WAPD-TM-1289
DOE RESEARCH AND
DEVELOPMENT REPORT

DEVELOPMENT AND CONTROL OF THE PROCESS FOR THE MANUFACTURE OF ZIRCALOY-4 TUBING FOR LWBR FUEL RODS

(LWBR Development Program)

JANUARY 1981

CONTRACT DE-AC11-76PN00014

BETTIS ATOMIC POWER LABORATORY
WEST MIFFLIN, PENNSYLVANIA
Operated for the U. S. Department of Energy by
WESTINGHOUSE ELECTRIC CORPORATION

DISCLAIMER

DEVELOPMENT AND CONTROL OF THE PROCESS FOR THE MANUFACTURE OF ZIRCALOY-4 TUBING FOR LWBR FUEL RODS
(LWBR Development Program)

John H. Eyler

Contract No. DE-AC11-76PN00014

JANUARY 1981

Printed in the United States of America
Available from the National Technical Information Service
U. S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22151

NOTE

This document is an interim memorandum prepared primarily for internal reference and does not represent a final expression of the opinion of Westinghouse. When this memorandum is distributed externally, it is with the express understanding that Westinghouse makes no representation as to completeness, accuracy, or usability of information container therein.

BETTIS ATOMIC POWER LABORATORY WEST MIFFLIN, PENNSYLVANIA 15122
Operated for the U.S. Department of Energy by
WESTINGHOUSE ELECTRIC CORPORATION

FOREWORD

The Shippingport Atomic Power Station located in Shippingport, Pennsylvania was the first large-scale, central-station nuclear power plant in the United States and the first plant of such size in the world operated solely to produce electric power. This program was started in 1953 to confirm the practical application of nuclear power for large-scale electric power generation. It has provided much of the technology being used for design and operation of the commercial, central-station nuclear power plants now in use.

Subsequent to development and successful operation of the Pressurized Water Reactor in the Atomic Energy Commission (now Department of Energy, DOE) owned reactor plant at the Shippingport Atomic Power Station, the Atomic Energy Commission in 1965 undertook a research and development program to design and build a Light Water Breeder Reactor core for operation in the Shippingport Station.

The objective of the Light Water Breeder Reactor (LWBR) program has been to develop a technology that would significantly improve the utilization of the nation's nuclear fuel resources employing the well-established water reactor technology. To achieve this objective, work has been directed toward analysis, design, component tests, and fabrication of a water-cooled, thorium oxide-uranium oxide fuel cycle breeder reactor for installation and operation at the Shippingport Station. The LWBR core started operation in the Shippingport Station in the Fall of 1977 and is expected to be operated for about 4 to 5 years or more. At the end of this period, the core will be removed and the spent fuel shipped to the Naval Reactors Expended Core Facility for a detailed examination to verify core performance including an evaluation of breeding characteristics.

In 1976, with fabrication of the Shippingport LWBR core nearing completion, the Energy Research and Development Administration, now DOE, established the Advanced Water Breeder Applications (AWBA) program to develop and disseminate technical information which would assist U.S. industry in evaluating the LWBR concept for commercial-scale applications. The program is exploring some of the problems that would be faced by industry in adapting technology confirmed in the LWBR program. Information being developed includes concepts for commercial-scale prebreeder cores which would produce uranium-233 for light water breeder cores while producing electric power, improvements for breeder cores based on the technology developed to fabricate and operate the Shippingport LWBR core, and other information and technology to aid in evaluating commercial-scale application of the LWBR concept.

All three development programs (Pressurized Water Reactor, Light Water Breeder Reactor, and Advanced Water Breeder Applications) are under the technical direction of the Office of the Deputy Assistant Secretary for Naval Reactors of DOE. They have the goal of developing practical improvements in the utilization of nuclear fuel resources for generation of electrical energy using water-cooled nuclear reactors.

Technical information developed under the Shippingport, LWBR, and AWBA programs has been and will continue to be published in technical memoranda, one of which is this present report.

INTENTIONALLY BLANK

TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

TABLE OF CONTENTS (continued)

TABLE OF CONTENTS (continued)

The technical requirements for the Light Water Breeder Reactor (LWBR) fuel elements (fuel rods) imposed certain unique requirements for the low hafnium Zircaloy-4 tubing used as fuel rod cladding. These requirements were not generally available through normal commercial tube fabrication techniques used in the 1971 to 1973 time period. This report describes, in detail, the tube manufacturing process, the product and process controls used, the inspections and tests performed, and the efforts involved in refining a commercial tube reducing process to produce tubes that would satisfy the requirements for LWBR fuel rod cladding. Dimensional restrictions for some attributes were tighter than the commercial tolerances suggested in ASTM Designation B-353-1977. Definition of a machining specification for the extruded base tube and development of improved process controls were instrumental in meeting the dimensional tolerances and the other requirements on texture, straightness, wall eccentricity, residual stress, physical properties, and the wavelength of helical wall eccentricity. In addition, the use of low hafnium Zircaloy was specified to reduce parasitic neutron absorption in the cladding. The process modifications and the process controls implemented resulted in overall manufacturing yields comparable to the yields attained in normal commercial practice. The quality of these cladding tubes significantly improved the calculated performance capability, reliability, integrity and breeding performance of the LWBR fuel rods.

DEVELOPMENT AND CONTROL OF THE PROCESS FOR THE MANUFACTURE OF ZIRCALOY-4 TUBING FOR LWBR FUEL RODS

(LWBR Development)

John H. Eyler

I. INTRODUCTION

The LWBR core is a seed-blanket configuration consisting of an inner region containing twelve movable seed assemblies, each surrounded by a blanket assembly. This inner region is surrounded by an outer reflector region containing fifteen reflector modules. Fuel elements required for this core consisted of twenty-three different types of fuel rods in four diameters. Each fuel rod is approximately ten feet long. The pellet column and a plenum spring were inserted into a seamless Zircaloy-4 tube which was sealed by fusion welding of Zircaloy-4 endcaps into the ends of the tube. The 0.310" OD tube for the seed fuel rod received a final recrystallization anneal (RXA) heat treatment.* The 0.531, 0.576 and 0.835 inch OD tubes for the power flattening blanket (PFB), standard blanket (Std.B) and reflector (Refl.) fuel rods respectively, received a final stress relief anneal (SRA) heat treatment.* See Table A-3 of Appendix A for dimensions of the purchased tube and of the clad in the finished fuel rod.

Because of the specific design objectives and constraints unique to the LWBR core, Zircaloy-4 tubing fabricated for LWBR fuel rod cladding was required to satisfy many technical requirements in addition to those previously specified for light water reactor tubing. Tube technical requirements were more complete and definitive for some attributes than the requirements for tubing in commercial reactors because of: (a) the technical definition of how tubing attributes interact with fuel rod performance using the analytical techniques developed as part of the LWBR program, and (b) the need to have high assurance of successful fuel rod performance for the LWBR core. These technical requirements could be applied to tubing used in other light water reactors to achieve improved performance and reliability.

Extensive efforts were expended to develop a manufacturing process which would satisfy the requirements defined for LWBR cladding tubes. These items include:

1. Proper heat treatment. It is well known that the innermost tube of an externally heated array reaches temperature later than the external tubes. The time delay depends on the load size and the temperature. Appendix D discusses the effort to assure that all tubes in the load had the desired minimum heat treatment without the external tubes receiving an excessive heat treatment. Figure D-2 illustrates the time delay involved.

* See Section D of Table A-2 in Appendix A for the heat treating requirements (times and temperatures) for RXA and SRA tubing.

2. Texture control. The behavior of tubes under biaxial stress can be predicted if the crystallographic orientation of the material is known. Attachment C discusses the development of a mechanical measure of texture and the development of a manufacturing sequence that would routinely produce the desired texture. Figures C-8 and C-9 in Appendix C point out that texture is an end result of the cumulative effect of each reduction on the texture produced in the prior reduction and that internal friction prevents the realization of potential crystal alignment indicated by the reduction parameters.

3. Wall thickness eccentricity. The variation of wall thickness around the tube and along the tube length have a direct bearing on fuel rod performance in the core environment. Following an evaluation of how eccentricity was developed, the eccentricity of the stock was minimized by the innovative, but straight forward, approach of machining the desired concentricity into the starting base tube.

4. Wavelength (pitch) of the wall eccentricity helix. The rotation of the location of the thickest wall along the tube affects rod performance and bow. The development effort discussed in Appendix B identified those factors which affected the spiral of wall eccentricity. Subsequent experiments related the contribution of these factors in each tube reduction to the wavelength of the finished tube.

5. Straightness. The straightness of the tube affects the straightness and performance in the fuel rod. To maximize straightness, the annealing basket was modified to provide a level base for the stacking of the tubes. The tubes in the bottom layer were laid out flat and parallel. Each tube in subsequent layers was laid in the natural channel formed by adjacent tubes in the lower layer. In addition, all tubes were passed through an offset roll straightener and all tube handling operations were modified to minimize handling stresses.

6. Residual strain. Residual strain in recrystallize annealed seed tubes can affect creep behavior of the seed fuel rod cladding which is designed to be free standing (no support from the fuel) throughout core life. To control this factor, a stress calculation was made of the strains induced in the roll straightener and limits were placed on that operation. As a check on compliance, a heat treating technique was developed to detect residual strain exceeding the 3% limit. The technique development is discussed in Appendix E.

7. Hafnium content. Hafnium in Zircaloy-4 tubing contributes to the parasitic absorption of neutrons which reduces breeding performance and fuel utilization. The Zircaloy-4 ingots used for LWBR tubing were obtained from the regular production of the zirconium alloy ingot vendors, but the selected ingots satisfied a hafnium limit that was lower than the limit normally specified.

This report describes the process that was used to manufacture Zircaloy-4 tubing for the LWBR fuel rods, the various process and product controls that were established, and the inspection and tests performed on the finished tubing. The development efforts made to assure that the Zircaloy-4 tubing satisfied the established requirements are summarized.

Discussion of the tubing technical requirements as they relate to the fuel rod cladding requirements is presented in Section II. In Section III, a detailed description is provided of the tubing manufacturing process and process controls. Finally, Section IV describes the specific inspections and tests performed on the finished tubing to assure that technical requirements were satisfied. The effects of certain process parameters on the attributes of the finished tubing and how these parameters were specified and controlled during fabrication are discussed in the appendices.

II. TUBING TECHNICAL REQUIREMENTS

A. Fuel Rod Cladding Requirements

LWBR fuel elements utilize high density thoria and thoria-urania fuel pellets contained in low hafnium Zircaloy-4 tubes. The size, quantity, and heat treatment of the tubes required for each rod type are shown in Table A-3 of Appendix A. Seed fuel rods are the smallest in diameter and contain both thoria and thoria-urania fuel pellets encapsulated in recrystallize annealed (RXA) Zircaloy-4 tubing. The seed fuel rod is designed to be free standing (i.e., the tube will not collapse onto the fuel during core lifetime). The seed rod has a relatively thick wall and a fuel-clad gap sized to minimize pellet-clad interaction during core operation early-in-life when the tube yield strength is relatively low. Later in life when the fuel-clad interaction forces increase, advantage is taken of the in-pile creep of the RXA tube which is lower than that of stress relief annealed (SRA) tube, to maintain the fuel-clad gap until very late in reactor lifetime. There are two blanket fuel rod sizes, both of which contain thoria-urania and thoria fuel pellets encapsulated in SRA Zircaloy-4 tubing. The blanket fuel rods are non-free standing; they have thinner wall (with respect to their larger diameter) and a smaller fuel-clad gap than seed rods and thus require the higher yield strength of SRA tubing early-in-life when the fuel-clad interaction forces are relatively high. Reflector fuel rods are also non-free standing and are the largest in diameter, containing only thoria pellets encapsulated in SRA Zircaloy-4 tubing. Reflector rods, which have about the same wall thickness to diameter ratio as blanket rods and a small fuel-clad gap, operate at low power throughout core life.

The closely packed array of the LWBR design required tubing with attributes that minimize bowing of the fuel rods throughout core life. These attributes include specific limits on wall thickness eccentricity (in both magnitude and pitch of rotation), initial straightness, I.D. ovality and texture. Zircaloy-4 with hafnium content lower than that normally specified for commercial light water reactor applications was used to enhance breeding. In addition, all attributes which are normally controlled for light water reactor application were also controlled for LWBR; these include dimensional tolerances, surface condition, surface chemistry, hydride orientation, grain size, material quality, and mechanical properties. These attributes are discussed in the next section and all the characteristics of LWBR tubes are presented in detail in Reference (a).

B. Tubing Technical Requirements

The detailed technical requirements for each fuel rod type (seed, blanket, reflector) are summaried in Table A-2 of Appendix A. These technical requirements were established from extensive in-pile and out-of-pile test programs and analyses of the effects of tubing attributes on fuel rod power and lifetime capability. The relationship of rod performance to specific tubing attributes is discussed below. (See Bibliography for a selected list of Technical Memoranda relating to LWBR Zircaloy-4 tubing.)

1. Dimensions

Both outer and inner diameter were controlled. However, the inside diameter tolerance was specified to be tighter than the outside diameter tolerance, since the former with the pellet O.D. tolerance determine the fuel-clad diametral gap tolerance range. The fuel rod lifetime performance is sensitive to fuel-clad gap size with respect to peak fuel temperature, pellet-clad interaction (PCI) and local clad deformations such as axial wrinkling and circumferential ridging at pellet-pellet interfaces. The tolerances on tube I.D. and pellet O.D. were set to produce an as-assembled fuel-clad gap of .0085 to .0115 inch over seed binary pellets and a gap of 0.005 to .008 inch over seed thoria and in all other types of fuel rods. Minimum wall thickness was set to limit clad stress during normal operation and during unusual events such as a loss of cooling accident. The nominal tube O.D. was set to allow for additional pickling during fuel rod fabrication, and tolerances were set to provide manufacturing flexibility for pickling. I.D. ovality and internal free path were set to ensure against premature pellet-clad interaction.

Fuel rod bowing has been found to be sensitive to wall thickness eccentricity and initial straightness. When one side of a fuel rod has thinner wall than the opposite side, the clad stress and resulting creep strain are larger on the thinner side; this condition can result in rod bowing. The magnitude of the stress difference depends on the magnitude of the eccentricity. If the eccentricity is all in one plane axially, rather than in a spiral along the tube length, the rod support system (grids) can keep the rod straight with little bow between grids. However, if the eccentricity spirals along the rod length with a pitch (wavelength) of about two grid spans, the resulting bow cannot be restrained by the grids. Wall thickness eccentricity is also important for fuel rod performance during up-power maneuvering or reactivity insertion accidents since clad cracks tend to initiate at the thinnest part of the wall in a cross section. This is particularly important for fast transients where plastic instability is the design concern and strain can locally accumulate at the thin wall section by necking.

Thus, it was necessary to control both the magnitude and wavelength of the wall thickness eccentricity. The maximum wall eccentricity limits set for LWBR tubes ranged from 5.1% of nominal wall thickness for reflector tubes to 6.1% for PFB tubes. Sorting at Bettis rejected tubes with eccentricities exceeding the LWBR limits of Section A-4 of Table A-2. The minimum wavelength of 70 inches for reflector and 80 inches in the other three sizes was equivalent to five grid-to-grid lengths for seed and blanket tubing and about three grid-to-grid lengths for the lower duty, stiffer reflector rods. Although final straightness requirements applied to the finished fuel rod, the straightness limits were also applied to the tubing since it is more likely to fabricate a straight fuel rod if a straight tube is used.

Dimensional limits were checked by one hundred percent inspection of all finished tubes.

2. Mechanical Properties

Fuel rod performance has been found to be sensitive to the initial tube mechanical properties such as yield strength, ductility, and texture. Minimum values were specified for yield strength and total elongation in the longitudinal tensile test, both at room temperature and 700°F and for circumferential ductility in the 700°F burst test. Of special note are the minimum limits specified for the ratio of ultimate-to-yield strength in uniaxial tensile test. These limits, which are not normally specified for light water reactor cladding tubes, were established to provide satisfactory early-in-life ductility for operation at stresses above unirradiated yield stress before significant irradiation hardening occurs. Minimum and maximum limits for contractile strain ratio were set, since cladding texture determines strain distribution under a biaxial stress and therefore affects rod dimensional changes such as bowing, increasing ovality and elongation, during core operation. The average cross-section temperature of the tube wall in the hottest core fuel rod was calculated to be 700°F. This worst case temperature was selected for elevated temperature testing.

Mechanical property limits were met by sampling each tubing lot and by applying standard statistical data evaluation techniques.

3. Metallography

Metallographic requirements were established to provide assurance that tubing was of proper quality and was representative of the tubing used in design analysis and in testing (both in-pile and out-of-pile). The grain size requirement assured normal mechanical property attributes. The requirement that there be no evidence of equiaxed grains was applied to finished blanket and reflector tubing to detect improper final heat treatment. The hydride orientation requirement was specified to assure a specific crystallographic texture and in particular to ensure that the preferred hydride orientation was not normal to the hoop tensile stress. In addition, all metallographic samples were inspected for internal flaws such as pores and cracks.

Metallography was performed on samples of tubing from each tubing lot.

4. Chemistry

Basic chemistry requirements were specified for the Zircaloy-4 ingot, as shown in Table A-1 of Appendix A. These requirements were specified to ensure obtaining tubing with the correct alloy composition; to limit harmful impurities, both with respect to nuclear and structural characteristics; and to minimize potential for flaws and inclusions in the finished tubing. For LWBR breeding requirements, hafnium limits were set at 35 ppm maximum, in contrast to the 100 ppm maximum normally found in Zircaloy. Ingots meeting these requirements were obtained from the normal production of the Zircaloy ingot vendors.

In addition, nitrogen, oxygen and hydrogen limits were specified for the finished tubing, since there is a potential for contamination from air and hydrogeneous materials during tube fabrication heat treatments. Nitrogen degrades Zircaloy-4 corrosion performance while oxygen affects mechanical properties. Ingots with oxygen high in the allowable range were selected for seed tubing to maximize the early-in-life physical properties. The limit for hydrogen was set at a low value to ensure against premature degradation of mechanical properties as a result of hydriding during core operation. Analyses were also made for nickel and hafnium on a sample from each lot to verify that the correct alloy (low hafnium Zircaloy-4) had been used to make the tubing.

Chemistry requirements were met by analyzing samples from each lot of tubing.

5. Other Requirements

a. Visual

The O.D. and I.D. surfaces of all tubes were routinely inspected visually to detect material defects such as laps and seams, gross surface imperfections such as dents, pits, and scratches, and the presence of any foreign material. These conditions could result in degraded stress limits or poor corrosion performance.

b. Surface Finish

Maximum surface roughness limits were specified for both O.D. and I.D. surfaces. Surface roughness affects fuel-clad interface heat conductance and the fuel-clad friction coefficient. The rougher the surface, the lower the heat conductance, resulting in higher fuel pellet temperatures. Similarly, the rougher the surface, the greater the friction coefficient and therefore the larger the clad stresses due to differential pellet-clad thermal expansion. The upper limit values were used in design analyses of rod performance capability.

Measurements were obtained on samples from each lot.

c. Ultrasonic Flaw Detection

All tubes were given a final ultrasonic inspection to detect material flaws that could result in premature loss of fuel rod clad integrity during core operation. Limits were established based on the effect of flaws on fuel rod performance and on the reliable limits of flaw detection for the equipment used.

d. Corrosion Resistance

Tube samples from each lot were autoclave tested in 750°F steam for fourteen days to detect any degraded corrosion performance. Both weight gain limits and visual standards were established. The weight gain limits were specified to detect any overall degraded material corrosion resistance, and the visual standards were used to detect any small local areas of poor corrosion resistance. All finished fuel rods were corrosion filmed for 3-1/2 days in 645°F water at 2107 psi as a final step in fuel rod fabrication.

e. Post-Anneal Cold Work

This requirement specified a limit on the cold working of seed tubing following the final recrystallization anneal to minimize the strain induced during the straightening of the tubing. If large amounts of strain are experienced by seed tubing after the final heat treatment, an alteration in mechanical properties could result. The 3% limit assured retention of the desirable properties.

The limit was met by detailed analysis of the straightener roll positions and tube flexures while the tube passed through the straightener; calculations demonstrated that the strain induced was no more than 3%. This was converted to functional limits on the operation of the straightener in terms of limits on roll offset and relative position of the rolls and limitation on the number of passes. No hand straightening was allowed. Samples from each lot were tested to detect evidence of residual strains exceeding the 3% limit.

III. TUBING MANUFACTURE AND PROCESS CONTROL

A. Introduction

LWBR tube manufacture was based on standard commercial operations, which included primary ingot breakdown (forging and rolling) beta quenching as 6 inch rounds, machining of the rolled 4 inch rounds to produce machined and drilled billets (MDB's), extruding the billets into starting base tubes (SBT's), machining of the SBT's to achieve high concentricity and uniformity as machined SBT's *(MSBT's), alternately cold reducing* and heat treating to near-finished size, and the finishing operations (heat treatment,* straightening,* cutting to final length, and pickling* to finished dimensions). However, many of the requirements which were stipulated for LWBR tubing were new to the industry; these included control of the helical wall eccentricity wavelength, control of furnace load size during heat treatment, and control of texture by selection of specific tube reduction sequences. Therefore, an extensive process development effort was necessary to achieve these requirements. Fabrication parameters had to be determined, inspection procedure had to be developed, and process controls had to be established. All of the development effort was designed to use good commercial manufacturing practices and standard fabrication techniques. Some manufacturing details such as extrusion and tube reducer tooling designs, tube reducer lubricants, etc., were considered proprietary by Wolverine Tube Division (WTD) of Union Oil Products Corporation and were not made known to Bettis. The use and control of these items was achieved by WTD through a coded identity for each of the proprietary items and proprietary techniques used in tube fabrication, and by WTD assuring Bettis that no changes would be made in these manufacturing details without prior Bettis approval. The manufacturing process and process controls are described in detail in Appendix A. Table A-4 is a process flow chart highlighting the key operations in processing an ingot into finished Zircaloy-4 tubing, including the specially controlled items noted above with the (*) symbol. Details of the fabrication operations are found in Appendix A.

After completion of process development, the LWBR tube manufacturing process was formulated. Specific controls were imposed on the production operations from ingot manufacturing through the tube finishing operations to assure that all procedures would be consistently maintained to produce Zircaloy tubing meeting all requirements for the LWBR application. This assurance of WTD's capability was considered particularly necessary and important in view of the proprietary nature of many of WTD's manufacturing operations.

Primary control of the manufacturing process was dictated by the requirements of the LWBR tubing specification, which covered such specific areas as written procedures for manufacturing, inspection, and repair operations, procedure modifications, quality control plans, retention of records and samples, and sampling for compliance with the requirements of the tubing specification. The major features which provided process control included the following:

1. Prior to fabrication, WTD was required to submit to Bettis, for approval, a detailed process outline showing all manufacturing operations, inspections and release points associated with each production step. Any changes in the approved process outlines, manufacturing operations and inspection procedures required the approval of Bettis. If such modifications were made after the process had been qualified, WTD was required to re-qualify that procedure, unless it could otherwise adequately demonstrate to the satisifaction of Bettis that material manufactured by the modified procedures was in accordance with all specification requirements.

2. WTD was required to prepare a detailed quality plan for each process outline. This plan was approved by Bettis prior to commencing manufacture and deviation from the plan was not allowed without Bettis approval. The plan included, as a minimum, a description of the minimum inspection system requirements, statisitical procedures, and control of process variability.

3. Procedures and equipment for manufacturing, testing, and inspection of tubing had to be qualified during preproduction before tubing production was initiated.

As a control on the ability of the tube manufacturer to produce tubing meeting all the requirements of the purchase order and of the tube specification, WTD was required to produce a preproduction run consisting of at least one lot of tubing (a minimum of 200 feet or a minimum of 0.5% of the quantity of each size, whichever was greater) using the equipment and procedures proposed for the production order. This preproduction run, if successful, proved and qualified WTD's equipment and procedures and at the same time minimized the overall risk in committing only sufficient materials for the preproduction run. After successful completion of the preproduction run, WTD was released to start the production manufacturing run.

As a general control, only the quantity (weight) of ingot necessary to fill the order was released at the time of order placement. The quantity released was based on a 50% (by weight) yield from ingot to finished tube. At specifically designated points during production, product yields were reviewed, and additional material was released, if required.

B. Processing of Ingots Into Starting Base Tubes

The ingots were hot forged (1200 to 1910°F) to 6 inch diameter rounds, beta quenched, and hot rolled (1000 to 1475°F) to 4 inch rounds by Latrobe Steel Company of Latrobe, Pennsylvania. The 4 inch diameter rounds were machined into extrusion hollows or machined drilled billets (MDB's) by AMAX Corporation of Akron, New York. The MDB's were copper clad and warm (1200°F) extruded into starting base tubes (SBT's) and pickled to remove the copper clad at WTD.

C. Machining of the Starting Base Tubes

The SBT's were machined on O.D. and I.D. surfaces by Howard Dearborn Corporation of Fryeburg, Maine. The use of machined SBT's (MSBT's) made a significant improvement in the surface finish, surface quality, and tube concentricity such that the overall yields improved despite the metal losses incurred in the machining of the SBT's.

D. Tube Manufacture

All of the tubing for LWBR was produced by the tube reducing process at the Dearborn Heights facility of Wolverine Tube Division (WTD) of Union Oil Products Corporation. To meet the requirements described in Section II.B and detailed in Table A-2 of Appendix A, more controls were defined and imposed on many aspects of the manufacturing process than on prior commercial tube products. A number of these controls were the end result of development programs initiated to study the effect of process variables on the finished tube and on manufacturing yields. The process controls included the following:

1. Machining of the starting base tubes to control eccentricity and bow:

2. Specific reduction schedules to control texture, physical properties, and wavelength of wall eccentricity;

3. Control of heat treatment parameters: load size and time at temperature (see Appendix D);

4. In-process inspections of the tube reduced product for surface quality (I.D. and O.D.) to detect galling, mandrel pickup or tooling deterioration;

5. Control of the rotation of the tube stock in relation to its forward motion into the reduction dies;

6. Qualification of specific tube reduction machines, tooling, and heat treatment furnaces for the productin of LWBR tubing;

7. Control of pickling and straightening processes;

8. Ultrasonic defect inspection requirements;

9. Use of testing techniques to assure that the tubing met all of the product requirements.

E. Finished Tubing

The finished tubing is described in Table A-2. All tubes used to produce LWBR fuel rods met all of the requirements of Table A-2. The completed fuel rod was pickled to reduce the tube O.D. (and nominal wall) to the dimensions listed in Table A-3.

F. Manufacturing Yields

Although some of the technical requirements for LWBR tubing were more restrictive than those for light water reactor tubing, the innovations in preparation of the SBT's and the close process control resulted in yields equivalent to commercial practice. WTD used a 50% yield from ingot to delivered tube in estimating the weight of ingot needed to deliver the desired quantity of tubes in a commercial order. Table A-8 shows the manufacturing yields experienced in producing each size of LWBR tubing. The first 3 entries are identical for all sizes of tube except for machining reflector MDB's, where the lower reflector yield is due to the larger I.D. of the reflector MDB's. The lower overall yields for the seed is due in part to the small size as well as to the use of three reductions from MSBT to final size versus two reductions for the three larger sizes. Note that the yield improved with increased tube size, with the two blanket sizes showing equivalent yields in all evaluations cited.

IV. INSPECTION AND TESTING OF TUBING

A. Introduction

The manufactured tubes were inspected and tested to assure compliance with the requirements listed in Table A-2 of Appendix A. The nondestructive and destructive inspections performed on the tubes are listed in Tables 1 and 2 respectively, together with the frequency of inspections for each attribute and the applicable statistical confidence statement. The inspection technique, combined with suppression of limits, satisfied the confidence statements of Tables 1 and 2. The techniques used and data obtained for each of the tests listed in Tables 1 and 2 are discussed in detail in Reference (a).

B. Non-Destruction Inspection

1. Inside Diameter

The inside diameter was measured with a capacitance gage which passed through the tube as the tube was rotated. The maximum forward motion of the gage for each 360° revolution of the tube was limited to 0.4 inch for seed, 0.5 inch for PFB, 0.65 inch for standard blanket, and 1.0 inch for reflector. The actual rpm of the tube is listed on the I.D. trace. The diameter measurements were recorded as a continuous trace for each tube and included a calibration standard. The tube was placed in the fixture and held in place adjacent to the calibration ring standards and rotated. The capacitance gage passed through the standards and traversed the length of the tube recording the I.D. variations as it progressed through the tube. On reaching the far end, the rotation and recording stopped and the gage was withdrawn. The trace was identified with the tube serial number and was the basis for proof of compliance with both the local I.D. and average I.D. requirements. The local diameter is represented by each discrete location along the trace while the average is, in effect, the average of the min and max at any axial location. The gage calibration was within ± 0.0001 inch of the standard. As part of the calibration procedure for each capacitance gage, a series of inspections of the ring gage standard provided a minimum and maximum for the gage versus the absolute limit. The variation of the capacitance gage readings from the standard was treated as a normal distribution. The suppression used on each local I.D. limit was the product of t times s, where t was Student's t for a one-sided limit which included 95% of the population, and the s was the standard deviation of the gage variations from the standard. All calculated suppression values were rounded up to the next tenth of a mil (0.0001 inch) but not less than 0.0002 inch. The absolute

I.D. limits were suppressed a minimum of 0.0002 inch on local diameter and a minimum of 0.0001 inch on the average I.D. values to allow for measurement error and thus assure that all tubes accepted met the limit. The suppression of the limits for average I.D. was 1/2 of that calculated for local I.D. measurements. The minimum suppression for average I.D. limits was 0.0001 inch.

2. Outside Diameter

The O.D. of each tube was measured using a two-hole air gage as the first dimensional inspection off the production line. The absolute limits were suppressed by 0.0002 inch to allow for measurement error. The inspection consisted of a 360° rotation of the tube at 6 inch intervals along the length and a spiral inspection path between the 6 inch points. At locations of "extreme" dimensions, a local search was made to find the local maximum (or minimum). Any reading outside the suppressed limits was cause for rejection. Measurement of all tubes satisfied the statistical requirements of Table 1.

3. Wall Thickness

The wall thickness of each tube was measured over a spiral pattern as the tube rotated and advanced under the transducer station, which used a high frequency ultrasonic pulse-echo measuring technique. The wall thickness was recorded on a strip chart, together with a record of the test calibration. This chart record was the basis for proof of compliance with the requirements for both wall thickness and wall thickness eccentricity. The search helix was adjusted to have a pitch not to exceed 1/2 the nominal O.D. rounded down to the next 0.1 inch. For 0.531 inch O.D. PFB tubes, the pitch of the UT wall search helix was 0.2 inch maximum. The maximum search helix pitch was 0.1", 0.2", 0.4" for seed, blanket, and reflector tubes, respectively.

On evaluation of the traces, a suppresion of 0.0003 inches was applied to the minimum wall trace information to allow for measurement error and thus assure that all tubes met the minimum wall limit.

4. Wall Thickness Eccentricity

Inspection for wall thickness produced a chart of wall thickness that was also used to measure wall thickness eccentricity. No suppression was needed to determine wall eccentricity, which is the difference the adjacent maximum and minimum wall thickness on the trace since the range of data was calibrated and the error in absolute data cancelled.

5. Wavelength of Wall Thickness Eccentricity

The ultrasonic pulse-echo technique was also used to measure the wall thickness over an axial path along the non-rotating tube. The wall thickness was recorded on a strip chart. The variation of wall thickness along one path over the tube length exhibited a generally sinusoidal pattern for which the wavelength is the attribute measured. Four tracks were measured, two at a time, at 90° intervals around the tube (at 0°, 90°, 180°, and 270° orientations). The wavelengths of the four tracks were used to determine the wavelength characteristic of each tube. The axial progression of the maximum and minimum as shown on the four charts permit determination of the direction of rotation of the eccentricity along the tube. The direction of rotation (clockwise or counterclockwise) defined the path of rotation of the location of maximum eccentricity going away from the observer looking into the end of the tube. For some tubes that were formed in part under cross-head indexing and in part under output indexing, two distinct wavelength patterns were discernible. The shorter of the two wavelengths was recorded to characterize the tube in relation to the technical requirements. See Attachment B for details on the formation and control of this attribute.

A sample of the strip chart record generated for this inspection is shown in Figure A-2 of Appendix A. The trace reflects every variation in wall thickness and the cumulative effects of several simultaneous variations on local wall thickness. Variations with very short wavelengths included variations due to local metal flow from each rocking action of the die and local surface variations from pitting, galling, pickling, abrading, etc. The wavelength of wall eccentricity may be obscured by these local variations and may not be apparent if wall eccentricity is very small or if a very long wavelength is present. In many cases, all four traces were needed to detect the wavelength of wall eccentricity.

6. Length

The length of each tube was measured in a calibrated length gage to suppressed limits. The result of this go-no-go inspection was recorded for each tube versus the serial number etched on the O.D. surface.

7. Perpendicularity of End Face

Since both ends of the tube, as delivered to Bettis, were to be cropped at Bettis, this attribute was not required of the tubing vendor. Perpendicularity of end face was measured at Bettis by gripping the tube in a collet and measuring the variation of the plane of the end face from the plane normal to axis of rotation and the diameter of the circle of measurement to obtain the inches of variation per inch of inspection span (diameter). Perpendicular end faces are required to provide a seat for the shouldered end cap to be pressed into the end of the tube. The end of the tube and the radial face of the end cap shoulder, when pressed into intimate contact, provided alignment for the long end caps with the tube centerline. A lack of perpendicularity greater than the 0.006 inch per inch limit of the tube end face could cause a varying gap between the tube and the end cap shoulder which has been shown to contribute to the formation of weld defects.

