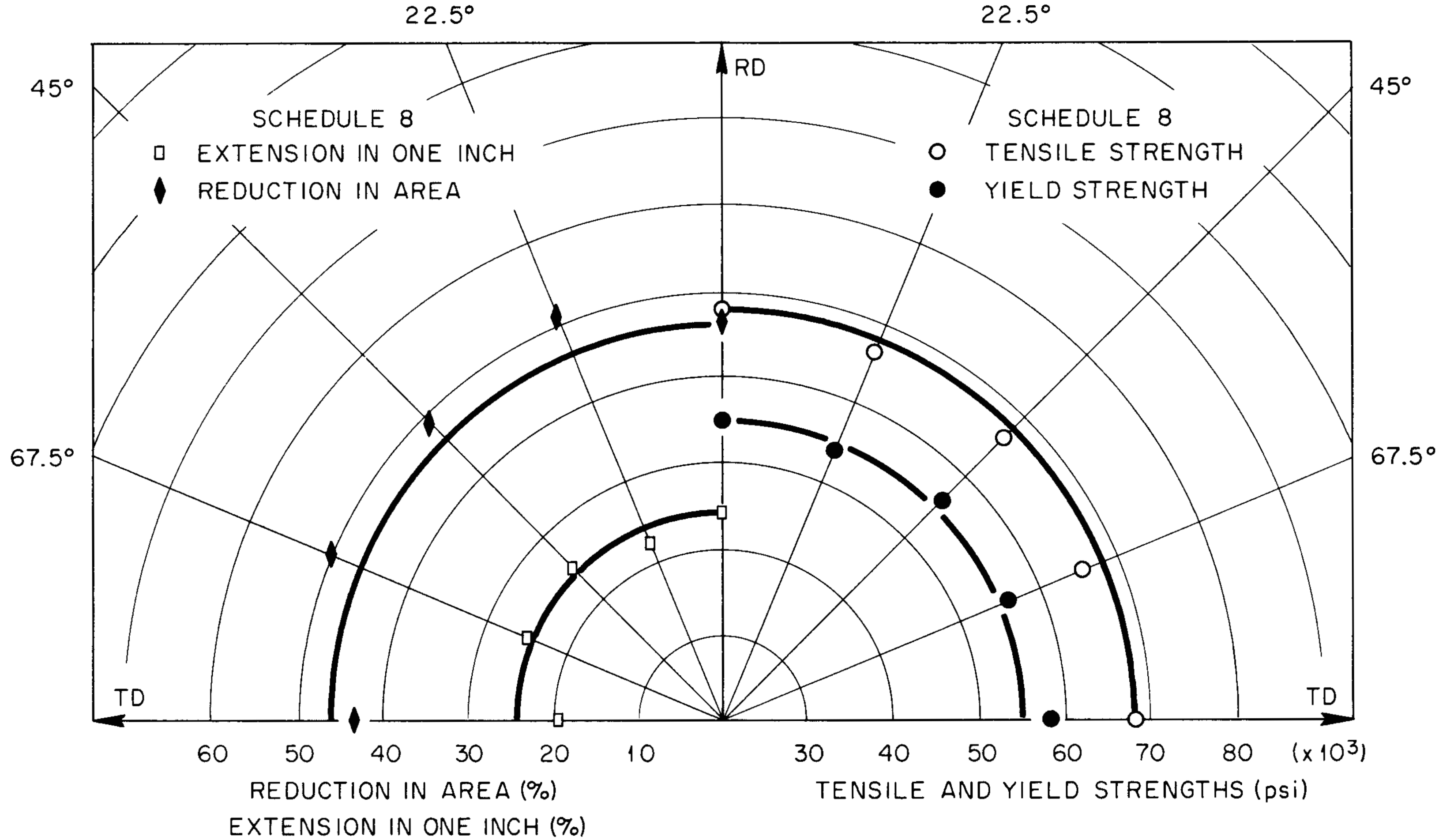

Fig. 14. Tensile Properties of Schedule 8 Zircaloy−2 as a Function of Tensile Axis in the Plane of the Plate. Schedule 8: α Worked, 70 Per Cent Low α.

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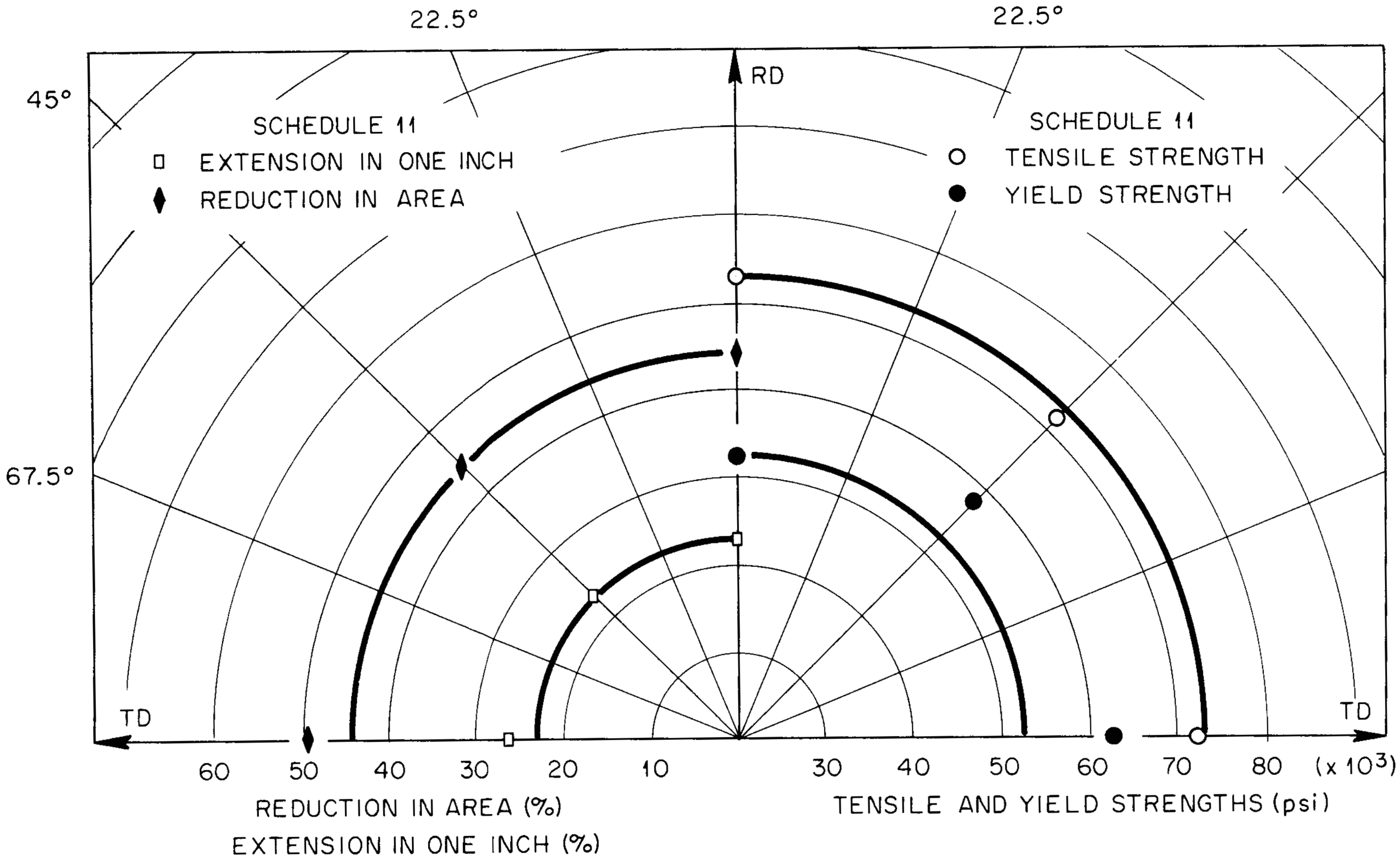

Fig. 15. Tensile Properties of Schedule 11 Zircaloy-2 as a Function of Tensile Axis in the Plane of the Plate. Schedule 11: HRP Commercial Fabrication Procedure, 25 Per Cent Final Reduction.

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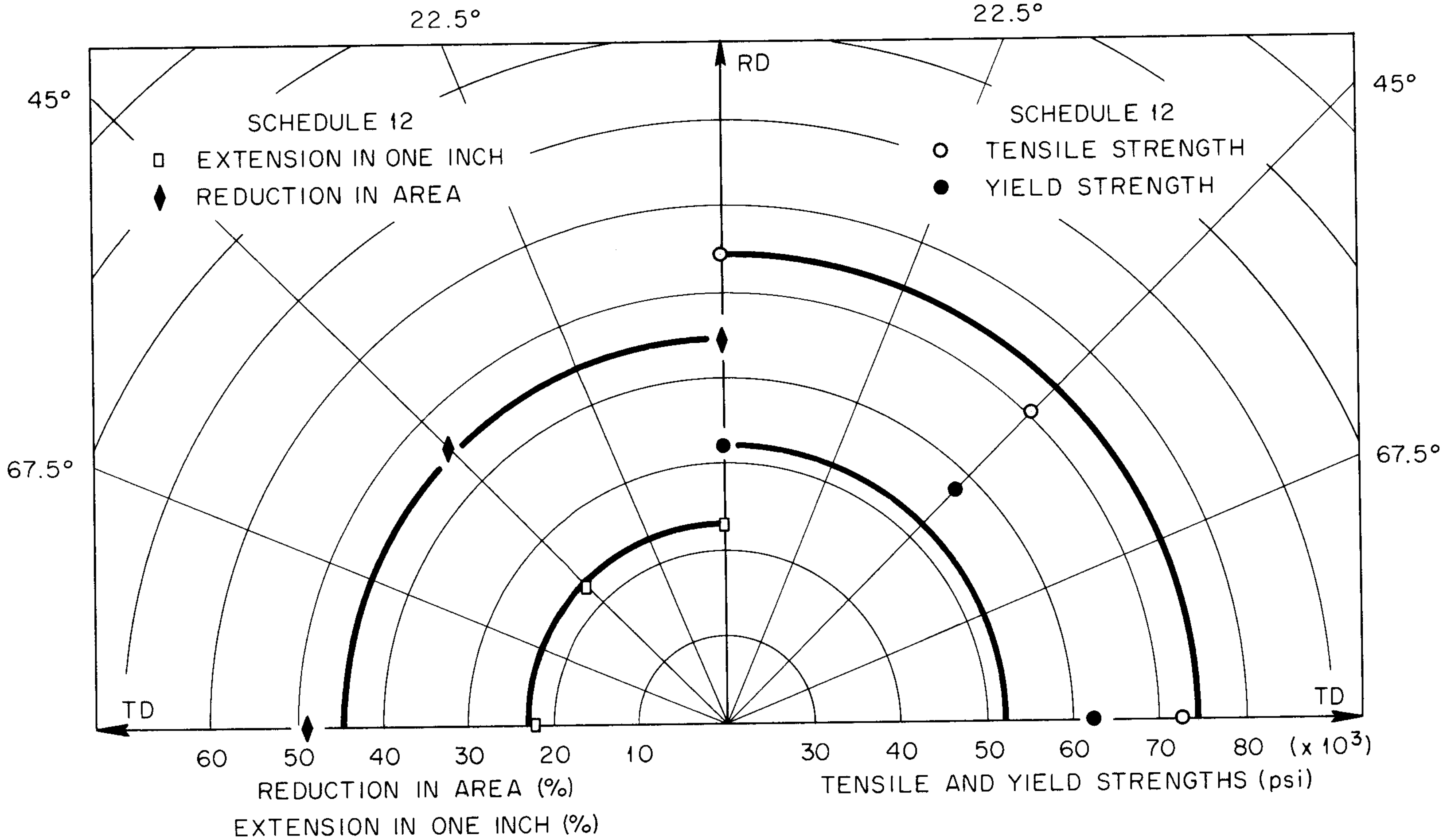

Fig. 16. Tensile Properties of Schedule 12 Zircaloy-2 as a Function of Tensile Axis in the Plane of the Plate. Schedule 12: HRP Commercial Fabrication Procedure, 40 Per Cent Final Reduction.

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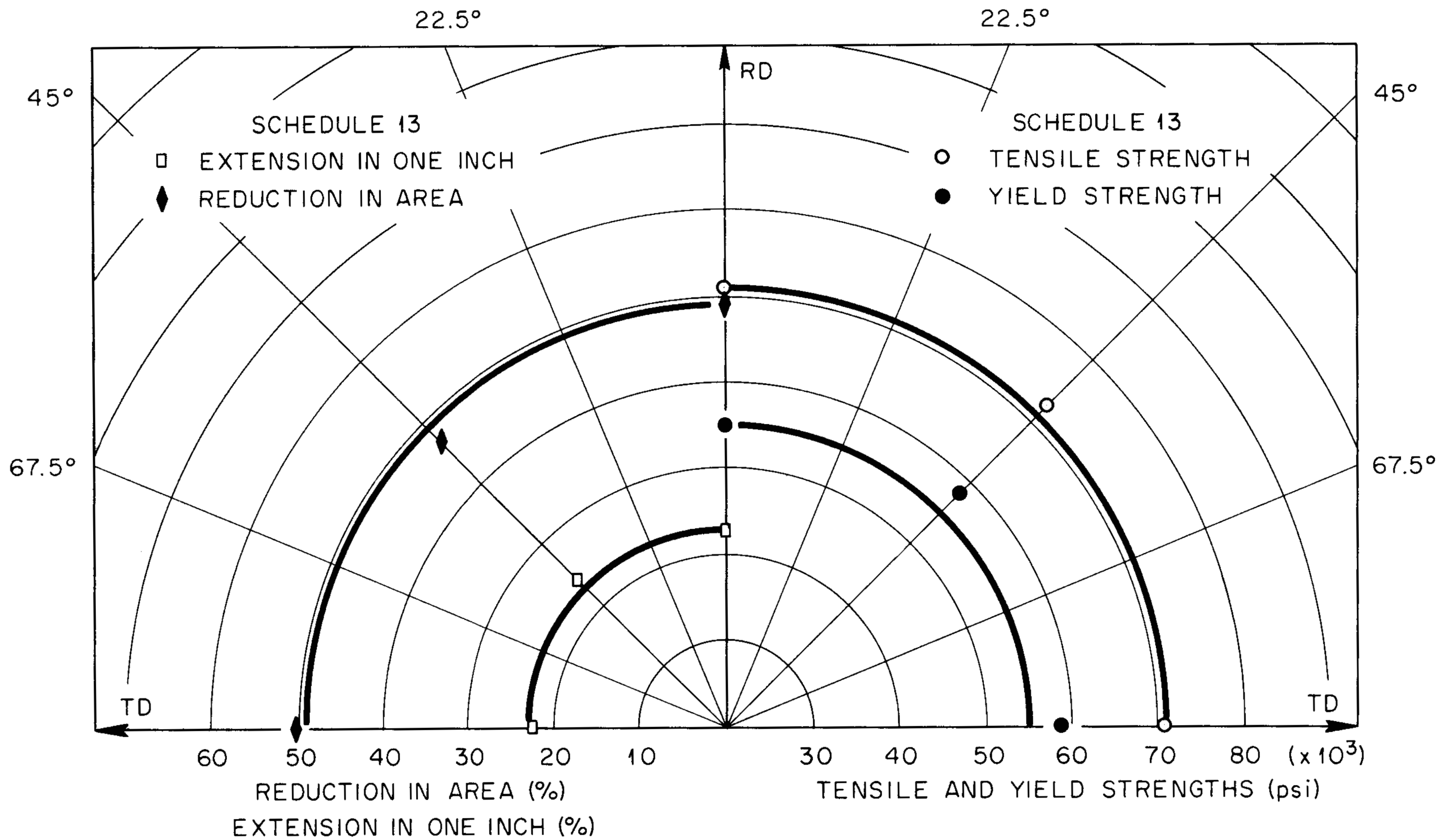

Fig. 17. Tensile Properties of Schedule 13 Zircaloy-2 as a Function of Tensile Axis in the Plane of the Plate. Schedule 13: Cross-Rolled after β Heat-Treatment.

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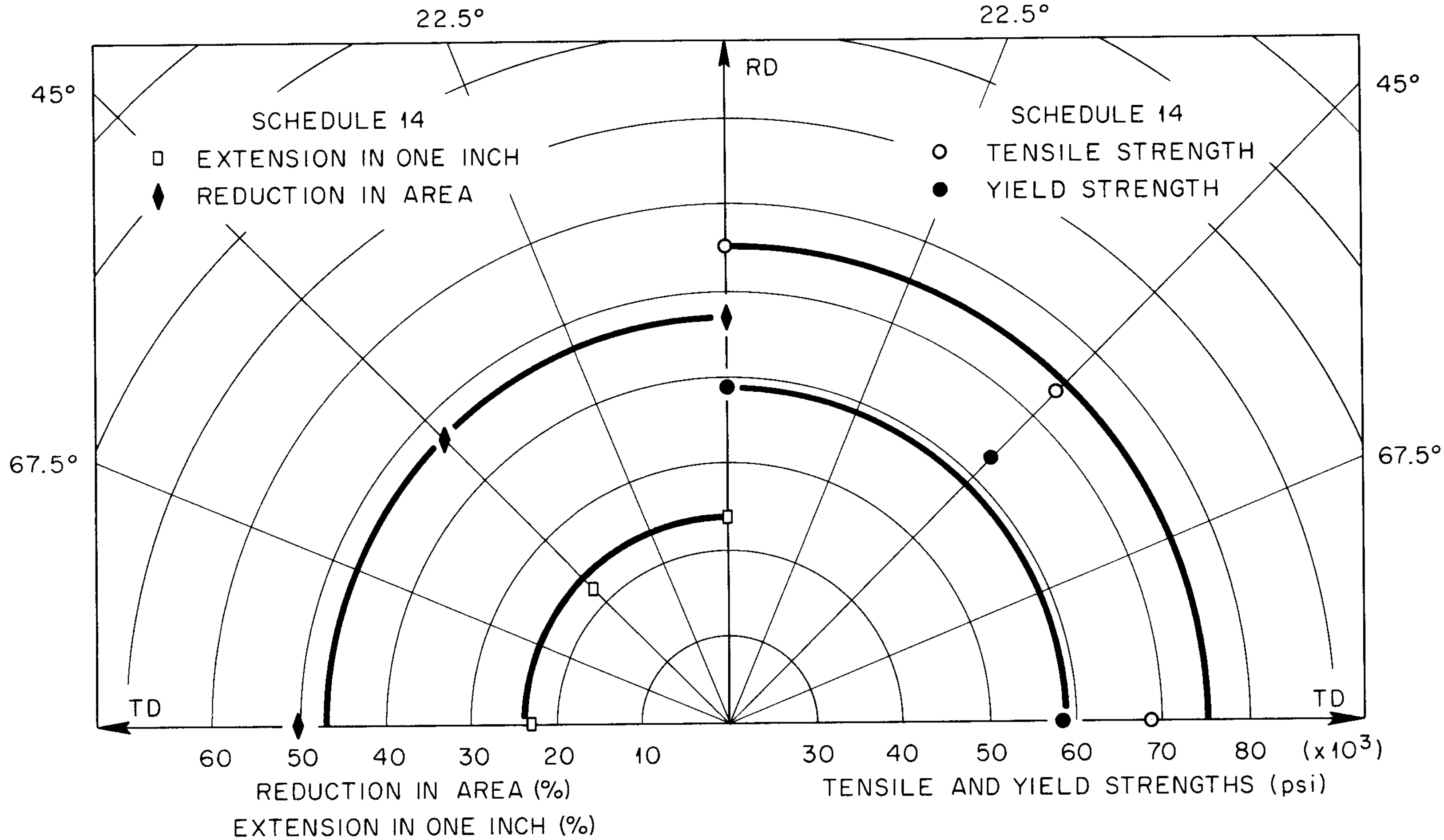

Fig. 18. Tensile Properties of Schedule 14 Zircaloy-2 as a Function of Tensile Axis in the Plane of the Plate. Schedule 14: Cross-Rolled During High α Reduction.

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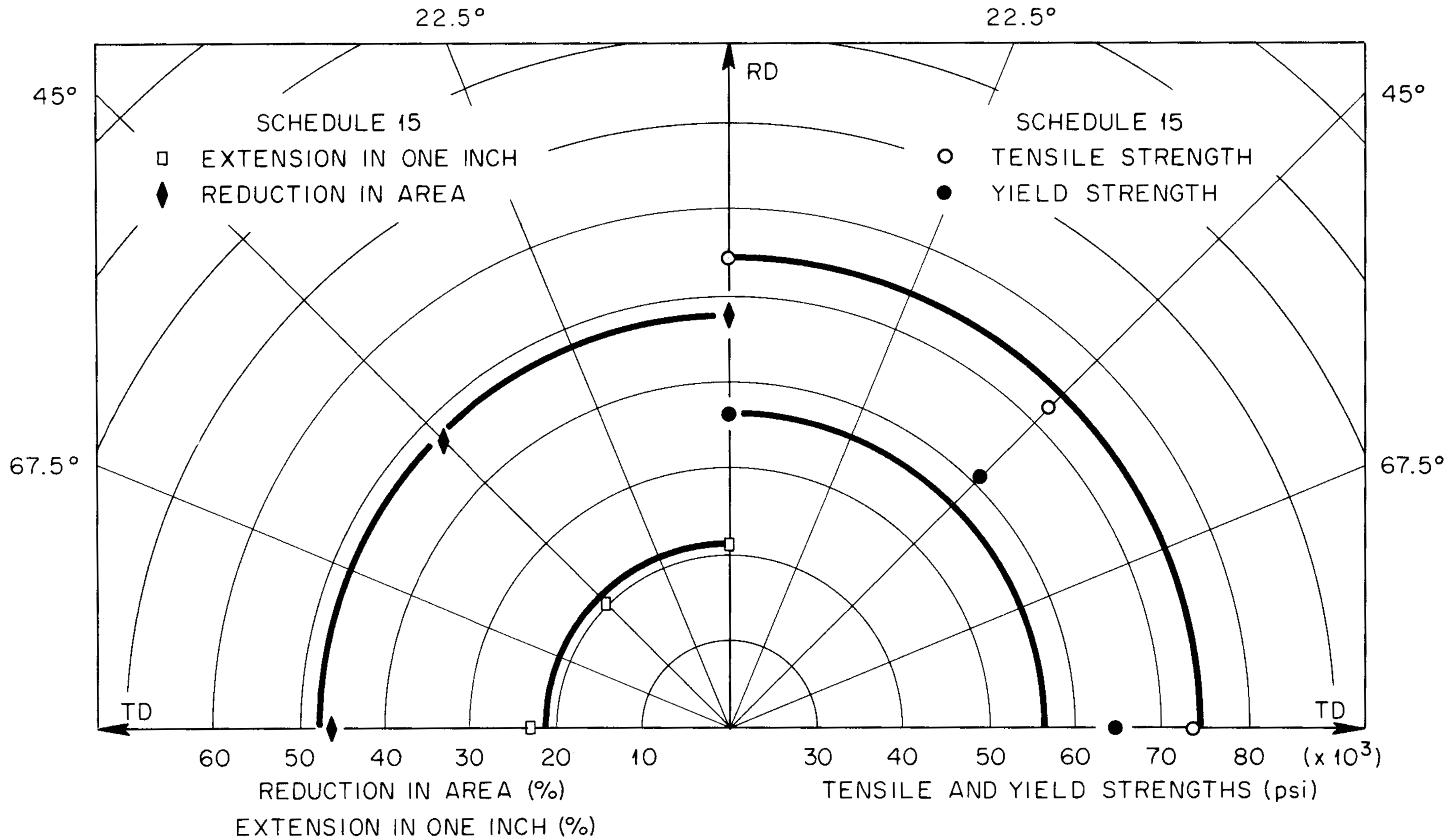

Fig. 19. Tensile Properties of Schedule 15 Zircaloy-2 as a Function of Tensile Axis in the Plane of the Plate. Schedule 15: Straight-Rolled During β Reduction.

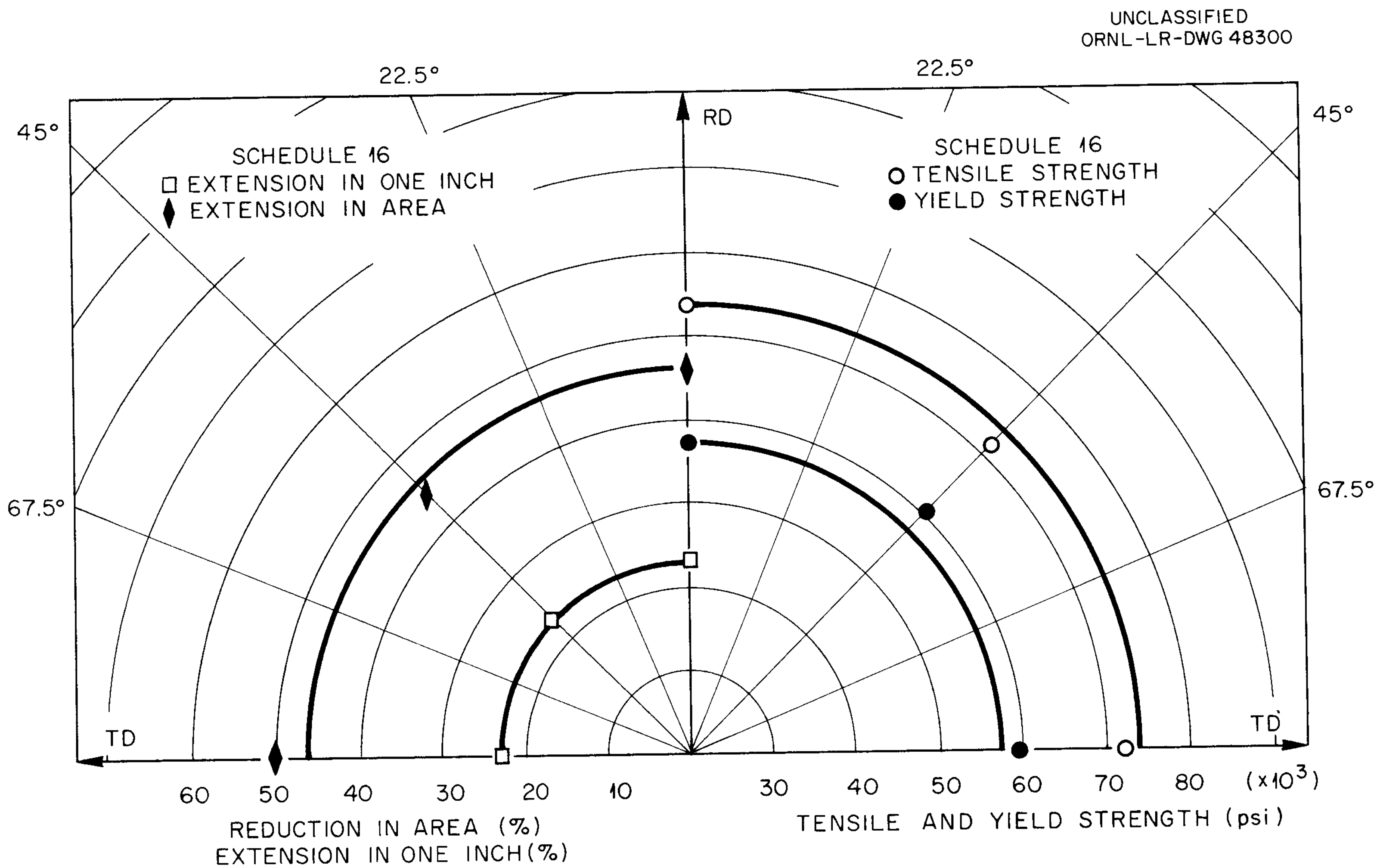

Fig. 20. Tensile Properties of Schedule 16 Zircaloy-2 as a Function of Tensile Axis in the Plane of the Plate. Schedule 16: Cross-Rolled During β Reduction.