8. Edge Squareness

This attribute, which is a measure of wall thinning at the very end of the tube, was inspected using pin-tip micrometer and visual standards. The inspections to satisfy this requirement were performed at Bettis following the cropping of the tube. The end cap was pressed into the tube and joined by a tungsten inert gas fusion weld. Lack of squareness of the tube edge entrapped helium which entered the weld pool to form porosity and toroidal cavity weld defects. In addition, any metal absent prior to welding resulted in deeper weld depressions and a thinner clad in the local weld area.

9. Straightness

Every tube was inspected by the vendor for straightness, initially by observation of the smoothness of motion as the tube was rolled on a surface plate. Those tubes that exhibited a significant amount of wobble were measured using a straightness gage with a fixed span. The gage was placed against the tube and the deflection of the tube at mid-span was measured by the travel of the stem of a dial indicator. The amount of deflection from a straight line at any measured location had to be within the limits imposed by Table A-2. This requirement was overchecked at Bettis using the "free hanging bow" facility, where tubes from each lot were hung from one end and the curvature of the tube profile was measured (right edge only) at three positions (0°, 45° and 90°). These data were converted, via a computer program, to evaluate the probable rod bow between grid levels and to calculate the load required to be exerted at each grid spring location to straighten the fuel rod. Based on the results of the sample inspection, it was concluded that the tubing was sufficiently straight to allow fabrication into fuel rods with the high probability of producing acceptably straight fuel rods. See Reference (b) for discussion of free hanging bow measurements.

10. Internal Free Path

This was the last inspection performed prior to shipment and consisted of passing the test plug through the entire length of each tube. This inspection provided additional assurance of: (a) internal cleanliness, as in freedom from galled areas, debris, etc.; (b) freedom from dents, kinks, etc.; (c) satisfying minimum I.D. requirements. Based on the minimum average I.D. for each tube size and the maximum O.D. for the corresponding plug, the tube-to-plug diametral clearances were 0.002 inch for seed, 0.0025 for both blankets, and 0.003 inch for reflector. The length of the right cylindrical section of the plug, exclusive of lead-in taper, was four times the nominal

I.D. of the tube and was from 70% to 330% longer than the pellets to be loaded into the tube.

11. Visual Inspection

The O.D. surface of the tubes were visually inspected for cleanliness and for freedom from defects as was that portion of the I.D. surface visible from each end. As a check on the cleanliness, a section of KIMWIPE (a commercial paper towel) was blown through each tube using clean dry compressed air and then compared to visual cleanliness standards. Following receipt at Bettis, the tubes were again cleaned and inspected for cleanliness. The I.D. surface was inspected using a boroscope and physical standards selected to illustrate the defined defects. Boroscopic inspection is detailed in Appendix A. As a final check, clean white nylon patches were passed through the tube to detect any internal contamination. Boroscopic inspection of the I.D. surface of tubes with white light was a new method of evaluation applied to LWBR tubing.

12. Surface Finish

The majority of the surface finish inspections were performed by visual comparison with standards of known roughness. Selected tubes and tube samples were inspected on a profilometer where the vertical movement of the surface contact probe, as it travelled across the test surface, was integrated into a surface roughness value indicated as micro-inches AA (arithmetic average).

13. Material Quality

All tubes were ultrasonically inspected for the presence of flaws exceeding area limits defined in Table A-2. The test had to be sensitive enough to reproducibly detect flaws with reflecting areas of 0.001" x 0.020". A high-frequency pulse-echo ultrasonic test was employed using a highly damped spherically focused transducer. The echo signal was printed out on a strip chart, calibrated with echo signals from known sizes of defects. These charts were retained as a permanent record of the internal quality of each tube. Controls on the test frequency, focal spot diameter, rpm and axial speed of this inspection provided assurance that 100% of the volume of the tube wall was inspected twice, once with a search beam traveling in the axial direction and once with a search beam traveling circumferentially through the tube wall. Defects of known size and location in a calibration standard had to be detected at least twice on each inspection of the standard with a minimum echo-signal intensity. Another set of sensors monitored the uniformity of the forward motion of the tube, causing an "event" mark to appear at regular intervals along the edge of the trace as the end of the tube past each detector location. Test qualification and adherence to the restrictions and requirements of the ultrasonic flaw detection test provided assurance that the tube was free of defects in excess of the established standards.

C. Destructive Testing

1. General

Samples of tubes from each lot were destructively evaluated to assure compliance with the chemical, mechanical, and microstructural requirements of Table A-2. The destructive evaluations performed on tube samples are itemized in Table 2 showing the test, the minimal test frequency, and statistical requirements where applicable. With the exception of fluorine analysis, no two samples for a given test were taken from the same tube.

2. Tube Chemistry

Five elements were analyzed for process control purposes. The three gas analyses (H_2, N_2, O_2) were a check on possible contamination during the heat treatments. Three samples per lot were a minimum sampling plan for control of the three gases. The two metal analyses (Ni, Hf - one each per lot) were used as material control checks for the proper alloy. Zircaloy-4 has no nickel alloy addition as compared to the nominal 0.05% in Zircaloy-2, and the hafnium in low-hafnium ingots is significantly lower than the hafnium content found in Zircaloy ingots which were not produced from low hafnium content sponge and solids. The ingot certification and the in-process analysis of MDB's provided the overall analysis of the tubes from each ingot. Subsequent thermal processing could only change the gas content through absorption during improper processing.

3. Surface Chemistry

Good rinsing procedures following pickling can produce tubes with low residual fluorine surface contamination. The analysis for fluorine on the I.D. surface at both ends and mid-length of one randomly selected tube from each lot was a spot check on proper post-pickle rinsing technique. This inspection, using the pyrohydrolytic analysis technique, was performed only at Bettis. 932°F (500°C) steam was passed through the sample to drive the fluorine ions from the I.D. surface. The fluorine content of the condensate was measured. A similar analysis on machined surfaces did not detect any F contribution from the base metal. See Table A-2 for Bettis limits and Table A-9 for analytical results.

4. Corrosion Resistance

The 14-day accelerated (750°F steam) test of corrosion resistance, a standard materials test, was a check on proper thermal history and on the possibility of contamination during processing. The sampling plan and required testing are listed in Table 2. The limits are defined in Table A-2 of Appendix A.

5. Tensile Test

Tests at room temperature and at 700°F provided assurance that tubes in the lot would perform as expected. The results of all tests on all lots, when analyzed as a group, had to satisfy the statistical confidence statement for the Total Order Quantity (T.O.Q.) for each tube size, as noted in Table 2. The limits are defined in Table A-2 of Appendix A.

6. Burst Test or Circumferential Tensile Test

This test, another check on proper processing and heat treatment, is sensitive to proper texture. The property of concern is the ability of the clad to accommodate fuel expansion; thus, the only attribute specified is the percent increase in circumference which is a measure of the ductility of the tubing under 2:1 biaxial stress conditions. The statistical confidence requirement of Table 2 applies to the requirement defined in Table A-2 of Appendix A.

7. Texture

Contractile Strain Ratio (CSR) is a measure of orientation of the crystallographic structure within the tube wall. The crystal structure affects the flow of the material under plastic deformation. The CSR test was devised to measure the ratio of two major strains (radial and circumferential). The fabrication sequence controls texture formation. Contributing factors to the development of texture are percent cold work (percent reduction in cross-section area) and the deformation ratio or Q-value (the ratio of the percent change in wall to the percent change in diameter) in each reduction. All CSR values for each tube size and condition of heat treatment were combined and statistically evaluated to the limits of Table A-2. The technique for measuring CSR is defined in Appendix C. Experimental work described in Attachment C provided a correlation between CSR and x-ray texture based on basal pole intensities.

8. Hydride Orientation

Hydride orientation is another indication of texture obtained by measuring the percent of hydride needles or platelets aligned within 30° of the radial direction within the tube wall. Samples of tubes are intentionally hydrided to 125 ± 25 ppm of hydrogen and heat treated to promote absorption and diffusion through the tube wall. Metallographic samples are polished and etched to reveal the hydride needles. Metallographic evaluation determines the compliance with the requirement defined in Table A-2. This inspection is an indirect measure of basal pole alignment. The preferred location for precipitation of hydrides is near the basal plane of the hexagonal structure of the Zircaloy-4 grains. Hydrides parallel to the tube surface are preferred, since this is parallel to the principal stress plane under internal pressure and the hydrides formed in this orientation during core operation will result in a minimum reduction in ductility of the tube.

9. Post Annealed Cold Work (PACW)

This test, not usually performed for light water reactor Zircaloy tubing, was performed to detect signs of excessive strains in RXA seed tubing following the final heat treatment. The development of this test is described in detail in Appendix E. The primary source of strains in RXA tubes is in the controlled straightening operation. Samples of finished tubing are heated to induce excessive grain growth, polished and etched to show grain structure, and examined metallographically to determine if exaggerated grain growth has occurred. The presence of large grains indicates that strain in the sample exceeds the 3% limit set to ensure desirable mechanical properties.

10. Grain Size

A sample of tubing was metallographically examined for grain size. Highly cold worked tubing recrystallized in the range of 1200 to 1300°F should produce a fine grained structure equivalent to ASTM 10. The grain size increases with increasing recrystallization temperature. The ASTM 9 max grain size for seed versus the ASTM 8 limit for the SRA non-seed sizes reflects the differences in the heat treatment prior to sampling. The seed size is sampled after final RXA @ 1225°F while the blanket and reflector sizes are sampled following the 1300°F in process RXA just prior to the last tube reduction. The average grain size for all four sizes in longitudinal and transverse sections ranged from 10.1 to 10.6 ASTM grain size, with a range of 9.5 to 11.0 for all samples from all lots.

11. Equiaxed Grains

Samples of final heat-treated SRA tubes (non-seed sizes) were polished and etched and inspected metallographically for the presence of equiaxed grains. The presence of equiaxed grains in the distorted grain structure of SRA material would indicate that an excessive heat treatment had occurred. Any excess temperature or excess time at temperature could potentially cause localized recrystallization in the highly stressed microstructure which results from high cold work in the final reduction. This test is, in effect, a process control inspection.

12. Metallographic Inspection for Defects Exceeding 0.004 Inch

All metallographic samples prepared for the inspections discussed above were also inspected for the presence of defects exceeding 0.004 inch in any dimension. This is a low frequency spot check on the nondestructive tests performed on the tubing, primarily surface visual and UT flaw inspection (items 11 and 13 of Table 1). A defect at 0.0040 inch in one dimension is at the threshhold of detection by the prescribed UT flaw test where a 0.001 inch deep by 0.020 inch long standard defect (test sensitivity notch) must be detected on a minimum of two successive rotations of the defect past the transducer station.

V. SUMMARY

Tubing with the product requirements established for the cladding of LWBR fuel rods was manufactured using both newly developed techniques and good commercial practice. Definition of the machining required for the extruded base tube and development of improved process controls were instrumental in meeting the tolerances on dimensions and on allowable defect size and in meeting the other requirements of texture, physical properties, straightness, wall eccentricity and the wavelength of helical wall eccentricity. The process modifications and process controls resulted in overall manufacturing yields comparable to the yields attained for typical commercial light water reactor Zircaloy tubing despite the additional product requirements. The improved tube quality permits improved fuel rod performance capabilities and provides a high reliability during in-core service.

Developmental efforts leading to the establishment of the reference manufacturing process defined the following relationships which affect properties of the tubing produced:

a. The effect of the reduction sequence on texture;
b. The equivalency of CSR and x-ray texture;
c. The machining of the starting base tube which resulted in improvements in processing yields, concentricity, wall uniformity and surface quality in the finished tubing;
d. The relation of the control of the tube reducer operation parameters in successive reductions on the formation and control of the wavelength of helical wall eccentricity and of texture (CSR).
e. The effects of time, temperature, and load cross section in a given heat treating furnace on the uniformity of heat treatment (and on physical properties) of all tubes in a single heat treatment and on the reproducibility of that heat treatment;
f. Control of the roller straightener to minimize strain buildup and to minimize the reduction of fatigue life of the tubes in core environment.

In addition, specialized testing was developed to measure certain properties not usually measured for light water reactor Zircaloy tubing:

a. An ultrasonic test and associated controls to detect defects as small as the 0.001 inch x 0.010 inch which is half the length of the sensitivity notch. The sensitivity notch (and all notches) must be seen clearly and reproducibily in a minimum of two successive rotations of the notch past the transducer station;
b. Non-rotating ultrasonic measure of wall thickness along the length of the tube to determine the wavelength of helical wall eccentricity;
c. Contractile strain ratio as a mechanical measure of the crystallographic texture in the tube;

d. The use of the exaggerated grain growth phenomenon in zirconium to detect a specific strain level using a specific heat treatment.

The selected manufacturing process, combined with regular in-process checks, produced tubing which met all of the criteria established for the clad tubes for LWBR fuel rods, with commercially acceptable yields.

VI. ACKNOWLEDGMENTS

The author is indebted to G. Schoenberger and P.F. Thompson for their help in compiling the experimental data discussed in the appendices. I. Goldberg's contribution to Section II is gratefully acknowledged. The critical reviews and comments of T.H. Alff, Dr. J. Bell, R.A. Frederickson, I. Goldberg, and Dr. B. Lustman were most helpful in preparing the final manuscript.

VII. REFERENCES

(a) J.H. Eyler, "The Characteristics of the Zircaloy-4 Tubing in LWBR Fuel Rods", WAPD-TM-869, November 1979.

(b) A.J. Caffarel, "Free Hanging Bow Measurements of LWBR Fuel Rods," WAPD-TM-1270, March 1979.

(c) ASTM Standard ANSI/ASTM B 353-77, "Wrought Zirconium and Zirconium Alloy Seamless and Welded Tubes for Nuclear Service" in ASTM Annual Standards (1977) Part 8, pages 282 thru 290.

(d) O.M. Katz, "Recovery and Recrystallization Kinetics of Cold Worked Zircaloy-4 Plate and Tubing," WAPD-TM-590, February, 1968.

(e) D.O. Hobson, "Texture Changes Produced During Zircaloy-4 Tubing Fabrication From Forged Billet to Finished Tubing," Application Related Phenomena in Zirconium and Its Alloy, p. 37, ASTM Special Publication 458, December 1969.

(f) E. Tenckhoff and P.L. Rittenhouse, "Texture Development and Texture Gradient in Zircaloy Tubing," Application Related Phenomena in Zirconium and Its Alloys, p. 50, ASTM Special Publication 458, December 1969.

VIII. BIBLIOGRAPHY OF DOCUMENTS IN THE LWBR TECHNICAL MEMORANDUM SERIES RELEVENT TO THE REQUIREMENTS FOR AND TO THE FABRICATION AND INSPECTION OF LWBR FUEL ROD CLADDING TUBES

A. Procedure for Obtaining LWBR Technical Reports

Technical information developed under the LWBR program has been and will be published in technical reports. In this way, vendors, utilities, and other interested organizations will be able to determine the degree to which they desire to apply the LWBR technology to their own programs.

These reports are announced in the "Energy Research Abstracts" (formerly the "Nuclear Science Abstracts") published by the Department of Energy's Technical Information Center, P.O.Box 62, Oak Ridge, Tennessee 37830. The abstracts document is distributed to a number of universities and DOE facilities throughout the country or it may be obtained from the Government Printing Office, Washington, D.C. 20402. Most of the LWBR technical reports will be published by the Bettis Atomic Power Laboratory and may be identified in the abstracts document by looking for numbers with the letter prefix "WAPD-TM-xxx" or referencing the topical headings: "Breeder Reactors," "Water Cooled," and "LWBR Type Reactors." In addition, the titles of the reports will in most cases be followed by the statement, "LWBR Development Program".

The LWBR reports may be purchased from the National Technical Information Service (NTIS), Department of Commerce, Springfield, Virginia, 22161. Both paper copy and microfiche copy are available. The NTIS also announces the reports in its announcement journal "Government Reports Abstracts."

B. Selected Relevant Technical Memoranda

Report No.	Title	Published
TM-472	Thermal Expansion and Preferred Orientation in Zircaloy	Nov. 1965
TM-585	Properties of Zircaloy-4 Tubing	Dec. 1966
TM-590	Recovery and Recrystallization Kinetics of Cold Worked Zircaloy-4 Plate and Tubing	Feb. 1968
TM-591	Deformation and Collapse of Fuel Rod Cladding Due to External Pressure	Jan. 1967
TM-628	Behavior of an Intentionally Defected Fuel Rod Which Ruptured During Irradiation	July 1969
TM-629	Irradiation Behavior of Zircaloy-Clad Fuel Rods Containing Dished-Ended UO_2 Pellets	July 1967
TM-651	Fracture of Cylindrical Fuel Rod Cladding Due to Plastic Instability	April 1967
TM-652	An Analysis of Transient Clad Strains in Cylindrical Fuel Elements Including the Effects of Oxide Pellet Cracking (STRIPE)	Feb. 1970
TM-714	Effect of Cladding Ovality and Diametral Creep on Fuel Rod Support Systems	Dec. 1970
TM-726	Elastic Analysis of Thermal Gradient Bowing in Rod-Type Fuel Elements Subjected to Axial Thrust	Jan. 1968
TM-756	Estimated Creep Properties of Zircaloy-4 Tubing During Neutron Irradiation	May 1968
TM-782	Effects of Pressure Upon the Corrosion of Zircaloy-4	Oct. 1968
TM-847	ROBOT - A Computer Program to Solve the Bowing Problem in Rod-Type Fuel Elements	July 1969
TM-869	The Characteristics of the Zircaloy-4 Tubing in LWBR Fuel Rods	Nov. 1979
TM-900	High Temperature Deformation and Burst Characteristics of Recrystalized Zircaloy-4 Tubing	Jan. 1970

Report No.	Title	Published
TM-906	The Influence of Prior Corrosion History Upon the Hydrogen Pickup by Zircaloy During Subsequent Exposure in Hot Water	Dec. 1970
TM-956	A Method of Analysis for the Creep-Buckling of Tubes Under External Pressure	Oct. 1970
TM-973	In-Pile Dimensional Changes of Zircaloy-4 Tubing Having Low Hoop Stress	July 1971
TM-986	In-Pile Dimensional Changes of ThO_2-UO_2 Fuel Rods with Nonfree Standing Cladding	Nov. 1970
TM-1043	High Temperature, Time-Dependent Deformation in Internally Pressurized Zircaloy-4 Tubing	Oct. 1974
TM-1060	Plastic Anisotropy of Zircaloy Tubing	Feb. 1976
TM-1086	Inelastic Column Buckling of Internally Pressurized Tubes	April 1973
TM-1104	The Relationship Between Failure Strains in Burst Tests on Zircaloy Tubing and Wall Thickness Eccentricity	Jan. 1973
TM-1149	Halogen Stress Corrosion Cracking of Zircaloy-4 Tubing	July 1974
TM-1203	An analysis of Iodine Stress Corrosion Cracking of Zircaloy-4 Tubing	Feb. 1976
TM-1228	Ultrasonic Testing of Nuclear Fuel Rod Welds and Clad	Feb. 1979
TM-1235	Fuel Rod Welding	Feb. 1979
TM-1239	Inspection of Assembled LWBR Fuel Rods for Internal Dimensions and Pellet Integrity Utilizing In-Motion Radiography	Feb. 1979
TM-1243	Some High Temperature Mechanical Properties of Internally Pressurized Zircaloy-4 Tubing	Feb.1976
TM-1248	The Effects of Internal Surface Flaws, Iodine Concentration and Temperature on the Stress Corrosion Cracking Behavior of Zircaloy-4 Tubing	Feb. 1976

Report No.	Title	Published
TM-1270	Free Hanging Bow Measurements of LWBR Fuel Rods	Mar. 1979
TM-1272	Sources of Internal Hydriding in Unirradiated Thoria-Fueled Zircaloy Rods	Feb. 1979
TM-1300	The CYGRO-4 Fuel Rod Analysis Computer Program	July 1977
TM-1313	The Susceptibility of Unirradiated Recrystallized Zircaloy-4 Tubing to Stress Corrosion Cracking	Oct. 1977
TM-1320	Low Strain Diameter Expansion of Internally Pressurized Zircaloy-4 Tubing at High Temperatures	Mar. 1978
TM-1322	Corrosion of Zircaloy-4 Tubing in 680°F Water	Dec. 1978
TM-1324	Effect of Fuel Chips on Cladding Stress in Zircaloy Clad Oxide Fuel Rods	Nov. 1978
TM-1404	Ex-Reactor Deformation of Externally Pressurized Short Lengths of Fuel Rod Cladding	May 1979

TABLE 1

NON-DESTRUCTIVE INSPECTION OF LWBR CORE TUBING

(See Table A-2 in Appendix A for Actual Requirements)

Attribute	Notes*	Vendors Inspection Frequency	Statistical Requirements*
1. Inside Diameter			
a. Average of Local Cross Section	c	100%	a
b. Local Dimension	c	100%	a
2. Outside Diameter - Local	-	100%	a
3. Wall Thickness	c	100%	a
4. Wall Eccentricity	c	100%	a
5. Wavelength of Wall Eccentricity	c	100%	-
6. Length	-	100%	b
7. Perpendicularity of End Face	d	-	b
8. Edge Squareness	d	-	b
9. Straightness	-	100%	a
10. Internal Free Path	-	100%	-
11. Surface Visual	-	100%	b
12. Surface Finish (Roughness)	-	10 per lot	b
13. Material Quality (UT Flaw)	c	100%	-

*NOTES:

a. 95% confidence that 99% of all locations on each tube satisfy the requirements.

b. 95% confidence that 99% of all tubes in the lot satisfy the requirements.

c. A permanent autographic record of this inspection is required for each length of tube.

d. This attribute was applied at Bettis after cutting the tube to length for fuel rod assembly.

TABLE 2

DESTRUCTIVE TESTING OF LWBR CORE TUBING

(See Table A-2 in Appendix A for Actual Requirements)

Attribute	Minimum Test Frequency (per lot)	Statistical Requirement
1. Tube Chemistry		
a. Gases: H_2, N_2, O_2	3	None
b. Metals: Ni, Hf	1	None
2. Surface Chemistry: Fluorine	3(a)	None
3. Corrosion Resistance (750°F)	6	None
4. Tensile Test		
a. Room Temperature	3	(b)
b. 700°F	3	(b)
5. Burst Test - 700°F	3	(b)
6. Texture (CSR)	3	(b)
7. Hydride Orientation	3	None
8. Post Anneal Cold Work (RXA Only)	3	None
9. Grain Size	3(c)	None
10. Metallographic Inspection		
a. Equiaxed Grains (SRA Only)	10	None
b. Defects > 0.0040 inch	10(d)	None

NOTES:
a. Samples from each end and mid-length on one tube length.
b. 95% confidence that 95% of the TOQ* of each tube type meets the requirement.
c. Samples of SRA (non-seed) tube were measured on RXA tube stock prior to last reduction. Samples of RXA (seed) tubes were measured after final heat treatment. Three longitudinal and three transverse sections.
d. All specimens prepared for any metallographic inspection were also inspected for this attribute. Reference items 7, 8, 9, and 10.a of this table.

*TOQ = Total order quantity.

APPENDIX A

LWBR TUBING REQUIREMENTS AND MANUFACTURING PROCESS

I. INTRODUCTION

LWBR tubing was tube reduced at the Dearborn Heights, Michigan facility of Wolverine Tube Division (WTD) of Union Oil Products Corporation in the 1971 to 1973 period. Every effort was made to optimize the quality of the tube, to optimize the manufacturing yields in all fabrication operations from the initial ingot through the final inspection of the finished tube, and to meet the product requirements developed for LWBR fuel rod cladding tubes.

II. INGOT REQUIREMENTS

The ingots, produced by Teledyne Wah Chang (TWCA) of Albany, Oregon and by AMAX Corporation of Akron, New York, met the requirements listed in Table A-1. These requirements are typical of those specified for light water reactor Zircaloy-4, but were modified slightly for LWBR tubing in the lower limit for hafnium. The 35 ppm limit for hafnium reflects the 25 ppm limit imposed on the selection of sponge batches and an allowance of 10 ppm for analytical error. As a further control of ingot quality, the starting stock for the ingot was limited to material of known chemical analyses (selected sponge batches, solids, and ingot turnings) and in the proportions shown in Table A-1.

III. TUBING REQUIREMENTS

Product requirements for LWBR tubing ordered in 1971 and 1972, included limitations on bow, ovality, wall eccentricity, tight tolerances on tube diameters and wall thickness, and a restriction on the rotation of wall eccentricity (location of maximum wall thickness in any cross section) along the tube length. In addition to these size limitations, product requirements were developed for texture (as measured by hydride orientation and contractile strain ratio) and grain size, as well as for mechanical and physical properties. The requirements for LWBR fuel rod cladding tubes are summarized in Table A-2, in the same sequence as the inspection and testing requirements are presented in Tables 1 and 2. Several of the technical requirements were not imposed on WTD, but were met by performing additional inspections at Bettis. The requirements which were met by such additional Bettis effort are noted in Table A-2 with the symbol (#). The size of the tubes purchases for LWBR is shown in Table A-3 together with the final heat treatment, the quantity of tubes needed, the final size of the cladding of the finished fuel rod and the number of different fuel rod types and the number fuel rods in each tube size in the LWBR core.

A comparison between the specified LWBR tube requirements and the commercial specification ASTM Designation B-353-1977 (Reference (c)) for zirconium alloy tubes for nuclear service, is shown in the following table. Only those LWBR requirements of Table A-2 which are different from, or not included in, ASTM-B-353-1977 have been listed. The LWBR specification is more restrictive than present commercial practice, as represented by ASTM-B-353-1977, in terms of both process capability and overall yields.

Wall eccentricity and the wavelength of helical wall eccentricity require development of process controls, which, when solved, will have a small effect on yields. The process that produces good texture should meet post-anneal cold work, the hydride orientation and the physical tests when properly heat treated. The ultrasonic test for material quality requires some sophisticated instrumentation on a precision tube tester, but good commercial practice and process control should keep any losses to a few percent.

SIGNIFICANT DIFFERENCES
IN LWBR AND ASTM DESIGNATION B-353 SPECIFICATIONS
FOR REACTOR GRADE SEAMLESS ZIRCALOY-4 TUBING

Item	LWBR (1971-1972)	ASTM-B-353-1977
1. Dimensional Tolerances		
a. I.D. Local (seed)	N ± 0.0015	N ± 0.0020
b. Wall Eccentricity (max)	0.07W	-
c. Straightness (deflection/span)(max)	1/1500	1/1200* or 1.57/1500*
d. Wavelength of Wall Eccentricity (min)	R	-
2. Internal Free Path	R	-
3. Material Quality (U.T. Reject Notch Size)		
a. Min Length Inches	0.02	0.10
b. Nominal Length	0.75W	M
c. Nominal Depth	0.075W	0.10W
4. Surface Chemistry (fluorine)	R	-
5. Burst Test	R	M
6. Texture (CSR)	R	-
7. Hydride Orientation	R	m
8. Post-Anneal Cold Work	R	-
9. Grain Size (ASTM No.)	8 to 12.5	7 or finer
10. Metallographic Defects	R	-

- Not mentioned in this specification
* Using a common radius of curvature
M Listed as an item for mutual agreement
m Mutual agreement item not expected to pose a problem
R Required in LWBR specification
W Nominal wall thickness

The tubing requirements are discussed below in the same sequence as listed in Table A-2 and in Tables 1 and 2 of this report.

III. A. Non-Destructive Inspection

1. I.D.

The tolerances on both local and average I.D. for any cross section relate to the small design clearance between the fuel pellets and tube I.D. which results in improved fuel element performance capability.

2. O.D.

The tolerances on O.D. are specified to be compatible with final fuel rod dimensions and the fuel rod pickling allowances.

3. Minimum Wall

This limit ensures that the stress limits for fuel rod cladding are satisfied.

4. Maximum Wall Eccentricity

This requirement was applied to minimize bowing of the fuel rod in the core environment. This requirement was tighter than WTD would guarantee. Tubes that did not meet these limits were culled at Bettis.

5. Minimum Wavelength of Wall Eccentricity

Special process controls were initiated on the tube reduction operations to maximize the wavelength, since the long wavelengths resulted in improved fuel rod performance. See Appendix B for the development effort and the process controls developed to produce tubing that met this requirement.

6. Length

The vendor supplied overlength tubes to a loose tolerance (-0, +0.5 inch) since the processing of tubes into fuel rods required machining at Bettis to several nominal lengths. Thus, tolerances on length and end conditions applied only to Bettis operations.

7. Perpendicularity of End Face

(and)

8. Edge Squareness

Both of these limits applied to Bettis operations and directly affected alignment of tube and endcap and the quality of the weld joining the tube to the endcap.

9. Straightness

This requirement is tighter than commercial tolerances. See the table in Section III above.

10. Internal Free Path

The passing of a plug, which was slightly larger in diameter and longer than the largest pellet, through the full length of each tube as the final inspection operation provided assurance that the appropriate pellet could pass freely through the tube during loading operations. This is unique to Bettis tubing procurements, but was not restrictive in actual practice. This test is not mentioned in ASTM-B-353-1977 Ref. (c). See Section III above.

11. Visual Surface Inspection

While a defect-free tube was required, the implementation of specific process controls facilitated the production of tubes which easily met this requirement. At Bettis, the visual surface inspection included a white light borescopic inspection of the full I.D. surface of the tubes.

During destructive evaluation of test rods, sectioning of the tubing for visual examination of the internal surface revealed the presence of local depressions or pits on the inside tube surface. These defects were attributed to local material buildup on the mandrel during tube reduction. Because they were areas of reduced wall thickness and were too local to guarantee detection by ultrasonic inspection, the borescope inspection was incorporated into the process to detect such conditions visually. The entire inside surface was inspected to and detect indications of surface depressions. Depressions in excess of an established visual standard resulted in rejection of the tube.

The facility for borescope inspection of tubes consisted of a tube holder and borescope guide mechanism, a TV viewing screen for the inspector and an in-process tube storage table. During operation, the tube to be inspected was placed on the tube holder and the borescope, which views 360° of the tube inside surface, was aligned with the tube end. The scope was driven into the tube beyond the mid-length, while the operator observed the image on the TV screen. The combination of image reflection and motion enabled the operator to detect discontinuities on the surface of the tube wall. The borescope travel could be stopped for stationary observation of an indication using the TV screen or by direct viewing through the eyepiece of the borescope. There was also a provision to rotate the tube to allow circumferential indexing while viewing. After viewing one-half the tube length, the tube was reversed end-for-end on the stand and the process repeated for the remaining half.

12. Surface Finish

This requirement was not restrictive to normal manufacturing practice at WTD. The bright pickled smooth surface aided the visual inspection.

13. Material Quality

The use of immersed pulse-echo ultrasonic inspection to detect flaws in tubes is not new nor unique. However, the test required by Bettis interrogated the quality of the full volume of the tube wall in an overlapping search helix using a calibration/rejection standard that was approximately 10% of the standard used commercially. Close control of the manufacturing operations and machining of the SBT's reduced the losses due to this tight inspection to less than those experienced in normal commercial practice. This stringent inspection improved confidence in fuel rod integrity and reliability.

B. Destructive Testing

1. Chemistry

The maximum oxygen limit of Table A-2 shows an increase in oxygen content compared to Table A-1 in recognition of the slight increase in oxygen associated with the multiple heat treatments used in processing of Zircaloy-4 from ingot through the last heat treatment after the final tube reduction. The slight increase in oxygen results in a small increase in the unirradiated yield strength. The hafnium limit for tubing was raised from the 35 ppm limit for ingots to 45 ppm maximum to allow for analytical error. The Hf analysis was used as a materials control check to preclude the accidental substitution of a Zircaloy-4 ingot having a significantly higher (>45 ppm) hafnium content. The tube manufacturing operations can not alter the hafnium content of the tubing alloy.

2. Surface Chemistry

Fluorine on the inside surface of the tube can lead to accelerated cladding corrosion in a defected fuel element. The acceleration of corrosion is proportional to the amount of excess fluorine present. While fluorine bearing residue is inherent in the nitric-hydrofluoric pickling of zirconium alloys, good pickling and rinsing techniques can minimize the amount of fluorine residue. One tube was randomly selected from each lot and analyzed at Bettis at three locations (mid-length and near each end) for fluorine on the inside surface using the pyrohydrolytic technique. This is a process control inspection. The expected average fluorine content of the three analyses is in the range of 30 to 40 micrograms of fluorine per square decimeter with values above 65 microgram per sq. dm. indicating a potentially undesirable post-pickling rinsing technique. The acid pickle of the finished tubes is discussed in Section XI of Attachment A.

3. Corrosion Resistance

This test is commonly utilized in detection of material with poor overall corrosion resistance or containing local areas of poor corrosion resistance.

4. Longitudinal Uniaxial Tensile Properties

These properties have a direct bearing on fuel rod performance analysis. A requirement, which is not normally specified, is the minimum "Ultimate to 0.2% Offset Yield" strength ratio. The ultimate strength requirement, which is normally specified, was omitted. The use of the "U/Y Ratio" better defines the tensile properties of strength and ductility required in fuel rod performance. These requirements were not restrictive to the tube manufacturing operations and did not affect process yields. No tube lot was rejected for any sample failing a required physical test.

5. Circumferential Tensile Properties (Burst Test)

The test was not restrictive in actual practice. The application of a correction factor to allow for wall eccentricity in the test specimen produced test results well above the specified minimum limit.

6. Texture (Contractile Strain Ratio or CSR)

CSR is the ratio of the circumferential strain to radial (wall thickness) strain during plastic deformation of the tube under an axial load. This value is an index of the relative movement of metal during deformation and is another factor used in fuel rod performance analysis. Selection of reduction sequences and associated process controls resulted in a product which easily met this requirement stated as a statistical confidence limit. CSR is not discussed in ASTM-B-353-1977 (Ref. (c)). See Appendix C for details on the test as well as on the development effort which resulted in a reduction sequence which produced tubes meeting this requirement.

7. Hydride Orientation

Hydride orientation is a measure of crystallographic orientation since the zirconium hydride platelets precipitate near the basal plane of the hexagonal zirconium crystal lattice. This method of evaluating texture is in addition to the contractile strain ratio method.

8. Post-Anneal Cold Work

Introducing strain in RXA tubing can result in a change in material properties, such that RXA tubing behaves more like SRA tubing. Since RXA properties are desired for seed fuel rod cladding, post-annealing strains can affect fatigue life, creep resistance and other performance aspects of seed fuel rods. Control of the straightening operation following final heat treatment assured that induced strains were sufficiently low to have an insignificant effect on tube properties and on the seed fuel rod performance. This requirement had no effect on overall process yields.

9. Grain Size

The grain size limits bracket the normal grain size which is characteristic of the highly cold worked and recrystallize annealed Zircaloy materials.

10. Metallographic Inspection

The inspection of metallographic mounts for equiaxed grains and for material defects was not included in ASTM-B-353 (Ref. (c)). These inspections did not result in any reduction of process yields. Both sample inspections provided additional assurance of the overall quality of the tubes.

IV. PRIMARY MATERIAL CONVERSION

A. Purpose

The purpose of the primary material conversion operation was to convert the 17" diameter Zircaloy-4 ingot into 3.9 inch diameter machined-and-drilled billets (MDB's) in preparation for extrusion.

B. Process Description

Primary material conversion consisted of heating the 17 inch ingot to 1885°F, forging above 1200°F, reheating as needed to reduce the ingot to a 6.5 inch round, and, after beta-quenching from 1885°F, rolling to a 4 inch round by a multipass sequence in the range of 1000 to 1475°F. A machining and boring operation completed the conversion to MDB's. These operations are detailed below.

1. Ingot Inspection and Conditioning

Zircaloy-4 ingot*, certified to the chemistry of Table A-1 was visually inspected for contamination (dirt, grease, etc.) and surface defects, including laps, seams, porosity, sharp corners, and cracks. All such noted defects were removed by grinding.

2. Initial Breakdown

a. The ingot was heated to 1885 ± 25°F and maintained at temperature for fifteen minutes, minimum.

---

* The 17 inch diameter ingots were manufactured by consumable electrode, double arc melting, in vacuum.

b. Using hot worked die steel (AISI "H" series) flat 14" x 30" dies, the ingot was forged to a 8 ± 1 inch square and cut into three equal lengths.

c. Two of the three lengths were reheated to 1885 ± 25°F while the third length was forged to a 6-1/2 ± 1/4 inch round. The two remaining pieces were then similarly forged to rounds. Minimum working temperature was established at 1200°F, and total furnace time for the material was not to exceed five hours. All 6-1/2 inch rounds were air cooled to room temperature after forging.

3. Solution Treatment

a. The 6-1/2 inch rounds were heated to 1885 ± 25°F and maintained at temperature for twenty to thirty minutes.

b. The rounds were quenched in agitated water with the minimum temperature prior to quenching being maintained at 1850°F. The rounds were kept submerged in the water for a minimum of twenty minutes or until the stock was cool enough to be touched with the bare hand. Metallographic inspection was performed to verify a 100% transformed beta (basket weave) microstructure.

4. Round Conditioning

a. The quenched rounds were shot (steel) blasted to remove oxide and surface ground (alumina wheels or discs) to remove surface defects to prevent laps during subsequent working. Rounds with depressions in excess of 1 inch were rejected.

b. The rounds were then pickled in a 10 to 40% HNO_3, 2 to 4% HF, balance water solution to remove smeared metal from the grinding operation. A tap water rinse followed.

5. Finish Rolling

a. The 6-1/2 inch rounds were heated to 1450 ± 25°F and held at temperature for fifteen minutes minimum.

b. Using high carbon low alloy rolls, the rounds were rolled to required size (4-1/8 inch diameter) using a rolling sequence consistent with good rolling practice (vendor proprietary - approximately twenty passes).

c. If reheats were necessary on any rounds (between passes), the reheat temperature was 1475°F maximum for ten minutes minimum.

d. Minimum working (rolling) temperature was 1000°F.

e. Total furnace time was four hours maximum.

f. The rolled rounds were air-cooled to room temperature.

6. Cleaning Finished Material

a. Oxide was removed from the rolled rounds by steel shot blasting.

b. A clean surface finish was obtained by pickling in a 10 to 40% HNO_3, 2 to 4% HF, balance water solution followed by a tap water rinse (two minutes minimum).

7. Billet Machining and Drilling

a. The 4-1/8 inch rolled rounds were cut into 10 inch long pieces.

b. The O.D. of each billet was machined to 3.915 ± 0.005 inch concurrent with twist drilling of the I.D.

c. The billet I.D. for the seed and both blanket sizes of tubing were finished to 0.950 ± 0.003 inch. The I.D. for the reflector billets was 1.075 ± 0.003 inch.

d. One end face was given a radius of 3/8 to 1/2 inch at the I.D. edge to facilitate the initiation of the extrusion cycle.

e. Each individual finished billet was inspected and actual measurements were recorded for:

(1) Outside diameter
(2) Inside diameter
(3) Length
(4) Eccentricity (maximum TIR = 0.005")

f. A 1/4 inch thick slice was cut from one billet of each ingot and chemically analyzed for all elements certified in the ingot.

g. The MDB's were visually inspected for cracks, seams, slivers, blisters, burrs, and any other imperfections considered injurious. Rework was permitted (machining/boring) as limited by dimensional tolerances.

C. Process Controls

Specific in-process attribute checks were established which provided a controlled release of production.

1. Following the forging and quenching operations, but directly prior to the rolling reductions, a cross section of each round was polished, etched, and inspected metallographically. Any round which did not contain the beta-quenched structure throughout the cross section (one requench was permitted) was not released for further processing.

2. WTD was required to inspect and test all MDB's to specific product requirements (chemistry, dimensions, surface visual) and to submit certified results for approval prior to releasing the material for subsequent extrusion and tube reducing. In addition to the preceding product control release points, a process control system was established for the forging, quenching, and rolling operations by invoking detailed step-by-step manufacturing procedures. These procedures were established in the form of a specification supplement to the normal processing specification, which required careful control of all processing variables (e.g., temperature control via continuous monitoring, inspection and surface condition controls, etc.) throughout the manufacturing sequence and a permanent record of all such controls for greater assurance of product quality.

V. EXTRUSION (With Subsequent Machining)

A. Purpose

Extrusion was performed to convert the machined-and-drilled billets (MDB's) into tube hollows or extruded base tubes (EBT's) in preparation for subsequent tube reduction. The EBT's were cleaned, pickled, and conditioned to become starting base tubes (SBT's). The SBT's were machined to become machined starting base tubes (MSBT's) to improve the concentricity of the EBT's.

B. Process Description

The MDB's were clad in high purity copper on all surfaces to protect the billet from oxidation or absorption of gases during heating and extrusion and to serve as a lubricant during extrusion. The clad billets were heated in a batch-type, gas-fired muffle furnace for a minimum of two hours at 1200 ± 25°F and extruded in a 750 ton Lowey Horizontal Hydropress. The EBT was declad in a nitric acid bath and machined to final MSBT dimensions.

C. Process Control

1. Tolerances on the copper sleeves for the billet were commercial ASTM standard, while the copper end discs for the billet were 0.025 inch ± 0.010 inch thick.

2. Billet cleanliness was maintained by cleaning with acetone and wiping until no dirt was visible on a cloth. The mating surfaces of the copper sleeves and end discs were similarly cleaned prior to assembly.

3. Standardized tool (die and mandrel) design was used throughout extrusion to minimize product variability (Vendor Proprietary).

4. Extrusion temperature was established at less than 1450°F to preclude partial transformation of the alpha-phase Zircaloy-4 to the beta-phase. To ensure maintenance of the temperature of the billets, a contact pyrometer was used to check the first and last billet of each furnace charge. A minimum furnace time of two hours was established for all billets to assure a uniform temperature throughout the MDB cross section.

5. 60 seconds was established as the maximum time allowed between the removal of the billet from the furnace to extrusion. If that time limit was exceeded, the billet was reheated and checked with a contact pyrometer to assure correct temperature was achieved prior to extrusion.

6. During extrusion, operating personnel were required to inspect each extruded base tube for evidence of clad tearing (OD and ID) and for any abnormal conditions requiring corrective action. The die and mandrel were also inspected for metal pickup as another indication of surface quality of the extrusion.

7. On completion of each extrusion, all extrusion parameters (e.g., extrusion speed, extrusion load, lubricant, etc.) were recorded.

8. A billet code identity system was maintained to assure material segregation by billet and ingot number. During the copper cladding operation, the billet identity code was transferred from the billet to the copper end disc. Prior to extrusion, a furnace load diagram was prepared listing the position of each billet. During extrusion, the billets were removed from the furnace in a predetermined sequence. At the completion of each extrusion, the copper clad was ground away locally and the proper identity code number was vibra-tooled onto the exposed Zircaloy-4 surface.

9. Copper was removed from the EBT by pickling a maximum of 25 EBT's at a time in a non-agitated acid tank containing equal quantities of industrial grade 50 percent nitric acid and cold tap water. An eight-hour limit for clad removal was established, after which a fresh pickling batch was prepared. Rinsing for acid removal was performed in a cold water rinse tank for a minimum of fifteen minutes. The EBT's with copper removed were the starting base tube (SBT) for commercial practice.

10. As further preparation for the start of commercial tube reduction, a minimum of 1 inch was cropped from each end of the SBT to remove any tapered end effects. If the cropped end exceeded the 15 percent maximum wall eccentricity limit, the out-of-specification end of the SBT was trimmed back until the 15% limit was met. If the length of the SBT was reduced by more than 12 inches, special disposition of the SBT was required.

11. The starting material for the high quality reactor grade LWBR Ziricaloy-4 tubing was required to be free of all visible flaws and imperfections. It was necessary to condition and inspect all SBT for such defects as surface oxides, gouges, inclusion, and tears. Conditioning techniques included grit blasting, filing, and hand grinding as needed, followed by pickling.

12. The initial LWBR fuel rod design requirements for the finished tubing included a maximum wall eccentricity limit of 5 percent. However, the process capability for extrusion had an upper limit of approximately 15 percent maximum wall eccentricity. Since tube reducing uses a free-floating mandrel, the as-extruded eccentricity was most likely to continue into the finished tubing. Therefore machining of the SBT was added to normal commercial practice to improve wall uniformity. The machining had the additional benefit of removing both O.D. and I.D. surface imperfections from the SBT, thus providing additional assurance that surface flaws in the final product were minimized. A 2 percent maximum limit on wall eccentricity was established for the machined starting base tube (MSBT). The I.D. was also honed to improve the surface quality. The nominal O.D. was maintained at a tolerance of ± 0.005 inch, while the I.D. was maintained at ± 0.003 inch. To assure maximum O.D. clean-up and less than the 2 percent eccentricity limit on the point end, the O.D. tolerance for a distance of 3 inch maximum (from the point end) was relaxed to + 0.005, -0.015 inch. The MSBT surface

condition was maintained as smooth as commercially possible to effect a high quality finished tubing product. Maximum surface finish limits of 200 micro-inch AA on the O.D. and 32 micro-inch AA on the I.D. were established for all MSBT's. Prior to the machining operation, the material identity code was transferred from the O.D. surface to the face of the point end to maintain identity during surface machining. Subsequent evaluation of the effect of wall eccentricity on fuel rod performance permitted the use of tubes with wall eccentricities shown in Section A-4 of Table A-2, i.e., wall eccentricities up to 6.1% of nominal wall thickness.

VI. TUBE REDUCING

A. Purpose

Tube reduction was performed to convert the machined starting base tubes (MSBT's) to a near-finished tube size by means of a series of cold reduction operations.

B. Process Description

The tube reducer decreases the diameter and wall thickness of the incoming tube hollow by advancing the hollow over a tapered mandrel and into a set of rocking dies containing tapered grooves (see Figure A-1). With the die roll at the input (large) end of the mandrel, the tube is advanced over the mandrel into the die grooves. The dies are rolled over on the tube hollow and the tube is deformed into contact with the tapered mandrel. At the end of the forming stroke, the tube is rotated or indexed a predetermined amount (generally 50 to 75 degrees) and the die returns to its initial position. The return stroke "rounds off" the tube to control both ovality and diameter. The specific tube reducer parameters for LWBR tubing are listed in Table A-5. For each tube reduction, the change in cross-section area (i.e., percent cold work) is reflected in a corresponding increase in length. For example, a 10-foot long tube cold worked 60 percent produces a smaller tube 25 feet long.

See Table A-6 for the dimensions of the products of each size change from MDB to finished tubes. For maximum utilization of material, once the processing sequence is fixed, the cut lengths for each reduction are calculated, starting with the finished tube and working toward the first reduction. In each case, allowances are made for cropping and process control samples. The length of the uniform hot zone in the heat treatment furnace fixes the upper limit on any inprocess length.

C. Process Control

1. Control of the Wavelength of the Helical Wall Eccentricity

A set of tube reducer controls was developed for the purpose of maximizing the pitch of the spiral formed by the location of the thickest part of the tube cross section along the length of the tube. This pattern of helical wall eccentricity is an inherent result of the tube reducing operation. No previous Bettis tubing procurement effort had included a requirement to control the pitch or wavelength of the helical pattern of wall eccentricity. A correlation was observed in the LWBR irradiations test program between the helical wall eccentricity pattern and susceptibility to rod bowing. It is now recognized that helical wall eccentricity can contribute to fuel rod bowing. It was necessary to develop special manufacturing and inspection techniques to assure compliance with this requirement, which is not included in commercial tube specifications.

A development program was conducted prior to initiation of tubing manufacture, and the results of that program are presented in detail in Appendix B. Based on that development program, it was concluded that long helical wall wavelengths were achievable by a technique including control of the direction and magnitude of indexing during each tube reduction operation. Processing parameters were established for tubing manufacture (for long wavelength control). Production of LWBR tubing was initiated based on the tube reducing parameters identified in Table A-5. Using these parameters, long wavelengths were achieved in the final product. Overall yields for product with long wavelengths (i.e., a minimum of 80 inches) were approximately 92% for both the seed and power flattening blanket tubing and approximately 88% for the standard blanket tubing.

Several interesting aspects of wavelength control are discussed below.

a. Effect of Lubricant

During the manufacture of reflector tubing, production was initiated using Code A lubricant (Vendor Proprietary). Long wavelengths were being generated at an index rate of five strokes per revolution, but difficulty was encountered with I.D. pickup and poor I.D. surface conditions. A switch to an alternate lubricant, identified as Code B (again, Vendor Proprietary) provided better I.D. lubrication than lubricant A, and the I.D. surface was improved considerably. However, this improved lubrication apparently affected the interaction (i.e., frictional forces) between the mandrel and the tube I.D., resulting in a change in the amount of tube twist during tube reducing. To overcome this effect, it was necessary to revise the index rate from "5" to "7" or "9" to obtain a long wavelength in the last pass.

It was also noted that insufficient lubrication was another source of wavelength variation. Occasionally lubrication to the I.D. surface was "pinched off," either by misalignment of the the mandrel or by normal equipment perturbations, since the tube reducer operation can generate a high level of vibration. These conditions generally led to I.D. pickup, or galling of the tube I.D. surface, which in turn led to greater torsional deformation and shorter wavelengths.

Another illustration of the effect of friction on wavelength occurred during the first pass reduction of blanket tubes. In a series of experiments to establish wavelength control, the MSBT was reduced using an index of 7CW. The resulting 0.84 inch OD output tubes had wavelengths in excess of 100 inches (a twist angle of about one degree). However, two tubes in that series had wavelengths of 60 and 80 inches (twist angles of 1.9 and 2.5 degrees respectively). In both cases, ID galling and metal pickup on the mandrel were found. The increased friction between the tube and the mandrel had significantly increased the torsional deformation of the tube.

This interdependency of lubrication and wavelength control highlighted the necessity for close in-process surveillance to assure a high yield of final product meeting the long wavelength requirement. The degree of lubrication that is achieved during a long production run may vary, not only due to normal tooling wear, but also due to perturbations in equipment operation. Changes in the process such as a new equipment setup, the addition of new or different tooling, or a change in lubrication will affect wavelength control.

The chart in Figure A-2 illustrates the wavelengths of helical wall eccentricity in tube reduced tubes. The traces are obtained by measuring and recording the variations in wall thickness along the length of a non-rotating tube. The traces are taken at 90° increments around the tube to have multiple measures of wavelength and to determine the direction of helical twist (clockwise or counterclockwise). The wavelength of helical wall eccentricity is easily seen in the axial offset of the peaks of the traces on adjacent tracks.

b. Effect of Tube Reducer Rack And Pinion Ratio

A development effort identified the tube reducer parameters which would produce the desired long wavelength. A shorter wavelength was intentionally produced in the first pass for untwisting during the second pass. During the initial blanket production, the vendor was not successful in obtaining a good tube reducer setup for the second tube reduction pass using parameters based on the results of the development phase. Principal problems encountered were lack of dimensional control and poor surface quality. A revised equipment setup, which involved a change in the rack and pinion gear ratio to modify the rocking stroke of the tube reducer die carriage, resulted in a high quality product. The effect on the final wavelength was surprising. In development, a second pass indexing rate of 17 had effected too much untwisting of the first pass wavelength, resulting in a short wavelength in the opposite direction. With the change in the rack and pinion ratio, the index rate of 17 resulted in a retention of the short wavelength from the first pass, indicating that insufficient untwisting had occurred.

The untwisting was subsequently increased by going to a higher index angle (i.e., lower index number) and long wavelengths were achieved at an index rate of 5 or 7. All blanket production was fabricated using this index setting.

The above experience indicates that tube reducer setup can play an important role in determining the operational parameters necessary for long wavelengths. Each setup change should require a specific qualification run to assure a continuing system consistent with target wavelength goals.

2. Control of Tubing Texture

The LWBR tubing specification included a requirement for texture, in the form of contractile strain ratio (CSR) limits. This attribute was unfamiliar to the tubing vendor, and there were no known tubing manufacturing parameters readily available that could assure attainment of the required CSR limits. It was necessary, therefore, to establish a comprehensive development program aimed at determining the reduction sequence (i.e., number of passes) as well as the area reduction and wall reduction ratio (WRR or Q-ratio) of each pass consistent with the texture goals, while at the same time maintaining good tube reducing practice. Appendix C describes the texture development program, while Table A-5 lists the specific production parameters used for each reduction pass for LWBR Core tubes and Table A-6 shows the tube sizes associated with each reduction. These parameters were established based on the results from the development program.

The CSR requirements of 1.2 to 2.3 were met without manufacturing difficulty. The fabrication sequence selected met all of the LWBR tubing requirements including the defined CSR limits.

3. In-Process Surveillance

An in-process surveillance system was maintained throughout LWBR tubing manufacture to assure that high quality tubing, meeting all requirements for LWBR fuel rod cladding tubes, was produced. Table A-7 summarizes all surveillance requirements for both new machine setup conditions as well as for normal production operations.

VII. FINAL HEAT TREATMENT

A. Purpose

After the last tube reduction pass, the tubing was subjected to a final thermal treatment that established the microstructural and mechanical properties of the finished tubing and relieved residual stresses. The required properties for each tube type/size are listed in Table A-2.

B. Process Requirements

The following heat treatment requirements were established for LWBR tubing.

		Heat Treatment Description Minimum Conditions		
Tube Type	Type	Temperature (°F)	Time (Hours)	Atmosphere
Seed	RXA	1200	2	Vacuum
Blanket & Reflector	SRA	900	1	Vacuum

C. Process Control

1. Heat Treat Furnace and Furnace Load Qualification

Heat treatment following the last cold reduction pass played a significant role in determining the properties of the finished tube and, therefore, required careful control to assure that finished tubes met the mechanical and microstructural requirements.

Vacuum heat treatment of the LWBR tubing depended on radiant heat transfer and on contact conduction between tubes. Convection heat transfer is negligible in vacuum furnaces. Therefore, the central tubes in the furnace load reached the desired heat treatment temperature sometime later than the peripheral tubes. The larger the array of tubes being heat treated, the more the central tube temperature would lag behind the temperature of the tubes at the periphery of the array. Thus, control was exercised on the size of the furnace load to ensure that the most lagging central tube experienced the minimum heat treatment noted in Section VII.B, and to control furnace run times such that peripheral tubes did not receive excessive heat treatment.

Furnace load depth was initially calculated on the basis of a cylindrical array of tubes using a surface emissivity of 0.3 for bright etched tubing. Since the load in the heat treat furnace had more of a slab like shape (see Figure A-3) a dimensional conversion factor was used to predict slab-like performance from results of the heat transfer analysis for a cylindrical array. Depending on elapsed time, the calculated factor ranged from 0.82 at time zero to 0.68 for infinite time. 0.75 was used as the factor which approximates real time performance.

For the recrystallization anneal heat treatment, the calculated load size was set on the basis that the centermost tube would experience a minimum temperature of 1100°F for a minimum of two hours when the load was in a furnace held at 1225°F for four hours. Complete recrystallization may be expected in two hours at temperatures above 1050°F. The cylindrical array which met these assumptions was 6.6 inch in diameter. The use of 0.75

conversion factor (cylinder to slab) resulted in a load depth of 5.0 inch. This depth was exclusive of any shroud tubes in the basket of the heat treat furnace. The zirconium-alloy shroud tubes and the stainless steel basket were thoroughly oxidized, prior to their use in the heat treating of the Zircaloy-4 tubes for LWBR, thus maximizing their emissivity.

The stress relief heat treatment of blanket and reflector size tubing posed a similar problem. Data in Reference (d) showed that two hours at 850°F was sufficient to achieve about 57 percent recovery of residual stresses compared to a maximum recovery of 70 percent available from two hours at 950°F, with longer times at 950°F leading to recrystallization of the material. Assuming four hours in a nominal 925°F furnace temperature, a load 8.2 inch in diameter met the above criterion of at least 57 percent recovery. Use of the 0.75 factor yielded a calculated allowable load depth of 6.1 inch.

Furnace load depth modifications were made to provide a degree of conservatism during thermal treatment, i.e., reduce the load size (mass) per run and thus reduce the time between the outermost and innermost tube reaching the required minimum temperature. Recrystallization loads were reduced to a 4 inch maximum depth while stress relief loads were reduced to a 5-1/4 inch maximum depth.

These furnace load depths were confirmed experimentally during a series of temperature-monitored heat treatments (designated as furnace load qualification heat treatments) as presented in Appendix D. The results indicated that the established load limits of 4 inches and 5-1/4 inches for recrystallization heat treatments and stress relief heat treatments, respectively, were acceptable for final heat treatment.

The following heat treatment requirements were established for the control of the specific heat treating furnace used during the heat treatment of LWBR tubing.

Furnace Operating Requirements

Tubing Type	Designation	Temperature*	Time* hrs	Atmosphere
Seed	Recrystallized	1200-1250°F	5 to 6	Vacuum**
Blanket and Reflector	Stress-Relieved	900-950°F	5.5 to 6.5	Vacuum**

* The specified ranges for time and temperature are absolute and include all allowances for errors in measurement or in process control.

** At an absolute pressure not to exceed that represented by a column of mercury one micron (0.001 millimeter) high. Actual pressure levels during most of the furnace runs were below the limit of detection, well below the pressure limit.

Note that, for the recrystallization heat treatment, a 4 inch load depth resulted in the center tube reaching 1200°F in approximately three hours, while the outside tube reached 1200°F in 1.5 hours. Furnace time for the final recrystallization heat treatment was established at five to six hours to assure a minimum of two hours at temperature for the tube in the center of the load while the longest time at temperature would not exceed 4.5 hours. For the stress-relief heat treatment, a 5 inch load depth resulted in the outside tube reaching 900°F in one hour with the center tube reaching 900°F in approximately 4-1/2 hours. the stress relief heat treatment time was established at 5.5 to 6.5 hours, thereby assuring a minimum of one hour and a maximum of 5.5 hour at 900°F. In both heat treatments, the maximum times at temperature were well within the allowable heat teatments compatible with the desired physical properties.

It was also necessary to qualify the furnace used to heat treat LWBR tubing to assure that the desired temperature and vacuum limits could be maintained throughout the effective hot zone of the furnace. Using a load of tubes of the specified depth, axial temperature profiles were taken within the load of tubes at 950°F and at 1250°F. These results, also presented in Appendix D, indicated that the furnace was qualified to heat treat LWBR tubing at both temperatures by maintaining a 12°F range along the entire length of the effective hot zone versus a ± 25°F tolerance permitted around the nominal heat treatment temperature.

2. Process Control Requirements

a. The furnace axial profile study and the furnace load depth qualification study confirmed limits restricting the size, geometry, and packing density for both tubing final heat treatments. The temperature in each production final heat treatment furnace load was monitored by three thermocouples placed in the load to check the temperature at the ends and at the middle of the load. The three thermocouples were positioned as described below and as illustrated in Figure A-3.

Transverse Position*	Axial Position Within Load*
A, Top Layer, Outside Location East Side	4-6 inches from North End
B, Center of Load Cross Section	Axial Center
C, Bottom Layer, Outside Location West Side	4-6 inches from South End

*Cold zone is at the north end of the furnace. Thermocouple leads exit at the south end of the furance.

b. The furnace vacuum was continuously monitored during pump down and throughout the heat treatment cycle. The hot and cold zones were equipped with independent vacuum instruments which included a maximum pressure audio-alarm preset at an absolute pressure of 1 micron Hg. Normally the vacuum in the furnace was maintained at less than 0.03 micron Hg throughout the furnace run and cooling cycle. Regular blank-off checks were made to measure the apparent leak rate of the vacuum chamber.

c. Before and during loading of the tubes into the basket, tube surfaces were inspected for cleanliness and for evidence of moisture or staining.

d. All tubing was loaded centrally within the furnace basket and therefore within the furnace hot zone. Each tube was placed in the natural channel formed by the preceding level (no crossing of tubing was permitted) and the top layer was maintained level and parallel to the bottom tubes in the load. The load depth for each furance charge was measured and recorded.

e. As an additional protection against minor surface contamination from minor leaks or furnace outgassing, the load was covered with zirconium or titanium foil to getter any atmospheric contamination before it reached the tubes.

f. Final heat treatment furnace loads were limited to Bettis Zircaloy-4 tubing to eliminate the possibility of material mixing or potential contamination.

g. The time the load was kept in the cold zone while the vacuum retort was evacuated depended on pumping capacity and condition of the load. Typically, approximately thirty minutes elapsed before the load of tubes was moved into the hot zone of the furnace. Cooling time in the cold zone was established at four hours minimum. Air cooling was not permitted, but the use of high purity helium or argon for rapid cooling was permitted in case of pump failure, electrical failure, or sudden leaks during the heat treatment cycle. This emergency technique was never used during production of LWBR tubes.

h. After the load was removed from the furnace, visual inspection for discoloration was made with special attention given to the end nearest the thermocouple exits at the south end of the furnace. A straw or light blue color on the outside surface was acceptable. A light blue tinge was permitted only on the end trim portion of the inside surface. A blue tinge in the inside beyond the trim or any dark gray discoloration was unacceptable. The visual check for discoloration is very sensitive to low level atmospheric contamination. Physical tests detect only high levels of contamination. Corrosion tests and chemical tests also guard against detrimental levels of gaseous contamination. The thin light layer of contamination that is permitted is easily removed during normal pickling operations. The heavier oxides are easily removed if lightly abraded before pickling.

i. On the first and every fourth final heat treatment charge, one full-length (approximately 30 foot) sample was selected from Position B (see Figure A-3) for each ingot in the load. These samples were reserved for special (i.e., over-and-above normal) mechanical testing to assure that uniform annealing had been achieved.

VIII. INTERMEDIATE HEAT TREATMENT

A vacuum recrystallization anneal heat treatment was performed after each intermediate tube reduction operation (i.e., after both the first and second passes for seed and after the first pass for the blanket and reflector tubes). The tubes were placed in the hot zone of a vacuum annealing furnace, which was controlled at 1300 ± 25°F, for three to four hours. The purpose of the intermediate heat treatment was to "soften" the tube-reduced hollow (i.e., relieve stresses induced by cold working by recrystallizing the metal to form equiaxed grains in the tube micro-structure) in preparation for the next reduction operation. Monitoring thermocouples were not used in these heat treatments. Except for the higher set temperature and shorter time in the hot zone, these intermediate recrystallization anneals were performed with same process controls as described for the final recrystallization heat treatment.

IX. STRAIGHTENING

A. Purpose

After final heat treatment, all tubing items were straightened to meet the specified straightness requirements. This operation is necessary to correct any bowing and/or twisting that may occur due to the relief of stresses during the final heat treatment.

B. Procedure

Straightening of multiple length tubes was performed in a mechanical five roll offset straightener (see Figure A-4). All five rolls are driven and are offset to the longitudinal axis of the tube. These rolls grip the flexed tube and simultaneously rotate the tube and drive it axially through the straightener. The heat-treated tube enters the mill through the entrance guide, passes between the first pair of opposed rolls and is driven axially across the center offset roll and through the second set of drive and backup rolls, and finally through the exit guide. Straightness is primarily established by controlling the amount of offset of the center roll.

During the LWBR tube straightening operation, the parameters for roll offset tube straightening were set and controlled (on the basis of a stress analysis calculation) to minimize post-anneal cold work and potential fatigue damage. A machine setup capable of meeting the final tube straightness requirements was achieved, and close control of all straightener parameters was maintained during each production run.

C. Process Control

Only one pass through the straightener was permitted under the conditions listed below. The maximum permissible center roll offset (with respect to the two pinch rolls on the same side of the tube) and the required straightener size are given in the following table for each tube type:

Tube Type	Sutton Straightener	Maximum Offset (inches)
Seed	26" Mill	0.35
PFBlanket	26" Mill	0.29
Std Blanket	26" Mill	0.27
Reflector	60" Mill	0.80

To assure minimal effect of the pinch rolls on the tube, other than providing axial translation, the vertical distance between the contact points on the pinch roll and the backup roll was set at 1.1 times the outside diameter of the tube being straightened. The axis of the drive roll on both straighteners is set at 36 ± 3 degrees to the tube axis while the backup roll spacing is 11 ± 0.5 inch from the center roll on the 26 inch mill and set at 23.5 inch on the 60 inch mill. Pinch rolls were located axially at a greater distance from the center roll than the backup rolls. The greater the axial distance between the pinch roll and the backup roll, the smaller the pinch load required to drive the tube through the straightener. The pinch rolls are on the same side of the tube as the offset roll while the backup rolls are on the opposite side from the offset (central) roller.

Prior to straightening a tubing lot, qualification of each straightener setup was required by straightening five tubes from that lot and comparing the before and after dimensions (O.D., I.D., and ovality) as well as evaluating final tubing straightness. During the straightening operation, continual in-process checks of straightness were made, initially by rolling the tubes on a flat surface; if a deviation condition was suspected, additional straightness measurements were performed using a straightness gage. If an out-of-specification condition was confirmed, a new setup was made and another qualification was performed using a new set of heat-treated tubes.

All LWBR tubes were machine straightened using the 5 roll mill. Hand straightening was not permitted. To provide assurance that the induced cold work levels (from the straightening operation) for recrystallized annealed seed tubing did not exceed the established 3 percent maximum limit, a special PACW (post-anneal cold work) test was devised. This test was not applied to either blanket or reflector tubing which were stress relieved after the final cold reduction operation. The PACW test is discussed in Appendix E.

X. BELT POLISHING

A. Purpose

Following mechanical straightening, the O.D. of each tube was belt-polished to uniformly remove 0.0001 to 0.0002 inch from the tube surface. The two-stand belt polishing operation prepared the O.D. surface of the tube for the final bright pickling operation.

B. Procedure

Two Murray-Way planetary polishers were used. These polishers consisted of: (1) pinch rolls for feeding the tube through the polisher; (2) guide bushings to align the tube into and out of the polisher; and (3) a planetary polishing head. A rotating face plate in the polishing head supports two abrasive belts that abrade the surface as the tube is fed across the belts. Two adjustable air-actuated back-up rolls keep the tube in contact with the abrasive belts.

C. Process Control

Proper alignment was confirmed during setup by visual examination of the ground tube surface. If no spiral gooves or marks were observed, release was given for production processing. Primary control of the belt polishing operation was achieved by measuring the tube O.D., both before and after polishing.

XI. FINISH TUBE ACID PICKLE

A. Purpose

All tubes were pickled as the last processing operation to achieve final dimensional and surface finish requirements.

B. Procedure

Prior to final pickle, cleaning was performed using a proprietary water-soluble, fluoride-free, acid (approximately 4 pH) cleaner, followed by a cold water rinse. Two cleaning cycles were required; the first removed the bulk of the "dirt" and the second was a finish wash followed by a final rinse.