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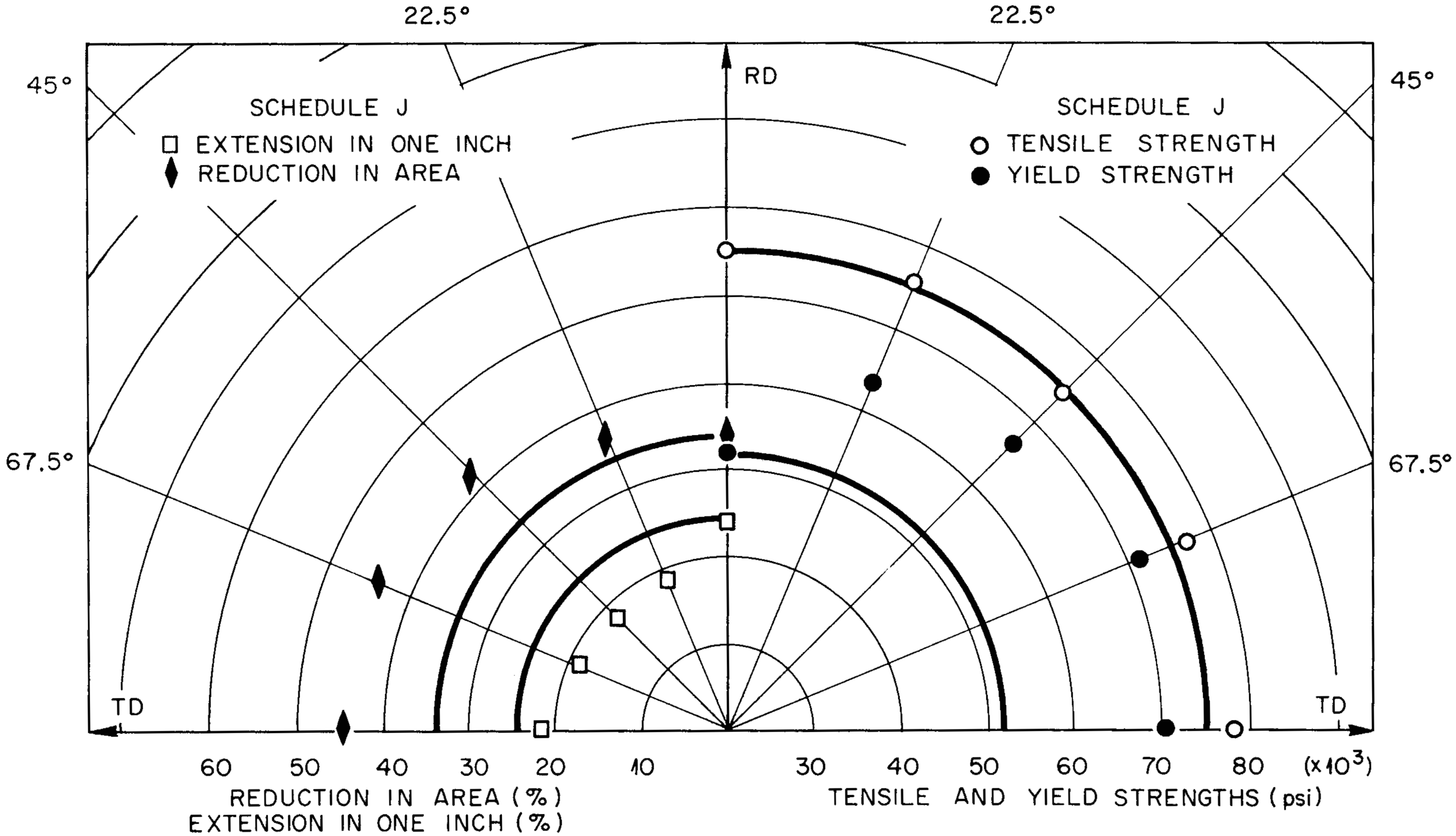

Fig. 21. Tensile Properties of Schedule J Zircaloy-2 as a Function of Tensile Axis in the Plane of the Plate. Schedule J: HRP Commercial Fabrication Proceedure for Wide Plate.

The variations in tensile strength were not quite as orderly nor were the differences quite as great as in the case of the yield strengths. Generally, the tensile strengths for all of the orientations fell within ± 1000 psi, nearly the proposed standard deviation. When values were seen to fall outside this spread, they were usually highest in the rolling direction and tended to be slightly lower for the intermediate orientations, usually being the lowest at 45°.

Although a definite directionality of both the percent extension and reduction in area existed, neither was as well defined as for the tensile or yield strengths. In most cases, but not all, the reduction in area was highest in the transverse direction. The values of the percent extension for all orientations were, for the greatest part, either within the standard deviation or varied so erratically that no systematic dependence on orientation could be proposed.

From examination of the variation in tensile properties as a function of tensile axis, Figs. 9-21, it is obvious that the principal axes of anisotropy, the orthogonal axes in the material about which the mechanical properties are symmetrical, are not necessarily those generally assumed. (In sheet and plate, the principal axes of anisotropy are usually taken to be the rolling and transverse directions and the direction normal to the plane of the plate.)[38,39] Also, the principal axes of anisotropy are not the same for each of the tensile properties. Because of these facts, it is necessary that specimens with tensile axes from the rolling direction through 180° be tested rather than specimens with tensile axes only from the rolling direction to the transverse direction (through 90°).

Contractile Strain Ratio. The tensile properties obtained for Zircaloy-2 fabricated by each of the twenty schedules are a measure only of the degree of directionality in the plane of the plate. To define the state of anisotropy of the bulk material it is necessary to consider also the properties in the normal direction. This can be accomplished by an analysis which involves the

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[38] L. J. Klingler and G. Sachs, J. Aeronaut. Sci., p. 599 (Oct., 1948).

[39] R. Hill, "A Theory of the Yielding and Plastic Flow of Anisotropic Metals," Proc. Roy. Soc. (London) A193, 281-297 (1948).

contractile strain ratio, the ratio of the natural contractile strain in the normal direction to the natural contractile strain in the plane of the plate at the fracture. For an isotropic material this ratio would be 1.0, regardless of the orientation of the tensile axis. Any deviation from this value, whether positive or negative, is an indication of anisotropy. If, as for schedule 8, the contractile strain ratios for all orientations in the plane of the plate are identical but not equal to 1.0, the material is essentially isotropic in the plane of the plate. The deviation of the absolute value from 1.0, which for schedule 8 was considerable, is a measure of the true state of anisotropy of the material. For most of the schedules, the strain ratios were closest to the isotropic ratio of 1.0 for specimens with tensile axes in the rolling direction and furthest from the isotropic ratio for specimens with tensile axes in the transverse direction. This indicated that the tensile properties in the transverse direction more nearly approached those in the normal direction than did those in the longitudinal direction.

Effect of Temperature on the Anisotropy of Tensile Properties. The effect of temperature on the directionality of yield strengths in the plane of the plate is shown in Fig. 6. Comparison of the mean curves for the transverse and longitudinal yield strengths shows that the difference between the two yield strengths decreased with temperature, being only half as great at 572°F as at room temperature, but remained approximately proportional to the average of the two strengths. No effect of temperature on the directionality of the other properties was obvious. In general, the contractile strain ratio was not changed with increasing test temperature. Minor changes were noted for some schedules, usually a change in value toward the isotropic ratio, but in no case were major differences observed.

Effect of Cross Rolling. The effect of cross rolling on the directionality of mechanical properties depends both on the temperature of rolling and on whether the cross rolling was unidirectional or whether the material was turned 90° after each pass. Schedules 13, 14, and 16 materials were cross rolled, each at a different rolling temperature and stage of fabrication, by turning the work piece 90° after each pass (called hereafter, rotational cross rolling). The cross rolling of schedule 13 material was performed after the major reduction and penultimate 1850°F anneal. Cross rolling of schedule 14 material was done at 1450°F, before the β heat treatment and final reduction, and cross rolling of schedule 16 material was done entirely in the β field at 1850°F (see Table II for exact fabrication procedure). Little directionality of tensile properties was shown by these cross-rolled materials, and on first examination, it might be said that the effect of rotational cross rolling was independent of rolling temperature and the stage of fabrication at which it occurred. The contractile strain ratios for these materials, however, were considerably different. The strain ratio did not change with tensile axes for schedule 13 material, being about one-third of the isotropic ratio. Although there was isotropy in the plane of the plate for schedule 13 material, this material was not nearly as isotropic as that for schedules 14 and 16 when all directions were considered. Schedule 14 material was nearly isotropic with respect to the logitudinal direction tensile axis, $R_{c\bar{\epsilon}} = 0.84$, but the contractile strain ratio for the transverse direction tensile axis was only 0.28, indicating that large differences existed between rolling direction and normal direction properties. The strain ratio for schedule 16 Zircaloy-2 varied from 0.58 for the longitudinal tensile axis to 0.44 for the transverse tensile axis. Thus, the normal direction properties must be quite different from either the transverse or rolling direction properties for schedule 16 material.

Schedule 15 material was fabricated to be compared with cross-rolled schedule 16 Zircaloy-2 (straight rolling vs rotational cross rolling during reduction in the β phase field). Rotational cross rolling during β reduction (schedule 16) produced somewhat greater anisotropy in contractile strain ratios, but decreased the differences in yield strengths in the rolling plane.

Unidirectional cross rolling, schedules 10, 18, and J, gave an entirely different result from the rotational cross rolling done for schedules 13, 14, and 16. It did not minimize directionality in the plane of the plate and, for schedules 18 and J, led to extreme directionality of properties in the rolling plane, especially in yield strengths. The contractile strain ratios also indicated that considerable differences existed between the properties in the plane of the plate and in the normal direction.

Effect of Ingot Axis Orientation During Rolling. A factor which should undoubtedly be considered in the comparison of the effects of cross rolling, as well as straight rolling, is the orientation of the original ingot axis with respect to the major sheet directions (rolling, transverse, and normal directions) of the fabricated plate. The ingot axes for schedules 18 and J were in the transverse directions of the plates, and for schedule 10, in the original rolling direction. For schedules 13, 14, and 16, which had ingot slices as their starting material, the ingot axes were in the normal direction. As it will be shown later by comparison of schedules 11 and 12 (ingot axes in the normal direction) with schedules 17 and 62 (ingot axes in the rolling direction), there was no effect found for the position of the ingot axis on the mechanical properties or contractile strain ratios for these schedules.

Effect of Percent Final Reduction. The effect of variation of the percent final reductions, 25, 50, and 70% at 1000°F, was shown by the properties of schedules 4, 5, and 6. The degree of directionality of properties in the plane of the plate was not appreciably affected, but the absolute values varied considerably. Strengths for the material with 50% final reduction (schedule 5) were approx 10,000 psi higher than for the other two reductions. The reason for this observation is quite obscure since the material reduced 70% ordinarily would be expected to have the maximum strength values. The contractile strain ratios varied with the percent final reduction, greater anisotropy in the normal direction being exhibited by the material (schedule 6) reduced 70% in the final rolling than by the materials reduced 25 and 50%.

Effect of Alpha Rolling Temperature. A comparison of the data for schedule 6 material with that for schedule 7, which received 70% final reduction at 1450°F, shows the effect of high vs low α reduction when no intermediate β heat treatment is performed. The high α rolling temperature produced greater anisotropy of mechanical properties in the plane of the plate, but the values of the contractile strain ratio were essentially the same for both schedules.

Both of the predominantly α worked materials, schedules 8 and 9, were almost completely isotropic in the rolling plane. The contractile strain ratios of both were quite low, $R_{c\bar{\epsilon}} < 0.2$, so that little contractile strain occurred in the normal direction for any of the orientations of tensile axes studied. Thus, even though examination of the standard tensile data would lead to the conclusion that the materials were isotropic, the properties in the direction normal to the rolling plane must have been considerably different from those in the rolling plane.

Effect of Number of Beta Heat Treatments and Quenching Rate. The effect of the number of β heat treatments on the directionality of mechanical properties was studied through schedules 1 and 3. Schedule 1 material received two intermediate anneals at 1832°F before the final reduction; schedule 3, only one. The largest effect produced was seen in the values for the contractile strain ratio, $R_{c\bar{\epsilon}}$, which varied from 0.92 in the longitudinal direction to 0.29 in the transverse direction for schedule 1, and which was approx 0.50 for all orientations of schedule 3. Schedule 2 Zircaloy-2, which differed from schedule 1 only in that all anneals were followed by a water quench rather than an air cool, showed considerably more directionality in yield strengths than did schedule 1 material. On the other hand, the variations in tensile strength and reduction in area were greater for schedule 1. The variation of the value of the contractile strain ratio, $R_{c\bar{\epsilon}}$, for schedule 2 material was from 0.62 in the longitudinal direction to 0.44 in the transverse direction, both values being intermediate to those for schedules 1 and 3.

An example of a material with no intermediate β heat treatment, but with an α penultimate anneal, is schedule 9. By interjecting an intermediate β heat treatment in place of the 1450°F anneal, it would have been possible to approximate the HRP commercially produced Zircaloy-2, which, after a β temperature breakdown, is rolled in the high α field before the β heat treatment and final reduction (schedules 12, 62). It is obvious, then, that the effect of the intermediate β heat treatment on the directionality of mechanical properties is appreciable, increasing the apparent anisotropy in the plane of the plate but decreasing the true anisotropy.

Comparison of Commercial and Laboratory Fabrication. Schedules 62 and 17 were lots of Zircaloy-2 produced by commercial fabricators to ORNL-HRP Metallurgy specifications. Schedules 11 and 12 were laboratory scale duplication of these commercially produced lots and were fabricated both to compare fabrication size effect and to show the effect of 25 vs 40% final reduction in the HRP Metallurgy fabrication schedule. The values of the yield strengths and the contractile strain ratios for these four fabrication schedules are presented in Table VII.

TABLE VII

ROOM TEMPERATURE YIELD STRENGTHS AND CONTRACTILE STRAIN RATIOS FOR ZIRCALOY-2 FABRICATED TO ORNL-HRP SPECIFICATIONS

Schedule	Specimen[(a)] Orientation	Yield Strength 10^3 psi	$R_{c\bar{\epsilon}}$ Contractile Strain Ratio	Ingot Axis[(a)] Orientation
11	RD	52.1	0.89	ND
	TD	62.6	0.54	ND
12	RD	52.5	0.69	ND
	TD	62.7	0.41	ND
17	RD	57.2	0.62	RD
	TD	69.2	0.38	RD
62	RD	55.8	0.71	RD
	TD	63.2	0.45	RD

(a) RD - Rolling direction
TD - Transverse direction
ND - Normal direction

The fabrication procedures for materials of schedules 17 and 62 were similar, but not exactly the same, so that the differences between the two schedules are not surprising. Comparison of the values of the contractile strain ratios showed that schedule 12 material more nearly approximated the commercially produced material than did schedule 11 material. The effect of the 40 vs the 25% final reduction was seen to be an increase in the differences between properties in the plane of the plate and properties in the direction normal to the plane of the plate. From an examination of the strengths and contractile strain ratios, it can be seen that variation of the ingot axis orientation from the rolling direction to the normal direction had little effect on the final state of anisotropy.

Effect of Fabrication Variables on Impact Energy Temperature Values

Impact Testing. Impact tests have been developed as a tool for the interpretation and correlation of service failures with the brittle behavior of engineering structures.[40] The development of test procedures and analyses has been almost entirely by empirical methods, so that little, if any, information of a fundamental nature can be obtained. Fracture appearance and energy absorption transition temperatures are the criteria of evaluation which have been accepted.[40] Although a transition from high to low energy absorption occurs for Zircaloy-2, no fracture appearance transition has been observed. Since the fracture mode for Zircaloy-2 has been by shear at all temperatures, and since low energy fractures have previously been associated with cleavage,[40] the empirically developed impact energy analyses do not seem to be of value for the prediction of the behavior of Zircaloy-2. The use that the impact energy test does have, in the case of Zircaloy-2 and other anisotropic materials, is that of a qualitative measurement of anisotropy.

Effect of Notch Orientation. For a completely isotropic material, neither the orientation of the impact specimen axis nor the orientation of the notch should affect the results. Specimens of all orientations should give a single impact energy vs temperature curve. For an anisotropic material, however, the results obtained will vary markedly with specimen axis and notch orientation. Although, due to the complexity of the stress systems operating at the notch of the impact specimen during testing, little information of a quantitative nature other than the impact energy values can be obtained, examination and analysis of the data are still of value.

The impact energy curves for material of five fabrication schedules, which are presented in Figs. 22-26, are representative of the types of curves which were obtained for all of the schedules. On examination of these curves and those for each material presented in Appendix II, it can be seen that, in some cases, materials will appear to be isotropic when only one notch orientation is tested. Since hydrogen content is an important factor in the interpretation of the impact-test results, causing a decrease in impact energy and an increase in transition temperature, the hydrogen content for each of the fabrication schedules is shown in Table VIII.

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[40] E. R. Parker, Brittle Behavior of Engineering Structures, John Wiley and Sons, Incorporated, New York, 1957.

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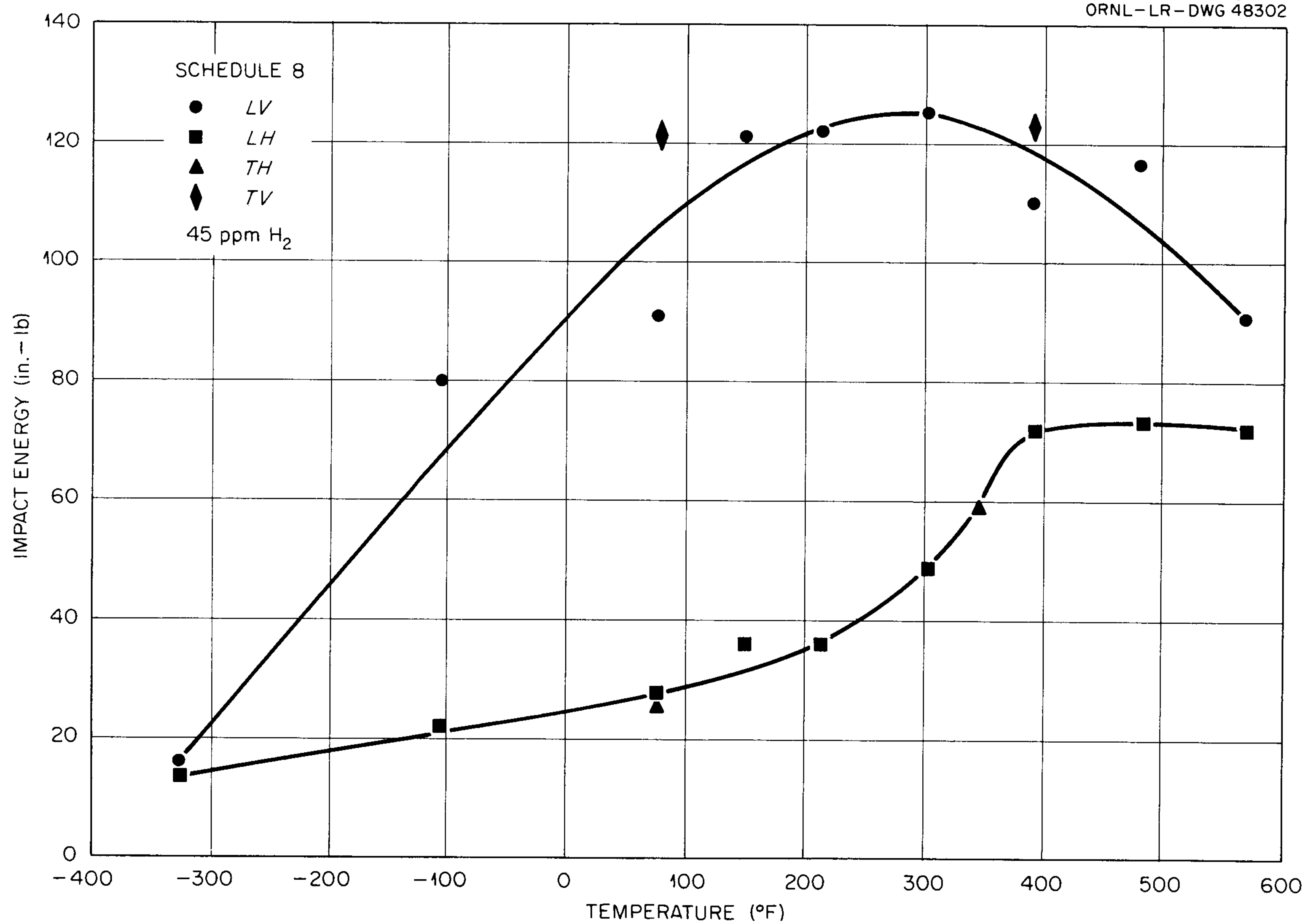

Fig. 22. Impact Energy Curves for Schedule 8 Zircaloy-2. Schedule 8: α Worked, 70 Per Cent Low α Reduction.

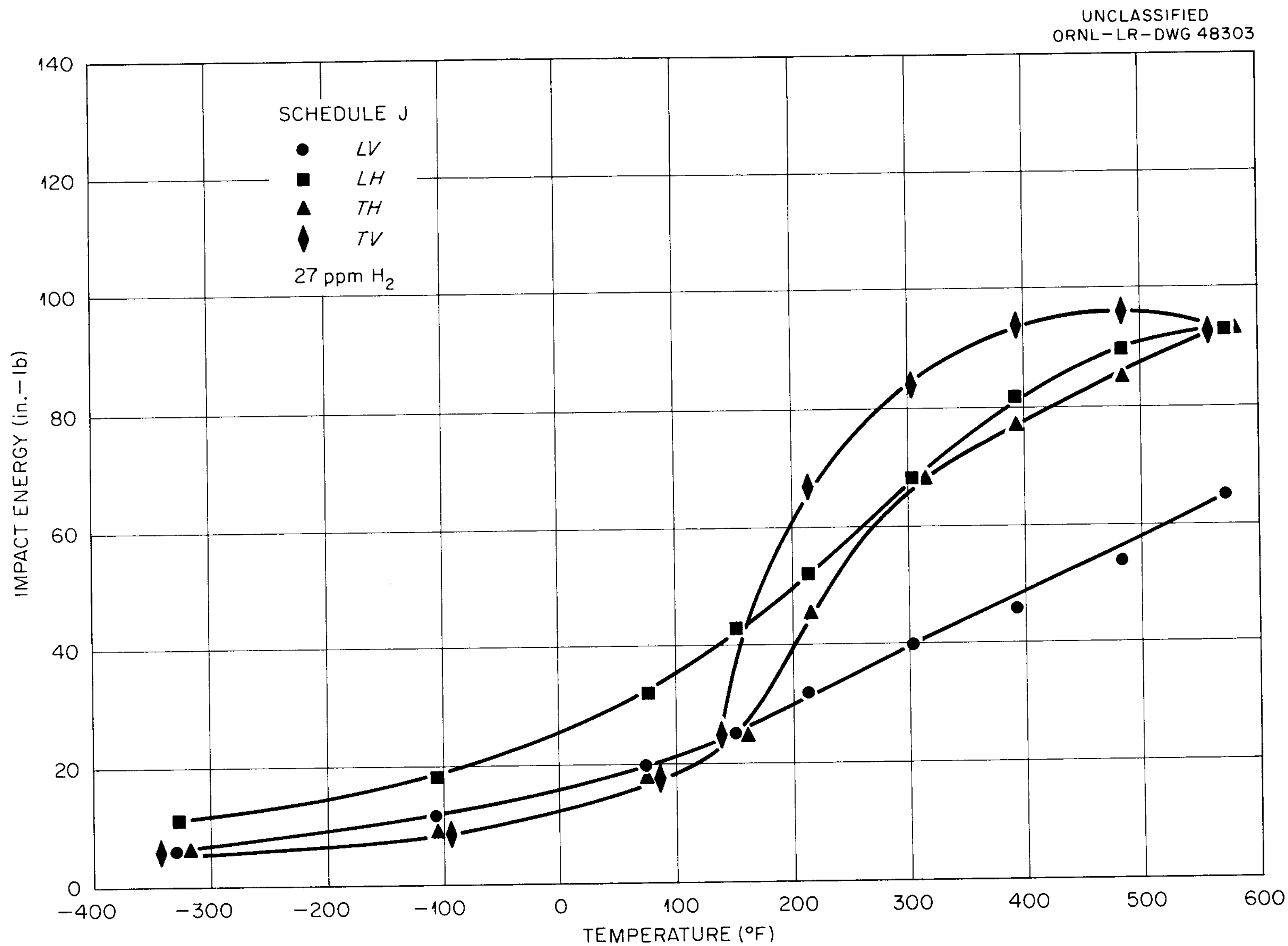

Fig. 23. Impact Energy Curves for Schedule J Zircaloy-2. Schedule J: HRP Commercial Fabrication Procedure for Wide Plate.