Final acid etch (bright pickling) was performed in an acid solution containing 60% by volume clean tap water, 38.2% by volume of industrial grade (70%) nitric acid, and 1.8% by volume of industrial grade (70%) hydrofluoric acid. Following pickling, the tubes were rinsed in free-flowing tap water and then air dried in a rack while in a near-vertical position. It should be noted that these tubes were detergent cleaned again at Bettis just prior to welding the initial endcap into the tube.

C. Process Control

The pickling rate for the acid bath was determined by selecting, at random, a minimum of three tube lengths and carefully measuring and recording the I.D., O.D., and wall at several locations. After immersion in the acid solution for a prescribed time, the selected tubes were remeasured to determine the rate of surface metal removal.

During final pickle of finished tubing lengths, a restriction of twenty tubes maximum was established for each pickling lot. Pickling was performed as a hand operation, and twenty tubes was the largest quantity that could be reasonably handled by the operator and still maintain a uniform bright pickling operation. All tubes were immersed in the acid bath at a 10°

to 30° angle from the horizontal to permit purging of air from the I.D. of the tube. As soon as all the air had escaped from the tubes, the tubes were laid flat on the bottom of the tank and rolled in a smooth constant motion from side-to-side for about fifteen seconds to allow uniform pickling over the entire tube surface. The tubes were then lifted out of the acid, flushed, and reimmersed in the acid at an angle to repurge with fresh acid. Total time in the acid was dependent on the pickling rate experienced by the last tube lot in the acid solution since the acid gets weaker as pickling continues, thus increasing the time needed to pickle the tube to final size.

After the pickling had been completed, the tubes were quickly raised above the tank at an approximate angle of 30 degrees to allow the acid to run out. As soon as, or just before the bulk of acid had drained from the tubes, the tubes were quickly submerged (at an angle of about 30 degrees) in the cold flowing rinse water so that the "drag over" acid was removed as quickly as possible.

For blanket and reflector tubing, a 10 second maximum elapsed time requirement was established from the time the tubes were completely out of the acid tank until they were completely submerged in the rinse tank. Once the tubes were purged with water, they were reflushed a total of three additional times by removing them (at an angle) from the rinse tank, and then resubmerged.

For seed tubing, the relatively small I.D. presented a particular problem in achieving a thorough rinse of the I.D. surface. A special forced flush fixture was devised and a 12 second maximum time limit was established for the transfer of the tubes from the acid tank into the rinse fixture. As the tubing bundle was submerged in the cold flowing water rinse tank, the end of the bundle was inserted into the collar of the forced flushing fixture and the I.D.'s of the tubes were flushed for a minimum of one minute.

The purpose of establishing a time limit for tube transfers out of the acid bath was to help prevent acid from drying on the tube I.D. surface.

All tubing, after initial rinsing described above, was laid flat on the tank bottom and rinsed for an additional thirty minutes minimum, in flowing cold water. Then the tubes were removed by hand and stood vertically (approximately 80 degrees from horizontal) at the drying rack. To keep the tubes clean and in particular to prevent acid fume staining, air exhaust systems were utilized in the drying area and in the nearby acid pickling facility.

Prior to transfer of the dried tubing to the final inspection area, an in-process inspection of the O.D. and I.D. surfaces was performed. When acid staining was observed, the tube was reconditioned either mechanically by silicon carbide grit blasting of the I.D. or chemically by re-pickling to remove additional metal from the O.D. and/or I.D. surface.

As an additional process control on the effectiveness of the post-pickling rinsing operation, the amount of fluorine residue on the I.D. surface of one tube per lot was analyzed for fluorine by the pyrohydrolytic technique using samples taken from each end and from the middle of the tube. The sample was heated in a muffle furnace to 500°C (932°F) and live steam was passed through the inside of the tube, where it effects a breakdown of the complex zirconium oxyfluoride deposited as a pickling residue. The fluorine is entrained in the steam which is then condensed and analyzed for its fluorine content. This technique removes all fluorine from the tube surface. An average residual fluorine deposit of approximately 35 to 40 micrograms per square decimeter is characteristic of good pickling practice.

The results of this overinspection, performed at Bettis are shown in Table A-9.

XII. MANUFACTURING YIELDS

The manufacturing yields listed in Table A-8 show that tubing for LWBR was manufactured with overall yields comparable to the 50 percent value used in estimating the weight of ingot needed to fulfill a commercial order for tubing. The tight LWBR requirements were offset by the innovative practices and good process control as discussed in the text of the report and in the preceding sections of Appendix A. Note that the processing yields (items D, E and F of Table A-8) decrease with tube size (and increasing manufacturing difficulty with the two blanket sizes experiencing nearly identical yields. The processing yields of Table A-8 which relate directly to the processing of LWBR tubes are repeated here for convenience.

	Seed	PFB	Std.B.	Refl.
a. Tube Reducing Operations	82.5%	91.3%	90.3%	97.0%
b. Final Processing and Inspection	75.0%	77.8%	78.1%	80.2%
c. MSBT To Accepted Tubes (a x b)	61.9%	71.0%	70.5%	77.8%

TABLE A-1

Ingot Requirements for LWBR Low Hafnium

Zircaloy-4 Tubing

I. Alloy Chemistry#

Element	Symbol	% Min.	% Max.
Tin	Sn	1.20	1.70
Iron	Fe	0.18	0.24
Chromium	Cr	0.07	0.13
Oxygen	O	0.09	0.15
Iron + Chromium	-	0.28	0.37
Zirconium	Zr	Remainder	

II. Group A Impurity Limits

Element	Symbol	ppm Max.	ASTM B-353-1977 ppm Max.+
Aluminum	Al	75	
Boron	B	0.5	
Cadmium	Cd	0.5	
Carbon	C	270	
Cobalt	Co	20	
Copper	Cu	50	
Hafnium	Hf	35	100
Hydrogen	H	25	
Magnesium	Mg	15	20
Manganese	Mn	50	
Nickel	Ni	70	
Niobium	Nb	100	
Nitrogen	N	60	80
Silicon	Si	110	200
Tantalum	Ta	200	
Titanium	Ti	40	50
Tungsten	W	80	100
Uranium	U	3	3.5
Uranium Isotope	U-235	0.025	

III. Group B Impurity Limits†

Element	Symbol	ppm Max.	ASTM B-353-1977 ppm Max.+
Chlorine	Cl*	15*	
Fluorine	F*	50*	
Gadolinium	Gd	5	
Lead	Pb	100	
Molybdenum	Mo	50	50
Phosphorus	P	50	
Samarium	Sm	10	
Thorium	Th	7	
Vanadium	V	50	
Zinc	Zn	100	

IV. Ingot Composition - Materials Source and Limits

Source	Limits
Sponge	50% min.
Solid Scrap	40% max.
Ingot Turnings	15% max.

V. Ingot Hardness - Brinell Hardness Number (BHN)

Test	10 mm ball, 3000 kg load
Limits	200 BHN max. individual 187 BHN max. average of 10 at room temperature

VI. Miscellaneous Tests

Ultrasonic Inspection
Surface Finish
Visual Inspection
Magnetic Inspection

---

* For information only.
\# Identical to ASTM B-353-1977 (Ref. (c)). except as noted.
† Only specified in ASTM B-353-1977 as noted.

TABLE A-2

REQUIREMENTS FOR LWBR TUBING

(See Tables 1 and 2 for Sampling Plans and Statistical Limits)

A. Nondestructive Inspections

1. Inside Diameter

a. Local

Type	Nominal*	Tolerance
Seed	0.262	± 0.0015
PFB	0.475	± 0.0020
Std. B.	0.516	± 0.0020
Refl.	0.748	± 0.0025

b. Average (All) Nominal ± 0.0010

2. Outside Diameter-Local

Type	Nominal*	Tolerance*
Seed	0.3105	± 0.0020
PFB	0.5310	± 0.0020
Std. B.	0.5760	± 0.0020
Refl.	0.8350	± 0.0025

3. Wall Thickness

Type	Nominal*	Minimum*
Seed	0.0243	0.0225
PFB	0.0280	0.0260
Std.B.	0.0300	0.0280
Refl.	0.0435	0.0413

4. Wall Eccentricity-Maximum*

	Limits Per Purchase Order					Final LWBR Limit#	
	Initial Lots		Remaining Lots		Target		% of Nominal
Type	No.	Limits	No.	Limit	Limit	Max	Wall Thickness
Seed	8	.0024	18	.0016	.0010	.0013	5.36
PFB	3	.0028	18	.0021	.0015	.0017	6.07
Std.B.	8	.0030	15	.0022	.0015	.0017	5.67
Refl.	All	.0035	-	-	.0022	.0022	5.06

*All dimensions are stated in inches.
#Limits achieved by additional inspection and/or sorting performed at Bettis.

TABLE A-2 (continued)

5. Wavelength of Helical Wall Eccentricity

Type	Minimum*
Seed	
PFB	80
Std. B.	
Refl.	70

6. Length

Type	Nominal*	Tolerance*
Seed	119	+0.5, -0.0
PFB	117	+0.5, -0.0
Std.B.	117	+0.5, -0.0
Refl.	110.5	+0.5, -0.0
At Bettis	Fuel Rod Nominal	±0.015

7. Perpendicularity of End Face (at Bettis only)

All The deviation from perpendicularity to the OD surface of the end two inches shall be limited to 0.006 in/in.

8. Edge Squareness (at Bettis only)

All The maximum deviation from square edges as chamfer or rounding of the ID or OD edge of the end face shall not reduce the local wall thickness at the end face by more than 0.003 inch.

9. Straightness

All 0.010 inch maximum deflection (bow) of the tube from the center of a 15 inch chord (gage length).

---

* All dimensions are stated in inches.

\# Limits achieved by additional inspection and/or sorting performed at Bettis.

TABLE A-2 (continued)

10. Internal Free Path

A right cylindrical plug (stainless steel) with an OD surface finish of 16 micro-inch AA or finer must pass freely through the full length of each finished tube as a last inspection prior to packing for shipment. The following plug sizes apply:

Tube Type	Seed*	PFB*	Std.B.*	Refl.*
Nominal Tube ID	0.262	0.475	0.516	0.748
Plug OD				
Min	0.2585	0.4710	0.5120	0.7435
Max	0.2590	0.4715	0.5125	0.7440
Length of Plug (excluding end taper, tolerance is ± 0.005)				
Nominal	1.048	1.900	2.064	2.999
Nominal Fuel Pellet O.D. (tolerance is ±0.0005)				
UO_2 in ThO_2	0.2520	0.4695	0.5105	0.7415
ThO_2 only	0.2555	0.4695	0.5105	0.7415
Nominal Fuel Pellet Length (Reference)				
UO_2 in ThO_2	0.615	0.870	0.875	NA
ThO_2 only	0.530	0.445	0.615	0.740

11. Visual Surface Inspection

The tubing OD and ID surfaces must be free of unacceptable surface conditions as determined by visual inspection. These unacceptable conditions include, but are not limited to, scratches, abrasions, nicks, dents, pits, holes, foreign material, and material defects (cracks, laps, seams, lamination, etc.).

12. Surface Finish

CONDITION: BRIGHT PICKLED
MAXIMUM SURFACE ROUGHNESS (MICROINCH A.A)

Tube Type	O.D.	I.D.
Seed		
Power Flattening Blanket	32	32
Standard Blanket		
Reflector	32	125

*All dimensions are stated in inches.

TABLE A-2 (continued)

13. Material Quality

The tubing must be free of material and fabrication defects which exhibit a stronger response to the ultrasonic search beam than 80% of the response exhibited by the standard notches contained in the test calibration tube. The dimensions of the standard notch are shown below. Test sensitivity notches, half the depth of the standard notches must be reproducibly detected. All dimensions are in inches.

Tube Type	Nom.Wall	Standard Defect Notch (Max) Depth	Length	Width
Seed	0.0242	0.0020	0.0200	0.003
PF Blanket	0.0280	0.0021	0.0210	0.003
Standard Blanket	0.0300	0.0022	0.0225	0.003
Reflector	0.0435	0.0032	0.0326	0.003

B. Destructive Testing

1. Chemistry

Compliance with the requirement for ingot composition (Table A-1) satisfies the basic chemistry requirements of the finished tubing. Samples from each lot of finished tubing must meet the limits noted for the five elements listed below.

Elements	ppm Max.	ppm Min.
Hydrogen	25	0
Nitrogen	80	0
Oxygen		
Individual Analysis	1800	900
Average from one ingot**		
Seed	1700	900
Blanket & Reflector	1600	900
Nickel	70	0
Hafnium	45	0

2. Surface Chemistry

Fluorine on ID surface in micrograms per square decimeter

Target 30 to 40
Alert 65

**Average of all finish tubing analyses from one ingot.

TABLE A-2 (continued)

3. Corrosion Resistance

Test Condition	Max. Weight Gain
a. 14 days in 750°F steam at 1500 psig	38 mg/dm^2
b. 14 days in 680°F water at 2705 psig	28 mg/dm^2 (preproduction only)

The corrosion tested tubing must exhibit a continuous lustrous, black, adherent, corrosion film consistent with established visual standards.

4. Longitudinal Uniaxial Tensile Properties

Tube Type	(U/Y Ratio) (Min)[a]	0.2% Offset Yield Strength (psi) Min.	Max.	% Total Elongation (b)
a. Room Temperature				
Seed	1.20	35,000	-	20.0
PF Blanket Standard Blanket Reflector	1.15	55,570	-	8.1
b. 700°F				
Seed	1.5	15,500	30,000	20.0
PF Blanket Standard Blanket Reflector	1.15	43,500	69,500	8.1

5. Circumferential Tensile Properties (Burst Test)

Tube Type	Minimum % Ductility at 700°F[c]
Seed	20
PF Blanket Standard Blanket Reflector	5

(a) Ratio of Ultimate Tensile Strength to 0.2% Offset Yield Strength
(b) Minimum in 2 inch gage length
(c) Percent increase in circumference of metallic portion of the bulge measured from fracture edge to fracture edge around the maximum circumference of the ruptured specimen.

TABLE A-2 (continued)

6. Texture (Contractile Strain Ratio or CSR)

Tube Type	Limits Min.	Max.
Seed PF Blanket Std.Blanket	1.2	2.0
Reflector	1.2	2.3

7. Hydride Orientation

The orientation of the zirconium hydride platelets (needles) in the finished tubing must be such that no more than the specified percent of the classifiable hydride needles are aligned within 30° of the radial direction (i.e., parallel to the tube radius).

	Max. Individual Wall Segment Reading O.D., Middle, or I.D. Third of Wall Thickness	Max. Avg. of Three Segments For Each Sample
Seed	50%	45%
Blanket & Reflector	30%	Not Applicable

8. Post-Anneal Cold Work

Seed (RXA)	3.0% Maximum
Blanket & Reflector (SRA)	Not Applicable

9. Grain Size

Seed	ASTM 9-12.5 (in the finished tubing)
Blanket & Reflector	ASTM 8-12.0 (at completion of the alpha recrystallization anneal prior to the last reduction)

10. Metallographic Inspection for Equiaxed Grains

Seed (RXA)	No distorted or non-equiaxed (non-recrystallized) grains permitted.
Blanket & Reflector (SRA)	There must be no evidence of recrystallization; i.e., there must be no equiaxed grains.

TABLE A-2 (continued)

11. Metallographic Defects

All Tube Types	All metallographic inspections for hydride orientation, post anneal cold work, grain size, and equiaxed grains shall include an inspection for the presence of any defects exceeding 0.0040 inch in any dimension. Defects in excess of 0.0040 inch are not permitted.

C. Cold Work in Final Reduction

The amount of cold work (CW)(*),or the reduction in cross-section area, in the last tube reduction shall be within the following ranges for the specified final heat treatment.

Tube Type	Final Reduction	Final Heat Treatment (d)
Seed	50 to 70%	RXA
PFB Std.B. Refl.	60 to 80%	SRA

D. Final Heat Treatment

All tubes shall have a final heat treatment within the specified limits for the tube type. The size and placement of the load within the furnace, the mass in the furance, and the furnace operating characteristics must be balanced such that the inntermost (slowest heating) tube in the load receives the minimum heat treatment while the outermost (fastest heating) tube does not receive an excessive heat treatment. The prescribed heat treatment parameters for all LWBR tubes are shown in the following table.

Final Heat Treatment(d)	Tube Type	Temperature (°F)		Hours Above Min. Temp.	
		Min.	Max.	Min.	Max.
RXA	Seed	1200	1250	2	4.5
SRA	PF Blanket Standard Blanket Reflector	900	950	1	5.5

(*) The calculation is

$$\% \ CW = \frac{A-a}{A} \times 100$$ where:

A = cross-section area before reduction
a = cross-section area after reduction

(d) RXA is recrystallization anneal and SRA is stress relief anneal.

TABLE A-3

LWBR ZIRCALOY-4 TUBING DIMENSIONS
CONDITIONS AND QUANTITIES

Tube Type	Tube Size (inches)[a] O.D.	I.D.	Length	Heat Treat Condition[b]	Number of Tubes Delivered (pcs)
Seed	0.3105	0.262	117	RXA	13,213
PF Blanket	0.531	0.475	119	SRA	6,457
Std.Blanket	0.576	0.516	119	SRA	6,768
Reflector	0.835	0.748	110.5	SRA	3,859

Fuel Rod Type	Nominal Finished O.D.	Tube Size In Fuel Rod (c) I.D.	Wall	No. of Rod Types	No. of Rods in LWBR
Seed	0.306	0.262	0.022	8	7,428
PF Blanket	0.527	0.475	0.026	7	3,585
Std. Blanket	0.572	0.516	0.028	6	3,234
Reflector	0.832	0.748	0.042	2	3,048

(a) Detailed requriements for the tubes, as purchased, are stated in Table A-2.

(b) RXA = Recrystallize annealed.
SRA = Stress relief annealed.
See Table A-2 Item D for details

(c) The final tube length varied with fuel rod type (and fuel loading arrangement) in the 23 different types of fuel rods used to assemble the LWBR Core.

TABLE A-4

CONVERSION OF INGOT TO TUBING

Operation	Product*	Heat Treatment: Minutes at Temperature Min	Minutes at Temperature Max	Product Temperature Min	Product Temperature Max
	17 inch diam. ingot				
1. Surface Condition					
2. Heat Treatment		15		1860	1910
3. Forge, Cut to Length				1200	1910
	8 inch square				
4. Heat Treatment		15		1860	1910
5. Forge				1200	1910
	6-1/2 inch round				
6. Heat Treatment		20	30	1860	1910
7. Beta Quench				RT	1910
8. Surface Condition					
9. Heat Treatment		15		1425	1475
10. Roll (approx. 24 passes)				1000	1475
11. Heat Treatment as needed		10			1475
12. Finish Rolling as needed				1000	1475
	4-1/8 inch round				
13. Cut to Length Machine OD and Drill ID					
	3.9 in. OD MDB				
14. Clad in Copper					
15. Heat Treatment		60		1200	1250
16. Extrude				1150	
17. Declad in Nitric Acid					
	EBT				
18. Surface Condition					
	SBT				
19. Machine OD & ID Concentric	(a)				
	MSBT				
20. Tube Reduce	(b)				
21. Clean & Pickle					
22. Heat Treatment		60	150	1275	1325
23. Cut to Length					
	I.P.				
24. Tube Reduce	(b)(c)				
25. Clean and Pickle					
26. Heat Treatment		60	150	1275	1325
27. Cut to Length					
	I.P.				
28. Final Tube Reduce	(b)				
29. Clean and Pickle					

TABLE A-3

LWBR ZIRCALOY-4 TUBING DIMENSIONS
CONDITIONS AND QUANTITIES

Tube Type	Tube Size (inches)[a] O.D.	I.D.	Length	Heat Treat Condition[b]	Number of Tubes Delivered (pcs)
Seed	0.3105	0.262	117	RXA	13,213
PF Blanket	0.531	0.475	119	SRA	6,457
Std.Blanket	0.576	0.516	119	SRA	6,768
Reflector	0.835	0.748	110.5	SRA	3,859

Fuel Rod Type	Nominal Finished O.D.	Tube Size In Fuel Rod (c) I.D.	Wall	No. of Rod Types	No. of Rods in LWBR
Seed	0.306	0.262	0.022	8	7,428
PF Blanket	0.527	0.475	0.026	7	3,585
Std. Blanket	0.572	0.516	0.028	6	3,234
Reflector	0.832	0.748	0.042	2	3,048

(a) Detailed requriements for the tubes, as purchased, are stated in Table A-2.

(b) RXA = Recrystallize annealed.
SRA = Stress relief annealed.
See Table A-2 Item D for details

(c) The final tube length varied with fuel rod type (and fuel loading arrangement) in the 23 different types of fuel rods used to assemble the LWBR Core.

TABLE A-4

CONVERSION OF INGOT TO TUBING

Operation	Product*	Heat Treatment: Minutes at Temperature Min	Heat Treatment: Minutes at Temperature Max	Heat Treatment: Product Temperature Min	Heat Treatment: Product Temperature Max
	17 inch diam. ingot				
1. Surface Condition					
2. Heat Treatment		15		1860	1910
3. Forge, Cut to Length				1200	1910
	8 inch square				
4. Heat Treatment		15		1860	1910
5. Forge				1200	1910
	6-1/2 inch round				
6. Heat Treatment		20	30	1860	1910
7. Beta Quench				RT	1910
8. Surface Condition					
9. Heat Treatment		15		1425	1475
10. Roll (approx. 24 passes)				1000	1475
11. Heat Treatment as needed		10			1475
12. Finish Rolling as needed				1000	1475
	4-1/8 inch round				
13. Cut to Length Machine OD and Drill ID					
	3.9 in. OD MDB				
14. Clad in Copper					
15. Heat Treatment		60		1200	1250
16. Extrude				1150	
17. Declad in Nitric Acid					
	EBT				
18. Surface Condition					
	SBT				
19. Machine OD & ID Concentric	(a)				
	MSBT				
20. Tube Reduce	(b)				
21. Clean & Pickle					
22. Heat Treatment		60	150	1275	1325
23. Cut to Length					
	I.P.				
24. Tube Reduce	(b)(c)				
25. Clean and Pickle					
26. Heat Treatment		60	150	1275	1325
27. Cut to Length					
	I.P.				
28. Final Tube Reduce	(b)				
29. Clean and Pickle					

TABLE A-4 (continued)

Operation	Product*		Heat Treatment Hours at Temperature Min	Max	Product Temperature Min	Max
30. Final Heat Treatment	(d)	RXA	2	4.5	1200	1250
		SRA	1	5.5	900	950
31. Straighten	(e)					
32. Belt Polish OD						
33. Cut to Length						
34. Bright Pickle to Size						
	Finished Tubing					
35. Final Inspection	(f)					

*See Table A-6 for the size of these items for each tube type.

MDB = Machined drilled billet
EBT = Extruded base tube
SBT = Starting base tube
MSBT = Machined starting base tube
IP = Intermediate product

(a) Machining for concentricity was a Bettis innovation specified to reduce wall eccentricity in the final product.

(b) Specific controls were developed to assure that the finished tubing had the correct texture and acceptable wavelength of wall eccentricity.

(c) Omit operations 24 thru 27 from the PFB, Std. B. and Reflector tube fabrication sequences which are produced with a two tube reduction operations.

(d) The heat treatment parameters were developed via calculations supported by experimentation to assure that all tubes in the load had a satisfactory heat treatment.

(e) Limits were developed to minimize residual stress in the finished tube to minimize the reduction in fatigue life.

(f) This included: a rigorous ultrasonic inspection for materials defects; measurements for CSR; physical and metallographic testing; dimensional inspection; and visual inspection.

TABLE A-5

LWBR TUBE REDUCING PARAMETERS

Seed Tube Reductions (TR)

	1st TR	2nd TR	3rd TR
Tube Reducer	#23	#26	#24
Feed Rate (Strokes/In.)	20 ± 5	20 ± 5	33 ± 3
Index (Steps/360°)*	5 or 7	5 to17	7 to 17
Rotation	Clockwise	Clockwise	Counterclockwise
Gripping	Input or Output	Input or Output	Input or Output
Finished O.D. (inches)	.750	.500	.311
Finished Wall(inches)	.100	.050	.025
Nominal % Reduction	76.8	65.4	67.8
Nominal WRR	1.32	1.50	1.31

Power Flattening Blanket Tube Reductions

	1st TR	2nd TR
Tube Reducer	#25	#28
Feed Rate (Strokes/In.)	20 ± 5	25 ± 2
Index (Steps/360°)*	5 or 7	5 to 17
Rotation	Clockwise	Counterclockwise
Gripping	Input or Output	Input or Output
Finished O.D. (inches)	.840	.532
Finished Wall (inches)	.065	.029
Nominal % Reduction	82.0	70.8
Nominal WRR	1.90	1.50

Standard Blanket Tube Reductions

	1st TR	2nd TR
Tube Reducer	#25	#27
Feed Rate (Strokes/In.)	20 ± 5	25 ± 2
Index (Steps/360°)*	5 or 7	5 to 17
Rotation	Clockwise	Counterclockwise
Gripping	Input or Output	Input or Output
Finished O.D. (inches)	.840	.577
Finished Wall (inches)	.065	.031
Nominal % Reduction	82.0	66.2
Nominal WRR	1.90	1.66

* See next page.

TABLE A-5 (continued)

Reflector Tube Reductions

	1st TR	2nd TR
Tube Reducer	#23	#22
Feed Rate (Strokes/In.)	14 ± 5	28 ± 5
Index (Steps/360°)*	5 or 7	7 or 9
Rotation	Clockwise	Counterclockwise
Gripping	Input or Output	Input or Output
Finished O.D. (inches)	1.125	.836
Finished Wall (inches)	.115	.0445
Nominal % Reduction	69.5	69.7
Nominal WRR	1.99	2.39

Definition of Terms

Tube Reducer	Refers to the specific tube reducing machine used.
Feed Rate	Number of tube reducer strokes or rocks per inch of input material.
Index	Number of tube rotations or steps per 360° (e.g., an index of 5 equals a tube rotation of 360°/5 or 72°).
Rotation	Index direction of tube hollow when facing the output end.
Gripping	Identifies the end of the tube that is held while the tube is rotated and advanced through the tube reducer (see Figure A-1)
Input Gripping	Tube movement is controlled by the crosshead on the input side of tube reducer.
Output Gripping	Tube movement is controlled by the indexer on the output side of the tube reducer.
% Reduction	% Reduction in cross section area = % cold work
WRR	Wall reduction ratio = % change in wall thickness divided by the % change in outside diameter in each reduction.

* Nominal for each lot was established during tube reduction with a tolerance of ± 1/2. Nominal is stated as an odd number only.

TABLE A-6

NOMINAL SIZES* AT EACH TUBE MANUFACTURING STEP

Tube Type	Seed			Power Flattening Blanket			Standard Blanket			Reflector		
	OD	ID	TR	OD	ID	TR	OD	ID	TR	OD	ID	TR
MDB*	3.915	0.950		3.915	0.950		3.915	0.950		3.915	1.075	
MSBT*	1.375	0.875		1.375	0.875		1.375	0.875		1.625	1.030	
1st TR**												
% CW			76.8			82.0			82.0			69.5
WRR			1.32			1.90			1.90			1.99
	0.750	0.550		0.840	0.710		0.840	0.710		1.125	0.895	
2nd TR**												
% CW			65.4			70.8			66.2			69.7
WRR			1.50			1.50			1.66			2.37
	0.500	0.400		0.532	0.474		0.577	0.515		0.836	0.747	
3rd TR**												
% CW			67.8			N/A			N/A			N/A
WRR			1.31									
	0.312	0.261										
Final Size*	0.310	0.262		0.531	0.475		0.576	0.516		0.835	0.748	

* All dimensions in inches, MDB = Machined and drilled billet, MSBT = Machined starting base tube

TR = Tube Reduction

** % CW = % cold work = % change in cross section area

WRR = wall reductions ratio = % change in wall thickness ÷ % change in outside diameter

N/A = Not applicable, only two tube reductions were used.

TABLE A-7

LWBR TUBE REDUCING: PROCESS CONTROL

A. Process Control Following a New Setup

A new setup is defined as anytime a die was either replaced or removed and subsequently remounted on the tube reducer.

1. On the first 6 inches of output tube, the tube dimensions (O.D., I.D., and wall) were measured and recorded.

2. If dimensions were acceptable, the following tube reducer parameters were recorded:

   a. Actual feed rate
   b. Actual index rate
   c. Direction of rotation
   d. Mandrel position (coded).

3. A 6-inch length sample of output tube was cleaned and sectioned longitudinally. The outside and inside surfaces were inspected for surface defects and then both 6-inch halves were flattened on an arbor press and visually inspected for cracks. If unacceptable, the flattened halves were acid etched, rinsed, wiped dry, and reinspected. If still unacceptable, corrective action (tube reducer adjustment) was taken and the preceding inspection operations were repeated.

4. Samples for wavelength of the helical wall eccentricity were required for the entire output length of the first two input tubes following each tool setup and from the output point and tail of one input tube midway through the remainder of the shift in which setup samples were taken. The sampling for wavelength applied to the following tube reducer passes:

TABLE A-7 (continued)

Seed Tubing	Second and third passes
Blanket Tubing (both)	First and second passes
Reflector Tubing	Second pass

5. A 4-inch minimum length sample for I.D. roughness and visual surface inspection was taken from the first two output tubes.

B. Process Control During Normal Machine Operation

A normal machine operation is defined as a production run of tube reducing that did not require new machine setups.

1. Dimensional Control

a. Wall

The minimum and maximum wall of the point and tail ends of one output length was measured and recorded to the nearest .0001" at the beginning of the shift and at least two additional times, equally spaced during each eight-hour shift.

b. Length

On all intermediate pass material, the tube hollow length or weight was recorded. On all finish pass material, the length of each piece was recorded.

c. O.D.

The first output tube on each shift and a minimum of two additional tubes, equally spaced during the shift, were checked for minimum and maximum O.D. at 18 inches from both ends and at mid-length and recorded to the nearest 0.0001".

TABLE A-7 (continued)

d. I.D.

After the final tube reduction pass, one finished tube length was cut from the tail end of every third input tube length and the ID was measured using an air gage. Out of specification I.D. size required adjustments of the tube reducer settings by the tube reducer operator.

2. Wavelength of Helical Wall Eccentricity

a. Four track helical wall wavelength traces were required for tube samples selected from the product of the following tube reduction passes:

Seed Tubing	Second and Third Passes
Blanket Tubing	First and Second Passes
Reflector Tubing	Second Pass

b. Samples for wavelength inspection were taken at the following times: (each sample was vibratooled with an identify code by the operator).

(1) The entire output length of the first two input tubes following a change to a different lubricant.

(2) The point and tail section from the output of one input tube midway through the remainder of the shift in which the change-of-lubricant samples were taken.

(3) The point and tail section from the output of one input tube at the middle of each shift of tube reducing.

TABLE A-7 (continued)

3. Surface Quality

a. The outside surface of the tube being produced was continuously checked by the tube reducer operator.

b. The inside surface following each intermediate pass was inspected by cutting a 2-inch piece from the point or tail of the product of at least every second seed and blanket input tube, then cleaning and visually examining the inside surface.

c. On the finish pass, the I.D. roughness samples (discussed in the following section) were also examined, O.D and I.D., for surface defect indications such as pits, pick-up, scuffing, side relief marking, etc.

4. I.D. Roughness

A 4-inch minimum length sample was taken for I.D. roughness measurement from the point end of output tubes at the following times:

a. The first two input tubes of each lot.
b. The first two input tubes after a mandrel change.
c. The first two input tubes after changing lubricants.
d. Every other input tube if initial samples (a through c) were satisfactory.
e. When the I.D. roughness of any tube sample was higher than 32 microinch (AA), a sample was taken from the prior output tube and a sample was taken from each subsequent input tube until the samples from two successive input tubes were acceptable.

TABLE A-7 (continued)

5. Tooling Inspection

   a. The mandrel position was measured and recorded at the beginning and middle of each shift.

   b. Whenever a mandrel problem was suspected, visual and dimensional inspections of the mandrel were performed.

   c. At the beginning of each shift, and whenever die problems were suspected, the die groove was inspected for visual defects. All inspection results were recorded.

6. Machine Operation

   a. When dimensional control problems were encountered, or a deterioration in tube integrity was suspected, the tube reducer setup was rechecked.

   b. During all tube reductions, the following information was measured and recorded:

      (1) Index rate at the cross-head clamps at least once for each input tube.

      (2) Feed rate and the direction of tube rotation at the feed clamps at the beginning of the shift and at intervals not to exceed two hours.

7. Identification

A tube identity code was vibratooled on the tail end of each output length and on all cut samples.

TABLE A-8
TUBE FABRICATION PROCESS YIELDS

Processing Steps	Tube Type			
	Seed	PFB	Std.Blkt.	Refl.
A. Ingot to 4-1/8" Diameter Round[a]	95%	95%	95%	96%
B. 4-1/8" Round to MDB (3.915" O.D.)[a]	80%	80%	80%	78%
C. MDB through Extrusion to MSBT[a][d]	98%	98%	98%	98%
D. MSBT through Final Reduction[b]	82.5%	91.3%	90.3%	97.0%
E. Final Processing & Inspection[c]	75.0%	77.8%	78.1%	80.2%
F. Processing at WTD, MSBT to Final Acceptance (D x E)	61.9%	71.0%	70.5%	77.8%
G. Overall Yield, - Ingot to Accepted Tube (A x B x C x D x E)	46.1%	52.9%	52.5%	56.5%

(a) Normal machining losses, based on weight losses at each operation, produced a combined yield of 74.5% (72.6% for reflector due to the larger I.D. of the MDB). (A x B x C)

(b) A piece count evaluation based on the maximum number of tubes that could be produced from the number of MSBT's used.

(c) A piece count evaluation based on the number of tubes produced and the number of tubes accepted.

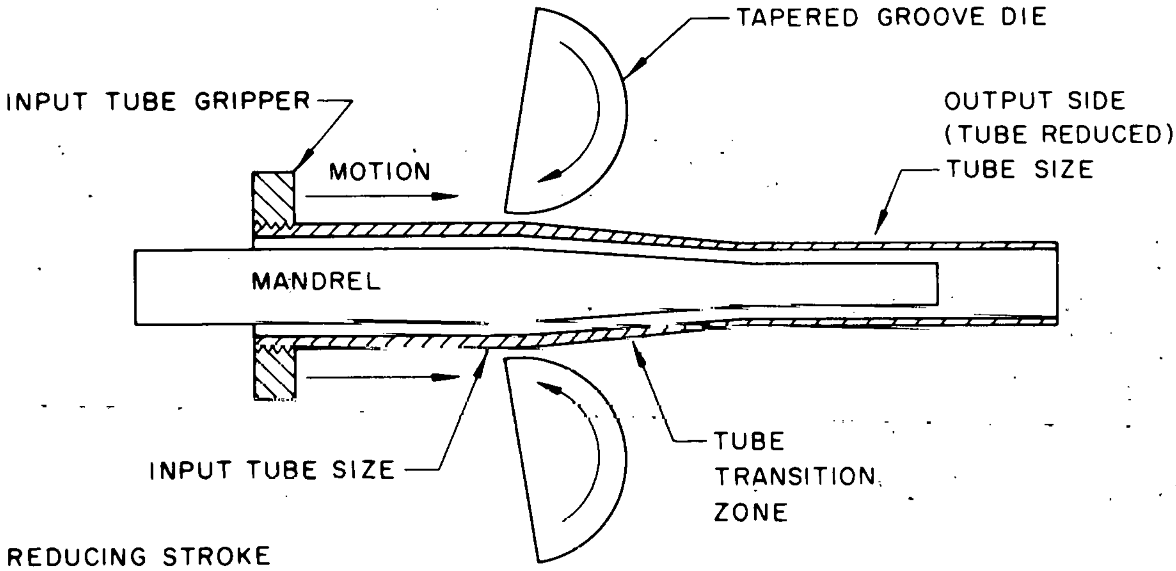
(d) Most of this loss was unique to the LWBR operation since the machining of the starting base tube for concentricity was not normal commercial practice prior to 1973.

TABLE A-9

SURFACE CHEMISTRY-FLUORINE ON INSIDE SURFACE OF PICKLED TUBES
(MICROGRAM PER SQ. DECIMETER)

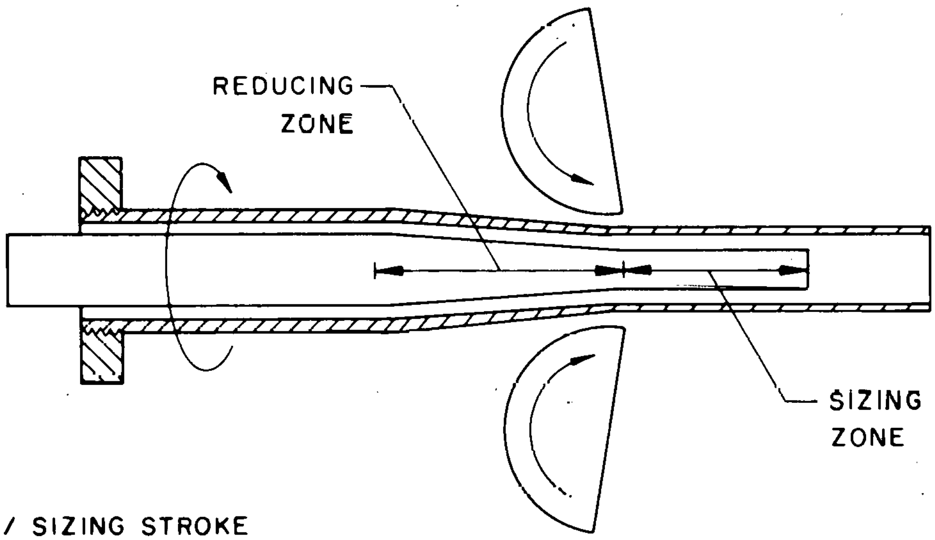
	Tube Location			Tube	All	One-Sided 95/95 Confidence
	Point	Middle	Tail	Average	Data	Limit
Seed						
Average	38.30	42.38	38.44	39.71	39.71	
Std.Deviation	12.11	9.31	13.48	6.72	11.79	
No.of Anal.	26	26	26	26	78	
Minimum	16	27	11	23.3	11	
Maximum	63	66	62	49.3	66	62.9
P.F.Blkt.						
Average	34.14	35.57	34.43	34.71	34.71	
Std.Deviation	6.34	7.99	9.20	6.70	7.83	
No.of Anal.	21	21	21	21	63	
Minimum	24	22	24	26.7	22	
Maximum	50	58	54	54.0	58	50.5
Std.Blkt.						
Average	29.46	36.04	34.42	33.31	33.31	
Std.Devidation	6.37	7.36	8.17	5.88	7.76	
No.of Anal.	24	24	24	24	72	
Minimun	18	18	19	19.7	18	
Maximum	46	51	49	44.7	51	48.7
Reflector						
Average	37.83	37.56	41.28	38.89	38.89	
Std.Deviation	11.81	7.73	12.01	9.08	10.64	
No. of Anal.	18	18	18	18	54	
Minimum	12	14	12	12.7	12	
Maximum	63	46	58	50.0	63	60.9
Prior Experiments Using 0.216 Inch I.D. x 0.253 inch O.D. Tubing						
Average					42.83	
Std.Deviation					16.72	
No. of Anal.					26	
Minimum					19	
Maximum					76	80.9

0116-79A/0082L



REDUCING STROKE

1. TUBE GRIPPER AXIALLY ADVANCES THE TUBE HOLLOW (NO ROTATION)
2. THE DIES ARE ROCKED IN OUTPUT DIRECTION OVER THE TAPERED MANDREL, REDUCING DIAMETER AND WALL

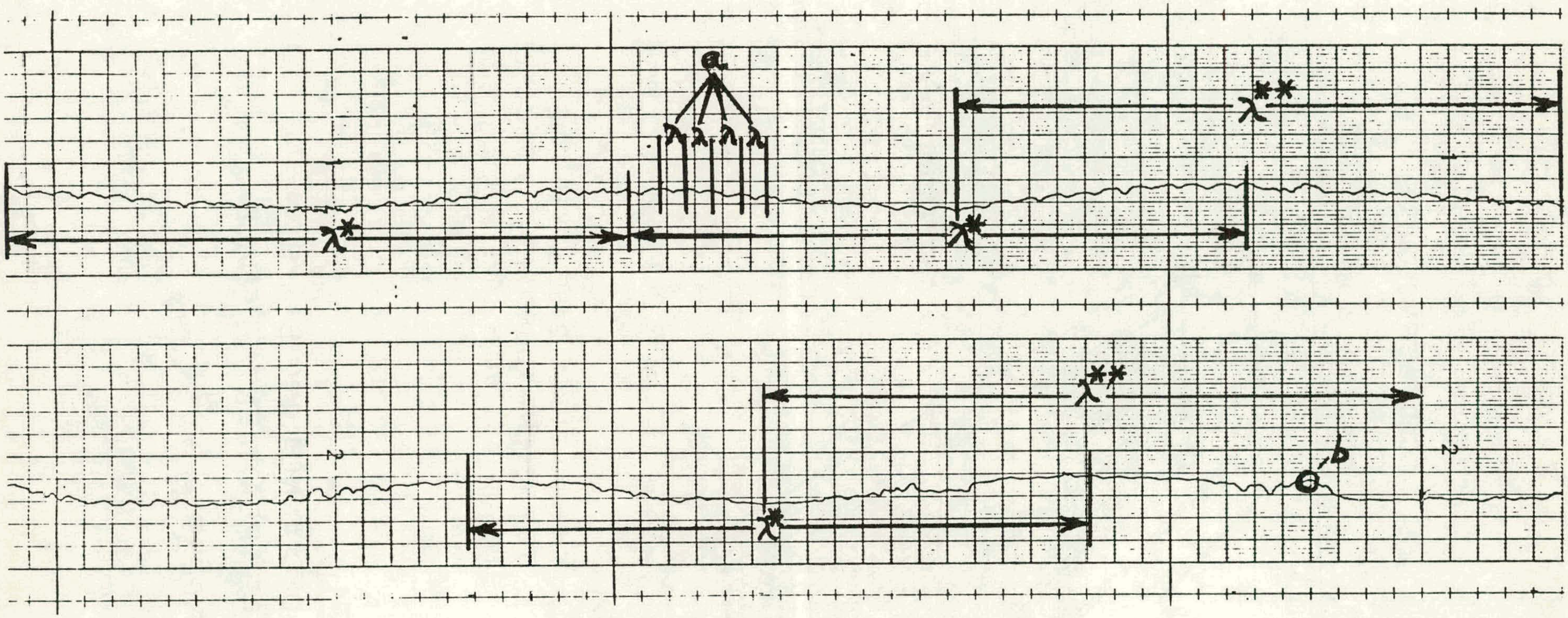


RETURN / SIZING STROKE

1. TUBE GRIPPERS ROTATE THE TUBE HOLLOW (NO AXIAL MOTION)
2. THE DIES ARE ROCKED TOWARD INPUT END, ROUNDING TUBE AND IMPROVING WALL THICKNESS UNIFORMITY

SCHEMATIC TUBE REDUCTION SEQUENCE

FIGURE A-1



LENGTH OF TUBE WITH ONE PREDOMINANT WAVELENGTH AND SHORTER SUPERIMPOSED WAVELENGTHS

λ^* = Predominant Wavelength between Maximums ($\lambda^* = \lambda^{**}$).

λ^{**} = Predominant Wavelength between Minimums ($\lambda^* = \lambda^{**}$).

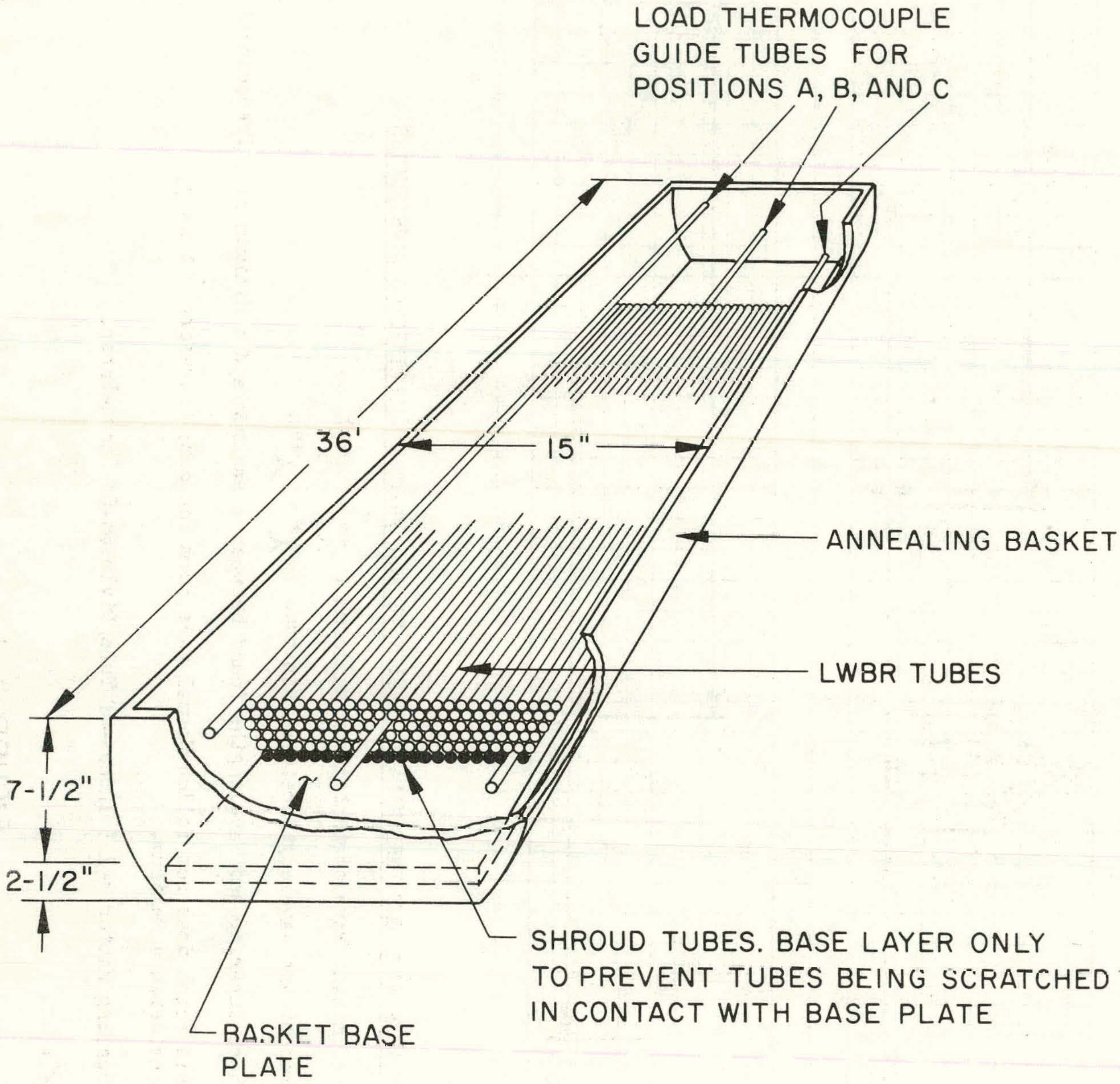
a Short Superimposed Wavelengths found between a Maximum and a Minimum of a Predominant Wavelength.

b This Point does not follow Normal Wave Form Contour; therefore, it is not considered a Maximum.

Length Scaling Factor ~1.5 Inches-Of-Tube/Division-Of-Chart-Paper.

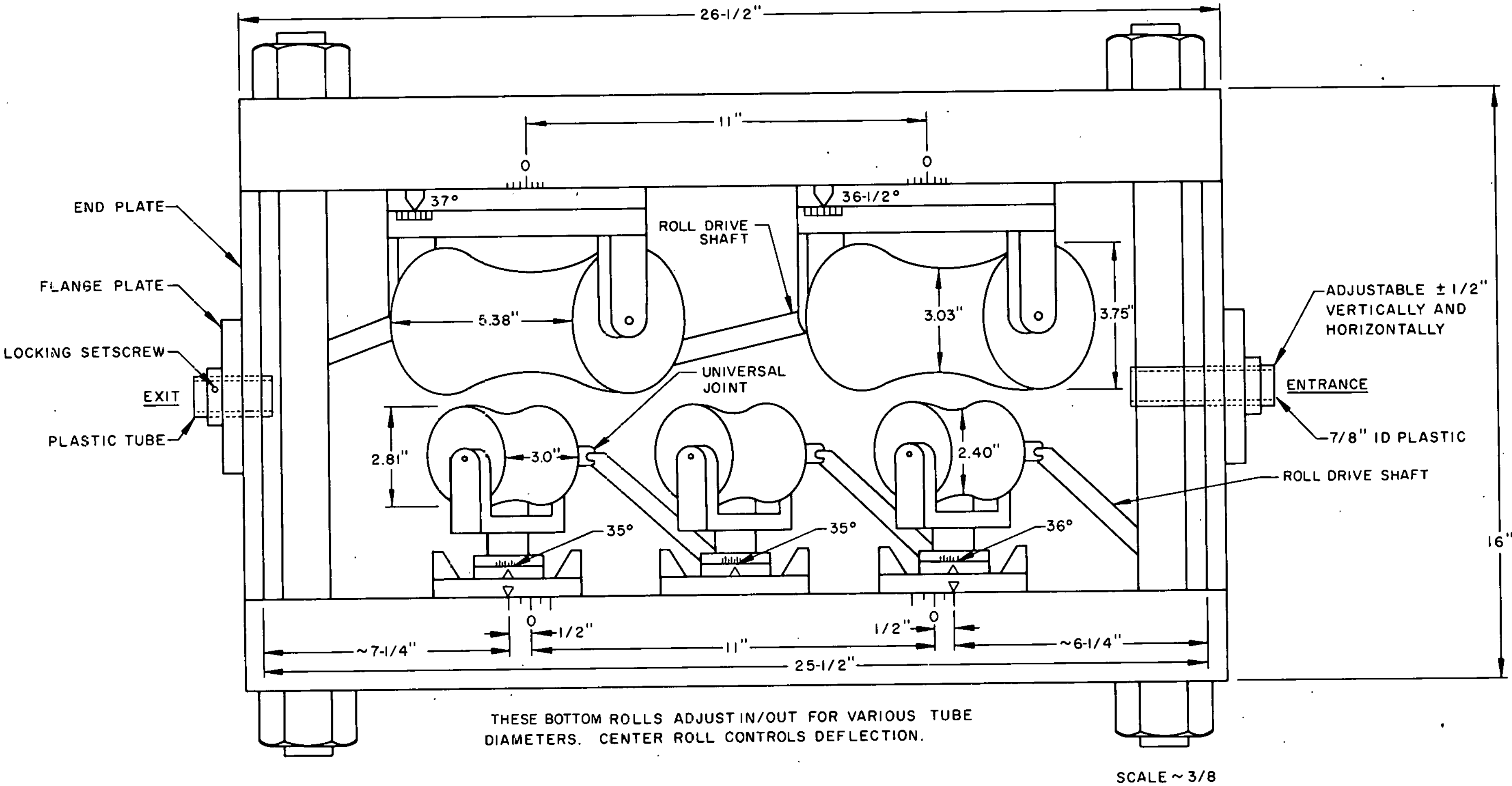
$\lambda^* \sim 32''$.

FIGURE A-2.



SKETCH OF LOADED ANNEALING BASKET
FOR VACUUM HEAT TREATMENT FURNACE

FIGURE A-3



SUTTON STRAIGHTENER

FIGURE A-4

APPENDIX B

CONTROL OF THE WAVE PATTERN OF THE HELICAL WALL ECCENTRICITY IN TUBE-REDUCED LWBR ZIRCALOY-4 TUBING

I. Introduction

Analysis of wall thickness variations on tube-reduced tubes revealed the existence of a spiral pattern of wall eccentricity in the tube. This condition is introduced during the tube reducing operation since the extruded product showed no such pattern.

The helical pattern of wall thickness eccentricity is the result of the die design and the spiral motion of the tube as it is both rotated and advanced through the die and over the mandrel. The mandrel is circular in all cross sections while the tube reducer dies are designed with a side relief to trap and deform the tube without producing "flashing" in the parting line between dies (See Figure B-1). The amount of the side relief varies throughout the tapered tube reduction zone and is minimal in the runout (sizing) portion of the die. As a result, the tube is deformed into a slightly oval O.D. shape over a substantial portion of the reduction zone. In the reduction zone, this ovality is erased in deforming incrementally into successively smaller cross sections. When the tube emerges into the sizing region of the die, the sizing deformation is not enough to erase the ovality present at the last reduction increment. The residue of this ovality appears as the helical wall eccentricity in the tube. Ideally, this is a double helix of wall thickness occurring 180° apart on the tube, reflecting the side relief on each side of the die, while in practice it is single helix observable only when a detectable amount of eccentricity occurs in the tube.

0116-79A/0082L

In operation, the tube is moved (some 0.03 to 0.07 inch) into the die and the die rolls toward the output side squeezing the tube incrementally into a smaller size and into the side relief of the die. At the end of the reducing stroke of the die, toward the output side of the tube reducer, the tube is rotated (some 20 to 75°) and the dies roll back over the tube in a sizing operation. (The tube reducer parameters are listed in Table A-5.) Now the oval tube, at the beginning of the sizing stroke, has the bulge in a thinner part of the die opening. On the sizing stroke, the die makes initial contact with the bulges in each cross section. This asymmetrical load on the tube leads to "shape deformation." Some torsional yielding occurs locally, and the tube ahead of the moving die rotates some amount, moving the "bulge" toward the nearest side relief cavity. Since the mandrel is free floating and follows the ID, wall eccentricity in the input stock is not significantly affected by tube reduction.

In addition to such factors as feed rate, index rate and direction, die design, and asymmetrical loading during sizing, the output wavelength is also affected by the wavelength and direction of rotation in the intermediate tube hollow, the total reduction (percent cold work), gripping/rotation mechanism, the lubricity of the lubricant, and the loads exerted by the dies. Thus a direct calculation of the expected wavelength was not possible given the tube reduction parameters listed in Table A-5 of Appendix A.

II. OLD-PRODUCT EVALUATION

Since control of wall eccentricity wavelength had not been developed prior to LWBR, four types of LWBR development tubing, manufactured without wavelength control, were evaluated to determine not only the wavelength pattern in the finished product, but also the development of that wavelength during the intermediate tube reductions. The results of that evaluation are presented in Table B-I and clearly demonstrate that:

(1) Twisting did not occur during extrusion; the wavelength, if present, is very long.

(2) The then-existing manufacturing parameters for seed and blanket tubing were not conducive to long (> 80 inches) wavelengths.

(3) The direction of twist in the product of the first tube reduction was opposite to the direction of index rotation.

(4) Repeat passes with the same rotation produced successively shorter wavelengths in the tubes produced.

(5) Changing the direction of tube rotation on successive passes tended to produce tubes with long wavelengths.

Thus, to obtain a long wavelength in the product of the final reduction, the next-to-last tube reduction had to be controlled to obtain a short wavelength. The object of the last reduction was to untwist that short wavelength and effect a final product with a long helical wall eccentricity wavelength, i.e., approaching zero twist and an infinite wavelength.

III. DEVELOPMENT PROGRAM

A. Indexing Magnitude and Direction

A wall eccentricity wavelength development program was initiated for seed and blanket tubing. Reflector wavelengths were considered satisfactory, based on the fabrication sequence presented in Table B-1 and Table A-5 of Appendix A. A three-pass sequence was selected for the seed and a two-pass sequence was chosen for both blanket items. For seed tubing, the plan was to tube reduce the first two passes in the same direction, using standard tube reducer parameters to achieve a short wavelength, and then reverse direction in the last pass, thereby untwisitng the short wavelength to a long one. For the blanket items, the plan was similar to that for reflector, i.e., tube reduce the first pass in one direction and tube reduce the second pass in the opposite direction. It was assumed that the process parameters generated during the development phase would not be directly applicable to a tube manufacturing system employing different tool designs and/or tube reducers.

Summaries of the development programs are presented in Tables B-2, B-3, and B-4, showing the fabrication routes that were investigated prior to selecting the basic controls for obtaining long wavelength during the manufacture of LWBR seed and blanket tubing. To understand the results of the study, a discussion of the tube reducer gripping mechanism is necessary.

Initially, as a tube hollow is loaded on a tube reducer, one end is inserted in the positive grips of the crosshead mechanism (Figure B-2). During tube reduction, the crosshead advances the tube-hollow through the dies in small incremental moves each time the dies are over the input tube, i.e., closest to the crosshead. The rate of tube hollow advancement is described in terms of the "feed rate," defined as the number of reducing strokes received by the tube hollow per inch of advancement of the input-tube. During LWBR tubing manufacture, nominal feed rates ranged from 14 to 33 advances per inch of input tube. The crosshead has the additional function of indexing or rotating the tube hollow when the dies are farthest from the crosshead. No axial displacement (feed) occurs during this rotation, since the primary purpose of the tube rotation is for the return or sizing stroke to round-off the ovality created by the side-relief portion of the dies during the reduction stroke. The magnitude of the rotation is described by the index number, defined as the number of indexing steps per 360 degree rotation. For example, an index of 5 equals a tube rotation of 72 degrees. During LWBR tubing manufacture, the nominal rotation index ranged between 5 and 17 (72° and 21° respectively). No even numbers were used. For example, an index of 10 is the same as 5 since the sixth strike is a mirror image of the first stroke in the cycle. In retrospect, index values of 12 and 16 could have helped in fine tuning the process as equivalent indices of 6 and 8.

After approximately 75 percent of the tube hollow is fed through the dies by the crosshead mechanism, the tube hollow is released from the crosshead grippers. The crosshead is returned to its original starting position where it is connected to a new tube hollow. The tube reduction is restarted such that the old (partially reduced) tube hollow is pushed through the dies by the new tube hollow, which is being advanced by the crosshead mechanism. The indexing or rotational function for the "old" hollow is assumed by the output indexer (friction grip) which is synchronized with the crosshead indexer.

The significance of the indexing mode is that the tube is in a clamped-end configuration while the tube hollow is controlled by the crosshead indexer; whereas, the tube is in a free-end configuration while the rotation is controlled by the output indexer. The twist rate is different for the two conditions, and this is confirmed by the results of the development program (Tables B-2, B-3, and B-4). Note that the wavelength data is presented as a function of both gripping modes.

The basic purpose of the development program was to establish a set of tube reducer controls capable of converting the variable wavelength characteristic of the product of the next-to-the-last tube reduction to a long wavelength during last tube reduction for both input (crosshead) and output indexing.

The results of the seed development program, as summarized in Table B-2, demonstrated that a long (> 80 inches) wall eccentricity wavelength pattern was achievable in the finished tube by control of the indexing direction and magnitude in each of the three passes. It was noted during the second pass that:

1. The resultant wall twist is opposite in direction to the indexing direction.

2. The higher angular rotation (index = 5 or 72 degrees) resulted in greater twisting than the lower rotation (index = 7 or 51.4 degrees).

3. Controlling the tube motion with the crosshead (input) gripper resulted in more twisting than when the output indexer was used.

The third pass data confirmed the second pass observations that:

1. The resultant tube twist was opposite in direction to the indexing direction. The single exception in Table B-2, third pass condition (2), shows the output gripped piece was twisted past straight (the wavelength approaches infinity with a twist angle of zero degrees) into counterclockwise twist while the condition (3) tubes had wavelengths too long to determine direction of twist.

2. The higher rotation (lower index number) resulted in greater twisting than the lower angular rotation (higher index number).

Most significantly, the results demonstrated that seed size tubing could be manufactured by control of tube reducer parameters (primarily index magnitude and direction) to meet the wall eccentricity wavelength requirement. The results of the power flattening blanket and standard blanket development programs are presented in Tables B-3 and B-4. The first reduction pass was common to both blanket sizes. An index rate of 7 resulted in rather long (> 100 inches) wavelengths. During the second pass, the lowest possible index rate of 17 (i.e., lowest possible while still retaining a high quality and dimensionally acceptable product) was used, but resulted in too much twist using output grippers. It would be possible to employ crosshead gripping only during the initial portion of tube reduction of a tube hollow, and then switch to the output grippers as soon as possible. This method would result in scrapping that portion of the tube controlled by the crosshead, estimated to be 10 to 20 percent of the output product.

As an alternate solution to the wavelength problem, the first pass tube reducer index was changed to 5, aiming for a shorter wavelength after the first pass which could be untwisted during the second pass. This method produced long wavelengths using both input and output gripping.

B. Feed Rate and Mandrel Position

Several experiments were run to measure the effect of tubing feed rate and mandrel position on the resultant wavelength. It was concluded that, at a given index rate, the mandrel position and feed rate could not be greatly varied without affecting surface quality or dimensional control. Mandrel position is closely related to the groove dimensions in the die roll and thus only minor axial adjustments can be tolerated. Therefore, within the range established for good tube reduction practice, wavelength was not affected by the minor variations in either feed rate or mandrel position. The tolerance on feed rate is listed in Table A-5 for all of the tube reductions used to produce the LWBR core tubing.

C. Effect of Lubricant on Wavelength

An interaction exists among the mechanical motions of the equipment, the mandrel and die design, the material feed and index rate and the frictional forces generated during the actual deformation of the tubes, with the lubricant moderating the friction load and providing a separating film between tube and tooling.

In several instances of lubrication failure, intimate contact between tube and mandrel resulted in pickup on the mandrel, galling of the I.D. surface of the tube, and higher friction forces on the tube. Substitution of a second lubricant corrected the mandrel pickup and galling problem, reduced the frictional forces and affected the wavelength of the helical wall eccentricity. An adjustment in the index rate to a smaller indexing angle (larger index number) resulted in the return of the wavelength of wall eccentricity to the desired long lengths. Discussion of the effect of lubricant is also presented in Section VI.C.1.a of Appendix A.

IV. OBSERVATIONS

A. Wall thickness eccentricity is an unavoidable characteristic of tubes manufactured by tube reduction. The pitch of the spiral of the location of the maximum wall thickness along the tube is described as the wavelength of wall eccentricity.

B. The pitch of the spiral is determined by measuring the wall thickness along a single axial path without tube rotation. The direction of rotation is shown by the progression of peaks on adjacent paths (0°, 90°, etc.)

C. For a given tube reduction operation, the wavelength of wall eccentricity of the output tube is affected by the following:

1. The wavelength, (twist) of input stock;
2. Angle and direction of the rotation of the tube in the tube reducer between incremental axial advances into the die;
3. Tool design;
4. Percent reduction of cross section;
5. Lubricant;
6. Mode of rotation (gripping of the tube on the input or output side of the tube reducer);
7. Gearing ratio of the rack and pinion drive of the tube reducer.

V. DISCUSSION

The extruded tube has no wavelength. The first tube reduction imparts a twist to the tube which is seen as wavelength if sufficient eccentricity exists to show thickness oscillation along the length. The twist angle is related to wavelength and diameter by the formula:

$$\text{Tangent of twist angle} = \pi \times \text{O.D.} \div \text{Wavelength.}$$

The wavelength produced by the second tube reduction is the product of two factors. The wavelength of the input tube is lengthened by the tube reduction factor, that is, a 60% reduction increases the input wavelength by a factor of 2.5, reducing the twist angle without changing the direction of rotation. As in the first reduction, the deformation mechanics imparts a twist to the tube. When the direction is changed on the second reduction, the twist is further reduced toward 0° in conjunction with the reduction factor. Ideally, the two factors would result in zero twist (infinite wavelength). The measuring system could not define the length nor the direction of rotation of very long wavelengths approaching zero degree twist.

The differences in the wavelength distribution of the product of the first and second blanket reductions is shown in the following table developed from the 700 pieces of data presented in Table B-5 and from the core average data for both blanket sizes presented in Table V of Reference (a).

	Distribution Mode			
	1st	2nd	3rd	Grand Average
First Tube Reduction				
Average wavelength (inch)	42	84	>120	>54
Maximum value	65	110	-	
% of population	79	11	10	
Type of distribution	Normal	Flat	-	

Second Tube Reduction	Distribution Mode 1st	2nd	3rd	Grand Average
Average wavelength (inch)	60	97	>120	>108
Maximum value	80	120	-	
% of population	10	25	65	
Type of distribution	Normal	Normal	-	

Continuous monitoring of the wavelength of the product of each tube reduction was maintained throughout production. The index rate, feed rate and other variables previously discussed were adjusted, as needed, to obtain the desired wave length. While the majority of the tubes were within the desired range of wavelengths, the wavelength varied appreciably. See Reference (a) for discussion of the tri-model distribution of wavelength found in finished tubing.

VI. CONCLUSION

The wavelength of wall eccentricity can be controlled by the use of the proper combination of the variables noted in Section IV.D above on each successive tube reduction for the selected manufacturing sequence (multiple tube reductions) and by regular monitoring the wavelength of the tubes as they are produced.

TABLE B-1

Wavelength of the Helical Wall Eccentricity in LWBR Development Tubing

Item No.*	Process Description	Nominal % Red.	Nominal WRR**	Direction of Tube Rotation***	Typical Wall Eccentricity Wavelength	
62	As extruded				****	
3-Pass	After 1 TR	79.9	1.46	CW	130"-230"	CCW
Seed	After 2 TR	74.0	1.28	CCW	18"-30"	CW
	After 3 TR	50.8	1.18	CCW	20"	CW
49	As Extruded				****	
4-Pass	After 1 TR	60.9	1.40	CW	220"-265"	CCW
Seed	After 2 TR	50.0	1.41	CCW	33"-75"	CW
	After 3 TR	76.6	1.40	CCW	25"-35"	CW
	After 4 TR	56.2	1.49	CCW	20"	CW
54	As Extruded				****	
3-pass	After 1 TR	70.0	1.86	CW	10"-50"	CW
Power	After 2 TR	57.8	1.83	CCW	85"->200"	CW
Flattening Blanket	After 3 TR	67.0	1.87	CCW	15"-40"	CW
#60	As Extruded				****	
Reflector	After 1 TR	69.5	1.99	CW	Undetermined	
	After 2 TR	69.7	2.39	CCW	100"-130"	CW

* Item no. refers to the fabrication sequence number in Table C-14 of Attachment C.

** WRR or Wall Reduction Ratio is also referred to as the Q-value and is the % change in wall thickness divided by % change in outside diameter.

*** Feed rate and index rate are undefined proprietary information. The actual values were those that produced good surfaces and good dimensional control in keeping with good commercial practice.