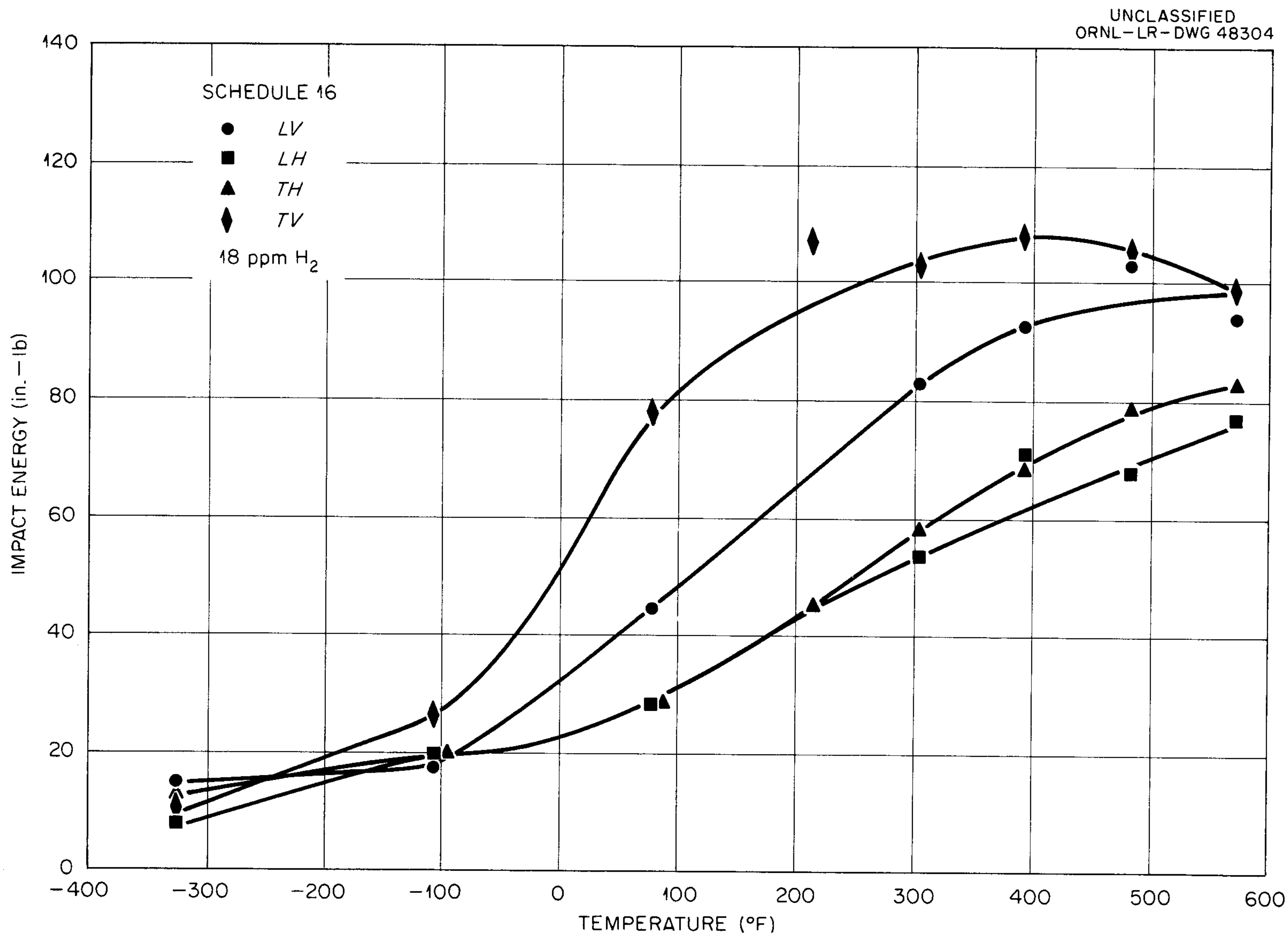

Fig. 24. Impact Energy Curves for Schedule 16 Zircaloy-2. Schedule 16: Cross-Rolled During β Reduction.

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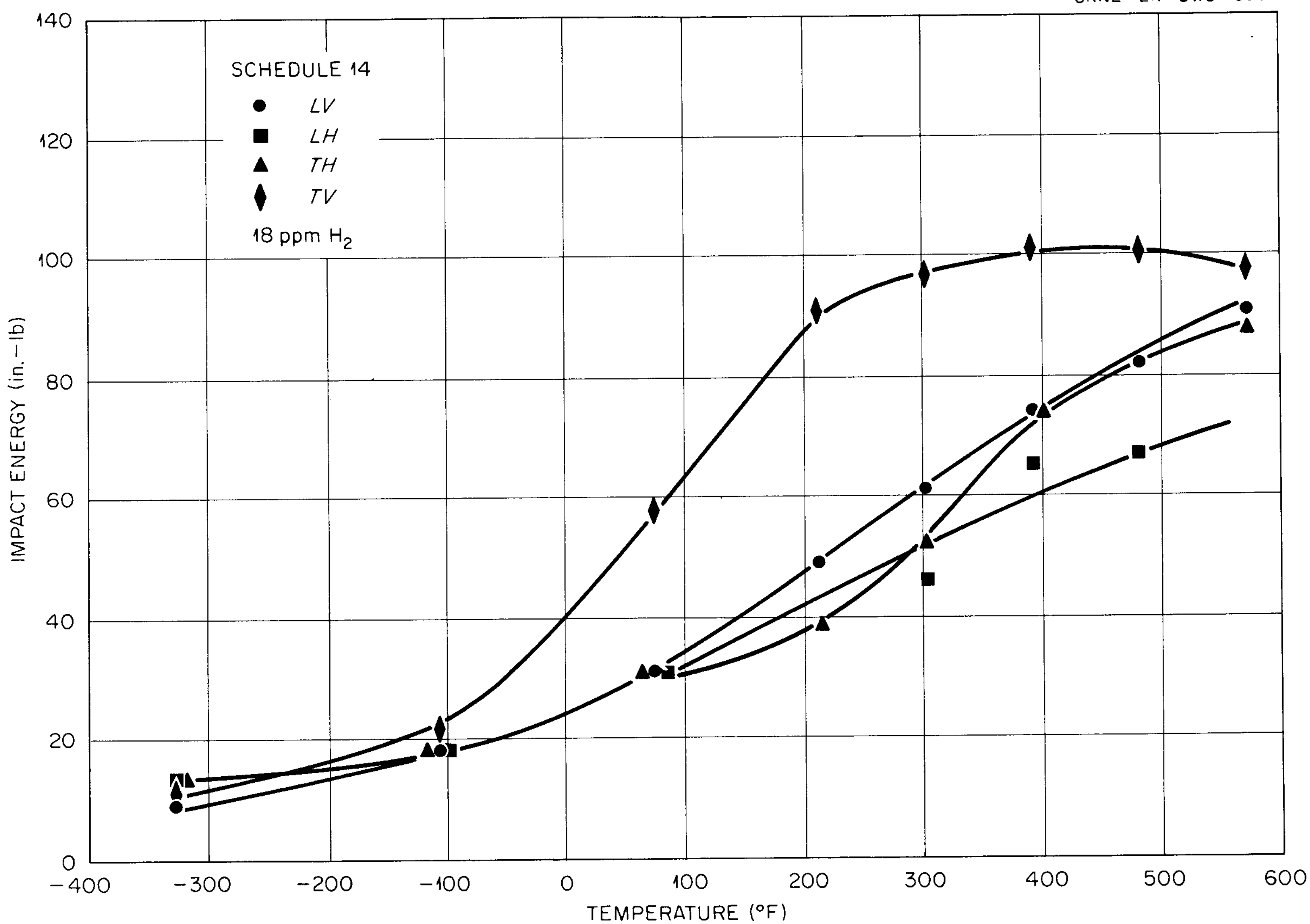

Fig. 25. Impact Energy Curves for Schedule 14 Zircaloy-2. Schedule 14: Cross-Rolled During High α Reduction.

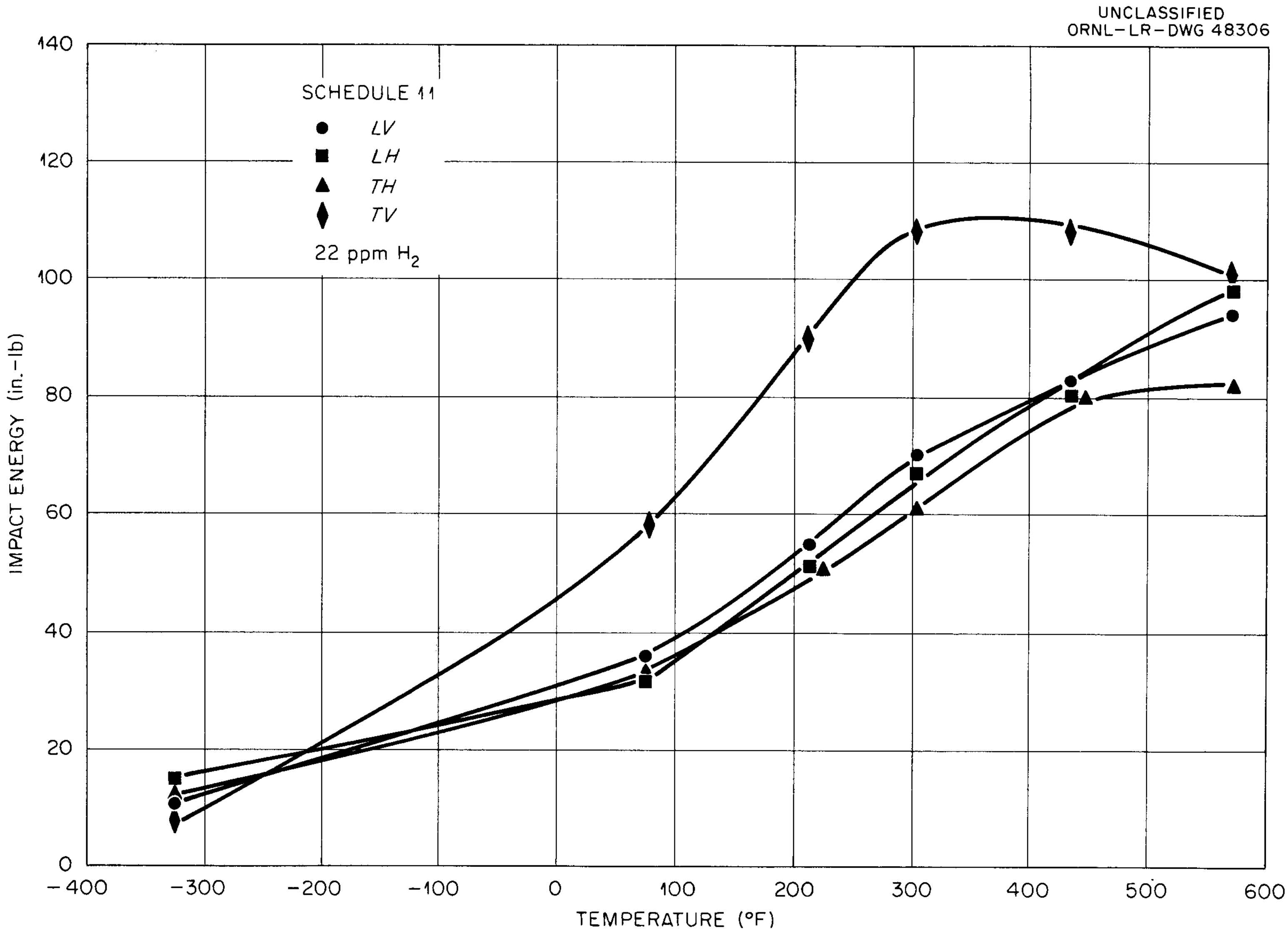

Fig. 26. Impact Energy Curves for Schedule 11 Zircaloy-2. Schedule 11: HRP Commercial Fabrication Procedure, 25 Per Cent Final Reduction.

TABLE VIII

HYDROGEN CONTENTS OF ZIRCALOY-2 IMPACT SPECIMENS[(a)]

Schedule	H_2-ppm	Schedule	H_2-ppm	Schedule	H_2-ppm	Schedule	H_2-ppm
1	45	6	42	11	22	16	18
2	12	7	72	12	22	17	21
3	37	8	45	13	17	18	18
4	14	9	40	14	18	62	76
5	43	10	59	15	21	J	27

(a) Three specimens for each schedule.

For schedule 8 material, Fig. 22, there were large differences in energy absorptions between specimens with variation in notch orientation, but none between specimens with variation in axis orientation. Obviously, then, impact energy testing of anisotropic materials is incomplete unless at least two notch and two specimen axis orientations are used.

Effect of Cross Rolling. Both the energy absorbed on fracture and the transition temperature were found to be a function of the fabrication variables. Unidirectional cross rolling at temperatures in the β field (schedules J and 18 with ingot axis in the transverse direction of the plate) caused the impact energy curves for the LV orientation to fall below those for the other orientations, while in all other cases the impact energy curves for the LV specimens were the highest or next to the highest. In contrast, when Zircaloy-2 was cross rolled in the β field but rotated 90° after each reduction (schedule 16 - ingot axis in the normal direction), the curves for the LV and TV orientations tended to converge and were considerably higher than those for the LH and TH orientations. This same convergence of the LV and TV curves was seen when cross rolling was done after a β heat treatment, whether or not the cross rolling was unidirectional. The impact energy curves of material produced by schedule 14, cross rolled at 1450°F before β heat treatment, were esentially no different from those of material (schedule 11) which had identical treatment except for the cross rolling.

Effect of Percent Final Reduction. Increased percent final reduction caused an increased divergence of the impact energy curves of specimens with vertical notch orientations from those with horizontal notch orientations. The positions of the LH and TH impact energy curves were unchanged by the percent final reduction, all of the increase in impact energy differences between the vertically and horizontally notched specimens having been due to an upward translation of the LV and TV curves. This has been found to be the rule in most cases. The positions of the impact energy curves of the horizontally notched specimens were relatively unaffected by the fabrication variables, while the transition temperatures and energy values for specimens with vertical notches were changed quite appreciably by the different fabrication procedures. In Fig. 27 is shown the scatter band of impact data for the LH orientation of eighteen of the fabrication schedules and in Fig. 28 is shown the variations found for the LV specimens of the same schedules.

Effect of Alpha-Working Temperature. A high α-working temperature for final reduction (schedule 7), 1450°F, did not give the divergence of impact energy curves for different notch orientations caused by a low α-working temperature (schedule 6), 1000°F, provided that both were preceded by a β heat treatment. If, instead of a β heat treatment, an α anneal preceded the final reduction, the divergence was found to be very large (schedules 8 and 9).

CONCLUSIONS

An analysis of the mechanical property data which has been presented and discussed does not allow a satisfactory evaluation of the effect of the fabrication variables on the state of anisotropy of Zircaloy-2. Even though an apparent qualitative analysis and evaluation of the directionality of properties can be made, it is valid only in the rolling plane of the plate and ignores any variation in the direction normal to the plate.

The inability of the analysis already presented to separate and evaluate the effects of the fabrication variables on the true state of anisotropy existing in the materials necessitates the development of other methods of analysis. The preferred orientation and strain-strain analyses which will be

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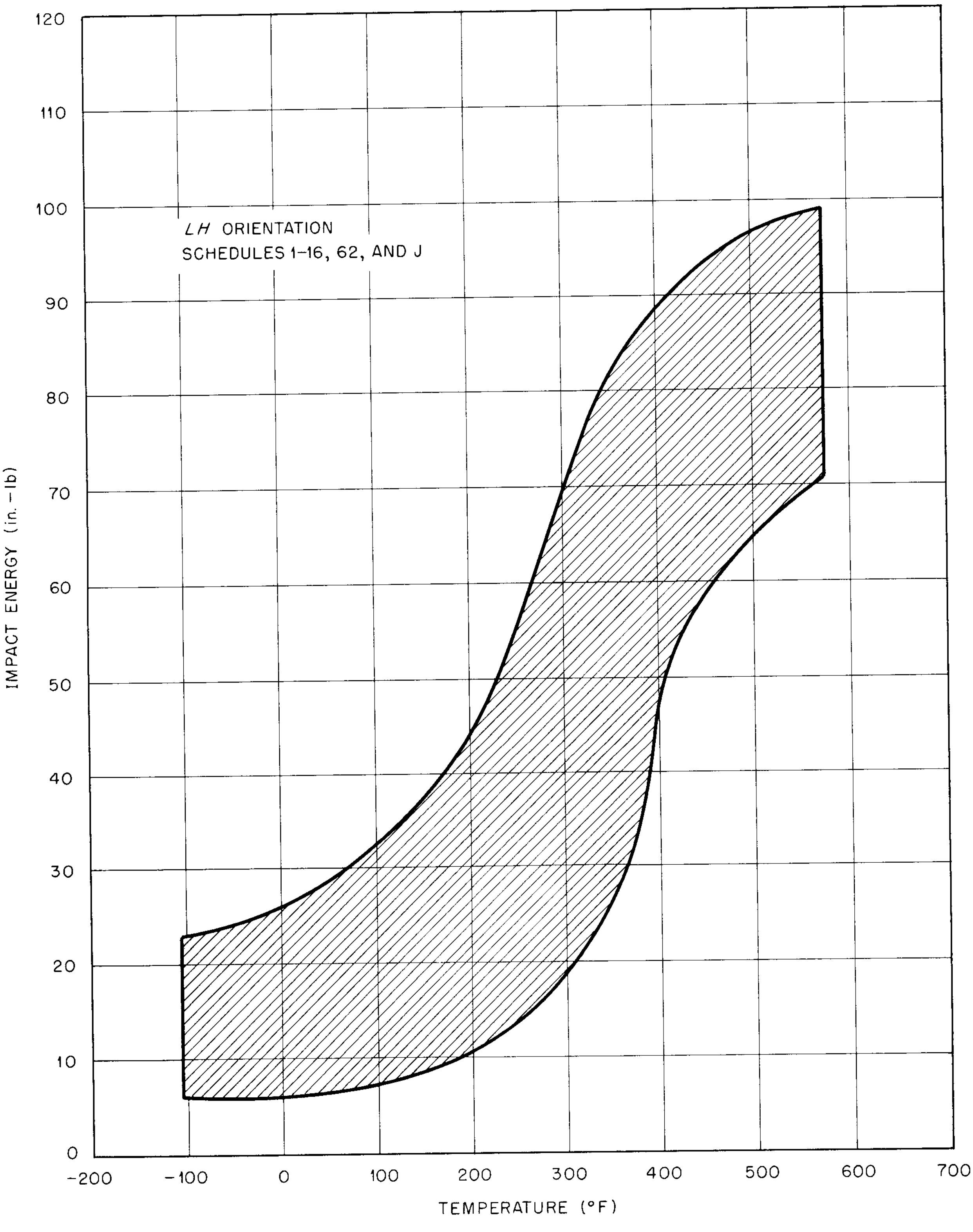

Fig. 27. *LH* Orientation Impact Energy Scatterband of Eighteen Schedules of Zircaloy-2.

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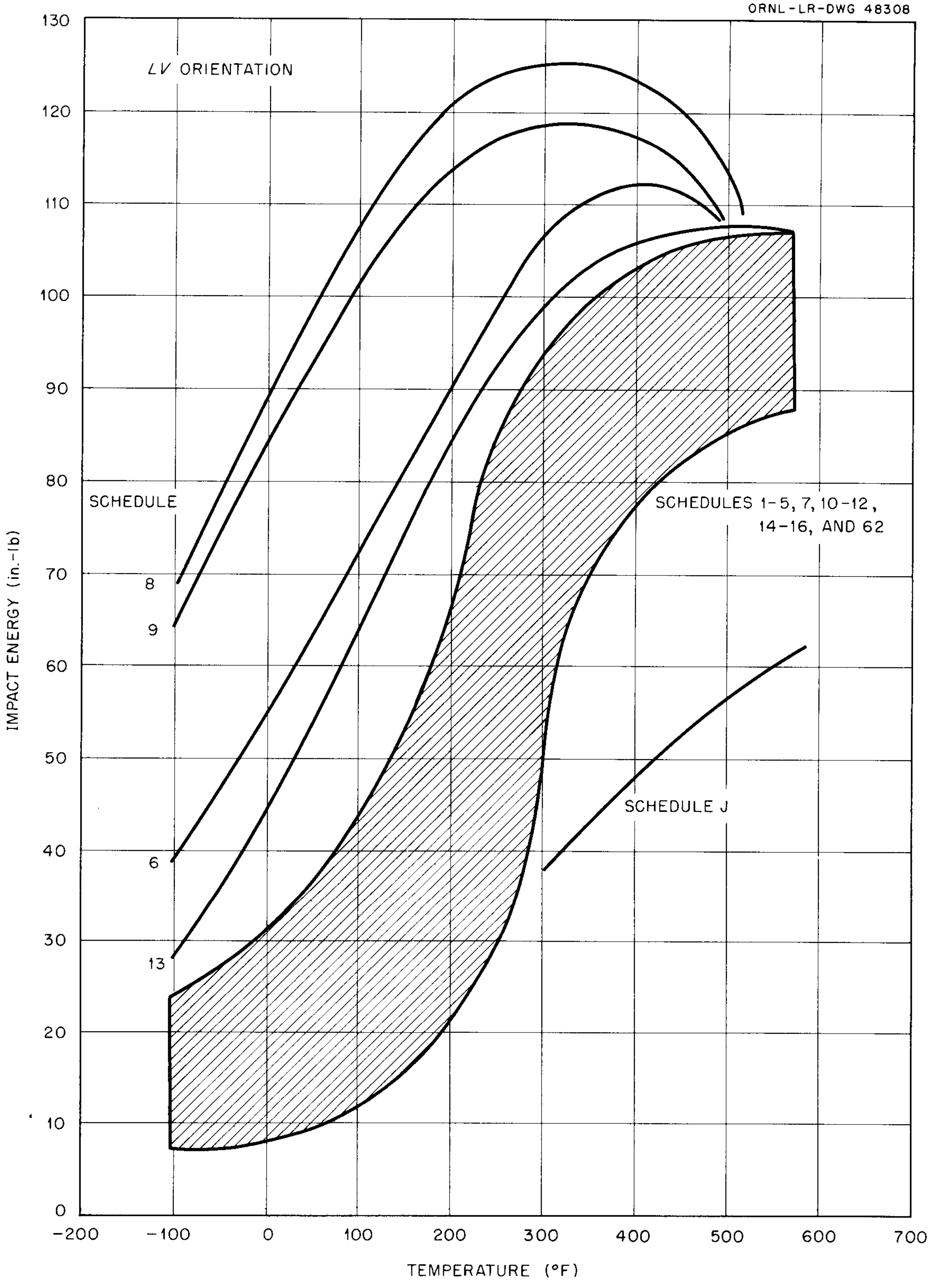

Fig. 28. Spectrun of *LV* Orientation Impact Energy Curves of Eighteen Fabrication Schedules of Zircaloy-2.

reported[41] permit a more complete and detailed evaluation of the variation of the true state of anisotropy with changes in fabrication procedure.

The following specific conclusions were drawn from the data presented:

1. The mechanical property values usually obtained in uniaxial tensile testing cannot be used alone to evaluate the effects of fabrication variables on the anisotropy of mechanical properties of Zircaloy-2. They do, however, give a measure of the directionality of properties in the plane of the plate. The yield strength was found to be the most useful property in the evaluation of the anisotropy of mechanical properties in the rolling plane.

2. In order to determine the principal axes of anisotropy of mechanical properties of Zircaloy-2, tensile specimens must be tested with a variation of tensile axes through 180° in the plane of the plate.

3. A ratio of the natural contractile strain in the direction normal to the rolling plane to the natural contractile strain in the plane of the plate, measured at the tensile specimen fracture, is helpful in avoiding misinterpretation of the data in the evaluation of the directionality of properties by use of the mechanical properties.

4. The testing temperature was found to have little or no effect on the directionality of the tensile properties existing in each material.

5. The effect of cross rolling depended on the temperature and stage of fabrication at which it was performed, and whether the cross rolling was unidirectional or rotational. Rotational cross rolling led to a minimization of directionality of the strength properties in the plane of the plate, but to varying degrees of anisotropy with regard to strain behavior. Unidirectional cross rolling generally increased the degree of directionality of properties in the plane of the plate.

6. The degree of directionality of mechanical properties in the rolling plane was not affected appreciably by the percent final reduction, although the absolute values varied considerably. The contractile strain ratios, however, decreased with increased percent final reduction, and thus showed that an increase in total anisotropy occurred with an increase in the percent final reduction.

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[41] P. L. Rittenhouse and M. L. Picklesimer, Metallurgy of Zircaloy-2 Part II The Effects of Fabrication Variables on the Preferred Orientation and Anisotropy of Strain Behavior, ORNL-2948 (to be published).

7. When no intermediate β heat treatment is given, a low α- rather than a high α-working temperature is to be preferred because a lower degree of anisotropy is produced.

8. An intermediate β heat treatment increased the degree of directionality in the plane of the plate, but decreased the degree of anisotropy existing in the material.

9. Whether the original ingot axis was in the rolling direction or normal direction of the finished plate had little effect on the values of or the degree of directionality of mechanical properties of Zircaloy-2.

10. The impact energy curves for Zircaloy-2 and other anisotropic metals may be used as a qualitative measurement of anisotropy if both horizontally and vertically notched longitudinal and transverse specimens are used.

11. Cross rolling (rotational) at temperatures in the β field before β heat treatment, cross rolling at temperatures in the α field after β heat treatment (both rotational and unidirectional), or the absence of a β heat treatment before the final reduction produced a convergence of the impact energy curves for specimens with the same notch orientation. The convergence of the curves was not seen when rotational cross rolling was performed at 1450°F before β heat treatment.

12. The LV impact energy curves, usually the highest or second highest in energy, became the low energy curves when the major reduction step was performed at temperatures in the β field and the ingot axis was in the transverse direction.

13. Increased percent final reduction caused an increased divergence between the impact energy curves for specimens with vertical notches and with horizontal notches.

14. When both were preceded by a β heat treatment, a high α final reduction temperature did not cause as great a divergence of impact energy curves for the same notch orientation as did a low α final reduction.

15. The divergence of the impact energy curves of notch orientation pairs (LH-TH from LV-TV) was observed to be due to a translation of the LV and TV curves to higher energy values. The positions or energy levels of the impact energy curves for specimens with horizontal notches were relatively unaffected by the fabrication variables.

RECOMMENDATIONS

Further effort directed at the study of the effects of fabrication variables on the anisotropy of mechanical properties is of limited use if only the usually determined mechanical property values are to be examined. The use of other methods of evaluation and interpretation of the changes effected by the fabrication variables is necessary to gain a true insight into the nature and solution of those problems which will most certainly arise in the use of Zircaloy-2 and other anisotropic metals as structural materials.

It is strongly recommended that round tensile specimens be used in all future studies of tensile properties of anisotropic metals so that the contractile strain ratio at fracture and the contractile strain-axial strain analysis[41] may be used in the evaluation of the variables of the study.

As the particular application of any material dictates whether complete isotropy or a particular degree of anisotropy is most desirable, no unqualified recommendation as to the "best" fabrication procedure for Zircaloy-2 may be given. If the application calls for an isotropic material, the fabrication procedure which will yield Zircaloy-2 that will most nearly meet this specification (yield the least anisotropic Zircaloy-2 as yet produced) is the schedule by which Zircaloy-2 for ORNL-HRP Metallurgy use is fabricated. The major features of this procedure are:

1. Ingot breakdown in the β phase (1800–1950°F);
2. Major reduction in the β (1800–1900°F) or α (1400–1490°F) phases;
3. A 30–45 min β heat treatment (1800–1850°F) followed by a rapid quench (water or forced air);
4. A final reduction (20% min) in the α phase (950–1100°F); and
5. A final anneal of 30–45 min at 1425°F.

APPENDIX I

Typical Load-Elongation Curves for Zircaloy-2

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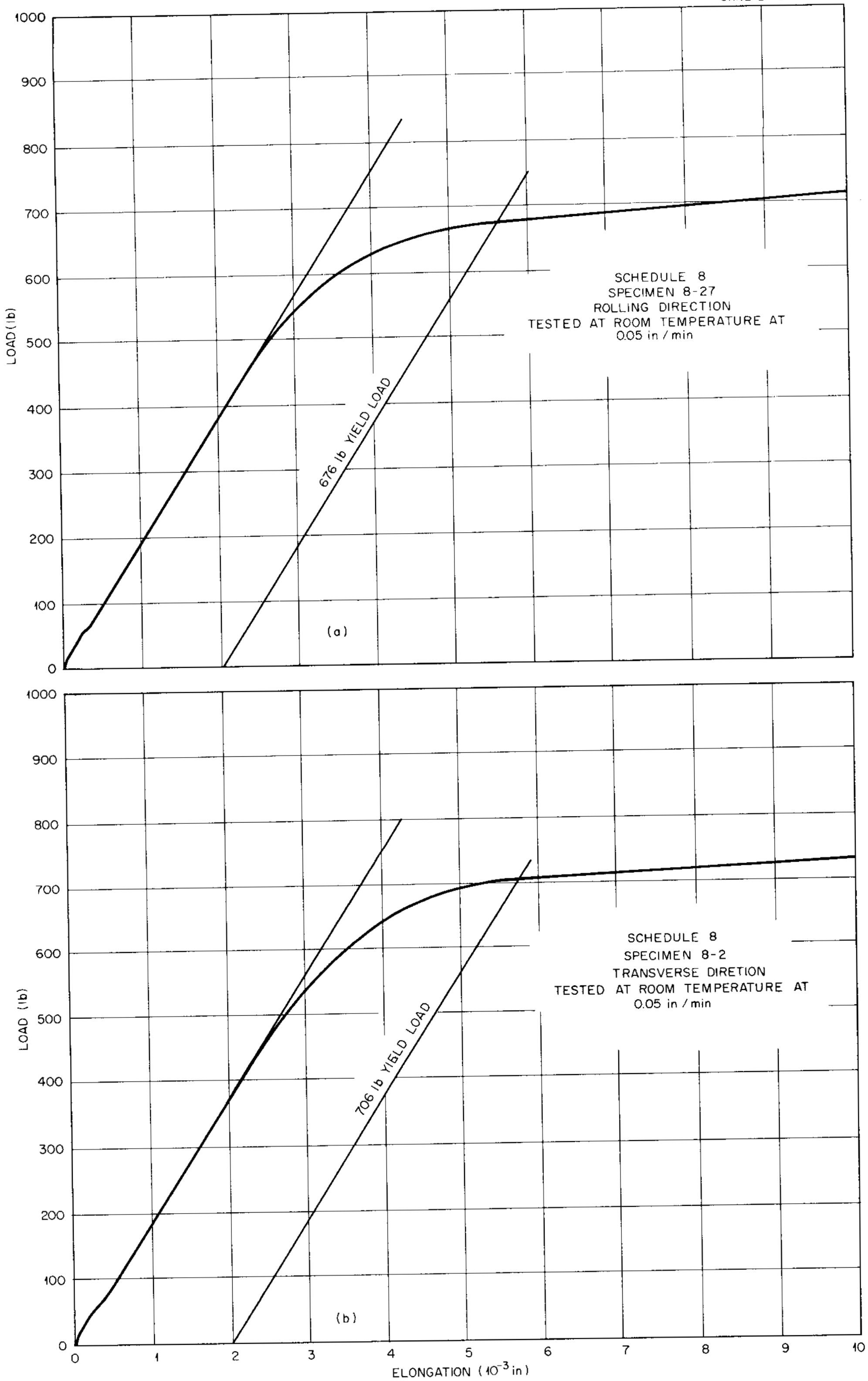

Fig.29. Load-Elongation Curves for Schedule 8 Zircaloy-2.

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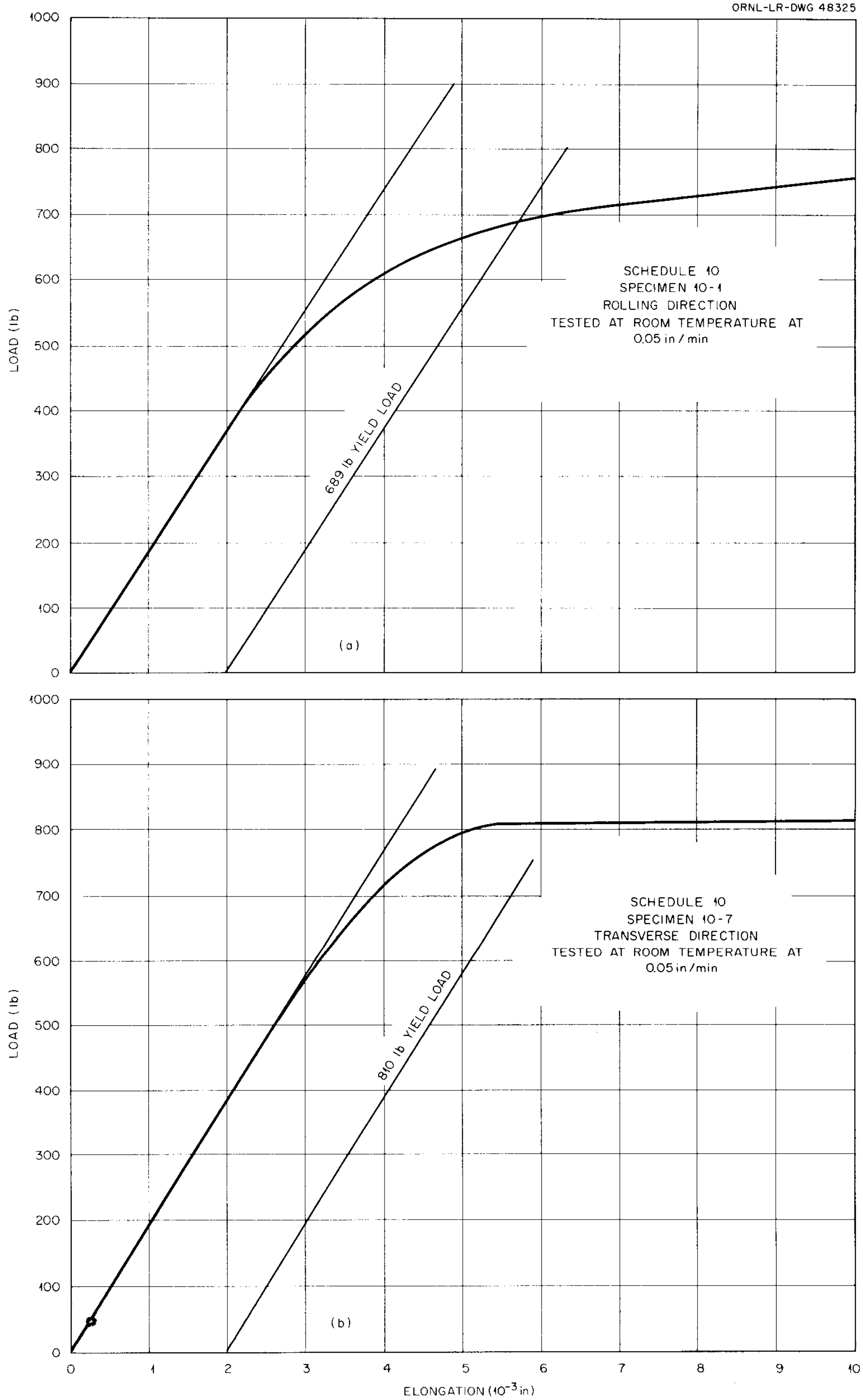

Fig. 30. Load-Elongation Curves for Schedule 10 Zircaloy-2.

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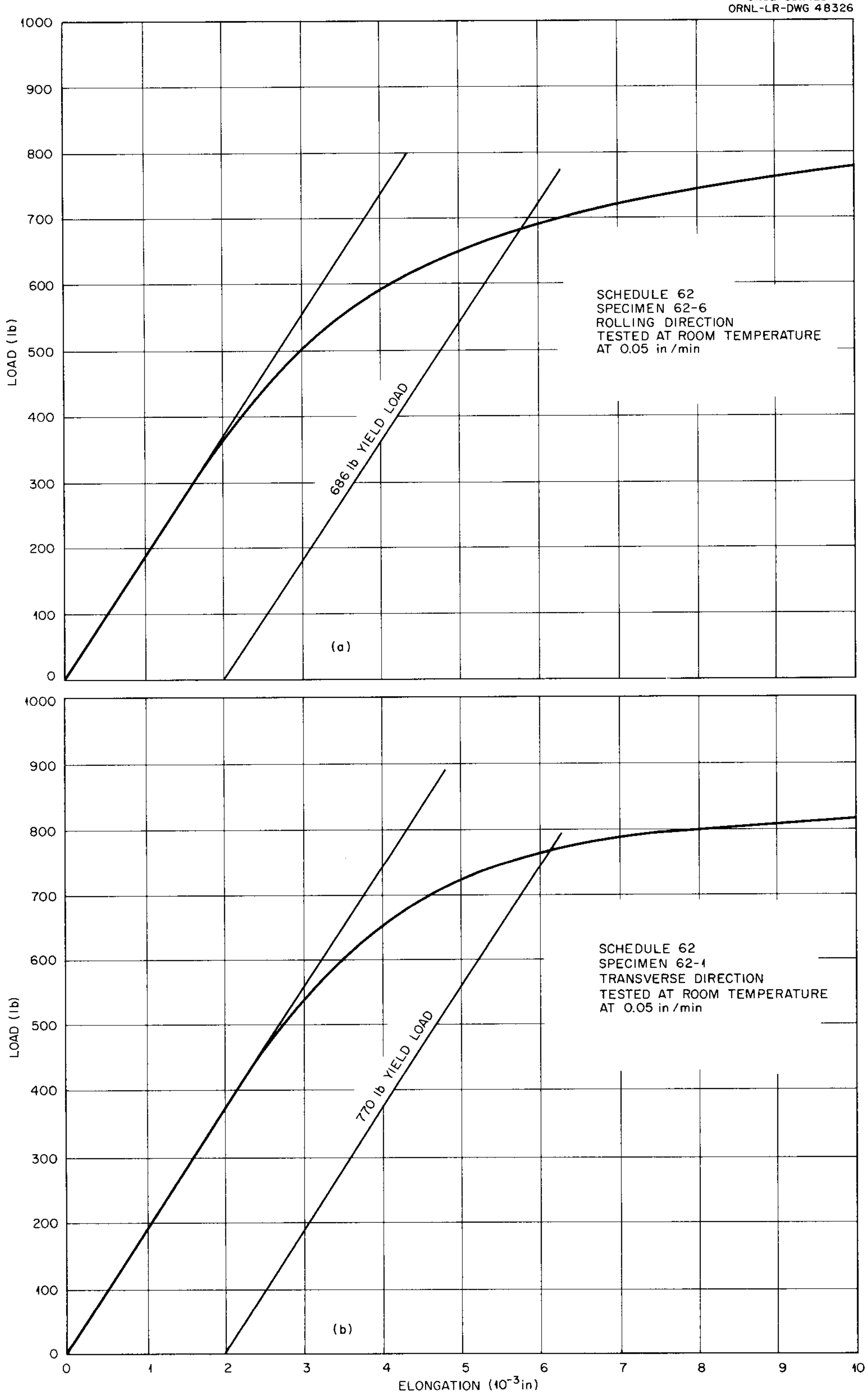

Fig. 31. Load-Elongation Curves for Schedule 62 Zircaloy-2.

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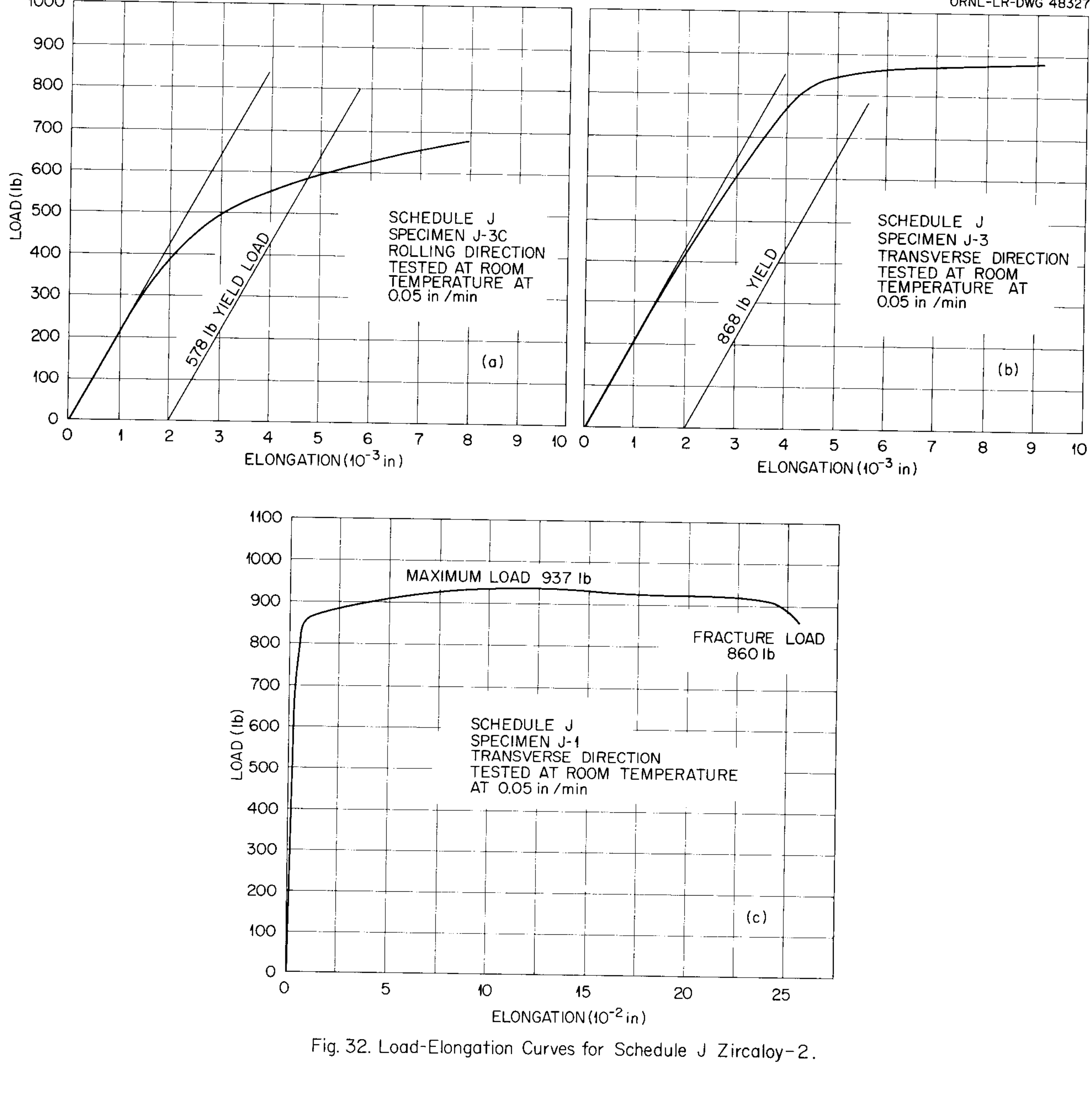

Fig. 32. Load-Elongation Curves for Schedule J Zircaloy-2.

APPENDIX II

Impact Energy Data and Curves

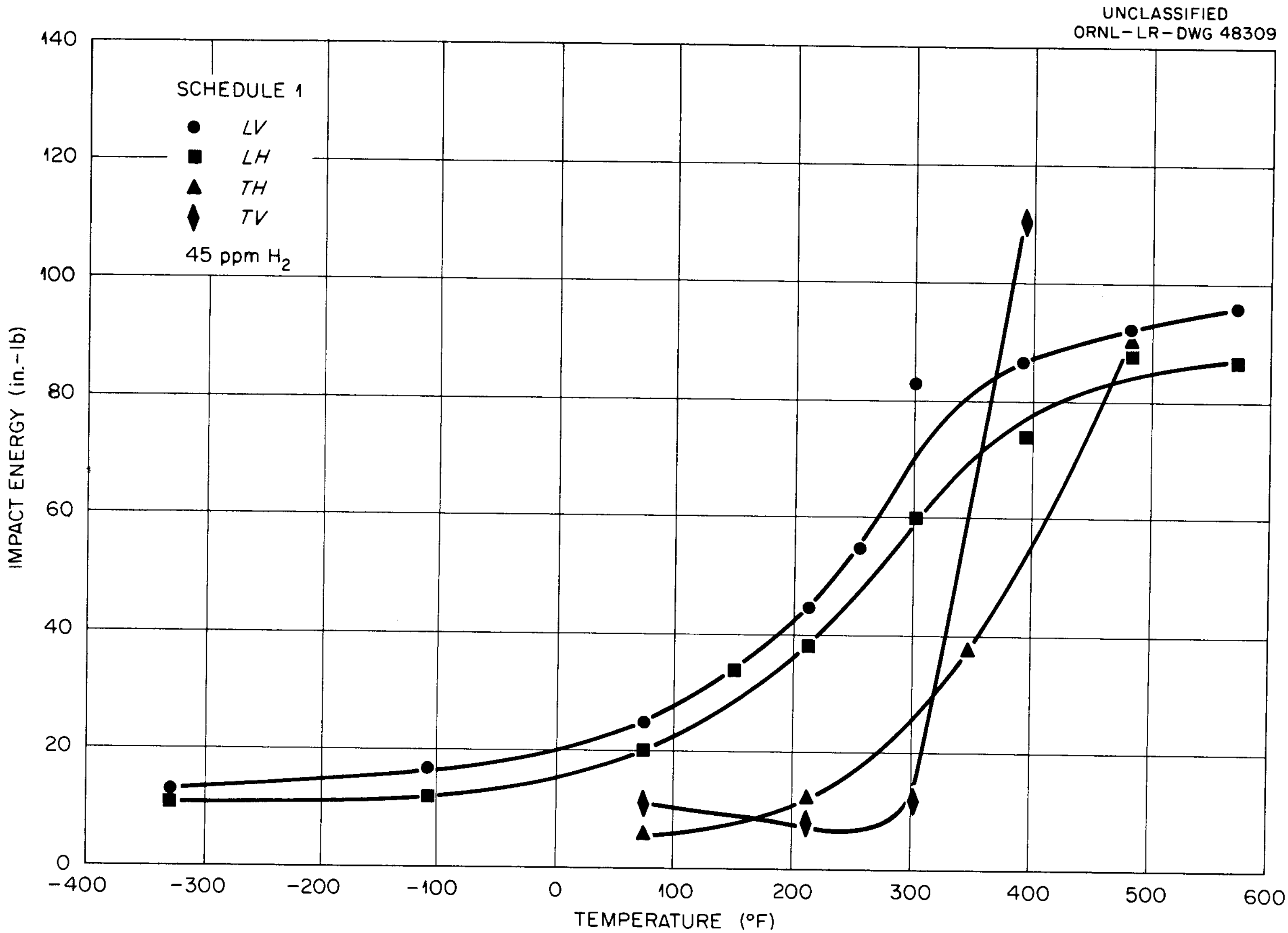

Fig. 33. Impact Energy Curves for Schedule 1 Zircaloy−2. Schedule 1: Two Intermediate β Heat-Treatments, Air Cooled.

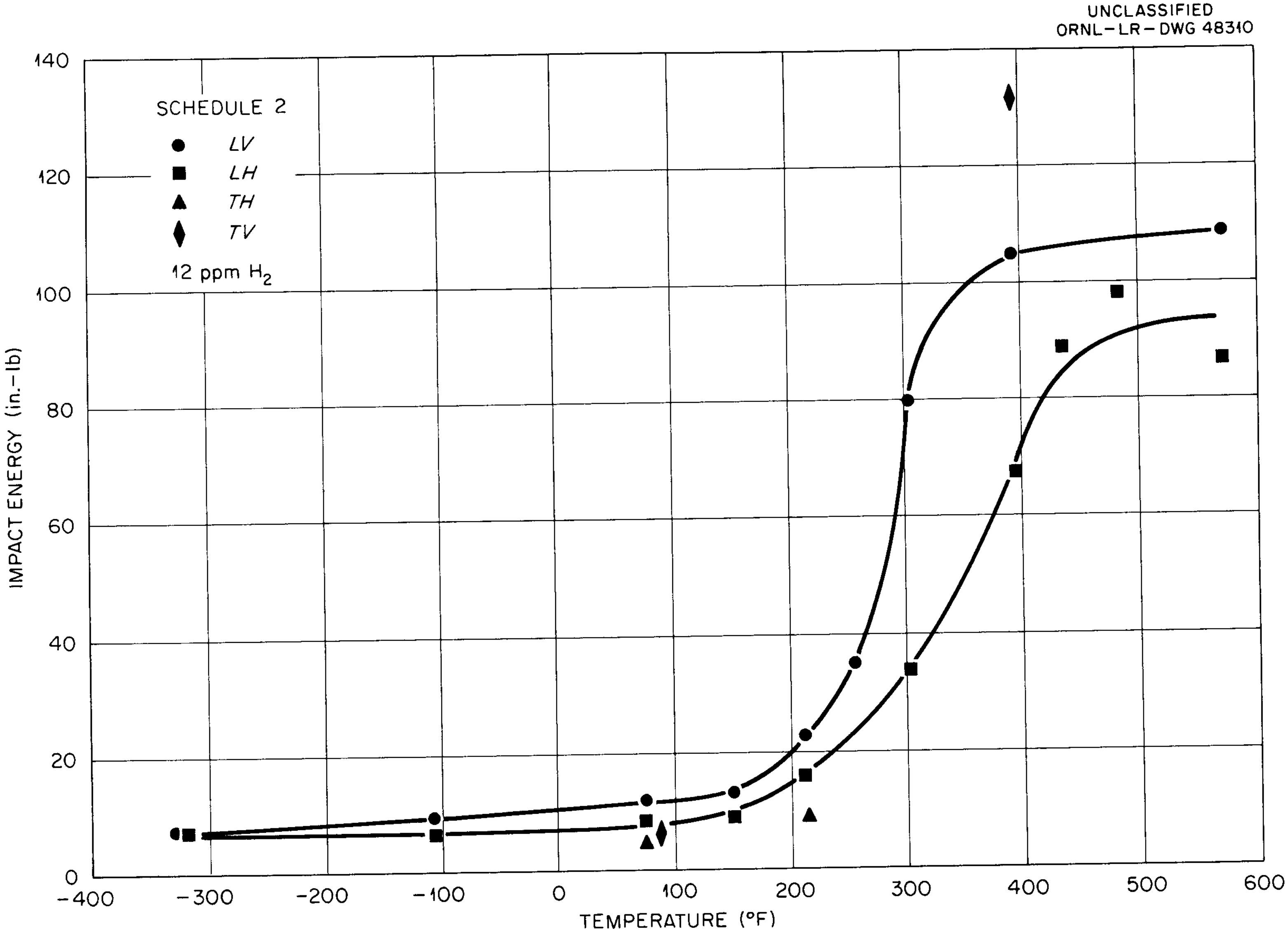

Fig. 34. Impact Energy Curves for Schedule 2 Zircaloy-2. Schedule 2: Two Intermediate β Heat-Treatments, Water Quenched.