**** No twist observed, therefore wavelength approaches infinity.

TABLE B-2

SUMMARY OF SEED WALL ECCENTRICITY WAVELENGTH DEVELOPMENT PROGRAM
FOR ITEM #53 TABLE C-14

	Input		Output - Twist*		
Operation	Stock Twist*	Tube Reducer Index** & Direction***	Input Gripping	Output Gripping	Comment
1st Pass (76.8% Red, 1.32 WRR)	None - AE	5 CW	> 120" CCW	> 120" CCW	-
2nd Pass (65.4% Red, 1.5 WRR)	(1) >120 CCW	7 CW	37" to 42" CCW	77" CCW	Change the index to 5 to obtain a shorter wavelength and to provide more flexibility during the third tube reducing pass.
	(2) > 120 CCW	5 CW	25" to 35" CCW	71" CCW	A change of index to 5 (from 7) has produced shorter wavelengths.
3rd Pass (67.8% Red, 1.31 WRR)	(1) 40" CCW	13 CCW	81" to 100" CW	> 100 CW	At an index of 13 CCW, the 40" CCW input wavelength is unwound past straight and into a CW twist. Longer wavelegths should be attained by using a lesser twist, i.e., a higher index number.

TABLE B-2 (continued)

Operation	Input		Output - Twist*		Comment
	Stock Twist*	Tube Reducer Index** & Direction***	Input Gripping	Output Gripping	
3rd Pass (continued)	(2) 40" CCW	17 CCW	> 120" CW	150" to 160" CCW	Long wavelengths are produced in the last reduction by both input and output gripping when the 40" CCW input wavelength (from the second pass) is used. Determine if long wavelengths are possible using 70" CCW input wavelengths.
	(3) 70" CCW	17 CCW	> 120"	> 120"	Long (> 80") wavelength final product is achievable using input and output gripping during 3rd Pass from both input and output indexed 2nd pass product.

* Wavelength of helical wall eccentricity in inches and direction rotation.

** An index number is defined as the number of indexes required to turn the tube 360°. For example, an index number of 5 is a rotation of 360°/5 or 72° on each movement. The index number is always an odd number.

*** Direction of rotation is defined while looking into the output side of the tube reducer.

Symbols

>	greater than
CW	clockwise
CCW	counterclockwise
AE	As extruded with wavelength approaching infinite length.

TABLE B-3

SUMMARY OF POWER FLATTENING BLANKET WALL ECCENTRICITY WAVELENGTH DEVELOPMENT PROGRAM
For Item #56 of Table C-14

Operation	Input		Output - Twist*		Comment
	Stock Twist*	Tube Reducer Index** & Direction***	Input Gripping	Output Gripping	
1st Pass (82.0% Red, 1.90 WRR)	(a) None - AE	7 CW	> 100" CCW	> 100" CCW	(a) Initial effort.
	(b) None - AE	5 CW	20" to 50" CCW	50" to 100" CCW	(b) Additional first pass testing based on the observations made on second pass testing.
2nd Pass (70.8% Red, 1.50 WRR)	(a) >100" CCW	17 CCW	49" to 55" CW	90" to 92" CW	(a) These results are consistent with Standard Blanket development using the same input conditions. Additional work is required to achieve a shorter input wavelength for the seond pass.
	(b) 50" CCW	5 to 11 CCW	80" to > 100" CW	> 120" CW	(b) Acceptable

* See Notes and Symbols on Table B-2
**
***

TABLE B-4

SUMMARY OF STANDARD BALNKET WALL ECCENTRICITY WAVELENGTH DEVELOPMENT PROGRAM
For Item #59 of Table C-14

	Input		Output - Twist*		
Operation	Stock Twist*	Tube Reducer Index** & Direction***	Input Gripping	Output Gripping	Comment
1st Pass (82.0% Red, 1.90 WRR)	(1) None - AE	7 CW	> 100" CCW	> 100" CCW	See comments on 1st pass reduction in Table B-3.
	(2) None - AE	5 CW	20 to 50" CCW	50" to 100" CCW	
2nd Pass (66.2% Red, 1.66 WRR)	(1a) >100" CCW	7 CCW	20" CW	Not Measured	Too much twist has occurred. A lower index rate (higher index number) with attendant lower twist forces is required.
	(1b) >100" CCW	11 CCW	25" to 35" CW	Not Measured	There is still too much twist. A lower index rate is required.
	(1c) >100" CCW	17 CCW	58" to 61" CW	86" to 100" CW	Long wavelengths are achievable using output grips. Additional work is required using an index of 5 during the first pass to achieve a shorter wavelength for input to second reduction.
	(2) 50 CCW	17 CCW	30" to 60" CW	50" to 100" CW	
		15 CCW	60" to 80" CW	70" to >120" CW	
		11 & 13 CCW	30" to 50" CW	60" to >100" CW	
		7 CCW	80 to >120" CW	80" to >120" CW	
		5 CCW	>120	>120	Used for most of LWBR Production.

* See Notes and Symbols on Table B-2
**
***

TABLE B-5

VARIABILITY OF WALL ECCENTRICITY WAVELENGTH FOLLOWING THE FIRST TUBE REDUCTION FOR BLANKET TUBES AT INDEX OF 7 (51°) FOR 700 MEASUREMENTS ON 175 TUBES

Class Midpoint (± 2)	Frequency		1st Mode Frequency		2nd Mode Frequency		3rd Mode Frequency	
	N	%	N	%	N	%	N	%
15	2	.3	2	.4				
20	12	1.7	12	2.2				
25	30	4.3	30	5.4				
30	71	10.1	71	12.8				
35	72	10.3	72	13.0				
40	128	18.3	128	23.0				
45	54	7.7	54	9.7				
50	104	14.9	104	18.7				
55	21	3.0	21	3.8				
60	62	8.9	62	11.2				
65	7	1.0			7	9.3		
70	11	1.6			11	14.7		
75	10	1.4			10	13.3		
80	7	1.0			7	9.3		
85	10	1.4			10	13.3		
90	8	1.1			8	10.7		
95	3	0.4			3	4.0		
100	17	2.4			17	22.7		
105	2	0.3			2	2.7		
110	-	-						
115	1	0.1					1	1.4
120	8	1.1					8	11.6
>120	60	8.6					60	87.0
Average	57.53		41.99		84.00		>120	
Standard Deviation	36.39		10.48		12.47		N/A	
Quantity	700		556		75		69	
% of 700	100		79.4		10.7		9.9	

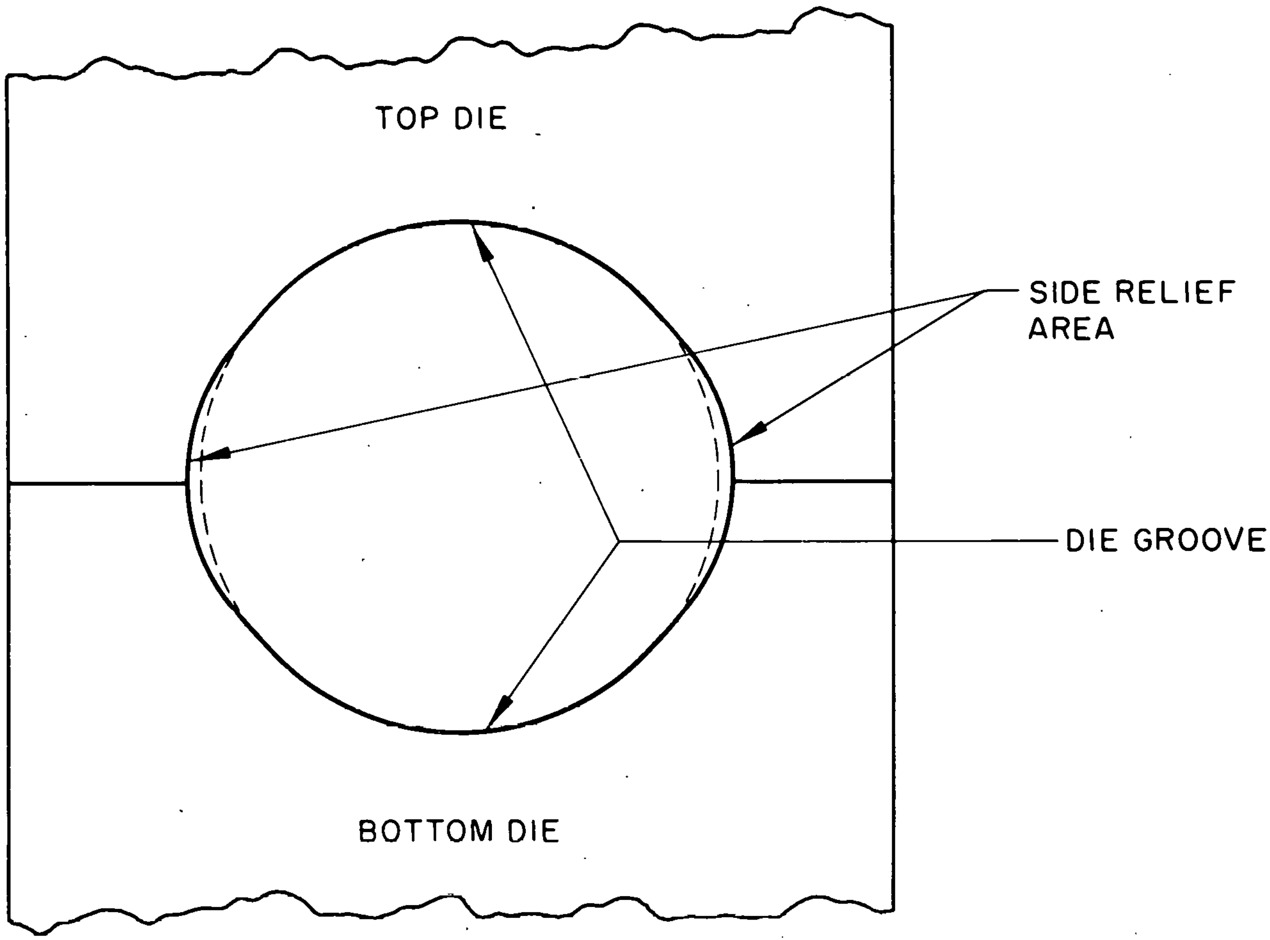


FIGURE B-1. SIDE RELIEF IN DIE GROOVE (EXAGGERATED)

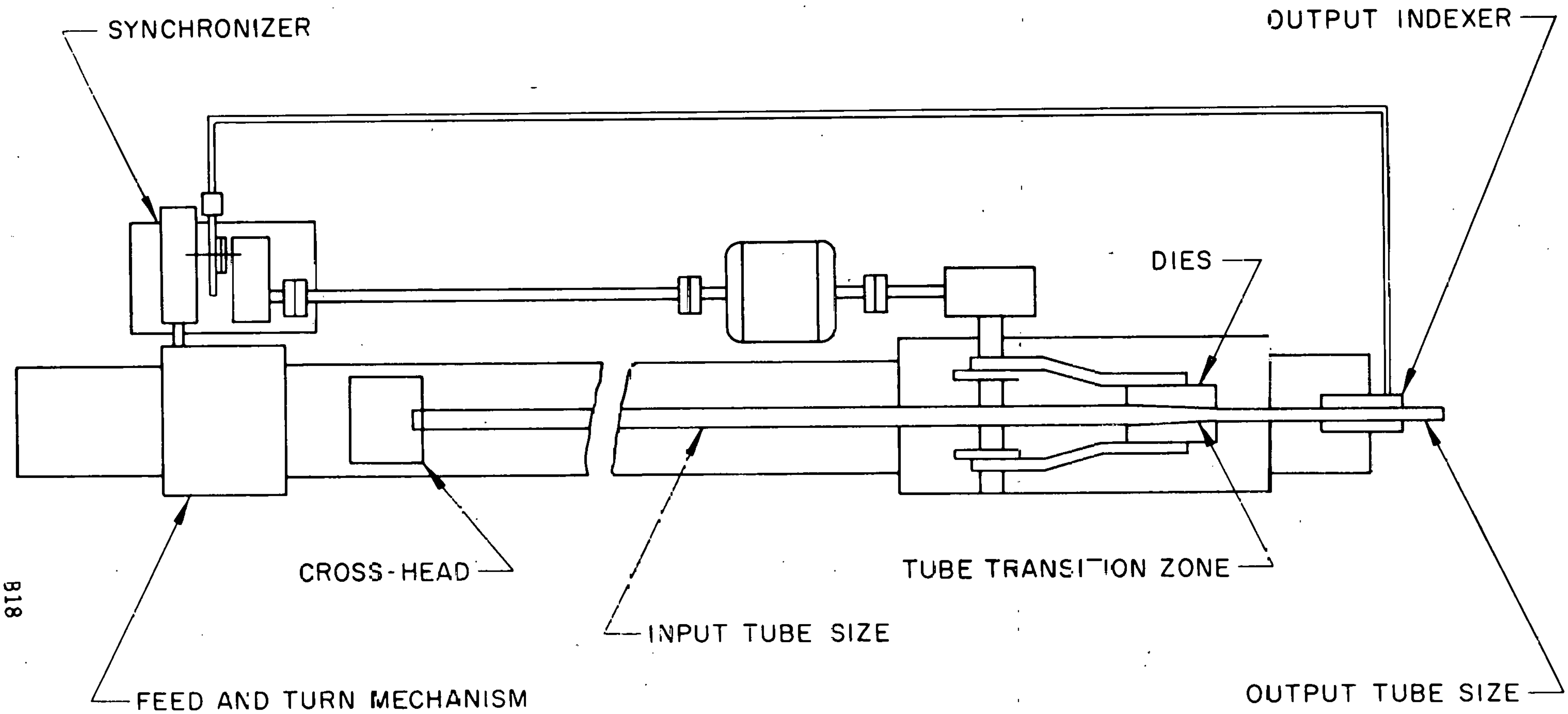


FIGURE B-2. SCHEMATIC OF TUBE REDUCER

APPENDIX C

TEXTURE DEVELOPMENT IN ZIRCALOY TUBING

I. INTRODUCTION

Preferred crystallographic orientation occurs during the manufacture of Zircaloy tubing because of the anisotropic deformation behavior of the hexagonal closed-packed crystal structure. The specific nature of the orientation is controlled by the direction and magnitude of major strains during the various cold reduction operations. During circumferential reduction the major strain is circumferential compression which tends to align the basal poles in the circumferential direction, while during wall thickness reduction the major strain is radial compression which tends to produce tubing with basal poles aligned in the desired radial direction. Since most tube fabrication operations consist of both circumferential and wall thickness reductions, the direction and magnitude of major compressive strain depend on the relative amount of each type of reduction (circumferential versus radial) taking place.

In normal tube reduction operations the finished tube contains very few grains with basal poles aligned in the axial direction. Essentially all of the basal poles are aligned within a few degrees of the diametral plane and are essentially perpendicular to the axial direction. It is therefore possible to obtain a numerical index of texture as the ratio of the concentration of basal poles in the radial direction to the concentration of basal poles in the circumferential direction.

Basal pole intensity determined by x-ray diffraction is the reference measurement technique, but it is not suitable for obtaining the hundreds of evaluations required for the certification of LWBR tubing. A mechanical measure of the relative concentration of basal pole alignments can be determined by the deformation of a specimen under uniaxial tension, since texture variations influence the deformation behavior of the tubing. For

0116-79B/0085L

tubing with basal poles oriented predominantly in the radial direction, deformation during axial lengthening occurs primarily through circumferential reduction via slip. The propensity for wall thickness reduction is relatively low, since this deformation mode would require twinning, which in turn requires a higher stress level. On the other hand, tubing with basal pole orientation predominantly in the circumferential direction deforms during axial lengthening primarily through wall reduction via slip, since circumferential reduction would require twinning to occur. For tubing with the basal poles randomly oriented in the diametral plane the axial strain (lengthening) results in approximately equal strains in the circumferential and radial directions through reduction of the diameter and wall thickness, respectively.

The measure of the relative strains and their comparison produces a numerical index of texture called "Contractile Strain Ratio" (CSR). A CSR value greater than 1.0 is indicative of tube deformation primarily in the circumferential direction with the basal pole orientation being mostly radial. A CSR value less than 1.0 correlates with deformation primarily by wall reduction and with most of the resolved fraction of all the basal poles being circumferentially oriented.

II. TEXTURE MEASURING TECHNIQUE

The technique for determining texture consists of measuring strains in the three mutually perpendicular directions. The ratio of strain in the radial direction (E_w) to strain in the circumferential direction (E_m) is a function of texture and is defined as Contractile Strain Ratio (CSR). Table C-1 shows the derivation of the use of the mid-wall diameter as one of the three dimensions.

In practice, the wall thickness and mid-wall diameter in the strained test specimen are difficult to measure. For LWBR, the easily obtained dimensions of length and outside diameter were used to calculate CSR. All of the CSR data used in this report were developed using the experimental procedure described in Table C-2.

The use of circumferential strain based on O.D. and axial strain to calculate CSR introduced an error, since true strain is based on changes in mid-wall diameter and wall thickness. As shown in Table C-3, the strain based on O.D. is used twice in determining the LWBR CSR data, once in place of E_m and again in replacing E_w with $(-E_L + E_D)$. The magnitude of the difference between CSR based on E_m and E_w and the LWBR CSR values varies with tube geometry (O.D.-to-wall ratio) and with the calculated CSR value. Table C-4 lists the corrections for LWBR values of CSR for a range of O.D.-to-wall ratios encompassed by the tubes tested and included in this report.

In subsequent discussions all CSR values will refer to CSR resulting from the LWBR "convenience" calculation. All other CSR data will be suitably noted as for example, CSR_m.

The O.D.-to-wall thickness ratio (OD/W) for the 32 tube sizes tested for the LWBR program ranged from 11.5 to 20.5 with one at 36.4. For LWBR, the seed tube had an O.D.-to-wall thickness ratio of 12.8, the power flattening blanket (PFB) had a ratio of 19.0, and both the standard blanket (Std.B.) and reflector tubes had a 19.2 ratio. As fuel rods, the O.D./W ratios were 13.9, 20.1, 20.3, and 19.7 respectively.

III. CORRELATION OF CSR AND X-RAY TEXTURE

X-ray texture is defined as the ratio of the Basal Pole Intensity (BPI) in the tangential (circumferential) direction to the BPI in the radial direction as determined from the inverse pole figures developed from sample surfaces parallel to and perpendicular to the tube radius, respectively. Both surfaces are also parallel to the longitudinal axis of the tube.

Samples from various tubing lots were tested to develop both the inverse pole figures and CSR values to show the correlation between x-ray texture and the mechanical measure of texture using the CSR technique discussed above. While the basic correlation was made with stress relief annealed (SRA) tubing, samples of some lots were also given a recrystallization anneal (RXA) prior to measuring CSR value. Since the alignment of basal poles is not affected by heat treatment, the comparison of x-ray texture to CSR values for both SRA and RXA tubing is valid.

The x-ray texture data and the corresponding average CSR data are shown in Table C-5. The LWBR data were corrected, as described in Section II, to obtain the true strain (CSR_m) values which are also listed in Table C-5. Linear regression analysis of the x-ray texture versus the corresponding average CSR values shown in Table C-5 produced for four straight line equations shown at the bottom of Table C-5. Note that the correlation coefficients of the four equations exceed 0.96. These data are also plotted in Figures C-1 (CSR LWBR) and C-2 (CSR_m).

IV. REPRODUCIBILITY OF THE CSR TEST MEASUREMENTS

Over 450 CSR measurements were made during the testing and certification of the four sizes of tubing produced for LWBR Core. The variability of the test results within any one size and heat treated condition is a good indication of the reproducibility of the CSR test. This variability includes measurement error, calculation error, test variation, and material variability. The CSR data, summarized in Table C-6, indicate a standard deviation of about 0.24 for recrystallize annealed seed and about 0.12 for the stress relieved non-seed sizes. It is suggested that measurement error (a constant) has a greater effect on the smaller size changes associated with tests of the seed size tubing (0.3105 inch O.D.) and is primarily responsible for the 2-to-1 ratio in standard deviations.

V. EFFECT OF HEAT TREATMENT ON CSR

The stress relief heat treatment of tubing produces no changes in crystal structure and should have no effect on the texture of non-heat-treated tubing. This is supported by comparison of the three sets of data in Table C-7. The variations are comparable to the reproducibility variations noted in Section IV. These data were combined and the average value was used as input for CSR as stress relieved in Table C-8.

While recrystallization does not affect the alignment of the basal poles, a rotation of the prism planes does occur. This realignment with respect to the principal stress directions affects the mode of deformation, and this change is reflected in the change in CSR values, as shown in Table C-8, where the average CSR value for each set of tests is recorded both as stress relieved and after a recrystallization anneal. A linear regression analysis of the 21 pairs of averages plotted in Figure C-3 produced the following trend line equation with a correlation coefficient of 0.977:

$$CSR_{(RXA)} = 1.26\ (CSR_{SRA}) + 0.040$$

The variation of the data around this trend line is due to factors previously mentioned and to variations in the final heat treatment used as reference during the tube development program. The effect of final heat treatment conditions in RXA tubing is illustrated in Table C-9 where samples from two lots of tubes were subjected to two different recrystallization heat-treatments: 5 hours at 1235°F (equivalent to 1 hour at 1300°F) and 4 hours at 1300°F. These data indicate that, while recrystallization is evident metallographically as shown by the equiaxed grain structure, recrystallization is not complete in terms of the rotation of the prism planes after 5 hours at 1235°F or 1 hour at 1300°F.

VI. CSR VERSUS AXIAL STRAIN

The establishment of parameters for CSR testing required selection of an axial strain range that would result in accurate and consistent CSR values. Very low strain levels are undesirable since, with the inherently small dimensional changes accompanying low strains, dimensional measurement inaccuracies can contribute heavily to variations in strain determination and, therefore, in determination of CSR. High strain levels that cause localized necking are also undesirable from the standpoint of determining a properly weighted average diameter to accommodate the effect of any highly localized axial strains on the overall elongation of the gage length. The CSR technique described in Section II assumes a uniform strain over the 3-inch gage. In determining an operational strain range for testing, a series of seed and blanket tubing specimens, representing both the stress relief annealed (SRA) and the recrystallize annealed (RXA) final heat-treat conditions, were axially strained at low strain levels (less than 1% elongation), measured and evaluated for CSR, and then restrained at higher strain levels and remeasured for CSR determination. Some specimens were restrained several times in order to characterize the tubing texture (CSR) over the entire uniform strain range. Tables C-10 and C-11 show the CSR value determined at each strain increment for seed and blanket size tubing respectively. The data in Tables C-10 and C-11 are plotted in Figures C-4, C-5, and C-6 to better illustrate the effect of elongation on the uniformity of the test results.

Figure C-4 is a plot of the data for seed SRA tubes listed in Table C-10. Straight lines connect sequential evaluations of the same test specimen. This plot illustrates the convergence of the data toward the characteristic CSR value with increasing axial strain. Some localized necking was observed at about 7 percent axial elongation. Figure C-5 is a plot of the CSR versus percent elongation for tubes with the same fabrication history as those plotted in Figure C-4 except that the final heat treatment was a recrystallization anneal. It appears that some local necking does not affect the CSR value.

Figure C-6 is a plot of the data for blanket size tubes listed in Table C-11. This data also illustrates the convergence of the test results to a characteristic CSR value with increasing levels of axial strain. As noted for the seed tubing in Figure C-4, the occurrence of some local necking does not affect the CSR value attained. However, to eliminate the problems of measuring and interpreting data posed by local necking, the limit on elongation was set nominally at 8 percent maximum with the specific limitation of stopping the elongation of the specimen when the ultimate stress for the specimen was reached.

The convergence of the test data to a characteristic value is attributed to the reduced effect of measurement error (essentially a constant) on the CSR calculation with the increasing changes in dimensions attendent on achieving higher elongations. Based on the preceding seed and blanket CSR testing data, an axial strain range of 3.5 percent to 8 pecent was established for CSR testing. For optimum accuracy and consistency, attempts were made to maintain testing in the higher (6 to 8 percent) end of the range.

VII. TUBE FABRICATION PARAMETERS

As discussed in Section I, the mode of deformation affects the development of texture in tubing. In commercial tubing practice, the relative amount of circumferential (diametral) to wall thickness reduction is measured by the Q-ratio, defined as the ratio of the percent wall reduction to the percent of diameter reduction and is expressed by the formula

$$Q = \left(1 - \frac{W_f}{W_o}\right) \div \left(1 - \frac{D_f}{D_o}\right)$$

For Q-ratios > 1, the wall is worked more than the diameter (commercially called "ironing"), while for Q-ratios < 1, the diameter is worked more than the wall (commercially called "sinking"). A pass with a Q-ratio = 1 is defined as a neutral pass, where the wall and diameter are worked equally. To be compatible with true strain, the Q-value should be based on the mid-wall diameter. However, since the O.D. was used in CSR calculations, it was also used in determining Q-values for LWBR. As with CSR, the correction from Q to Q_M based on mid-wall diameter is represented by a series of curves (equations) where the O.D.-to-wall ratio is the controlling parameter. Table C-12 contains a listing of corrections to convert from Q_{LWBR} to Q_M paralleling the presentation of the conversion from CSR_{LWBR} to CSR_M in Table C-4.

Another major factor in tube fabrication is the percent cold work or percent change in the cross-section area of the tube with each reduction operation. The amount of cold work is the driving force which effects the texture changes achieved by the Q-ratio used in a specific reduction.

VIII. TEXTURE DEVELOPMENT IN TUBING

Nine fabrication sequences, representative of seed, blanket, and reflector tubing were selected for texture characterization of intermediate product, starting with the extruded tube shell and continuing through each of the tube reduction operations. The extruded samples were tested in the as-extruded condition, while the intermediate tube reduced product (first pass through next-to-the-last pass) was tested in the tube-reduced-plus-recrystallize-annealed condition (standard heat treat condition in preparation for the next tube reduction operation). The finished tube-reduced product was tested in the final heat treat condition, i.e., recrystallize annealed for seed and stress relief anneal for blanket and reflector. The nine sequences are presented in Table C-13 together with the CSR data developed for each stage of the fabrication sequence. Four of the nine are seed size listed as items 49, 50, 62, and 63. Another four blanket size tubes are listed as items 47, 48, 54, and 57. The ninth, item 61, is reflector size tubing. Except for item 63 all fabrication operations following extrusion were performed by tube reduction technique. For item 63, the last reduction of item 62 was replaced by two plug drawing operations. The cumulative effect of texturing during tubing manufacture is shown in Figure C-7 for both seed and non-seed sizes. Initially, the extruded product is shown to have a slightly higher basal pole orientation in the circumferential direction with the CSR value less than 1.0. With successive tube reduction passes, basal pole orientation progressively shifts to the radial direction as reported by the increased CSR values. That is, of course, consistent with the Q-ratios, which are greater than 1.0, signifying "ironing" passes conducive to developing textures with CSR greater than 1.0.

The effect of each succeeding reduction on the texture of the product of the prior reduction is illustrated in Figures C-8 and C-9, where the CSR value in recrystallize annealed (RXA) tubing following each reduction is plotted versus the Q-value representative of that reduction for the tube items listed in Table C-13. For those tube sizes where only SRA data was available, the RXA versus SRA relationship shown in Figure C-3 was used to estimate a suitable RXA-CSR data point for the plots in Figures C-7 through C-9.

The plots in Figures C-8 and C-9 indicate that a given Q-value reduction does not achieve the maximum texturing (crystal orienting) possible. For item 50 of Figure C-9, three successive reductions at Q = 1.40 increased the CSR value. A similar effect is seen in the last three reductions of item 48 of Figure C-8. The same applies to three passes of item 49 in Figure C-9 and to the first two reductions of items 54 and 57 in Figure C-8. Successive passes with increasing Q-values have a great effect on improving texture (increasing CSR values). However, item 63 of Figure C-9 illustrates the effect of changing to a neutral reduction (Q = 1.0) or sinking (Q < 1.0) operation on the last pass on the CSR value.

It is important to recognize that the Q-ratio and Q_C-factor are useful in characterizing a tubing fabrication sequence, but they do not provide a direct correlation with the texture resulting from the use of a specific reduction schedule. It may require several parameters to fully describe that reduction. Another common parameter is area reduction, but other parameters such as D-ratios (ratio of initial diameter to final diameter) have also been used. If it is considered that no single parameter, by itself, can completely describe a reduction, then that parameter cannot be expected to correlate to the characterization of the product of that reduction. The data scatter of Figures C-7, C-8, and C-9, for example, attest to an inherent variability in attempting to directly correlate texture to any reduction parameter (Q, % CW, etc.). Note in Figure C-7 that the CSR data for item 50 shows a significantly higher radial texture than do items 49 and 62 in the first two reductions. This cannot be explained by Q-values. However, note that in the first two reductions the percent cold work for item 62 is significantly higher than that used on items 49 and 50 as shown in Table C-13. It is therefore concluded that, depending on the specific reductions involved, Q-ratios and Q_C-factors will provide inadequate correlation with tubing texture development and must be considered in conjunction with other reduction parameters in planning a reduction sequence to attain a specific texture.

IX. PROCESS DEVELOPMENT FOR TEXTURE CONTROL

CSR requirements for LWBR tubing were based on maintaining predominantly radially oriented basal poles (i.e., CSR > 1.2), not only to reduce the propensity for radial hydride formation, but also to increase the resistance to yielding under combined stress loading. It has been shown in work by Hobson (Reference (e)) and Tenchoff and Rittenhouse (Reference (f)) that high Q-ratios (the ratio of the percent wall reduction to the percent of diameter reduction) lead to alignment of the basal poles in a generally radial direction. Therefore, the development of fabrication parameters for LWBR tubing were based on maintaining Q-ratios > 1.

The initial phase of developing fabrication parameters to provide the desired texture consisted of testing of tubing already received at Bettis for other fuel rod related programs. The results of this and subsequent CSR testing are summarized in Tables C-14 (showing the reduction sequence) and C-15 (showing the CSR data). In Table C-16, the tube sequences are referenced, arranged by tube size to facilitate data comparisons by both tube size and fabrication history. The quantitative texture assessment of individual fabrication sequences was considered particularly essential, since this group, which represented the product of "good commercial practice," served as the basis for the establishment of manufacturing parameters for LWBR tubing. The items referred to throughout the text will refer to the particular tube fabrication sequences to be found on that line number in Table C-14.

A. <u>Blanket Tubing Development</u>

Items 28, 29, and 37 were the first group to be evaluated. Although the CSR tests for item 37 met the 1.2 minimum requirement, a slightly higher CSR value was desired. Fabrication sequences (items 54 and 57) with greater wall deformation were selected for development. The success of the effort was shown by the higher CSR values attained (1.5 to 2.5 for item 54 and 1.7 to 3.1 for item 57). However, these sequences were not compatible with good practice, leading to lubrication failure, galling, tool failure, and poor manufacturing yields.

The next effort utilized the seuences of items 55 and 56 for PFB and items 58 and 59 for Std.B. development. The CSR tests of the tubes produced by these sequences also met the 1.2 minimum CSR limit. Since items 56 and 59 demonstrated good fabricability, as well as good CSR values, they were selected for LWBR tube production fabrication sequence.

B. Reflector Tubing Development

The initial characterization of the reflector size tubing used tubing items 17 and 22 through 27. Although items 17 and 23 met the 1.2 minimum for CSR, a higher CSR value was desired. Fabrication sequence shown as item 39 was developed and the resulting tube showed an average CSR of 1.65, again showing that the heavier wall reductions produced a more radially textured tube with higher CSR values. A limited production run of item 60 was performed using a higher last pass wall reduction. This further improved the CSR value. The reduction sequence of item 60 was changed slightly to accommodate a small size change in reflector tubing for the LWBR Core. Item 61 describes the tubing produced for LWBR reflector fuel rods.

The CSR versus cumulative Q-value (Q_C) for items 23, 25, 27, and 39 show a nearly linear relation between average CSR and Q_C approximated by the equation CSR = $0.41\ Q_C - 0.19$. The preproduction run (item 60) produced a slightly higher average CSR than that indicated by the above equation. This was selected as the core fabrication sequence for LWBR refelctor tubes. The results of core testing are shown to be slightly higher as reported by the vendor (1.88 average) while Bettis overinspection saw no difference (1.71 for average of 32 tests). The effect of a sinking pass in changing the texture of the tube (lowering the CSR value) is again evident where the Q-values were reversed ($\sim$2.0 vs $\sim$1/2) in the last two passes for lots 22, 24, 26 and the resulting CSR values were essentially random (1.02, 1.07, and 0.95 respectively).

C. Seed Tubing Development

Determination of a fabrication route for seed-size tubing initially consisted of the CSR evaluation of a group of recrystallize annealed seed tubing representative of eight different fabrication histories. This group is identified as items 4, 7, 13, 14, 19, 20, 32, and 33 in Tables C-14 and C-15. The results clearly demonstrate increasing CSR values with increasing Q_C-factors. At the low end of the range is Item 4 with five sinking passes with Q-values from 0.0 to 0.8 which resulted in an average CSR value of 0.50 while at the high end of the range is Item 13 with an average CSR of 2.76 produced by five ironing passes with Q-values of 1.28, 1.69, 1.44, 1.80 and 1.60 with a Q_C of 7.85). Concurrently, a limited quantity of item 35 with Q Ratios of 1.46, 1.28 and 1.10 was made as expected from the progressively more neutral reductions, the average CSR value did not meet the specification requirement of 1.2 minimum.