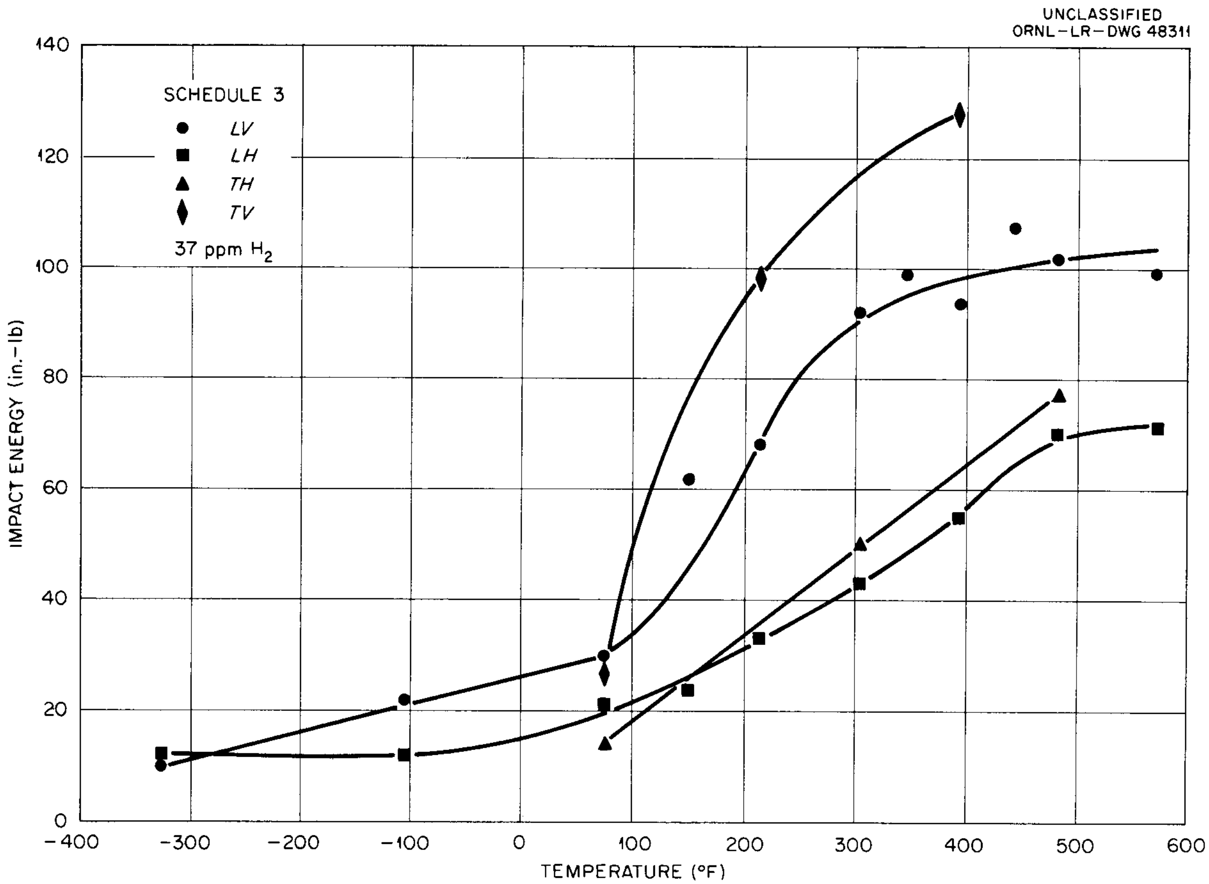

Fig. 35. Impact Energy Curves for Schedule 3 Zircaloy-2. Schedule 3: One Intermediate β Heat-Treatment.

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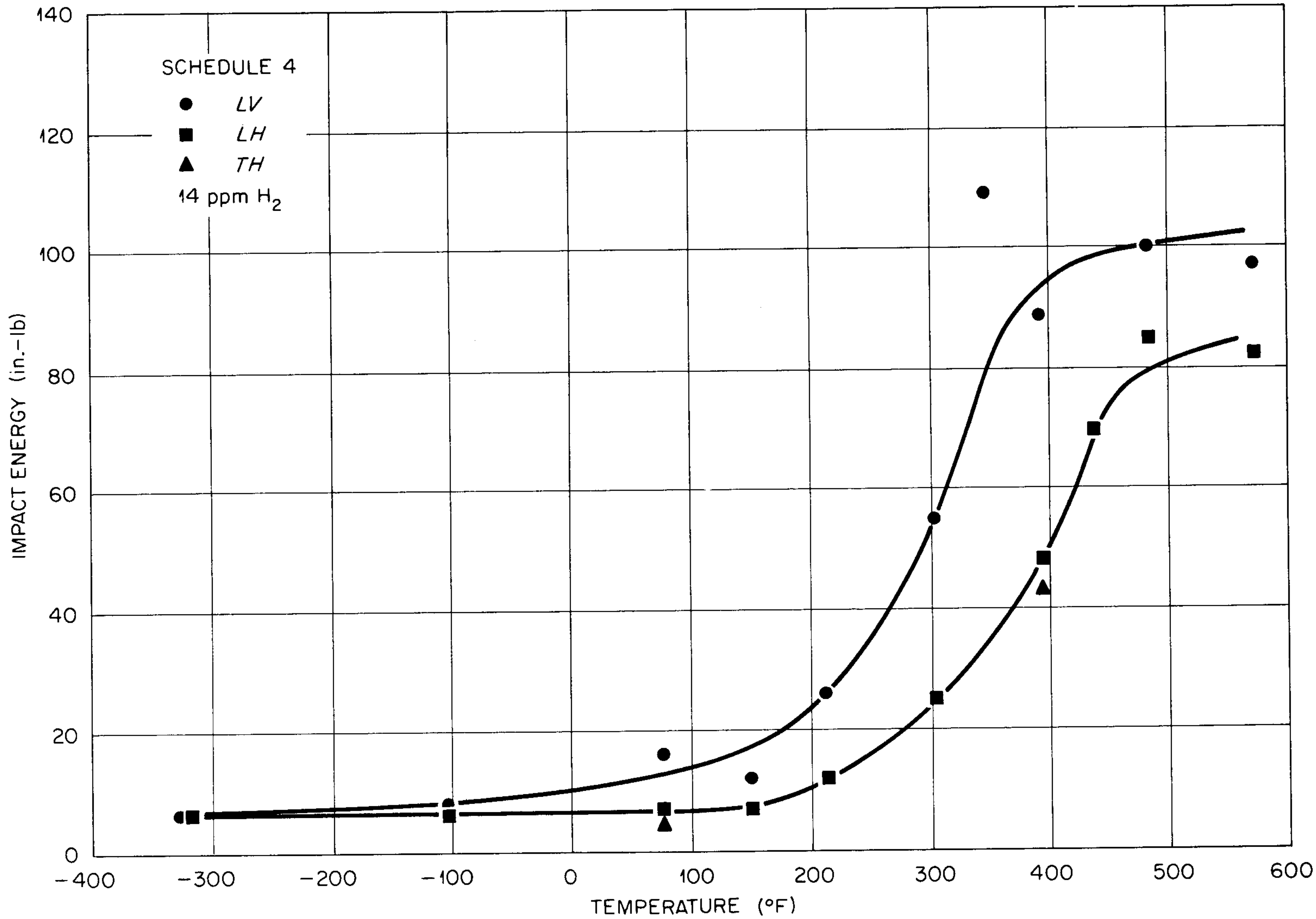

Fig. 36. Impact Energy Curves for Schedule 4 Zircaloy-2. Schedule 4: β Reduction Plus 25 Per Cent Low α Reduction.

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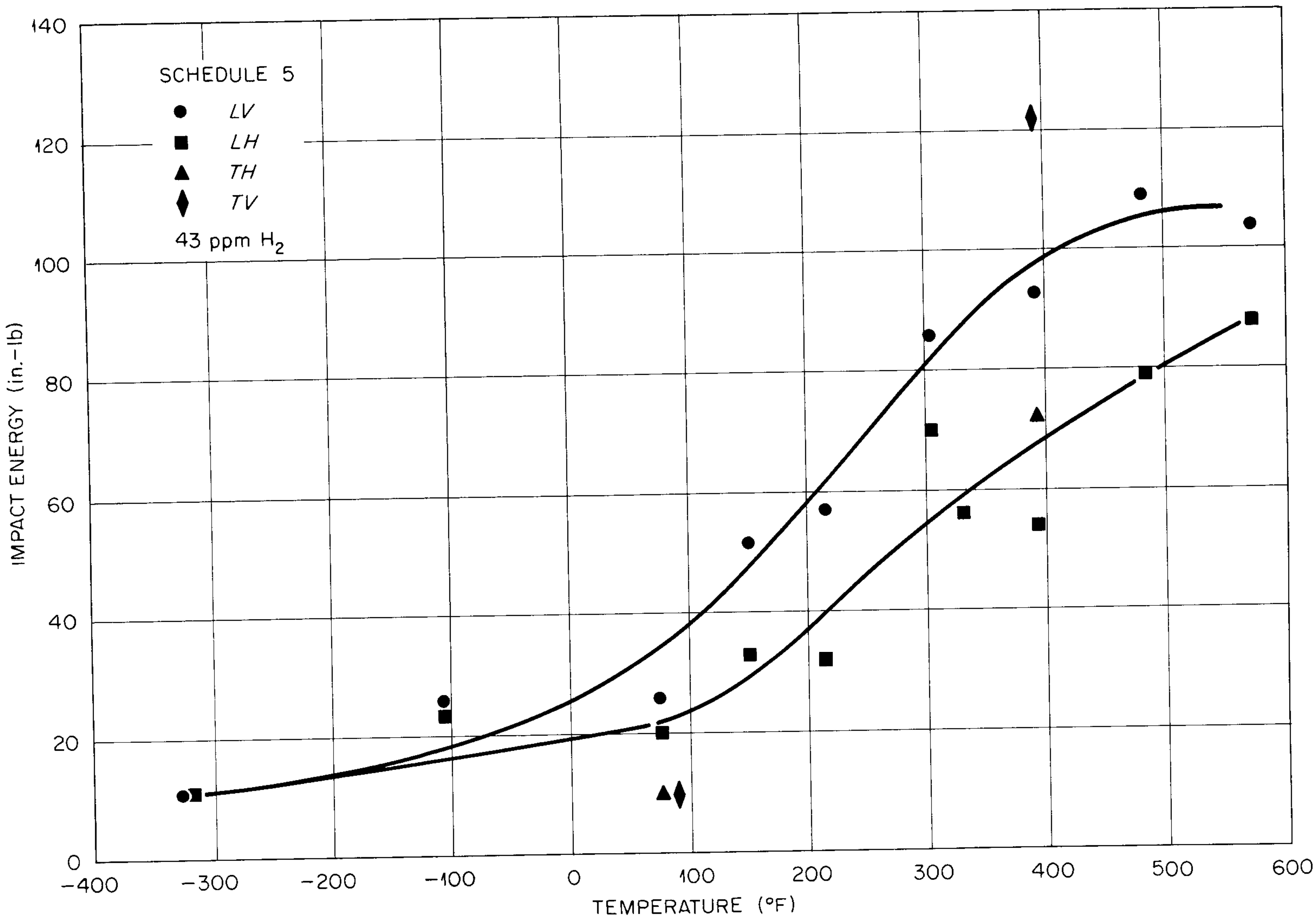

Fig. 37. Impact Energy Curves for Schedule 5 Zircaloy-2. Schedule 5: β Reduction Plus 50 Per Cent Low α Reduction.

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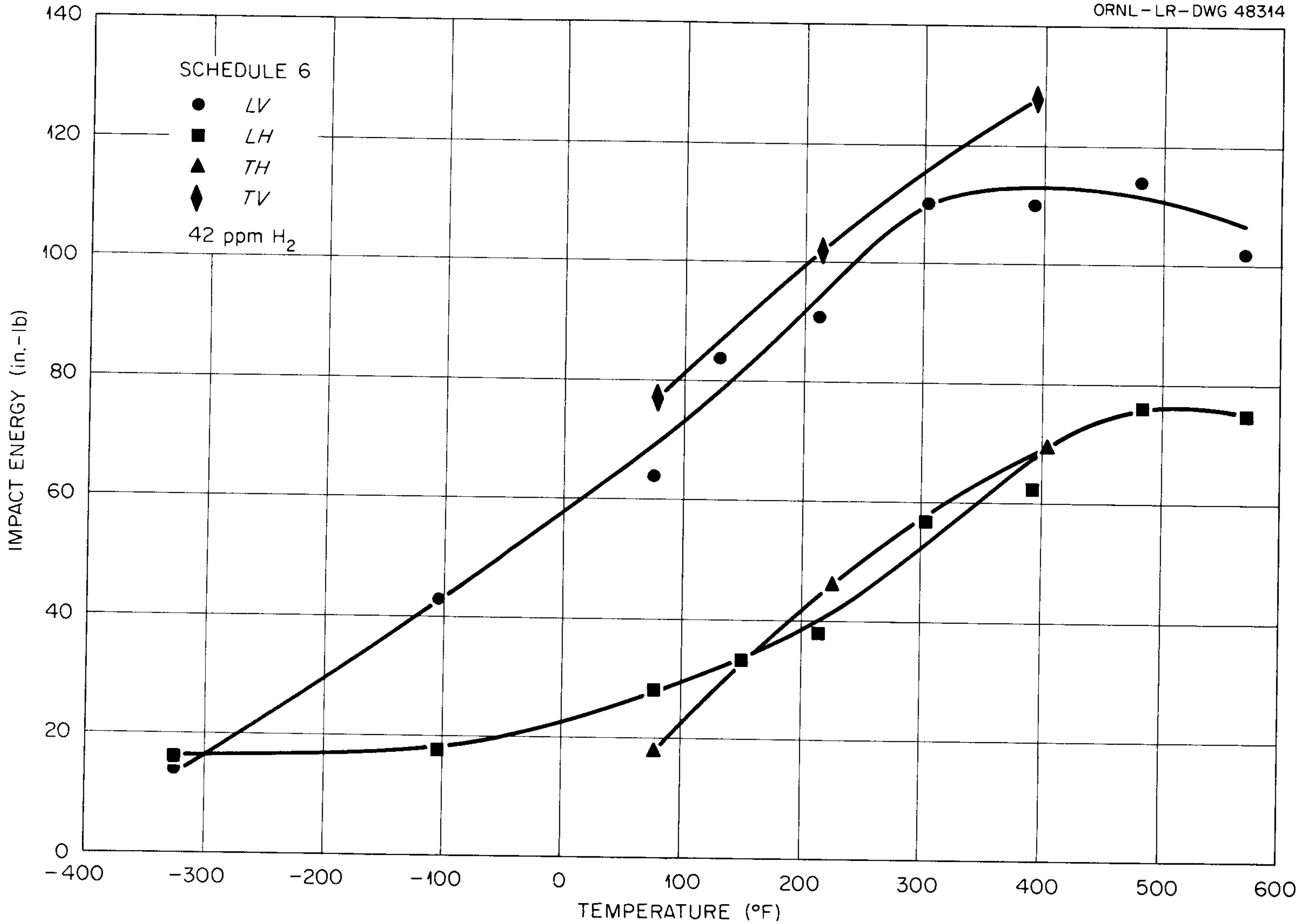

Fig. 38. Impact Energy Curves for Schedule 6 Zircaloy-2. Schedule 6: β Reduction Plus 70 Per Cent Low α Reduction.

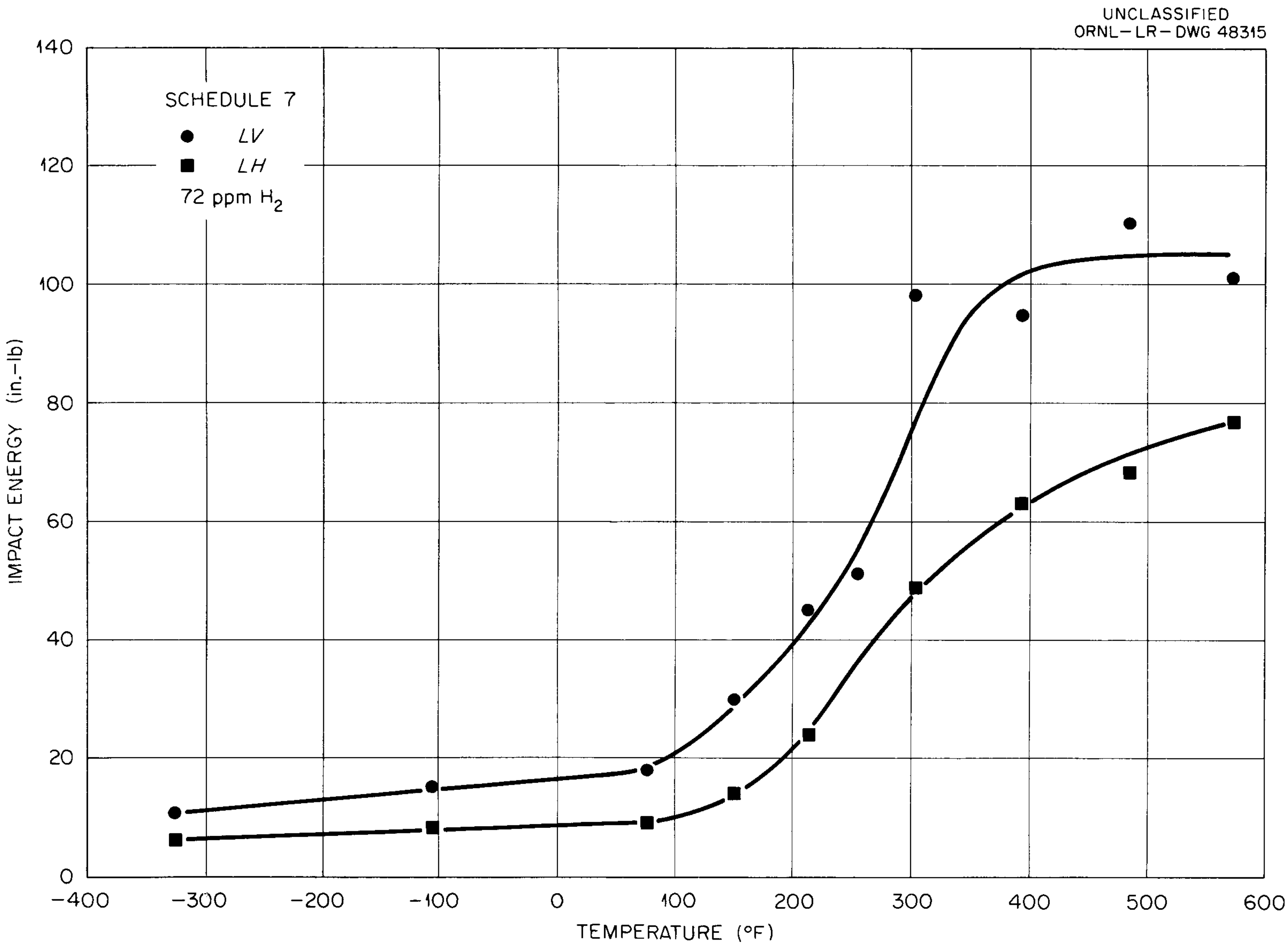

Fig. 39. Impact Energy Curves for Schedule 7 Zircaloy-2. Schedule 7: β Reduction Plus High α Reduction.

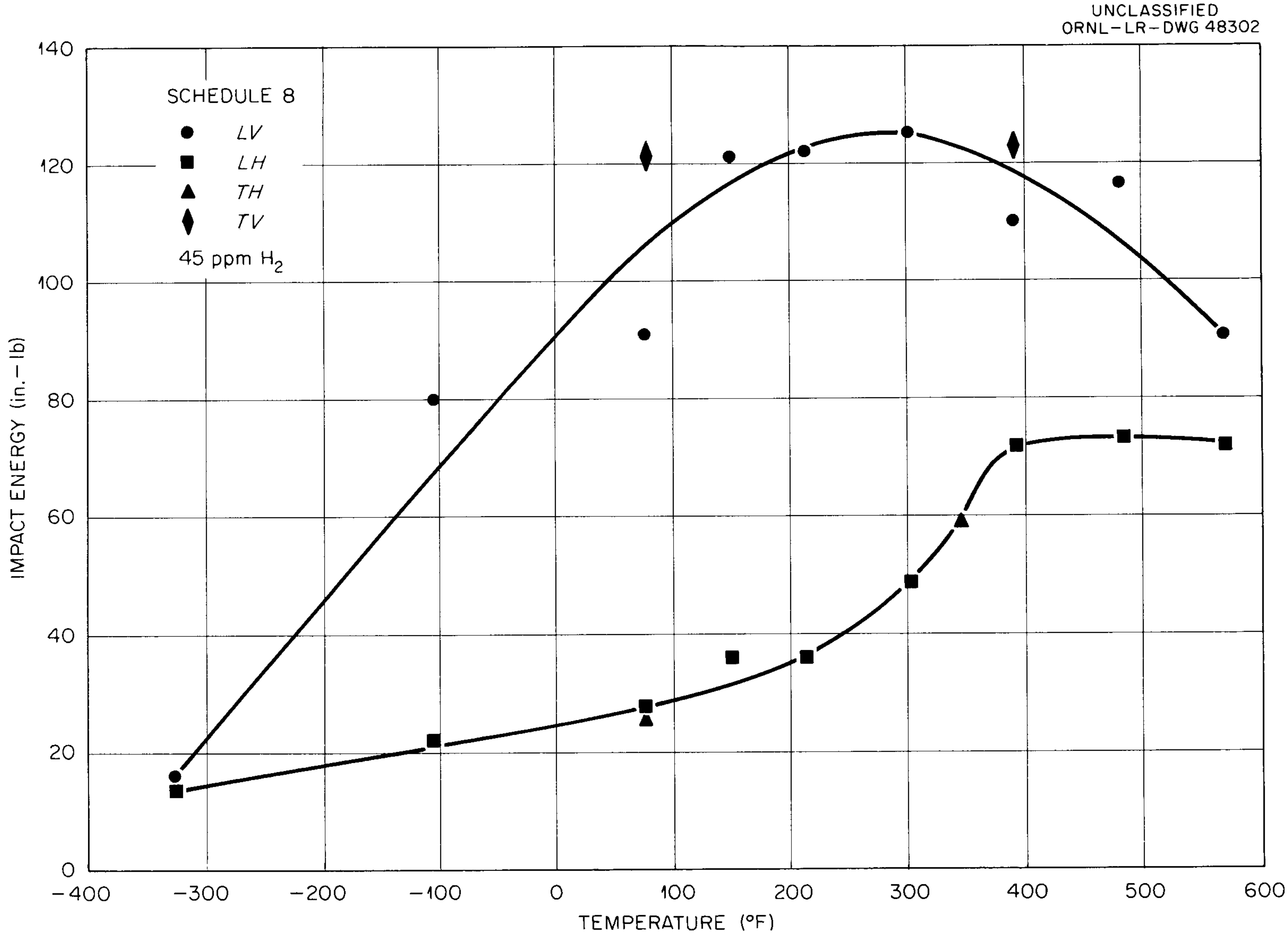

Fig. 40. Impact Energy Curves for Schedule 8 Zircaloy-2. Schedule 8: $\dot{\alpha}$ Worked, 70 Per Cent Low α Reduction.

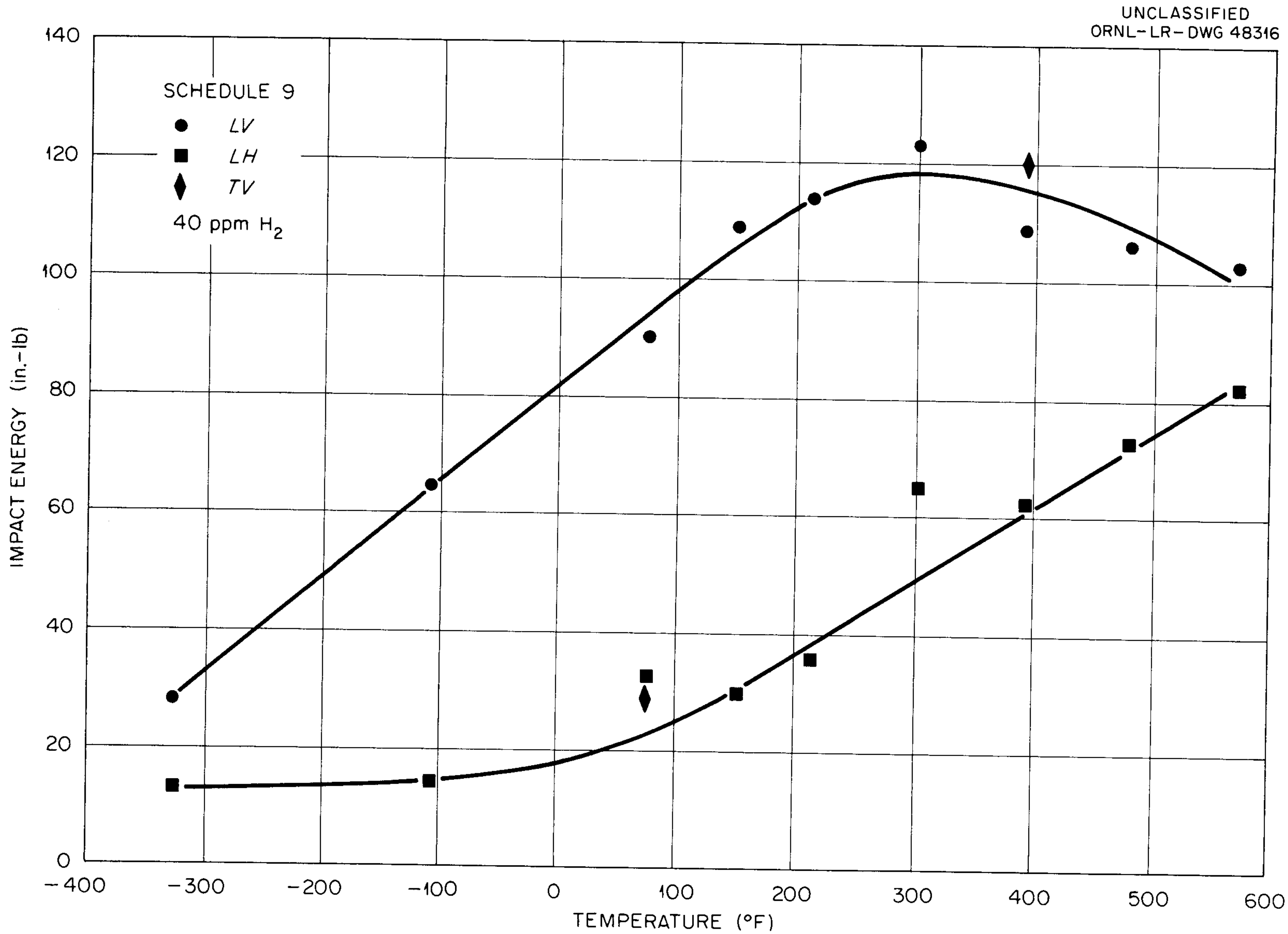

Fig. 41. Impact Energy Curves for Schedule 9 Zircaloy-2. Schedule 9: α Worked, 50 Per Cent Low α.

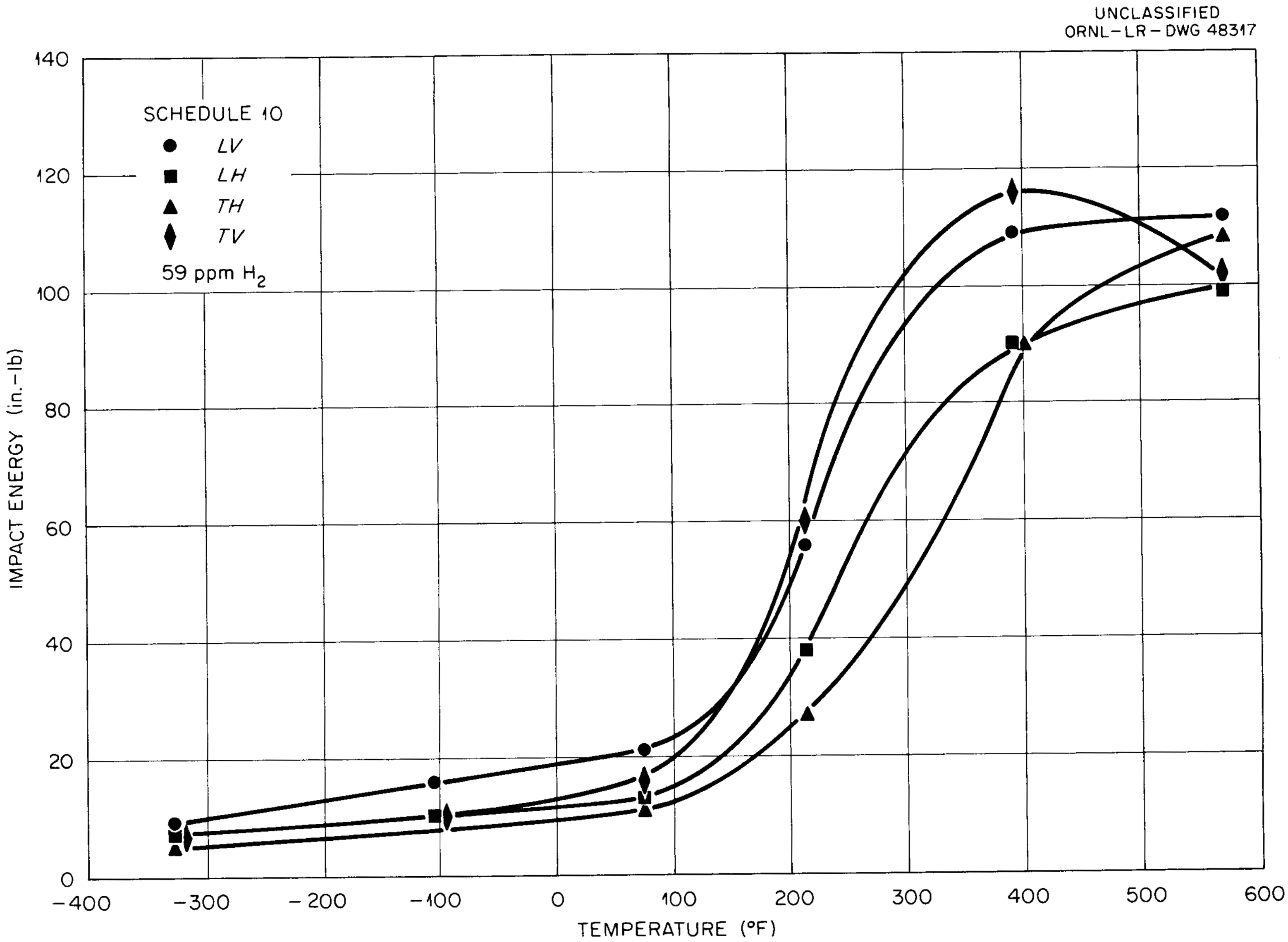

Fig. 42. Impact Energy Curves for Schedule 10 Zircaloy-2. Schedule 10: Cross-Rolled After β Heat-Treatment.

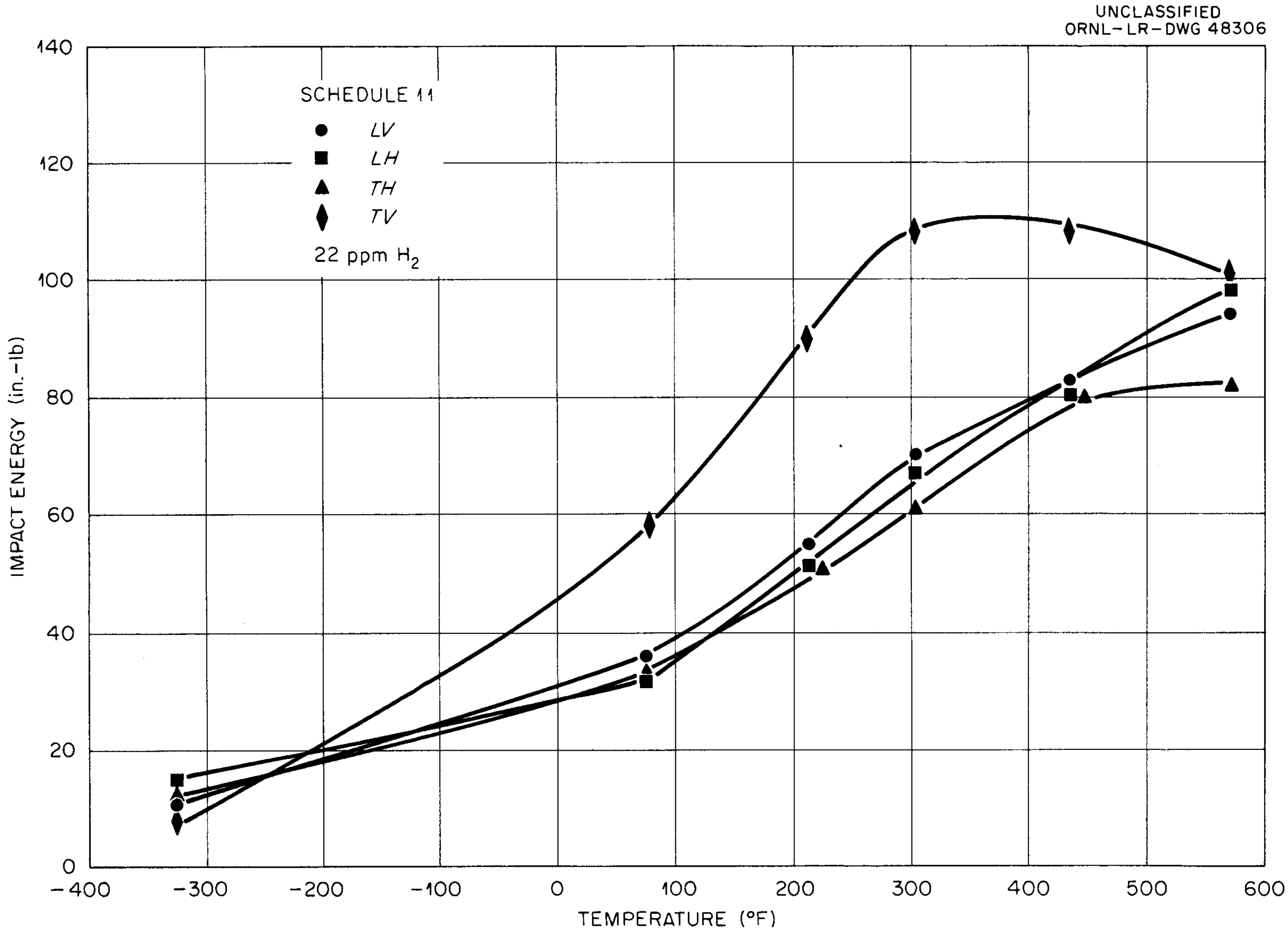

Fig. 43. Impact Energy Curves for Schedule 11 Zircaloy-2. Schedule 11: HRP Commercial Fabrication Procedure, 25 Per Cent Final Reduction.

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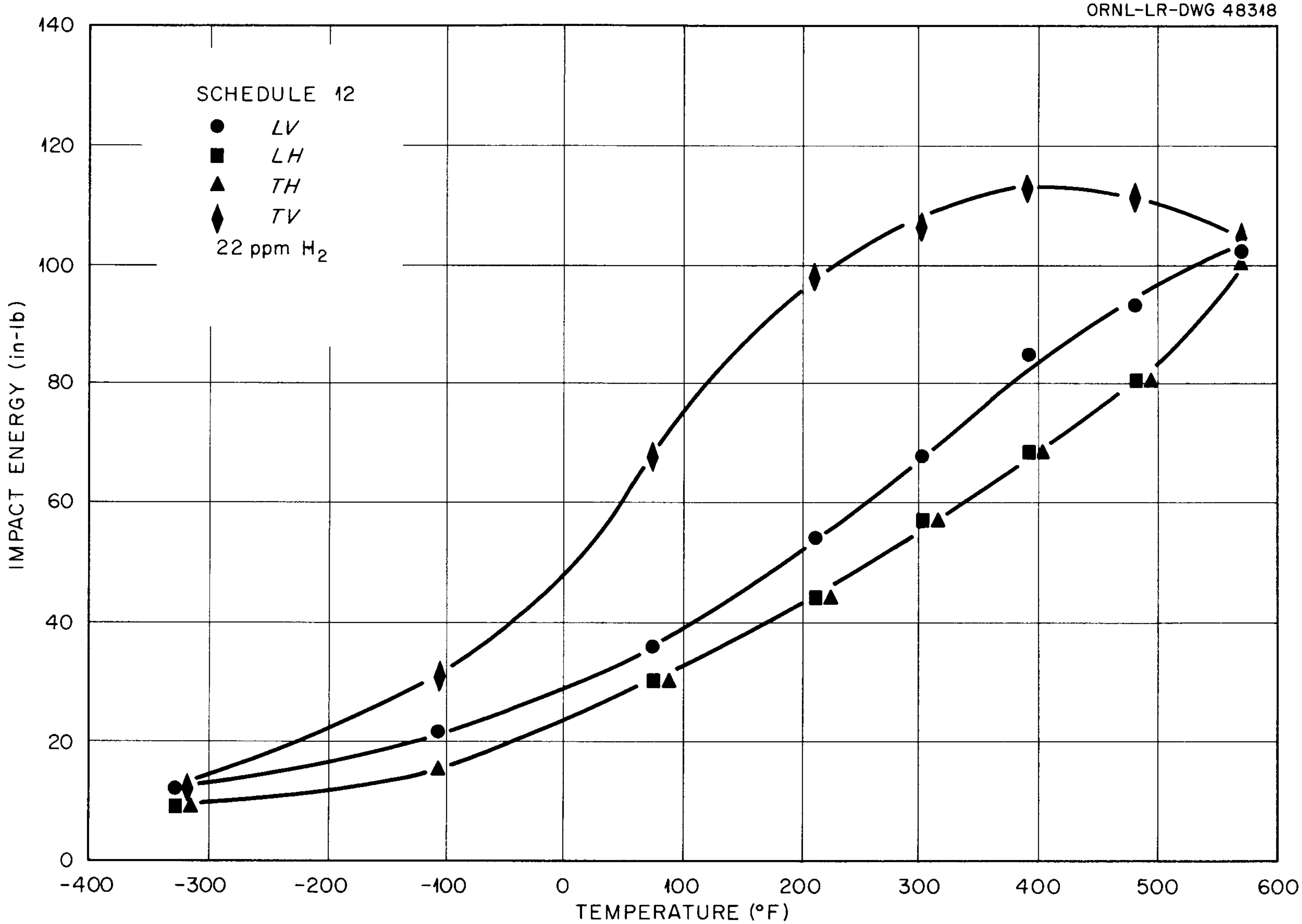

Fig. 44. Impact Energy Curves for Schedule 12 Zircaloy-2. Schedule 12: HRP Commercial Fabrication Proceedure, 40 Per Cent Final Reduction.

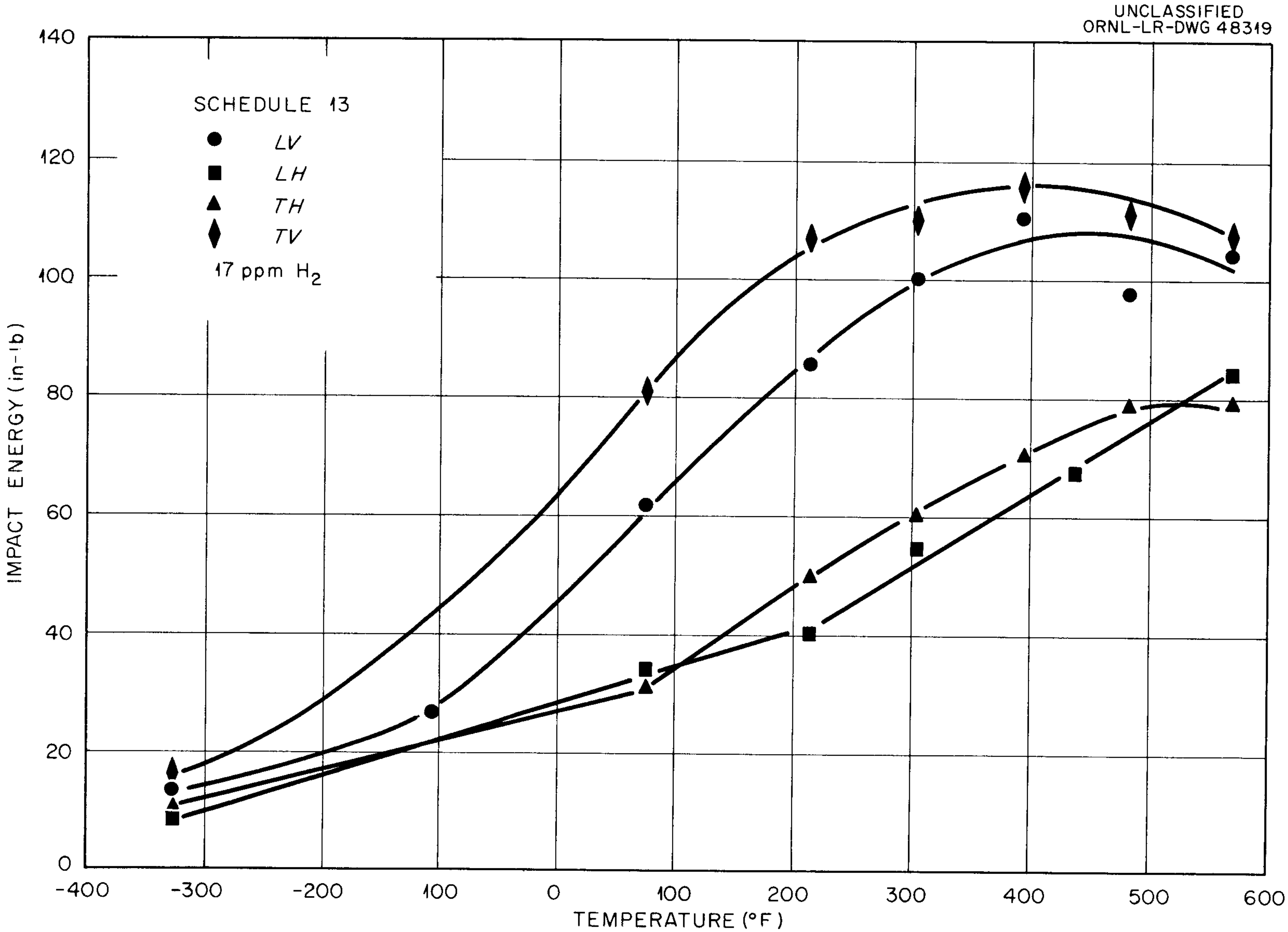

Fig. 45. Impact Energy Curves for Schedule 13 Zircaloy-2. Schedule 13: Cross-Rolled After β Heat-Treatment.

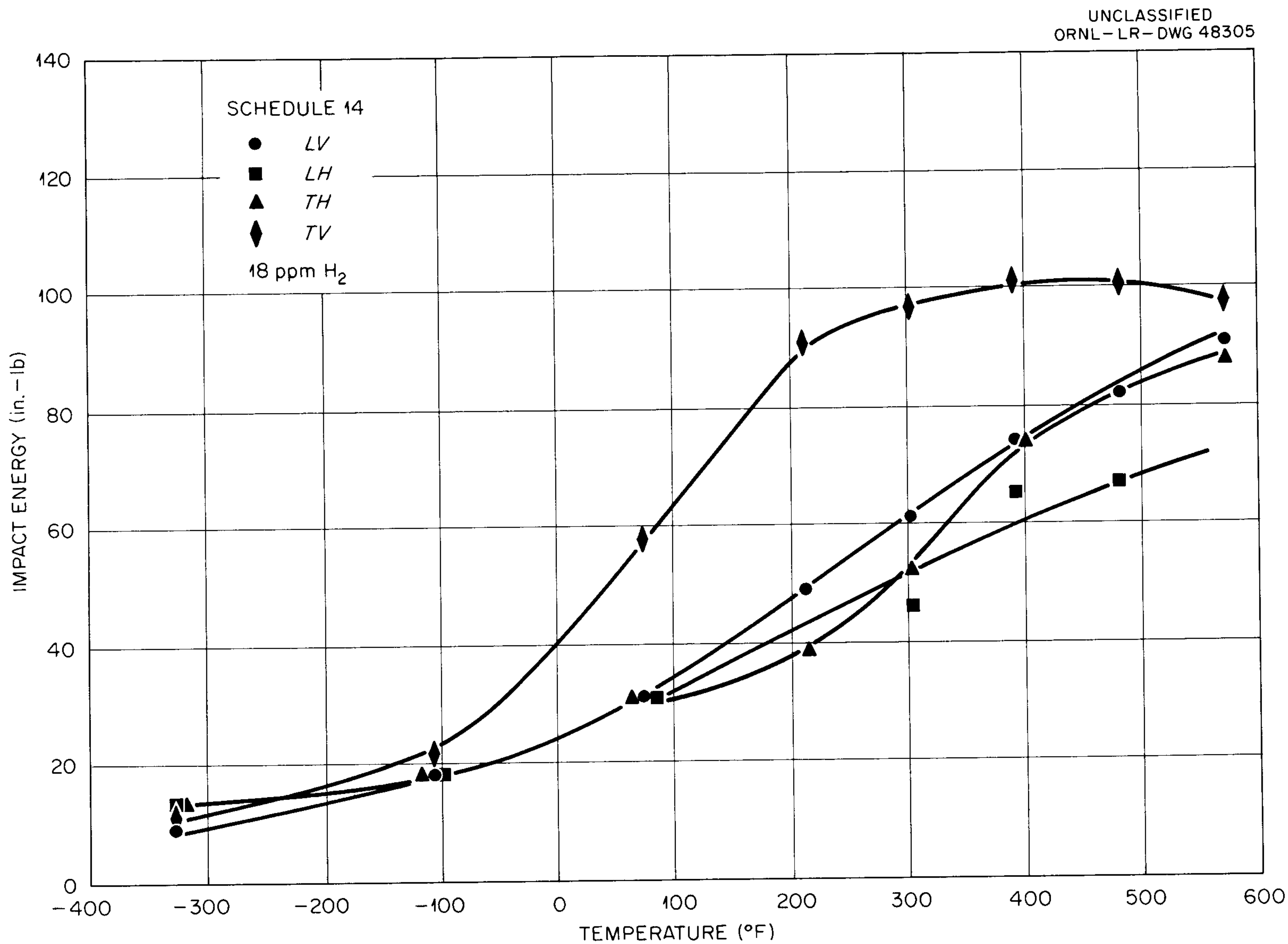

Fig. 46. Impact Energy Curves for Schedule 14 Zircaloy-2. Schedule 14: Cross-Rolled During High α Reduction.

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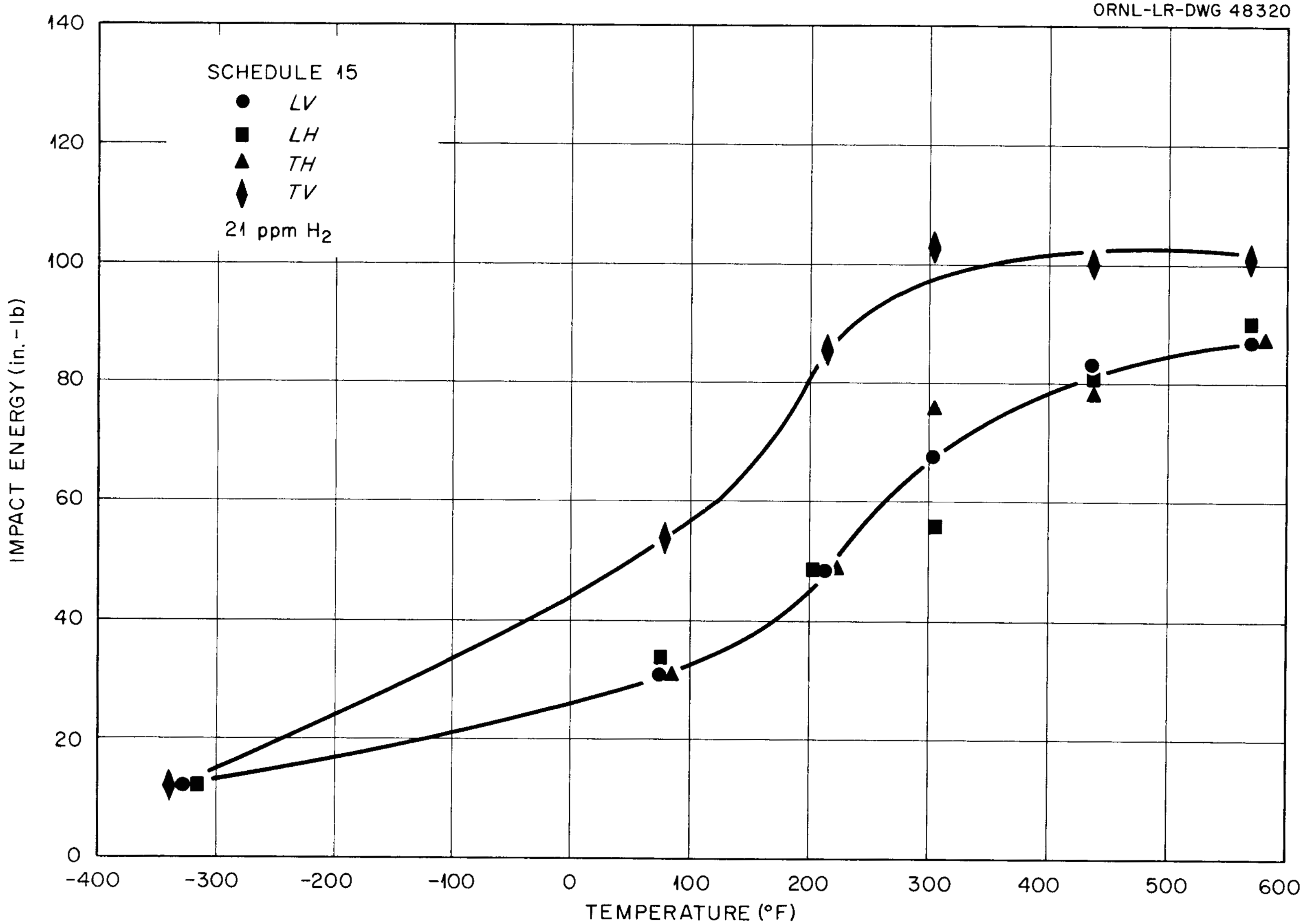

Fig. 47. Impact Energy Curves for Schedule 15 Zircaloy-2. Schedule 15 Straight-Rolled During β Reduction.

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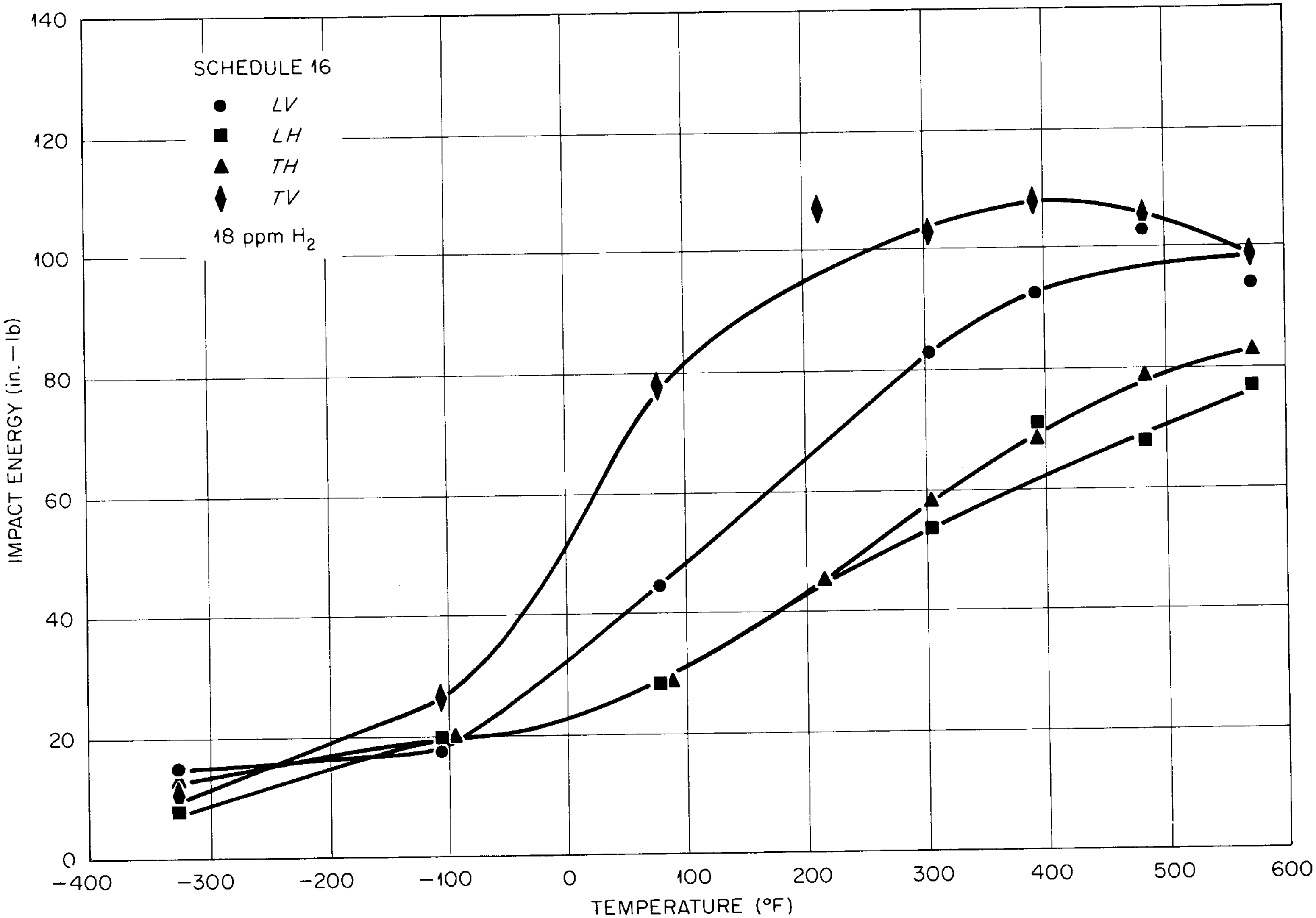

Fig. 48. Impact Energy Curves for Schedule 16 Zircaloy-2. Schedule 16: Cross-Rolled During β Reduction.