A texture development program was initiated to produce seed tubing by way of three different fabrication sequences: a 3-pass sequence, item 62; a 4-pass sequence, item 49; and a 5-pass sequence, item 50, with Q_C factors of 3.92, 5.70, and 7.13, respectively, as summarized in Table C-17 for convenient reference. The average CSR is shown to increase with increasing Q_C-factors. The effect of a fifth pass on increasing CSR is evident when comparing items 49 and 50 where the last four reductions are identical. Item 50 was processed from a larger extrusion and the first reduction brought item 50 to the size of the extrusion used as starting stock for item 49. The item 62 evaluation proved somewhat of a surprise, since the reported CSR range of 1.3 to 1.5 is considerably higher than anticipated, based on the results of item 35 (CSR = 0.9 to 1.3) which was fabricated by an almost identical reduction sequence. It is assumed that the 10 percent higher wall reduction ratio (1.18 for last pass of item 62 vs 1.10 for item 35) resulted in a higher ordering of the basal poles and this is shown in the higher CSR value. Items 49 and 50, while successful in meeting the desired CSR requirements, encountered the same difficulty as was previously discussed for Blanket Items 54 and 57, i.e., severe lubrication problems during the last reduction operation caused a degradiation of the surface finish of the tubes. The changes of CSR with Q in each reduction are illustrated in Figures C-7 and C-9. Based on the results of the item 62 development effort which had demonstrated that a seed tubing process of "good fabricability" could meet the minimum 1.2 CSR requirement, a preproduction program was initiated. This program included two fabrication routes - item 51, a duplication of item 62 except for a slight increase in Q in the last reduction pass to accommodate a small change in the final seed size; and item 53, a 3-pass reduction sequence with a somewhat higher Q-value than item 51 in the last two reductions for additional assurances of meeting the 1.2 minimum CSR requirement. The CSR data indicated that both items met the texture requirement, and since both items were manufactured without difficulty, either route was considered satisfactory for the reference seed process. The route represented by item 53 was selected for the production effort. No difficulty was encountered in meeting the required 1.2 to 2.3 range for LWBR core seed tubing.

X. CONCLUSIONS

1. The contractile strain ratio (CSR), defined as the ratio of circumferential to radial strain obtained during uniaxial tensile straining in the uniform strain range, can be used to characterize the preferred crystallographic orientation in Zircaloy-4 tubing. A correlation exists between CSR and X-Ray Texture.

2. The texture of tubing as measured by CSR is affected by the final heat treatment. The change in CSR with recrystallization is related to the 60° rotation of the prism planes about the basal pole of the crystal lattice during recrystallization. The CSR value for RXA tubes is larger than the CSR value for stress relieved tubing as shown by the equation: $CSR_R = 1.26\ CSR_S + 0.040$.

3. CSR is a reliable and reproducible measure of texture.

4. CSR testing should employ the maximum uniform strain possible, reaching ultimate stress, to reduce the effect of measurement error on CSR determination.

5. CSR based on true strain is directly related to the "convenience" CSR used in LWBR. The same applies to the Q-values used to characterize the individual reduction operation.

6. Good texture (CSR > 1.4) is compatible with good commercial pratice in the fabrication of tubing.

7. The Q_c-factor, defined as the sum of the individual tube reduction pass Q-ratios, serves as a reasonably good index of CSR and can be used to aid in the selection of specific reduction sequences to meet specific tubing texture (CSR) requirements.

8. Tube reducing passes, which cold work the tubing wall to a greater degree than the tubing diameter, result in basal poles oriented predominantly in the radial direction. This effect is cumulative from pass-to-pass.

9. A significant reversal or reduction in the Q-value on a subsequent reduction will effect a reduction in the CSR.

10. The effectiveness of a given reduction ratio (Q-value) in changing texture is dependent on the amount of cold work used in deforming the existing texture of the input tube.

TABLE C-1

DERIVATION OF DIMENSIONS AND FORMULA FOR CONTRACTILE STRAIN MEASUREMENTS

A. Derivation of Volume Formula

$$V = \frac{\pi}{4}(D^2 - d^2)L$$

$$= \frac{\pi}{4}((d + 2W)^2 - d^2)L$$

$$= \frac{\pi}{4}(d^2 + 4dW + 4W^2 - d^2)L$$

$$= \frac{\pi}{4}(4W)(d + W)L$$

$$= \pi WML$$

B. Derivation of Strain Formula

$$\frac{V_f}{V_o} = \frac{\pi W_f M_f L_f}{\pi W_o M_o L_o} = 1$$

$$\ln \frac{V_f}{V_o} = \ln \frac{W_f}{W_o} + \ln \frac{M_f}{M_o} + \ln \frac{L_f}{L_o} = \ln(1) = 0$$

$$0 = E_W + E_M + E_L$$

C. Texture (CSR) = $E_M \div E_W$

Symbols

D = outside diameter

d = inside diameter

M = midwall diameter

L = gage length

W = wall thickness

V = volume of tube segment

E = strain = ln (final dimension ÷ original dimension)

o = original dimension (subscript)

f = final dimension (subscript)

TABLE C-2

CONTRACTILE STRAIN RATIO
TESTING PROCEDURE
FOR LWBR

A. Specimen: A full cross-section tube with a 3-inch gage length and a one inch free zone adjacent to each side of the gage length. No tooling is to contact the tube within this 5-inch zone during straining.

B. Testing Conditions:

1. Temperature: Room temperature
2. Strain rate: 0.05 ± 0.005 inch per inch of gage length
3. Elongation: 3.5 to 8.0% (suggested, the higher strains produce better test results
4. Stress: Do not reach ultimate stress, stop as the load levels off
5. Clamping: Tubes to be supported internally under the grips with close fitting plugs positioned a minimum of one inch outside the 3-inch gage length.

C. Gage length preparation: Lightly scribe a grid consisting of:

1. 4 longitudinal lines at 90° intervals around the tube.
2. 4 circumferential lines at 1 inch increments along the tube (3 inch gage).

D. Measurements:

The following measurements are to be taken before the tube has been strained uniaxially and at the same locations after straining.

1. Gage length at each 90° location (4 total).
2. Diameter at 1/4 inch increments along the 3-inch gage at 0° and 90° (26 total).

E. Calculations:

1. Determine the average length and average diameter of the gage length both before and after elongation.
2. Calculate using average dimensions.

   a. Diametral strain = $E_D = \ln \frac{D_f}{D_o}$

   b. Axial strain = $E_L = \ln \frac{L_f}{L_o}$

   c. $\text{CSR} = \frac{E_D}{-E_L - E_D}$

TABLE C-3

STRAINS AND CONTRACTILE STRAIN RATIO EQUATIONS

1. Strains involved in CSR calculations

$$E_D = \ln \frac{D_f}{D_o} = \ln \frac{M_f + W_f}{M_o + W_o}$$

$$E_M = \ln \frac{M_f}{M_o}$$

$$E_W = \ln \frac{W_f}{W_o}$$

$$E_L = \ln \frac{L_f}{L_o}$$

$$E_M + E_W + E_L = 0 \neq E_D + E_W + E_L$$
$$E_M = E_D + \text{ERROR}$$

2. Contractile Strain Ratio (CSR)

A. True Strain CSR

$$CSR_M = E_M \div E_W$$

B. LWBR Convenience CSR

$$CSR_{LWBR} = E_D \div (-E_L - E_D)$$

C. Error (See Table C-4 for correction)

$$CSR_M = CSR_{LWBR} + \text{Correction}$$

TABLE C-4

TABLE OF CORRECTIONS FROM CSR_{LWBR} TO CSR_M

($CSR_M = CSR_{LWBR}$ + CORRECTION)

CSR_{LWBR}	O.D. to Wall Ratio				
	11.5	13.0	16.0	19.0	20.5
0.1	-.090	-.079	-.063	-.053	-.049
0.2	-.089	-.078	-.062	-.052	-.048
0.3	-.086	-.075	-.060	-.050	-.046
0.4	-.081	-.070	-.056	-.046	-.043
0.5	-.073	-.064	-.051	-.042	-.038
0.6	-.063	-.055	-.044	-.036	-.033
0.7	-.051	-.044	-.035	-.029	-.026
0.8	-.036	-.031	-.024	-.020	-.019
0.9	-.019	-.017	-.013	-.011	-.010
1.0	0	0	0	0	0
1.2	0.05	0.04	0.03	0.02	0.02
1.4	0.11	0.09	0.07	0.06	0.05
1.6	0.18	0.16	0.12	0.10	0.09
1.8	0.26	0.23	0.17	0.14	0.13
2.0	0.36	0.31	0.24	0.19	0.18
2.2	0.48	0.40	0.32	0.24	0.23
2.4	0.61	0.51	0.40	0.31	0.29
2.6	0.76	0.63	0.48	0.39	0.35
2.8	0.92	0.77	0.58	0.46	0.42
3.0	1.12	0.93	0.69	0.56	0.50
3.2	1.32	1.09	0.82	0.65	0.58
3.4	1.56	1.28	0.95	0.75	0.68
3.6	1.82	1.50	1.09	0.86	0.78
3.8	2.12	1.72	1.24	0.99	0.88
4.0	2.47	1.97	1.43	1.12	1.00
4.2	2.80	2.25	1.62	1.26	1.14
4.4	3.21	2.55	1.83	1.41	1.27
4.6	3.66	2.89	2.04	1.57	1.42
4.8	4.16	3.26	2.28	1.75	1.57
5.0	4.72	3.86	2.54	1.94	1.72

TABLE C-5

CORRELATION* OF X-RAY TEXTURE WITH CONTRACTILE STRAIN RATIO IN TUBING

Fabrication Sequence Line #	O.D. (Inch)	Ratio of O.D./W	X-Ray Texture <0001 > T / <0001 > R	Stress Relieved CSR (b)	CSR (c)M	Recrystallized CSR (d)	CSR (e)M
8	0.283	14.9	0.92	0.98	0.98	1.19	1.22
9	0.283	14.9	0.73	1.17	1.19	1.55	1.67
10(a)	0.283	14.9	0.29	2.02	2.29	-	-
11(a)	0.283	14.9	0.25	2.04	2.32	-	-
12	0.283	14.9	0.55	1.77	1.95	-	-
13	0.283	14.9	0.35	2.05	2.34	2.76	3.37
14	0.283	14.9	0.43	1.75	1.93	2.42	2.86
15	0.283	14.9	0.41	2.10	2.41	-	-
19	0.250	13.5	0.97	0.95	0.94	1.21	1.25

(a) Items 10 and 11 were identically processed except in the last reduction where the size change of #10 was achieved by plug drawing while #11 was tube reduced in all reductions.

(b),(d) CSR via LWBR convenience calculation using OD & L.

(c),(e) CSR via true strain calculation using Mid-wall Diam. & L.

* Linear Regression Equations of CSR versus X-Ray Texture (XRT)

CSR Column	Equation	Correlation Coefficient	Number of Data Points
b	XRT = 1.434 - 0.541 (CSR as SRA)	-0.966	9
c	XRT = 1.312 - 0.423 (CSR_M as SRA)	-0.963	9
d	XRT = 1.382 - 0.385 (CSR as RXA)	-0.988	5
e	XRT = 1.263 - 0.281 (CSR_M as RXA)	-0.985	5

TABLE C-6

REPRODUCIBILITY OF CSR MEASUREMENTS

Line #	Tube Type	O.D.	Ratio (O.D. ÷ W)	Average CSR	No. of Tests	Standard Deviation
53	Seed	0.3105	12.8	1.578	120	0.2357
56	PF Blkt	0.531	19.0	1.789	81	0.1115
59	Std.Blkt.	0.576	19.2	1.908	90	0.1098
60	Reflector	0.835	19.2	1.773	166	0.1380

TABLE C-7

EFFECT OF STRESS RELIEF ON CSR

Line #	O.D.	O.D./W	CSR-CW		CSR-SRA		Combined	
			Average	No.of Test	Average	No.of Test	Average	No.of Test
33	.259	11.9	1.49	3	1.53	4	1.51	7
47	.307	16.9	1.60	3	1.55	3	1.57	6
48	.600	36.4	3.66	3	3.24	3	3.45	6

TABLE C-8

EFFECT OF RECRYSTALLIATION ON CSR*
(SPECIMEN TESTED IN SAME FACILITY)

Line #	O.D.	O.D./W	CSR-SRA Average	CSR-SRA No.of Tests	CSR-RXA Average	CSR-RXA No.of Tests	AVERAGE CSR** SRA	AVERAGE CSR** RXA
17	.6265	16.9	1.62	12	2.17	9	1.72	2.46
18	.250	13.5	1.15	6	1.76	1	1.18	1.98
23	.7225	20.1	1.35	2	1.77	2	1.40	1.90
26	.7225	15.7	0.95	4	1.23	4	0.94	1.26
28	.522	16.3	0.87	4	1.22	4	0.86	1.25
29	.522	16.3	1.11	2	1.54	2	1.13	1.65
32	.254	11.6	0.98	2	1.32	2	0.98	1.40
33	.259	11.9	1.51	7	1.69	8	1.65	1.90
37	.529	17.9	1.35	15	1.87	5	1.40	2.05
39	.8355	18.6	1.65	21	1.78	5	1.76	1.92
41	.529	17.9	1.76	10	2.08	3	1.91	2.32
43	.574	18.2	1.98	12	2.29	2	2.20	2.59
45	.8355	18.6	1.68	12	2.30	2	1.80	2.59
47	.307	16.9	1.55	3	2.05	3	1.55	2.28
48	.600	36.4	3.45	6	4.31	3	4.05	5.40
49	.3074	12.7	1.19	2	1.48	20	1.23	1.60
8	.283	14.9	.98	2	1.19	2	0.98	1.22
9	.283	14.9	1.17	2	1.55	2	1.20	1.67
13	.283	14.9	2.05	2	2.76	2	2.35	3.40
14	.283	14.9	1.75	2	2.42	2	1.94	2.86
19	.250	13.5	0.95	12	1.21	8	0.94	1.25

* Linear Regression Equations	Correlation Coefficient
CSR(RXA) = 1.2615 [CSR(SRA)] + 0.040	0.9767
CSR_M(RXA) = 1.2967 [CSR_M(SRA)] + 0.086	0.9752

** The listed values of CSR_M were calculated using CSR_{LWBR} data in this table and the corrections shown in Table C-4.

TABLE C-9

EFFECT OF RECRYSTALLIZATION TIME AND TEMPERATURE ON CSR DATA (TUBE LINE #20)

Tube Data:		
O.D.	0.2595	
O.D./W	11.8	
Heat Treatment:		
Temperature °F	1235	1300
Time, Hours	5	4
CSR Values:		
Lot 30	1.266	1.629
	1.529	1.650
	1.392	1.274
		1.324
Average	1.396	1.469
Lot 40	1.426	1.847
	1.375	1.690
	1.327	1.665
	1.332	1.525
Average	1.365	1.682
Combined Average	1.378	1.576
No	7	8

TABLE C-10

CONTRACTILE STRAIN RATIO (CSR) VERSUS % AXIAL ELONGATION FOR SEED TUBES STRAINED AT ROOM TEMPERATURE IN UNIAXIAL TENSION

(Line #19, 0.250" O.D. x 0.0185" Wall, (O.D. ÷ W) = 13.5)

Tubing No.	Final Heat Treat*	Initial Strain % Elong.	Initial Strain CSR	Re-strain Cycle No. 1 % Elong.	Re-strain Cycle No. 1 CSR	Re-strain Cycle No. 2 % Elong.	Re-strain Cycle No. 2 CSR
5-1	SRA	0.47	0.34	4.42	0.84		
5-2	SRA	0.57	0.54	4.26	1.05		
5-3	SRA	0.93	0.53	5.94	0.91		
5-4	SRA	0.88	0.47	5.57	0.92		
15-2B	SRA	3.06	1.35	7.24	1.16	8.39	1.27
15-21A	SRA	1.38	0.89	5.80	0.99	10.97	1.13
15-21B	SRA	1.52	1.77	5.81	1.24	9.12	1.08
15-6B	SRA	1.40	1.09	5.33	1.06	7.71	0.99
20-11C	SRA	0.57	0.25	4.76	0.84		
20-11A	SRA	0.51	0.45	4.45	0.85		
21-21B	SRA	0.90	0.80	5.31	0.99		
20-9A	SRA	1.35	0.90	5.95	1.01		
5-7	RXA**	2.58	0.96	7.20	0.96		
5-8	RXA**	3.05	1.21	7.97	1.23		
5-9	RXA**	2.06	0.96	7.90	0.97		
5-10	RXA**	2.53	1.20	7.82	1.22		

*Final Heat-Treatment

SRA = Stress-Relief Annealed
RXA = Recrystallize Annealed

**Tubing was received from vendor in SRA condition and was recrystallized at Bettis by heat treating for 6 hours at 1237°F in vacuum.

TABLE C-11

CONTRACTILE STRAIN RATIO (CSR) VERSUS % AXIAL ELONGATION
FOR BLANKET TUBES STRAINED AT ROOM TEMPERATURE IN UNIAXIAL TENSION

(Line #17, 0.627" O.D. x 0.037" Wall, (O.D. ÷ W) = 16.9)

Tubing No.	Final Heat Treat*	Initial Strain		Re-strain Cycle No. 1		Re-strain Cycle No. 2		Re-strain Cycle No. 3	
		% Elong.	CSR	% Elong	CSR	% Elong.	CSR	% Elong.	CSR
B-1-11A	SRA	0.94	2.30	4.60	1.61	5.65	1.56	8.80	1.52
B-1-11B	SRA	0.96	2.97	5.18	1.68	7.15	1.56		
B-1-11C	SRA	1.02	2.26	5.01	1.67	5.97	1.56		
B-1-11D	SRA	1.01	1.98	4.93	1.63	6.12	1.50	13.07	1.61
B-1-12R	RXA**	2.18	1.77	6.41	1.86	10.96	2.24		
B-1-13R	RXA**	1.79	2.10	6.51	2.18	11.37	2.37		
B-1-14R	RXA**	1.85	2.89	6.65	2.31	11.03	2.16		
B-2	SRA	5.78	1.52						
B-2	SRA	6.09	1.63						
B-4	SRA	7.41	1.65						
B-4	SRA	6.57	1.61						

*Final Heat Treatment

SRA = Stress relief anneal
RXA = Recrystallization anneal

**Tubing purchased in SRA condition were recrystallized at Bettis for 6 hours invacuum furnace held at 1237°F.

TABLE C-12

TABLE OF CORRECTIONS OF Q BASED ON O.D. TO Q BASED ON MD*

Q_{OD}	O.D.-To-Wall Ratio				
	11.5	13.0	16.0	19.0	20.5
0.1	-.0079	-.0070	-.0055	-.0048	-.0044
0.2	-.0143	-.0126	-.0101	-.0085	-.0079
0.3	-.0188	-.0166	-.0135	-.0113	-.0104
0.4	-.0217	-.0190	-.0154	-.0130	-.0119
0.5	-.0227	-.0200	-.0162	-.0136	-.0125
0.6	-.0220	-.0193	-.0156	-.0130	-.0120
0.7	-.0194	-.0171	-.0138	-.0114	-.0106
0.8	-.0149	-.0130	-.0106	-.0088	-.0082
0.9	-.0083	-.0073	-.0059	-.0050	-.0046
1.0	0	0	0	0	0
1.2	0.03	0.02	0.02	0.02	0.02
1.4	0.06	0.05	0.04	0.03	0.03
1.6	0.10	0.08	0.07	0.06	0.05
1.8	0.15	0.13	0.10	0.08	0.07
2.0	0.21	0.18	0.14	0.12	0.11
2.2	0.28	0.24	0.19	0.16	0.14
2.4	0.37	0.32	0.24	0.20	0.18
2.6	0.46	0.40	0.31	0.25	0.23
2.8	0.58	0.49	0.38	0.31	0.28
3.0	0.71	0.60	0.46	0.37	0.34
3.2	0.85	0.72	0.55	0.44	0.41
3.4	1.01	0.85	0.65	0.53	0.48
3.6	1.19	1.00	0.76	0.61	0.55
3.8	1.38	1.16	0.87	0.70	0.64
4.0	1.60	1.34	1.00	0.80	0.73
4.2	1.84	1.53	1.14	0.91	0.83
4.4	2.10	1.74	1.28	1.03	0.93
4.6	2.40	1.97	1.46	1.15	1.04
4.8	2.73	2.23	1.62	1.29	1.17
5.0	3.08	2.50	1.82	1.44	1.29

* $Q_{MD} = Q_{OD}$ + Correction

$Q_{MD} = Q_{LWBR}$ + Correction

TABLE C-13

DEVELOPMENT OF TEXTURE THROUGH THE TUBE MANUFACTURING SEQUENCE*

Item	Tube Size OD	Tube Size ID	Information #	Extrusion	1st Pass	2nd Pass	3rd Pass	4th Pass	
62	.307"	.259"	Reduction	-	80.3%	73.6%	50.1%		
			Q Ratio		1.47	1.26	1.22		
			Q_c	-	1.47	2.73	3.95	N/A	
			O.D. ÷ W	5.5	9.09	11.33	12.65		
			CSR Range	.73-.77	1.21-1.26	1.40-1.52	1.33-1.52		
			CSR Average	.76	1.23	1.44	1.40		
			No.of Tests	3	3	3	10		
			Condition	As-Extruded	RXA	RXA	RXA		
63	.307"	.259"	Reduction	-	80.3%	73.6%	39.9%	16.9%	
			Q Ratio		1.47	1.26	2.07(PD)	0.28(PD)	
			Q_c	-	1.47	2.73	4.30	1.20	
			O.D. ÷ W	5.5	9.09	11.33	12.34	12.65	
			CSR Range	.73-.77	1.21-1.26	1.40-1.52	1.83-2.02	-	1.17-1.18
			CSR Average	.76	1.23	1.44	1.93	(1.50)**	1.17
			No.of Tests	3	3	3	3	-	2
			Condition	As-Extruded	RXA	RXA	RXA	RXA	SRA
49	.307"	.259"	Reduction	-	60.9%	50.0%	76.5%	56.2%	
			Q Ratio		1.40	1.41	1.40	1.49	
			Q_c	-	1.40	2.81	4.21	5.70	
			O.D. ÷ W	4.92	6.06	7.01	10.21	12.65	
			CSR Range	.75-.80	.92-.98	.92-.94	1.30-1.32	1.26-1.67	1.10-1.28
			CSR Average	.77	.95	.93	1.31	1.48	1.19
			No.of Tests	3	3	3	3	20	2
			Condition	As-Extruded	RXA	RXA	RXA	RXA	SRA

TABLE C-13 (continued)

Item	Tube Size OD	Tube Size ID	Information #	Extrusion	1st Pass		2nd Pass		3rd Pass		4th Pass	5th Pass
50	.307"	.259"	Reduction	-	51.7%		60.9%		50.0%		76.5%	56.2%
			Q Ratio		1.47		1.40		1.41		1.40	1.49
			Q_c	-	1.47		2.87		4.28		5.68	7.17
			O.D. ÷ W	4.17	4.92		6.06		7.01		10.12	12.65
			CSR Range	.81-.84	.83-.88		1.02-1.09		1.04-1.27		1.44-1.50	1.40-2.24
			CSR Average	.82	.85		1.04		1.13		1.48	1.75
			No.of Tests	2	3		3		3		3	20
			Condition	As-Extruded	RXA		RXA		RXA		RXA	RXA
54	.529"	.472"	Reduction	-	70%		57.8%		67.0%			
			Q Ratio		1.86		1.83		1.87			
			Q_c	-	1.86		3.69		5.56			
			O.D. ÷ W	4.92	8.33		11.54		18.56			
			CSR Range	.73-.80	1.43-1.93	1.08-1.33	-	1.42-1.70	-	1.48-2.46	N/A	N/A
			CSR Average	.76	1.68	1.24	(2.00)	1.58	(2.40)**	1.84		
			No.of Tests	6	5	5	-	6	-	23		
			Condition	As-Extruded	RXA	SRA	RXA	SRA	RXA	SRA		
57	.574"	.513"	Reduction	-	70.0%		57.8%		61.7%			
			Q Ratio		1.86		1.83		2.22			
			Q_c	-	1.86		3.69		5.91			
			O.D. ÷ W	4.92	8.33		11.54		18.82			
			CSR Range	.73-.80	1.43-1.93	1.08-1.33	-	1.42-1.70	-	1.76-3.14	N/A	N/A
			CSR Average	.76	1.68	1.24	(2.00)**	1.58	(2.71)**	2.12		
			No.of Tests	6	5	5	-	6	-	22		
			Condition	As-Extruded	RXA	SRA	RXA	SRA	RXA	SRA		

TABLE C-13 (Continued)

Item	Tube Size OD	Tube Size ID	Information #	Extrusion	1st Pass	2nd Pass		3rd Pass	4th Pass		
61	.835	".748"	Reduction	-	69.2%	69.7%					
			Q Ratio		1.98	2.39					
			Q_c	-	1.98	4.37					
			O.D. ÷ W	5.55	9.78	18.99					
			CSR Range	.74-.79	1.24-1.32	-	1.38-2.12	N/A		N/A	
			CSR Average	.75	1.29	(2.30)**	1.77				
			No.of Tests	3	3	-	166				
			Condition	As-Extruded	RXA	RXA	SRA				
47	.423"	.373"	Reduction	-	50.9%	52.0%		70.9%		77.4%	
			Q Ratio		0.99	1.18		1.48		2.54	
			Q_c	-	0.99	2.17		3.65		6.19	
			O.D. ÷ Wall	5.81	5.79	6.25		10.00		16.92	
			CSR Range	-	.75-.89	-		1.56-1.66	1.95-2.13	1.50-1.61	1.58-1.61
			CSR Average	-	0.82	(Est. 1.05)		1.61	2.05	1.54	1.59
			No.of Tests	-	3	-		4	3	3	3
			Condition	As-Extruded	RXA	-		RXA	RXA	SRA	CW
48	.600"	.574"	Reduction	-	50.9%	64.5%		77.4%		70.1%	
			Q Ratio		0.99	1.88		2.35		1.81	
			Q_c	-	0.99	2.87		5.22		7.03	
			O.D. ÷ Wall	5.81	5.79	8.86		20.88		36.36	
			CSR Range	-	0.75-0.89	1.37-1.44		2.87-3.00	3.93-4.62	2.91-3.44	3.59-3.72
			CSR Average	-	0.82	1.41		2.95	4.31	3.24	3.66
			No.of Tests	-	3	4		4	3	3	3
			Condition	As-Extruded	RXA	RXA		RXA	RXA	SRA	CW

#
Red = % area reduction
Q Ratio = % wall reduction ÷ % O.D. reduction
Q_c = Cumulative Q-ratio
W = Nominal wall thickness
OD = Nominal outside diameter
RXA = Recrystallize annealed
SRA = Stress relief annealed

* All passes following extrusion were tube reduced except 3rd and 4th pass of Item 63 which were plug drawn (PD)

** Calculated using Figure C-3 and the corresponding CSR-SRA data.

TABLE C-14

FABRICATION SEQUENCES OF TUBES
BY ITEM NUMBER OF THIS REPORT

Item No.	Tube Code No.	Nominal Dimensions O.D.	Nominal Dimensions Wall	Reduction Sequence 1st Pass % CW	1st Pass WRR	2nd Pass % CW	2nd Pass WRR	3rd Pass % CW	3rd Pass WRR	4th Pass % CW	4th Pass WRR	5th Pass % CW	5th Pass WRR	6th Pass % CW	6th Pass WRR
1	S-66576M PWR	0.4195	0.0305	59.1	1.09	51.6	1.16	45.2	2.22	43.9	0.28P	13.4	0.49P	-	-
2	W-306031 SABRE	0.566	0.0335	47.6	2.23	50.4	3.36	-	-	-	-	-	-	-	-
3	W-273688	0.573	0.0370	88.6	2.57	62.1	0.46	45.7	0.60P	-	-	-	-	-	-
4	W-273688	0.254	0.0180	88.6	2.57	62.1	0.46	55.4	0.75	49.8	0.37	14.2	-0.27S	22.1	0.26P
5	R-306088	0.6255	0.0365	N/A	N/A	67.0	2.36E	64.0	0.78	58.6	1.54	-	-	-	-
6	R-306088	0.6785	0.0405	N/A	N/A	67.0	2.36E	64.0	0.78	50.0	1.68	-	-	-	-
7	W-324635	0.2824	0.0187	65.0	1.19	74.0	1.31	78.0	1.13	-	-	-	-	-	-
8	S-337414-1	0.283	0.019	69.5	0.78	74.7	0.99	47.9	2.44	14.6	0.77P	-	-	-	-
9	S-337414-3	0.283	0.019	69.5	0.78	74.7	0.99	36.6	1.61	32.3	3.98P	-	-	-	-
10	W-335085-1	0.283	0.019	74.4	1.28	74.2	1.48	40.5	1.80	39.0	1.69	17.9	1.27	-	-
11	W-335085-2	0.283	0.019	74.4	1.28	74.2	1.48	40.5	1.80	39.0	1.69	17.9	1.27P	-	-
12	W-335085-3	0.283	0.019	74.4	1.28	74.2	1.48	64.8	1.66	17.9	1.27P	-	-	-	-
13	W-335085-4	0.283	0.019	74.4	1.28	55.3	1.69	41.4	1.44	40.5	1.80	52.0	1.61	-	-
14	W-335085-5	0.283	0.019	74.4	1.28	55.3	1.69	65.8	1.53	50.2	1.61	-	-	-	-
15	W-335085-6	0.283	0.019	74.4	1.28	74.2	1.48	72.3	1.58	-	-	-	-	-	-
16	W-335085-7	0.283	0.019	74.4	1.28	74.2	1.48	64.8	1.66B	17.9	1.27P	-	-	-	-
17	W-345610-1,7	0.6265	0.037	80.4	1.46	68.9	2.10	-	-	-	-	-	-	-	-
18	W-345610-3	0.250	0.0185	73.9	1.20	74.3	1.50	77.0	1.38	-	-	-	-	-	-
19	W-345610-3a	0.250	0.0185	73.9	1.20	72.6	1.87	78.4	1.18	-	-	-	-	-	-
20	W-345610-14	0.2595	0.0220	74.4	1.23	70.6	1.77	75.6	1.14	-	-	-	-	-	-
21	W-345610-18,19	0.5745	0.0318	79.8	1.87	64.4	2.83	34.4	0.60	-	-	-	-	-	-
22	W-369044-1A	0.7225	0.036	60.1	2.32	70.1	1.73	19.9	0.49	-	-	-	-	-	-
23	W-369044-1C,1D	0.7225	0.036	60.1	2.32	76.2	1.43	-	-	-	-	-	-	-	-
24	W-369044-2A	0.7225	0.041	76.0	1.69	44.6	2.20	19.4	0.44	-	-	-	-	-	-
25	W-349044-2C,2D	0.7225	0.041	50.7	1.74	78.4	1.52	-	-	-	-	-	-	-	-
26	W-369044-3A,3B	0.7225	0.046	72.3	1.52	46.2	2.33	20.4	0.53	-	-	-	-	-	-
27	W-369044-3C,3D	0.7225	0.046	50.7	1.74	76.1	1.43	-	-	-	-	-	-	-	-
28	W-369044-4A,4B	0.522	0.032	72.3	1.52	72.6	1.39	19.5	0.59	-	-	-	-	-	-
29	W-369044-4C,4D	0.522	0.032	77.1	1.39	73.5	1.57	-	-	-	-	-	-	-	-
30	W-369044-5A	0.254	0.022	75.9	1.33	67.6	1.62	71.4	1.29	19.6	0.52	-	-	-	-
31	W-369044-5D	0.254	0.022	75.9	1.33	67.6	1.62	77.2	1.15	-	-	-	-	-	-
32	W-369044-7C,7D	0.254	0.022	75.9	1.33	67.6	1.62	77.2	1.15	-	-	-	-	-	-
33	W369044-8,9	0.259	0.0218	71.8	1.40	61.2	1.50	68.3	1.31	47.9	1.27	-	-	-	-

TABLE C-14 (continued)