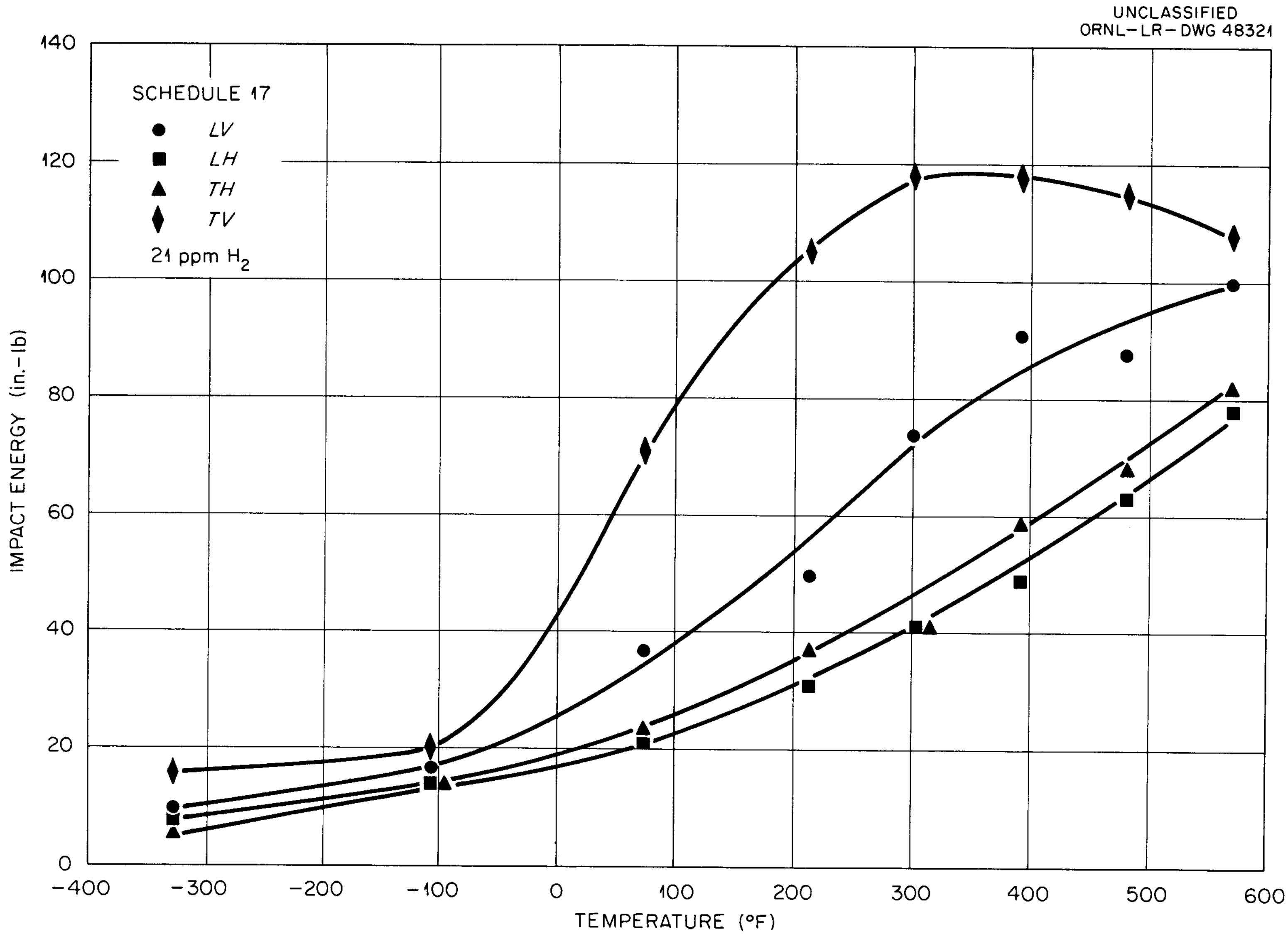

Fig. 49. Impact Energy Curves for Schedule 17 Zircaloy-2. Schedule 17: HRP Commercial Fabrication Procedure (Jessop Steel Co.).

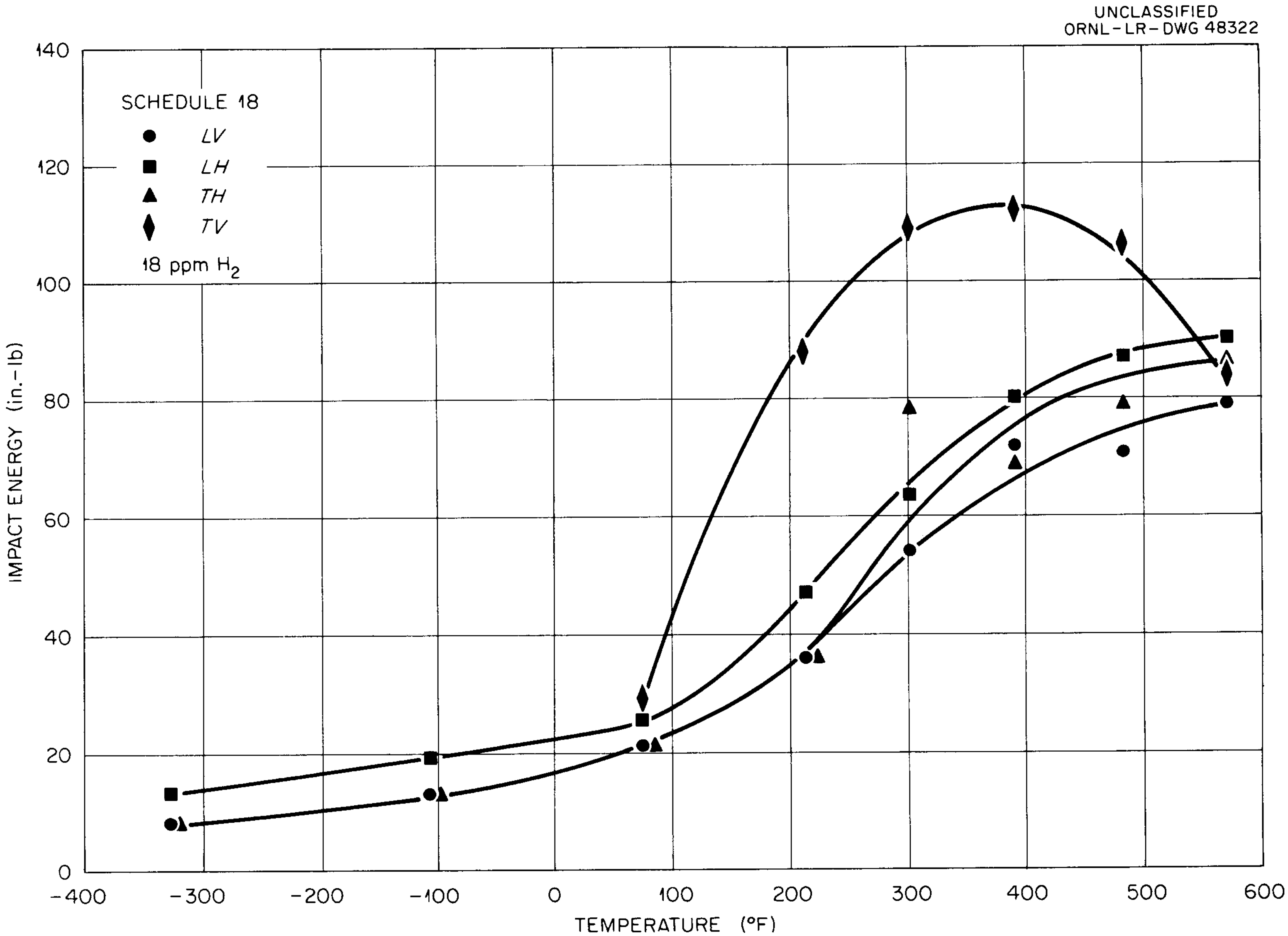

Fig. 50. Impact Energy Curves for Schedule 18 Zircaloy-2. Schedule 18: HRP Commercial Fabrication Procedure for Wide Plate (Jessop Steel Co.).

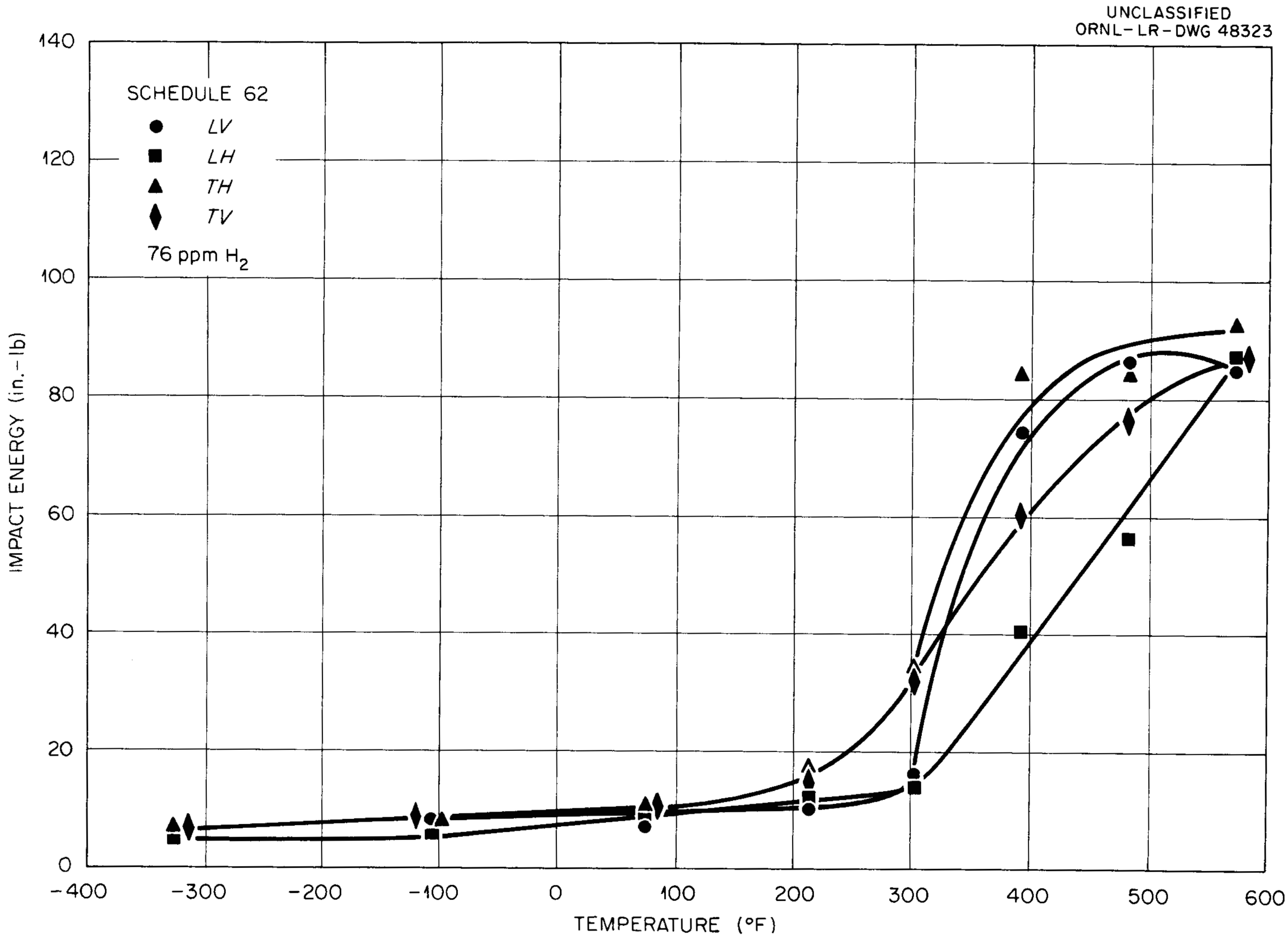

Fig. 51. Impact Energy Curves for Schedule 62 Zircaloy-2. Schedule 62: HRP Commercial Fabrication Procedure (Item 62. Allegheny-Ludlum Steel Co.)

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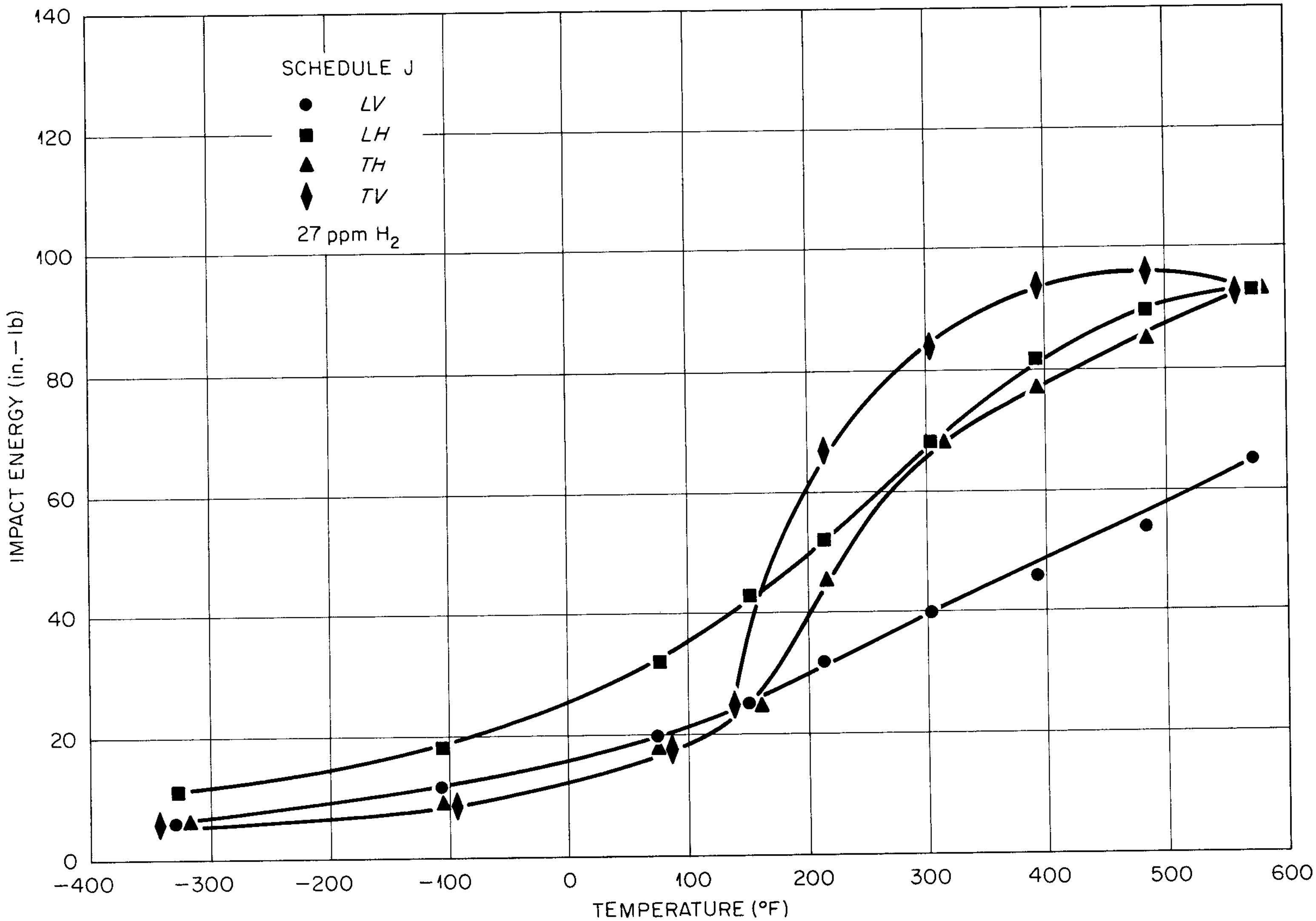


Fig. 52. Impact Energy Curves for Schedule J Zircaloy-2. Schedule J: HRP Commercial Fabrication Procedure for Wide Plate.

TABLE IX

ZIRCALOY-2 IMPACT DATA

Fabrication Schedule	Specimen Orientation[a]	Impact Energy (in.-lb)/% Fracture, Test Temperature (°F): -320	-103	75	149	212	257	302	347	392	437	482	572
1	LV	13/99	17/95	25/95	55/90	46/92	55/90	83/60	-	87/75	-	92/40	96/50
	TV	-	-	11/100	-	8/95	-	12/95	-	121/50	-	-	-
	LH	11/100	12/99	20/99	34/90	38/95	-	60/80	-	74/70	-	88/60	87/60
	TH	-	-	6/100	-	12/95	-	-	38/90	-	-	91/50	-
	22½°V	-	-	35/95	-	-	-	-	-	111/70	-	-	-
	45°V	-	-	19/95	-	-	-	-	-	116/60	-	-	-
	67½°V	-	-	26/99	-	-	-	-	-	110/50	-	-	-
2	LV	7/100	9/100	12/99	13/99	23/99	35/80	80/65	-	105/55	125/55	102/40	109/40
	TV	-	-	7/100	-	-	-	-	-	132/50	-	-	-
	LH	7/100	7/100	8/100	9/100	16/95	-	34/80	-	58/80	89/79	98/50	87/80
	TH	-	-	5/99	-	9/95	-	-	-	-	-	-	-
	22½°V	-	-	11/100	-	-	-	-	-	110/60	-	-	-
	45°V	-	-	12/100	-	-	-	-	-	118/50	-	-	-
	67½°V	-	-	9/100	-	-	-	-	-	125/50	-	-	-
3	LV	10/100	22/99	30/99	52/90	68/70	-	92/30	99/70	94/60	108/60	102/40	99/40
	TV	-	-	27/99	-	-	98/60	-	-	128/50	-	-	-
	LH	12/100	12/100	21/99	24/95	33/95	-	43/95	-	55/70	-	70/80	71/80
	TH	-	-	14/99	-	-	-	50/85	-	-	-	77/70	-
	22½°V	-	-	33/99	-	-	-	-	-	114/50	-	-	-
	45°V	-	-	21/99	-	-	-	-	-	112/60	-	-	-
	67½°V	-	-	23/99	-	-	-	-	-	119/50	-	-	-
4	LV	6/100	8/100	16/99	12/99	26/99	-	55/90	109/60	89/60	-	100/40	97/40
	LH	6/100	6/100	7/100	7/100	12/99	-	25/99	-	48/80	70/80	85/65	82/60
	TH	-	-	5/100	-	-	-	-	-	43/85	-	-	-
	22½°V	-	-	9/100	-	-	-	-	-	113/50	-	-	-
	45°V	-	-	8/100	-	-	-	-	-	108/60	-	-	-
	67½°V	-	-	8/100	-	-	-	-	-	92/30	-	-	-

TABLE IX(Cont'd)

ZIRCALOY-2 IMPACT DATA

Fabrication Schedule	Specimen Orientation[a]	Impact Energy (in.-lb)/% Fracture — Test Temperature (°F) -320	-103	75	149	212	257	302	347	392	437	482	572
5	LV	11/100	26/99	26/99	54/90	57/90	-	86/60	-	93/60	-	109/50	104/50
	TV	-	-	10/100	-	-	-	-	-	122/50	-	-	-
	LH	11/100	24/99	20/99	33/95	32/90	-	70/80	56/85	54/80	-	79/65	88/70
	TH	-	-	9/99	-	-	-	-	-	72/75	-	-	-
6	LV	14/99	43/99	64/80	84/70	91/70	-	110/55	-	110/45	-	114/30	102/50
	TV	-	-	77/80	-	102/60	-	-	-	128/50	-	-	-
	LH	16/100	18/99	28/99	33/95	38/90	-	56/85	-	62/80	-	76/70	75/70
	TH	-	-	18/95	-	-	46/90	-	-	-	69/80	-	-
	$22\frac{1}{2}$°V	-	-	69/80	-	-	-	-	-	119/50	-	-	-
	45°V	-	-	85/80	-	-	-	-	-	123/40	-	-	-
	$67\frac{1}{2}$°V	-	-	103/70	-	-	-	-	-	125/40	-	-	-
7	LV	11/100	15/99	28/95	30/99	45/80	51/90	98/55	-	95/62	-	110/45	101/80
	TV	-	-	5/100	-	-	-	16/90	-	-	-	-	-
	LH	6/100	8/100	9/100	14/95	24/95	-	49/90	-	63/80	-	68/80	77/70
8	LV	16/100	81/75	91/40	121/50	122/45	-	125/35	-	110/40	-	117/60	91/60
	TV	-	-	121/60	-	-	-	-	-	123/40	-	-	-
	LH	15/100	22/95	28/99	36/95	36/90	-	49/90	-	72/70	-	73/60	72/70
	TH	-	-	26/95	-	-	-	-	59/80	-	-	-	-
	$22\frac{1}{2}$°V	-	-	105/70	-	-	-	-	-	115/40	-	-	-
	45°V	-	-	117/60	-	-	-	-	-	128/45	-	-	-
	$67\frac{1}{2}$°V	-	-	117/60	-	-	-	-	-	120/30	-	-	-
9	LV	28/100	65/88	90/60	109/60	114/40	-	123/35	-	109/35	-	106/50	103/40
	TV	-	-	29/95	-	-	-	-	-	120/50	-	-	-
	LH	13/100	14/99	32/99	30/95	36/90	-	65/80	-	62/90	-	73/70	82/60
10	LV	9/100	16/99	21/99	-	56/70	-	-	-	109/30	-	-	112/20
	TV	7/100	10/100	16/99	-	60/90	-	-	-	116/20	-	-	102/20
	LH	7/100	10/99	13/99	-	38/99	-	-	-	90/40	-	-	99/40
	TH	6/100	-	12/99	-	27/95	-	-	-	90/40	-	-	108/50

TABLE IX(Cont'd)

ZIRCALOY-2 IMPACT DATA

Fabrication Schedule	Specimen Orientation[a]	Impact Energy (in.-lb)/% Fracture											
		Test Temperature (°F)											
		-320	-103	75	149	212	257	302	347	392	437	482	572
	LV	11/100	-	36/90	-	55/70	-	70/80	-	-	83/60	-	94/50
11	TV	9/100	-	58/90	-	90/80	-	108/50	-	-	108/55	-	100/50
	LH	15/99	-	32/95	-	51/85	-	67/80	-	-	79/60	-	98/50
	TH	12/100	-	33/95	-	51/85	-	61/80	-	-	80/60	-	82/60
	LV	12/100	22/95	36/95	-	54/90	-	68/85	-	85/70	-	93/70	102/40
	TV	12/100	31/95	78/80	-	98/70	-	107/60	-	113/50	-	111/50	104/35
12	LH	9/100	-	30/95	-	43/85	-	57/90	-	68/85	-	80/75	-
	TH	9/100	15/100	31/95	-	44/90	-	56/95	-	69/90	-	81/70	90/60
	LV	13/100	27/99	62/90	-	86/70	-	100/60	-	110/55	-	98/30	104/40
	TV	14/99	-	81/75	-	107/70	-	110/60	-	116/50	-	111/45	108/35
13	LH	9/100	-	34/95	-	40/95	-	54/90	-	-	67/90	-	84/60
	TH	11/100	-	31/95	-	50/95	-	60/95	-	70/90	-	78/80	79/60
	LV	9/100	18/99	31/95	-	49/95	-	61/90	-	74/75	-	82/80	91/80
	TV	12/99	22/99	58/80	-	91/85	-	97/60	-	101/60	-	101/55	98/50
14	LH	13/100	18/95	32/90	-	-	-	46/95	-	65/90	-	67/90	100/90
	TH	13/100	18/99	33/95	-	39/95	-	52/95	-	76/85	-	104/60	88/60
	LV	12/100	-	31/95	-	49/95	-	68/85	-	-	83/80	-	87/70
	TV	12/99	-	54/85	-	86/80	-	103/50	-	-	100/55	-	101/40
15	LH	13/99	-	34/95	-	47/85	-	56/90	-	-	80/70	-	90/50
	TH	-	-	31/95	-	49/95	-	76/80	-	-	78/70	-	87/60
	LV	15/99	18/99	45/90	-	100/50	-	83/80	-	93/75	-	104/50	94/55
	TV	11/100	27/99	78/80	-	107/45	-	103/70	-	108/60	-	105/50	99/60
16	LH	8/100	19/100	29/95	-	84/60	-	54/95	-	71/90	-	68/80	77/80
	TH	14/99	19/99	30/95	-	45/99	-	58/95	-	69/85	-	79/80	82/70
	LV	10/100	17/99	37/99	-	50/95	-	74/80	-	91/70	-	88/80	100/65
	TV	16/99	20/99	71/95	-	105/70	-	118/60	-	118/60	-	115/50	108/40
17	LH	8/100	14/99	21/99	-	31/95	-	41/99	-	49/95	-	63/90	78/80
	TH	6/100	14/99	23/99	-	37/95	-	41/95	-	59/95	-	68/95	82/80

TABLE IX(Cont'd)

ZIRCALOY-2 IMPACT DATA

Fabrication Schedule	Specimen Orientation[a]	Impact Energy (in.-lb)/% Fracture Test Temperature (°F) -320	-103	75	149	212	257	302	347	392	437	482	572
18	LV	8/100	13/99	21/99	-	36/100	-	54/90	-	72/85	-	71/80	79/60
	TV	-	-	29/99	-	88/90	-	109/55	-	112/55	-	106/40	84/40
	LH	13/100	19/99	25/99	-	47/95	-	63/95	-	80/70	-	87/80	90/40
	TH	8/100	12/100	20/99	-	35/99	-	78/80	-	69/85	-	79/90	86/75
62	LV	-	8/100	7/100	-	10/99	-	16/95	-	74/90	-	86/70	85/50
	TV	5/100	6/100	8/100	-	11/99	-	14/99	-	40/99	-	56/95	86/60
	LH	7/100	9/100	11/99	-	16/99	-	33/95	-	60/90	-	76/70	87/50
	TH	6/100	8/100	10/99	-	17/99	-	34/90	-	84/60	-	84/70	92/80
J	LV	6/100	12/100	20/99	-	32/95	-	40/90	-	46/80	-	54/70	65/50
	TV	5/100	10/100	18/99	-	67/90	-	84/45	-	94/40	-	97/40	92/40
	LH	11/100	18/95	32/95	43/90	52/80	-	68/60	-	82/60	-	90/30	93/30
	TH	6/100	9/100	18/99	24/95	45/95	-	69/80	-	77/65	-	85/45	92/50
	22½°V	-	-	20/99	-	-	-	-	-	54/40	-	-	-
	22½°H	-	-	24/99	-	-	-	-	-	94/40	-	-	-
	45°V	-	-	21/99	-	-	-	-	-	82/45	-	-	-
	45°H	-	-	22/99	-	-	-	-	-	80/50	-	-	-
	67½°V	-	-	24/99	-	-	-	-	-	-	-	-	-
	67½°H	-	-	21/99	-	-	-	-	-	80/70	-	-	-

(a) LV - Specimen axis: longitudinal (rolling) direction. Vertical notch.
TV - Specimen axis: transverse direction. Vertical notch.
LH - Specimen axis: longitudinal (rolling direction). Horizontal notch.
TH - Specimen axis: transverse direction. Horizontal notch.
22½°V - Specimen axis: 22½° from longitudinal direction. Vertical notch.
45°V - Specimen axis: 45° from longitudinal direction. Vertical notch.
67½°V - Specimen axis: 67½° from longitudinal direction. Vertical notch.

APPENDIX III

Photograph of Fabricated Plates of Zircaloy-2
Schedules 1–9

Unclassified
Y-24164

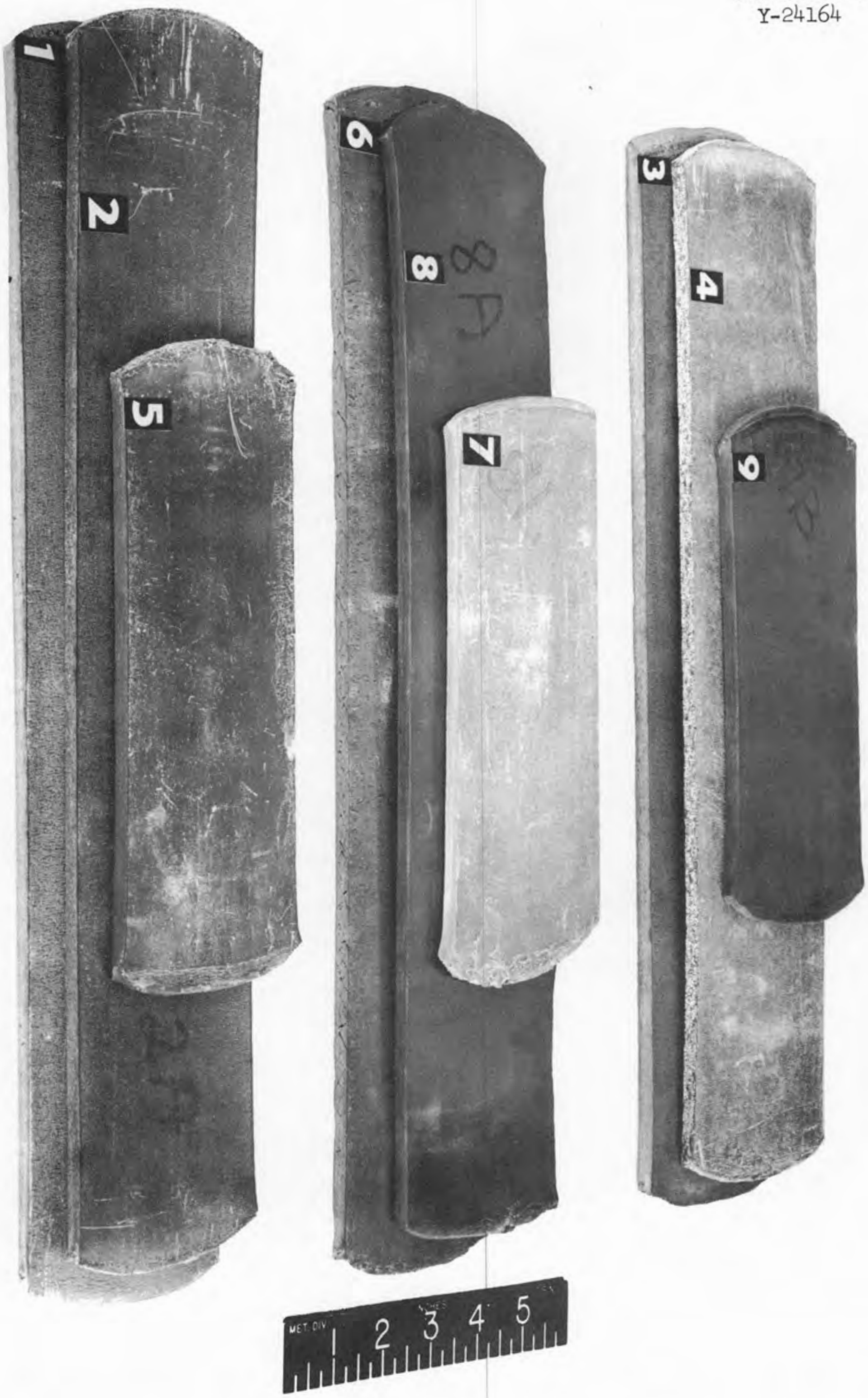
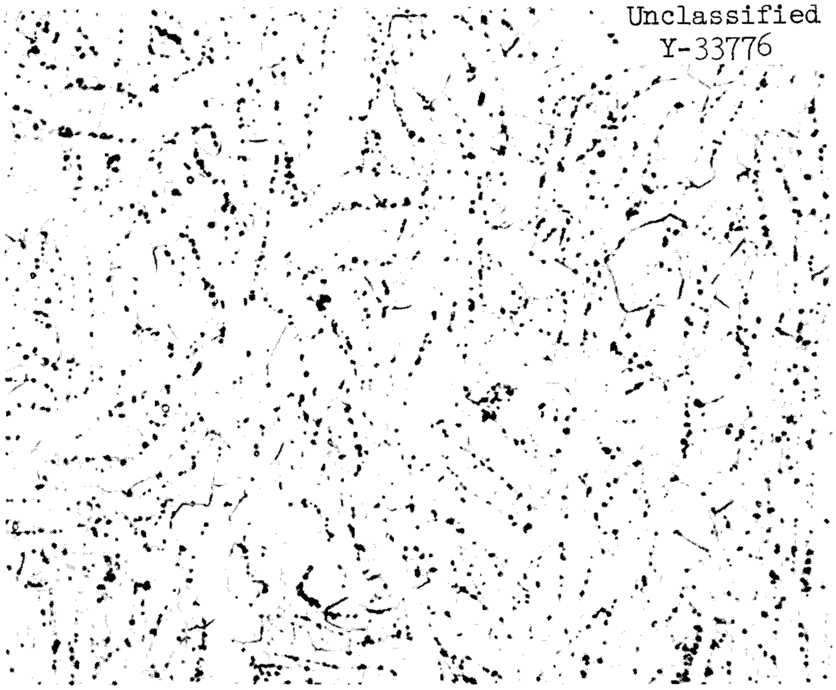


Fig. 53 Photograph of Fabricated Plates of Zircaloy-2. Schedules 1–9.

APPENDIX IV

Representative Photomicrographs of a Number of Schedules of Zircaloy-2

Bright Field



Polarized Light

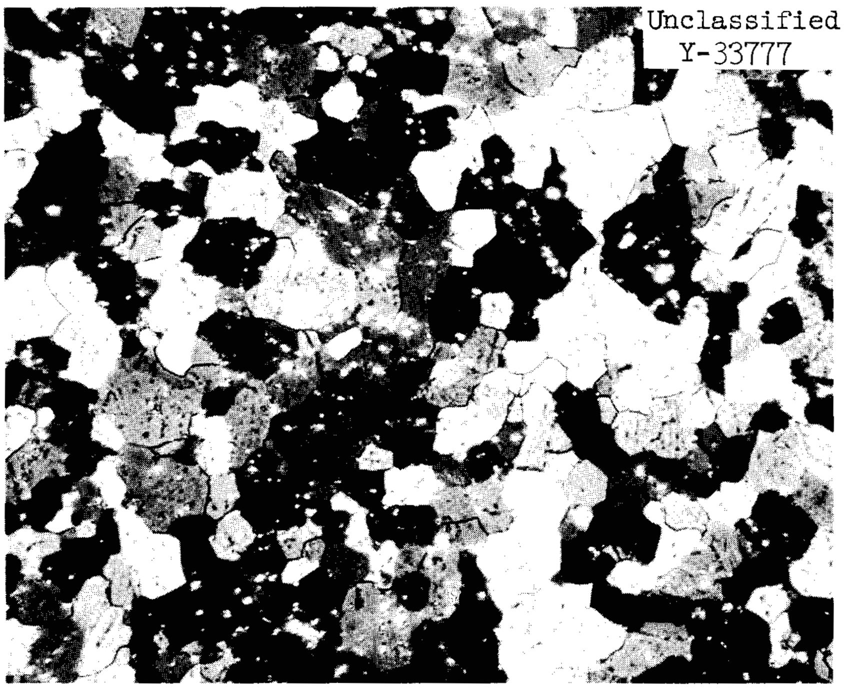
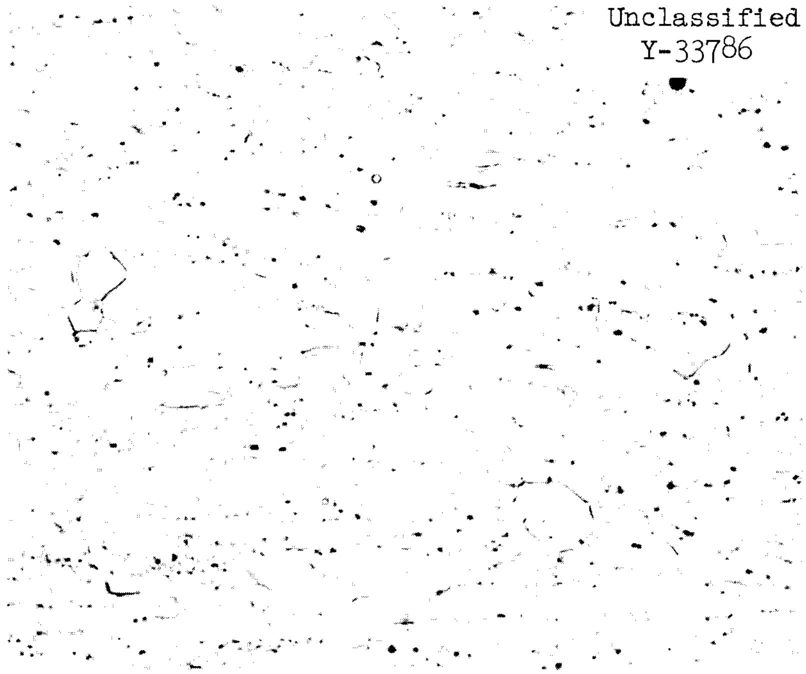


Fig. 54 Schedule 3 Zircaloy-2.

Bright Field



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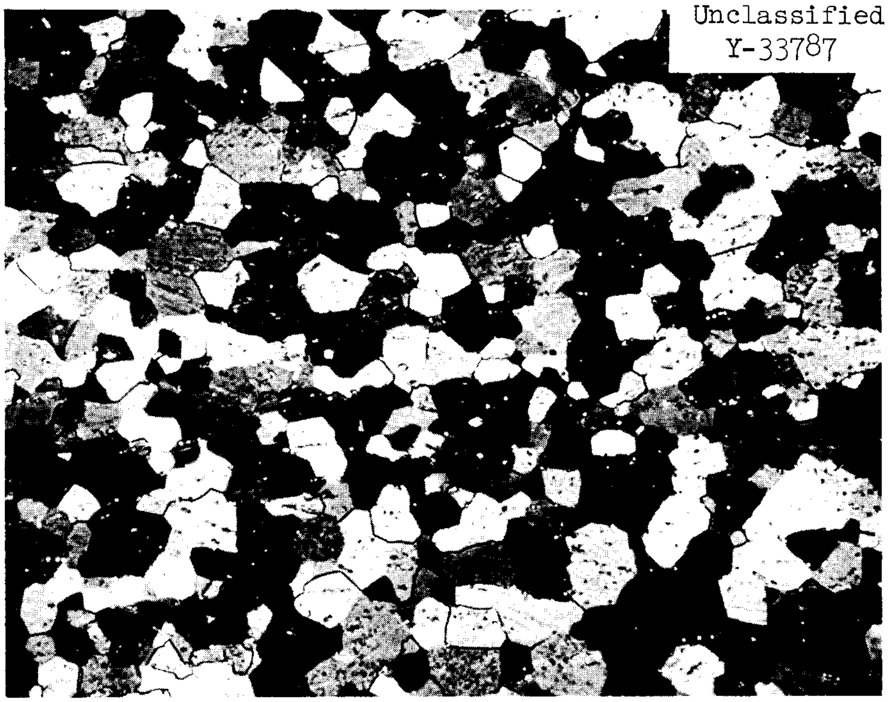
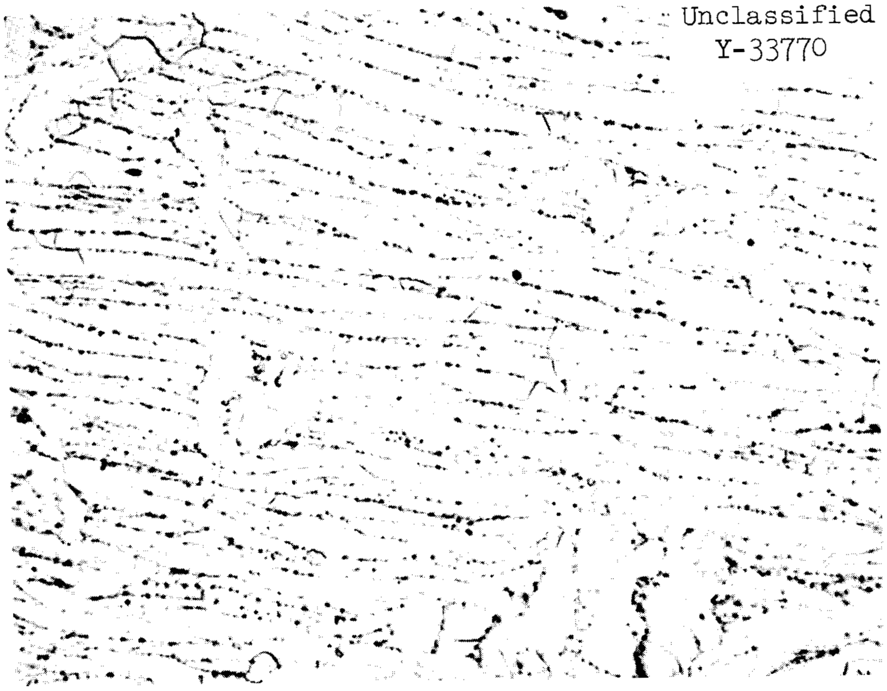


Fig. 55 Schedule 8 Zircaloy-2.

Bright Field



Polarized Light

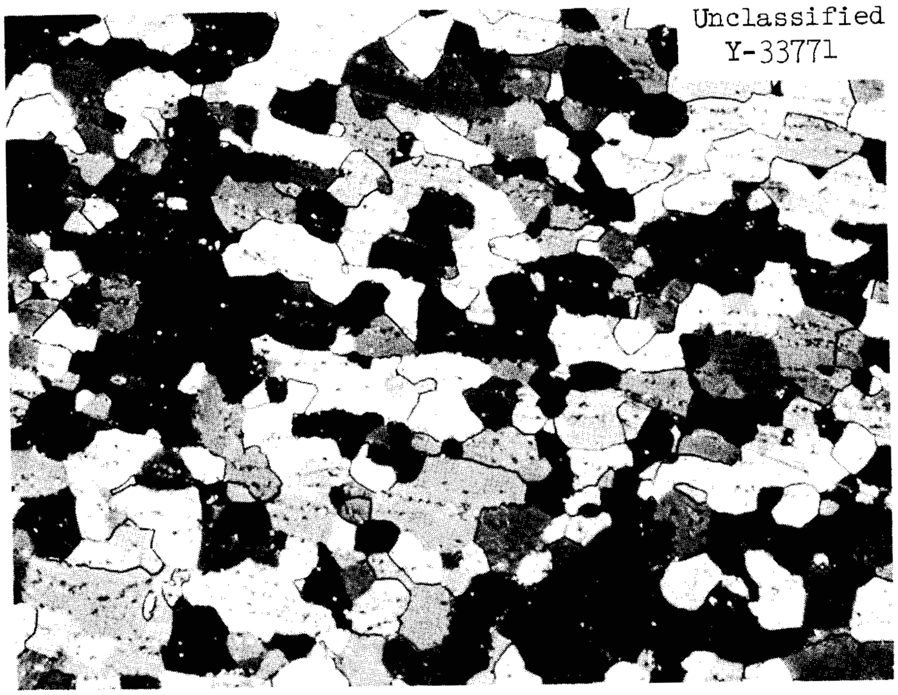
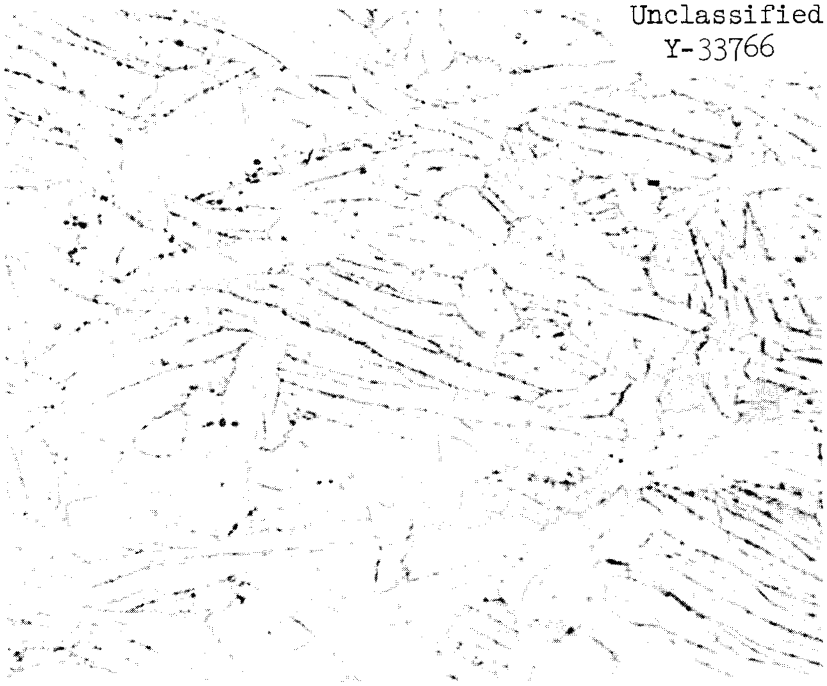


Fig. 56 Schedule 13 Zircaloy-2. 500X

Bright Field



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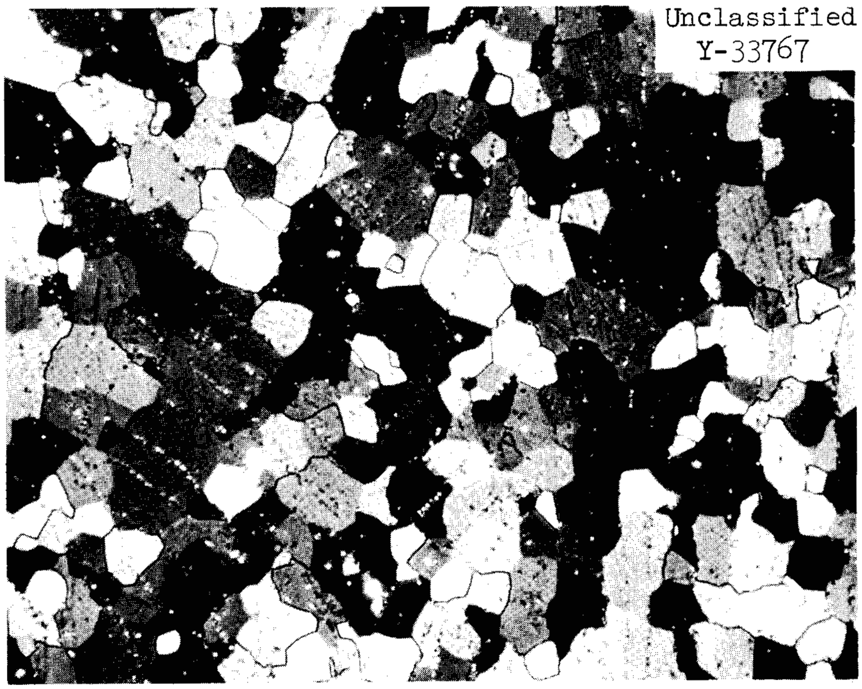
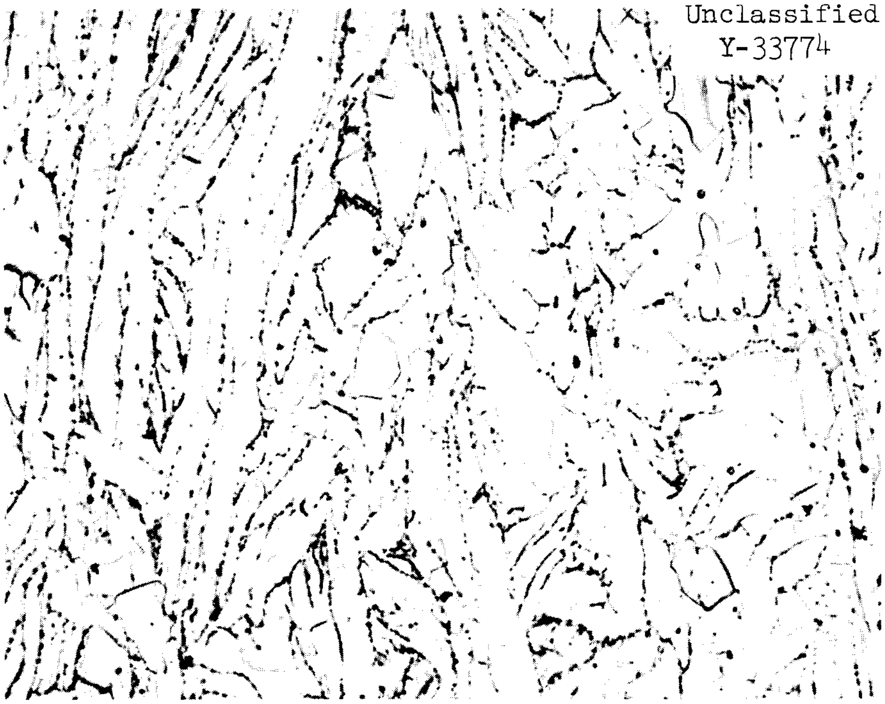


Fig. 57 Schedule 14 Zircaloy-2. 500X

Bright Field



Polarized Light

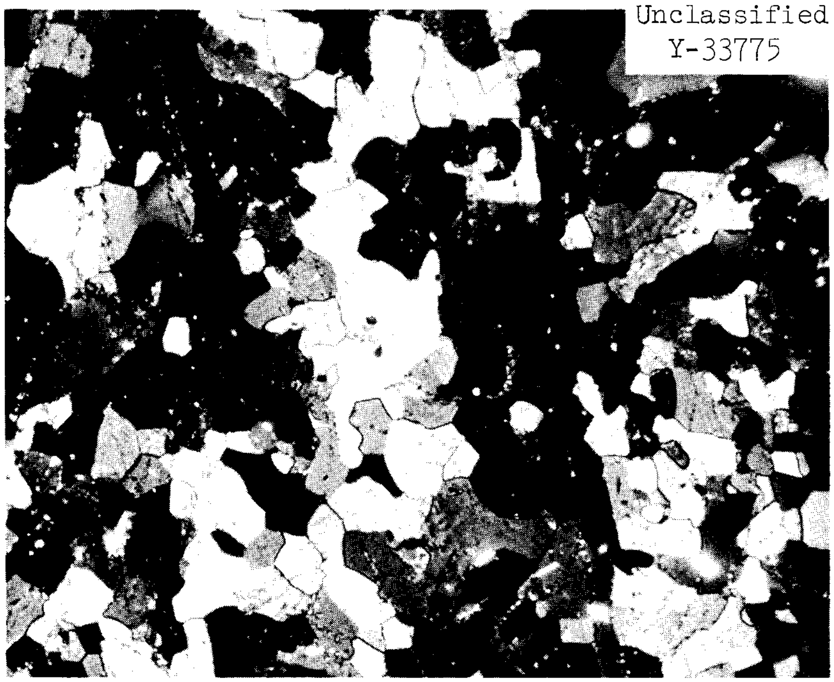


Fig. 58 Schedule J Zircaloy-2. 500X

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