Item No.	Tube Code No.	Nominal Dimensions O.D.	Nominal Dimensions Wall	1st Pass % CW	1st Pass WRR	2nd Pass % CW	2nd Pass WRR	3rd Pass % CW	3rd Pass WRR	4th Pass % CW	4th Pass WRR	5th Pass % CW	5th Pass WRR	6th Pass % CW	6th Pass WRR
34	W369044-10,11	0.259	0.0218	64.4	2.20	59.5	1.89	45.1	1.39	-	-	-	-	-	-
35	W377050-1	0.307	0.025	79.9	1.46	74.1	1.28	49.3	1.10	-	-	-	-	-	-
36	W377050-2	0.529	0.0295	65.7	1.21	70.2	1.89	47.5	1.40	-	-	-	-	-	-
37	W377050-3	0.529	0.0295	79.7	1.31	73.4	1.61	-	-	-	-	-	-	-	-
38	W377050-4	0.8355	0.045	75.7	2.25	47.3	1.14	-	-	-	-	-	-	-	-
39	W377050-5	0.8355	0.045	64.1	2.59	73.2	1.87	-	-	-	-	-	-	-	-
40	B379666-1,2	0.529	0.0295	68.8	2.10	79.5	1.28	43.3	1.74	-	-	-	-	-	-
41	B379666-3,4	0.529	0.0295	64.3	1.87	71.7	1.36	64.1	1.75	-	-	-	-	-	-
42	B379666-5,9	0.574	0.0315	68.8	2.10	76.0	1.33	42.4	1.76	-	-	-	-	-	-
43	B379666-6,10	0.574	0.0315	64.3	1.87	60.0	1.48	69.9	1.64	-	-	-	-	-	-
44	B379666-7	0.8355	0.045	68.8	2.10	50.1	1.96	43.3	2.08	-	-	-	-	-	-
45	B379666-8	0.8355	0.045	68.8	2.10	71.7	1.81	-	-	-	-	-	-	-	-
46	B379666-11	0.307	0.025	49.8	1.05	56.2	1.30	59.3	1.33	66.3	1.38	42.8	1.38	-	-
47	B Com X1	0.423	0.025	50.9	0.99	52.0	1.18	79.0	1.48	77.4	2.54	-	-	-	-
48	B Com X2	0.600	0.0165	50.9	0.99	64.5	1.88	74.4	2.35	70.1	1.81	-	-	-	-
49	W463075-II-1A4	0.3074	0.0243	60.9	1.40	50.0	1.41	76.6	1.40	56.2	1.49	-	-	-	-
50	W463075-II-1A5	0.3074	0.0243	51.7	1.43	60.9	1.40	50.0	1.41	76.6	1.40	56.2	1.49	-	-
51	W463075-IIA-1C3	0.3105	0.0243	80.3	1.47	73.6	1.26	50.1	1.22	-	-	-	-	-	-
52	W463075-IIA-1C3PD	0.3105	0.0243	80.3	1.47	73.6	1.26	39.9	2.07	16.9	0.28P	-	-	-	-
53	W463075-III,IIA	0.3105	0.0243	76.8	1.32	65.4	1.50	67.8	1.31	-	-	-	-	-	-
54	W463075-II	0.529	0.0285	70.0	1.86	57.8	1.83	67.0	1.87	-	-	-	-	-	-
55	W463075-IIA-P3	0.531	0.028	80.8	1.34	74.4	1.67	-	-	-	-	-	-	-	-
56	W463075-IIA,IIIB3	0.531	0.028	82.0	1.90	70.8	1.50	-	-	-	-	-	-	-	-
57	W463075-II	0.574	0.0305	70.0	1.86	57.8	1.83	61.7	2.22	-	-	-	-	-	-
58	W463075-IIA	0.576	0.030	80.8	1.34	70.3	1.87	-	-	-	-	-	-	-	-
59	W463075-IIA,III	0.576	0.030	82.0	1.90	66.2	1.66	-	-	-	-	-	-	-	-
60	W463075-II	0.8355	0.0440	69.2	1.98	69.7	2.39	-	-	-	-	-	-	-	-
61	W463075-III	0.835	0.0435	69.7	2.00	69.7	2.39	-	-	-	-	-	-	-	-
62	W463075-II, 1A3	0.3074	0.0243	79.9	1.46	74.0	1.28	50.8	1.18	-	-	-	-	-	-
63	W463075-II	0.3074	0.0243	79.9	1.46	74.0	1.28	39.9	2.07	16.9	0.28P	-	-	-	-

SYMBOLS (in WRR Columns)

B = Beta quenched following this reduction
P = Plug drawn pass
S = Sinking pass
N/A = Not Available
CW = Cold work or area reduction
WRR = Wall Reduction Ratio
E = Estimated

TABLE C-15

CSR CHARACTERIZATION OF ZIRCALOY TUBING

	Size			CSR Data					
Item No.*	O.D.	Wall	Condition**	Avg.	No. of Tests	Std. Deviation	Min	Max	No. of Lots
1	.4195	.0305	R	0.792	8	0.126	0.66	1.00	4
2	.566	.0335	R	1.426	3	-	1.39	1.46	1
3	.573		R	1.60	2	-	1.6	1.6	-
4	.254		R	0.496	4	-	0.42	0.58	3
5	.6255		R-1	1.545	9	0.233	1.20	1.93	5
6	.6785		R	1.62	2	-	1.53	1.71	1
7	.2824		R	0.971	4	-	0.83	1.03	2
8	.283	0.0190	R	1.185	2	-	1.14	1.23	1
8	.283	0.0190	S	0.985	2	-	0.97	1.00	1
9	.283	0.0190	R	1.55	2	-	1.54	1.56	1
9	.283	0.0190	S	1.17	2	-	1.02	1.32	1
10	.283	0.0190	R	2.02	2	-	1.74	2.29	1
11	.283	0.0190	R	2.04	2	-	2.01	2.07	1
12	.283	0.0190	R	1.77	2	-	1.73	1.81	1
13	.283	0.0190	R-2	2.76	2	-	2.65	2.87	1
13	.283	0.0190	S	2.05	2	-	1.99	2.11	1
14	.283	0.0190	R-2	2.42	2	-	2.24	2.59	1
14	.283	0.0190	S	1.75	2	-	1.47	2.03	1
15	.283	0.0190	S	2.10	1	-	-	-	1
16	.283	0.0190	S	0.68	2	-	0.57	0.79	1
17	.6265	.037	R	2.17	9	0.147	1.86	2.36	4
17	.6265	.037	S	1.62	12	0.058	1.52	1.72	4
18	.250	0.0185	S	1.	6	0.126	1.01	1.37	1
19	.250	0.0185	R-2	1.21	8	0.033	1.16	1.24	2
19	.250	0.0185	S	0.95	12	0.071	0.84	1.06	4
20	.2595	.0220	R-3	1.38	7	0.084	1.27	1.53	7
20	.2595	.0220	R-4	1.58	8	0.193	1.27	1.85	8
21	.5745	.0318	R	1.81	16	0.088	1.70	1.98	3
22	.7225	.036	S	1.02	4	-	0.96	1.07	1
23	.7225	.036	R	1.77	2	-	1.76	1.78	1
23	.7225	.036	S	1.35	2	-	1.34	1.37	1
24	.7225	.041	S	1.07	4	-	1.01	1.13	1
25	.7225	.041	S	1.11	4	-	0.90	1.24	2
26	.7225	.046	R	1.23	2	-	1.21	1.25	1
26	.7225	.046	S	0.95	4	-	0.92	0.98	1
26P	.7225	.046	S	0.96	4	-	0.89	1.05	1
27	.7225	.046	S	1.17	4	-	1.15	1.20	2
28	.522	.032	R	1.22	4	-	1.13	1.33	1
28	.522	.032	S	0.87	4	-	0.78	0.93	1
29	.522	.032	R	1.54	2	-	1.51	1.57	1
29	.522	.032	S	1.11	2	-	1.08	1.13	1
30	.254	.022	S	1.06	4	-	1.01	1.17	1
31	.254	.022	S	1.49	4	-	1.43	1.54	1
32	.254	.022	R-2	1.32	2	-	1.26	1.38	1

TABLE C-15 (continued)

Item No.*	Size O.D.	Size Wall	Condition**	CSR Data Avg.	No. of Tests	Std. Deviation	Min	Max	No. of Lots
32	.254	.022	S	0.98	2	-	0.81	1.14	1
33	.259	.0218	R-2	1.69	8	0.0685	1.61	1.79	2
33	.259	.0218	S	1.53	4	-	1.45	1.58	1
33	.259	.0218	C	1.49	3	-	1.48	1.50	1
35	.307	.025	R	1.11	31	0.1128	0.89	1.31	2
36	.529	.0295	R	1.64	38	0.085	1.45	1.88	1
37	.529	.0295	R	1.87	5	-	1.81	1.92	1
37	.529	.0295	S	1.40	25	0.080	1.21	1.58	1
38	.8355	.045	R	1.51	30	0.078	1.39	1.66	1
39	.8355	.045	R	1.78	5	0.061	1.74	1.89	1
39	.8355	.045	S	1.65	21	0.099	1.37	1.80	1
40	.529	.0295	R	2.20	22	0.090	2.04	2.38	1
41	.529	.0295	R	2.08	3	-	2.02	2.12	1
41	.529	.0295	S	1.83	20	0.117	1.59	2.08	1
42	.574	.0315	R	1.92	22	0.088	1.72	2.05	1
43	.574	.0315	R	2.29	2	-	2.26	2.31	1
43	.574	.0315	S	1.93	22	0.146	1.71	2.30	1
44	.8355	.045	R	2.04	22	0.112	1.81	2.24	1
45	.8355	.045	R	2.30	2	-	2.29	2.31	1
45	.8355	.045	S	1.67	22	0.093	1.49	1.81	1
46	.307	.025	R	1.34	22	0.086	1.19	1.51	1
47	.423	.025	R	2.05	3	-	1.97	2.15	1
47	.423	.025	S	1.54	3	-	1.50	1.62	1
47	.423	.025	C	1.60	3	-	1.58	1.61	1
48	.600	.0165	R	4.31	3	-	3.93	4.62	1
48	.600	.0165	S	3.24	3	-	2.91	3.44	1
48	.600	.0165	C	3.66	3	-	3.59	3.72	1
49	.3074	.0243	R	1.48	20	0.0940	1.26	1.67	1
49	.3074	.0243	S	1.19	2	-	1.10	1.28	1
50	.3074	.0243	R	1.75	20	0.229	1.40	2.24	2
53-L	.3105	.0243	R	1.59	120	0.101	1.31	1.97	33
54	.529	.0285	S	1.80	20	0.157	1.48	2.25	2
56-L	.531	.028	S	1.79	81	0.111	1.58	2.11	21
57	.574	.0305	S	2.04	20	0.132	1.76	2.33	2
59-L	.576	.030	S	1.91	90	0.110	1.69	2.18	23
60	.8355	.044	S	1.73	80	0.107	1.47	1.95	8
61-OI	.835	.0435	S	1.71	32	0.136	1.38	2.04	8
61-L	.835	.0435	S	1.88	54	0.123	1.61	2.12	18
60+61	.835	.0435	S	1.77	166	0.138	1.38	2.12	26
62	.3074	.0243	R	1.40	10	0.059	1.33	1.52	1
63	.3074	.0243	S	1.17	2	-	1.17	1.18	1

* L = LWBR
P = Plug drawn in last reduction
OI = Overinspection tests performed at Bettis.

**Final Heat Treatments
R = Recrystallization anneal
S = Stress relief anneal
C = No heat treamtent following final reduction
1 = 1.5 hours at 1325°F
2 = 6 hours at 1235°F
3 = 5 hours at 1235°F
4 = 4 hours at 1300°F

TABLE C-16

GROUPING OF TUBE DATA AND FABRICATION SEQUENCES BY TUBE SIZE VS LINE NUMBERS OF TABLES C-14 AND C-15

Tube Dimensions				Tube Line Numbers vs CSR Test Conditions		
O.D.	Wall	O.D./W	No. of Reductions	R	S	C
.250	.0185	13.51	3	-	18	-
.250	.0185	13.51	3	19	19	-
.254	.018	14.11	6	4	-	-
.254	.022	11.55	4	-	30	-
.254	.022	11.55	3	-	31	-
.254	.022	11.55	3	32	32	-
.259	.0218	11.88	4	33	33	33
.2595	.0220	11.80	3	20	-	-
.283	.0187	15.10	3	7	-	-
.283	.0190	14.89	4P	8	8	-
.283	.0190	14.89	4P	9	9	-
.283	.0190	14.89	5	10	10	-
.283	.0190	14.89	5P	11	-	-
.283	.0190	14.89	4P	-	12	-
.283	.0190	14.89	5	13	13	-
.283	.0190	14.89	4	14	14	-
.283	.0190	14.89	3	-	15	-
.283	.0190	14.89	4 B,P	-	16	-
.307	.025	12.28	3	35	-	-
.307	.025	12.28	5	46	-	-
.3074	.0243	12.65	3	62	-	-
.3074	.0243	12.65	4P	63	-	-
.3074	.0243	12.65	4	49	49	-
.3074	.0243	12.65	5	50	-	-
.3105	.0243	12.78	3	51	-	-
.3105	.0243	12.78	3	-	53	-
.420	.0305	13.75	5P	1	-	-
.423	.025	16.92	4	47	47	47
.522	.032	16.31	3	28	28	-
.522	.032	16.31	2	29	29	-
.529	.0295	17.93	3	36	-	-
.529	.0295	17.93	2	37	37	-
.529	.0295	17.93	3	-	40	-
.529	.0295	17.93	3	41	41	-
.529	.0285	18.56	3	54	-	-
.531	.0280	18.96	2	56	-	-
.566	.0335	16.89	2	2	-	-
.573	.037	15.49	3	3	-	-
.574	.0315	18.22	3	42	-	-
.574	.0315	18.22	3	43	43	-
.574	.0305	18.22	3	-	57	-
.5745	.0318	18.07	3	21	-	-

TABLE C-16 (continued)

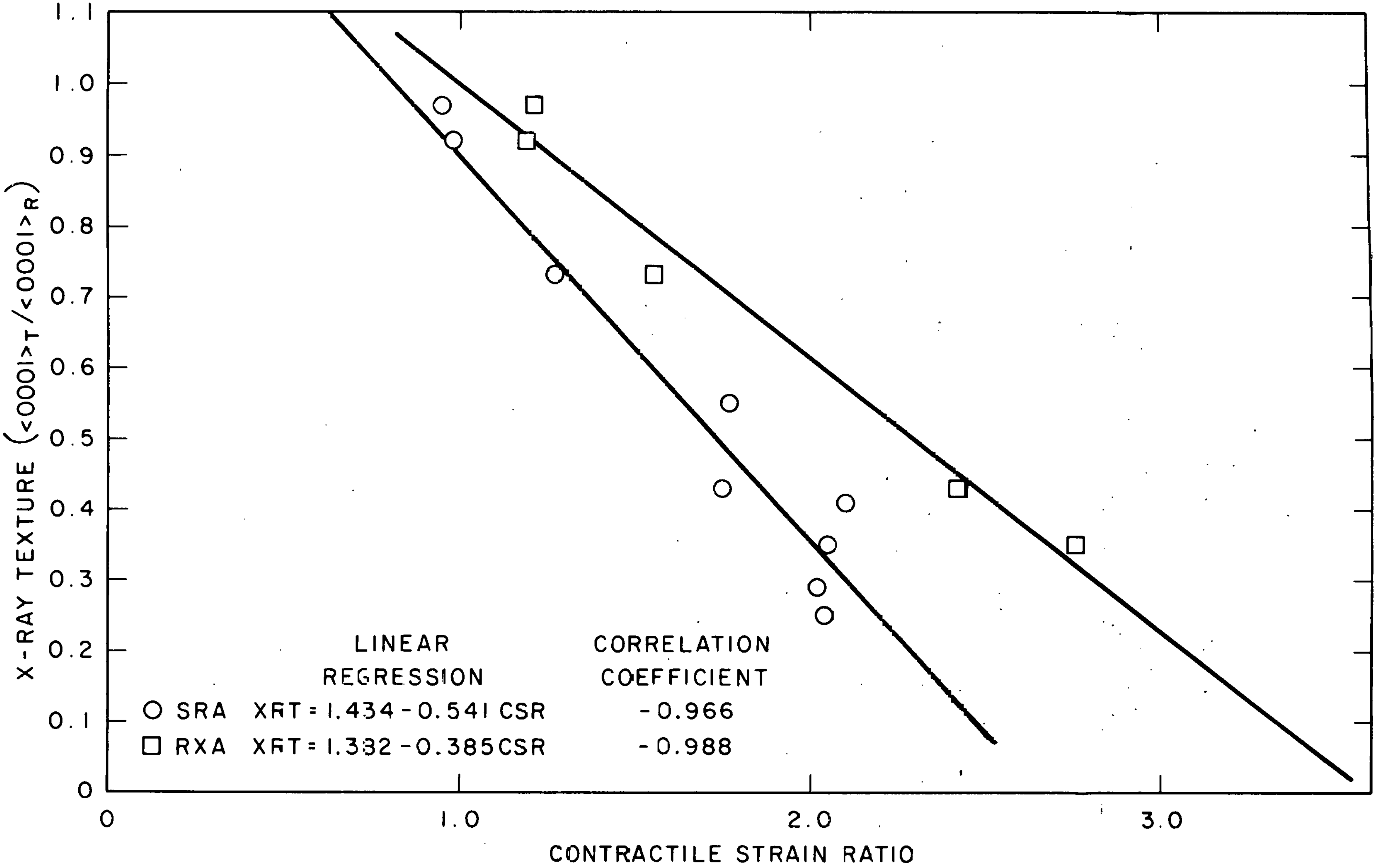
Tube Dimensions			No. of Reductions	Tube Line Numbers vs CSR Test Conditions		
O.D.	Wall	O.D./W		R	S	C
.576	.030	19.20	2	-	59	-
.600	.0165	36.36	4	48	48	48
.625	.0365	17.14	4	5	-	-
.627	.0370	16.93	2	17	17	-
.679	.0405	16.75	4	6	-	-
.7225	.036	20.07	3	-	22	-
.7225	.036	20.07	2	23	23	-
.7225	.041	17.62	3	-	24	-
.7225	.041	17.62	2	-	25	-
.7225	.046	15.71	3	26	26	-
.7225	.046	15.71	2	-	27	-
.8355	.045	18.57	2	38	-	-
.8355	.045	18.57	2	39	39	-
.8355	.045	18.57	3	44	-	-
.8355	.045	18.57	2	45	45	-
.8355	.044	18.99	2	-	60	-
.835	.0435	19.20	2	-	61	-

*B = Beta quenched prior to last reduction.
C = Cold worked,no heat treatment after final reduction.
P = Plug drawn in last pass.
R = Recrystallize annealed after last reduction.
S = Stress relief heat treated after last reduction.

TABLE C-17

SUMMARY OF SEED TEXTURE DEVELOPMENT DATA

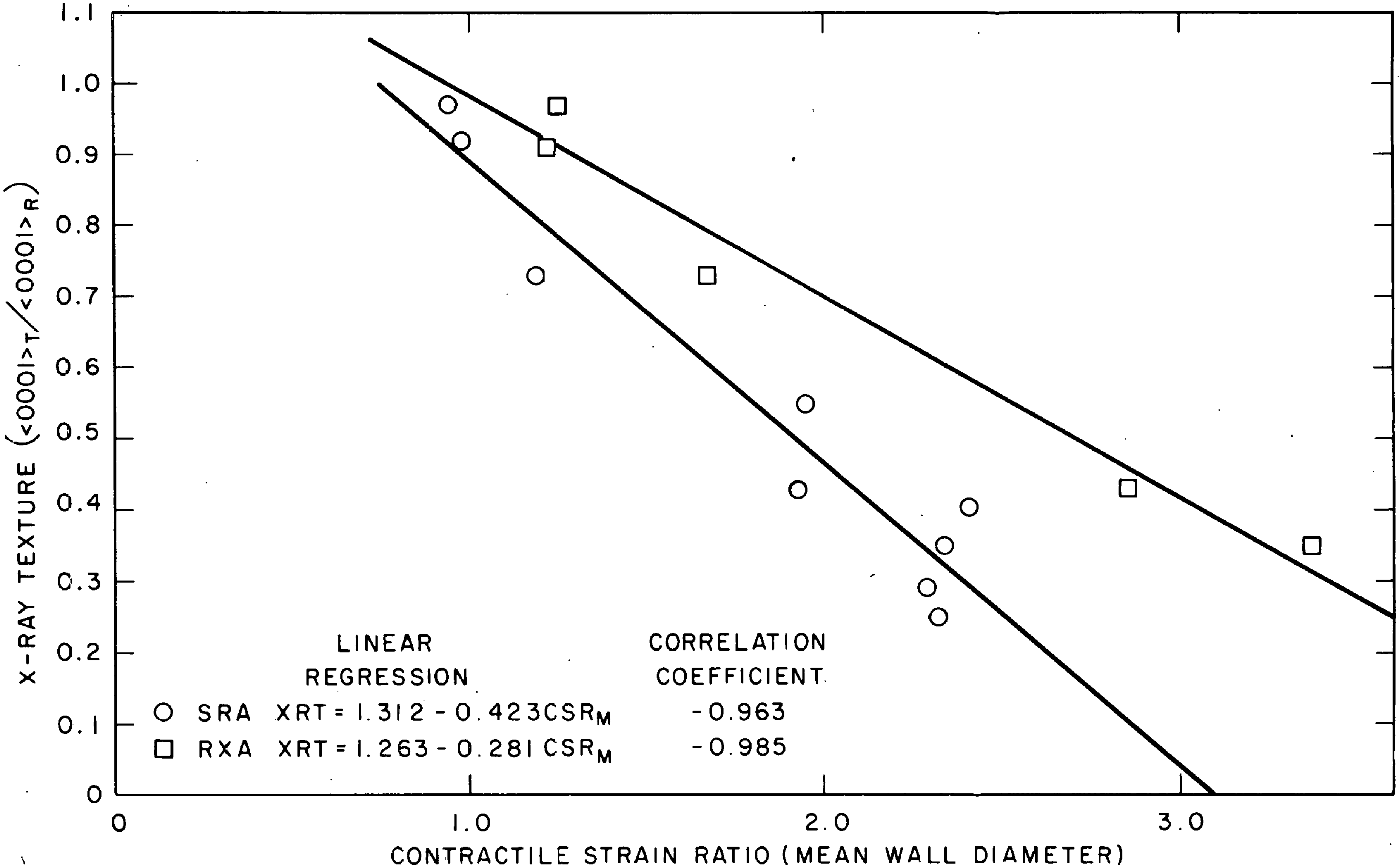
Item #	O.D.	Avg. CSR	Information	Pass In Reduction Sequence 1st	2nd	3rd	4th	5th	Q_c
35	.307	1.11	% CW	79.9	74.1	49.3			
			Q	1.46	1.28	1.10	-		3.84
62	.3074	1.40	% CW	79.9	74.0	50.8	-		
			Q	1.46	1.28	1.18	-		3.92
49	.3074	1.48	% CW	60.9	50.0	76.6	56.2	-	
			Q	1.40	1.41	1.40	1.49	-	5.70
50	.3074	1.75	% CW	51.7	60.9	50.0	76.6	56.2	
			Q	1.43	1.40	1.41	1.40	1.49	7.13
51	.3015	1.46	% CW	80.3	73.6	50.1	-		
			Q	1.47	1.26	1.22	-		3.95
53	.3105	1.44	% CW	76.8	65.4	67.8	-		
			Q	1.32	1.50	1.31	-		4.13
53-LWBR	.3105	1.58	% CW	76.8	65.4	67.8	-		
			Q	1.32	1.50	1.31	-		4.13



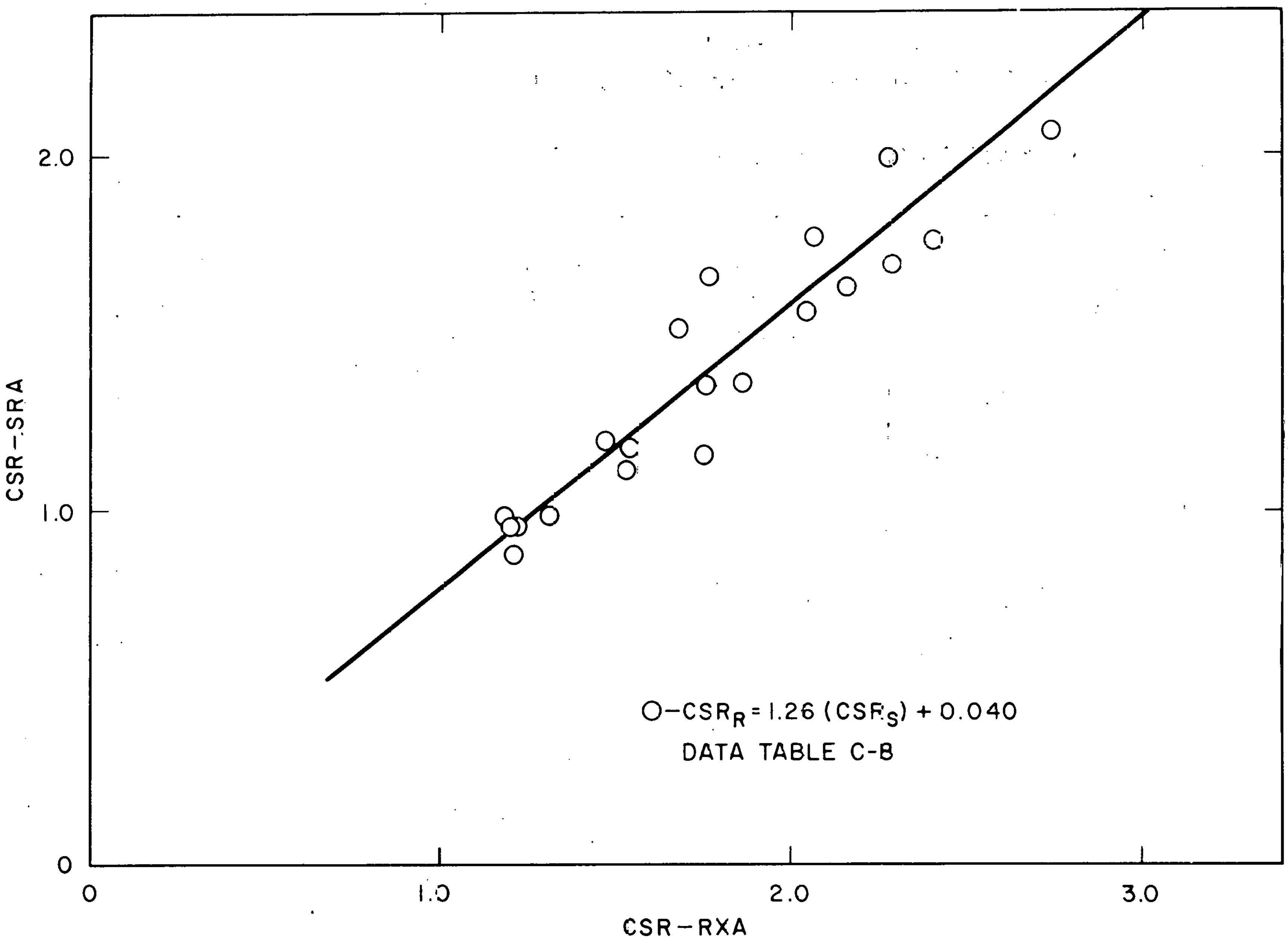
C36

CORRELATION OF X-RAY & CSR TEXTURE (LWBR)
FIGURE C-1

C37

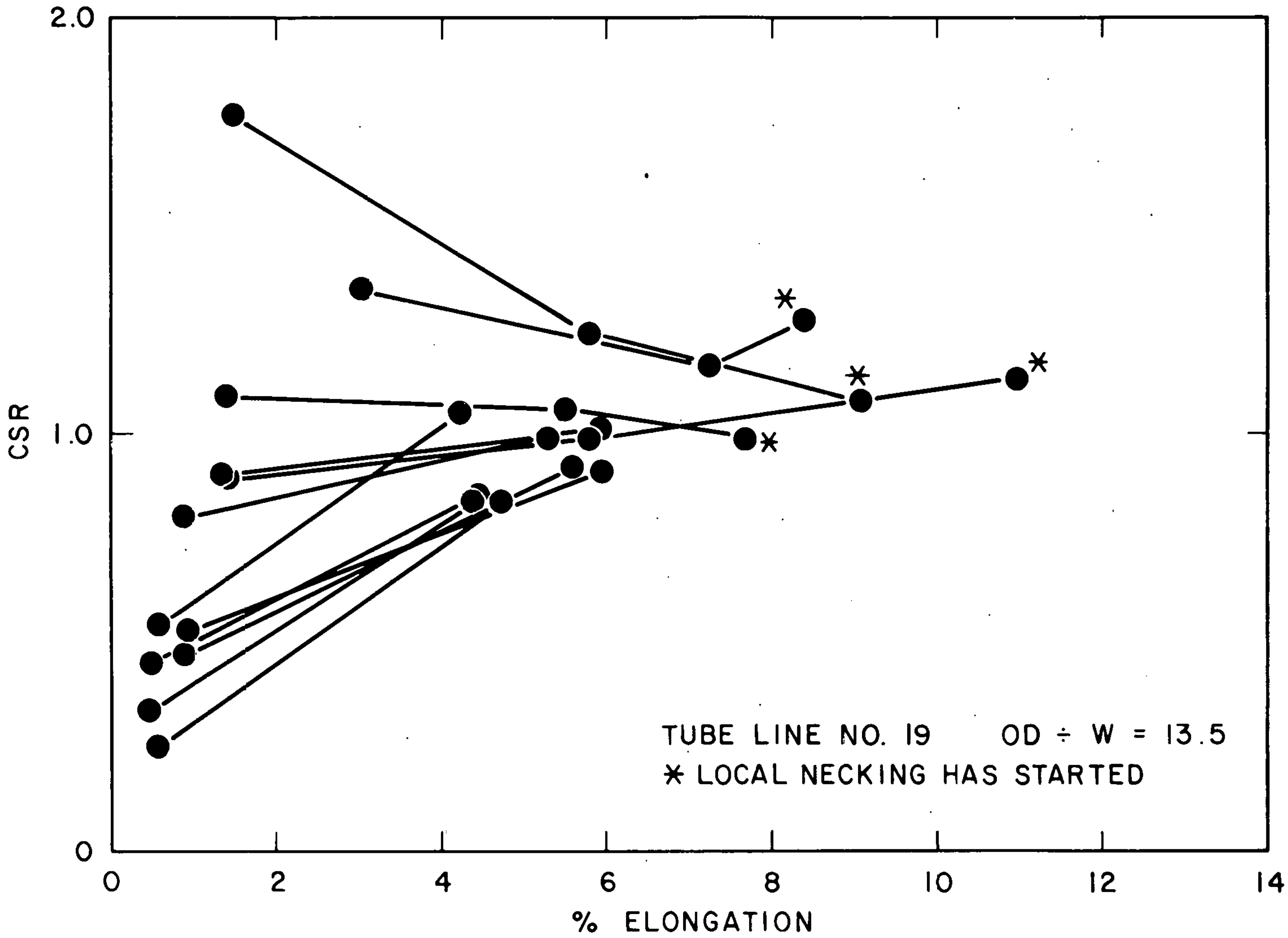


CORRELATION OF X-RAY & CSR TEXTURE
FIGURE C-2



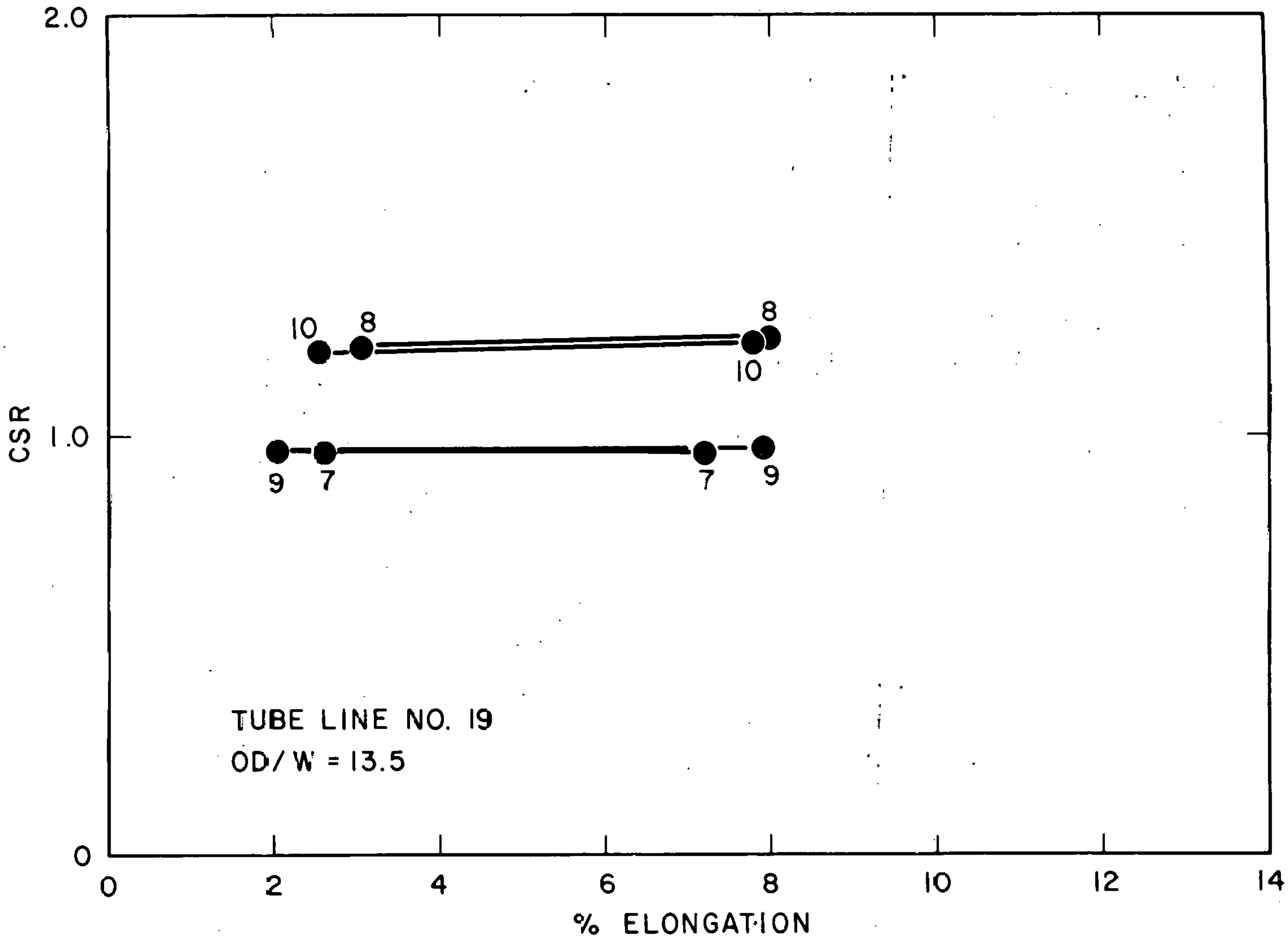
CORRELATION OF RXA & SRA TEXTURE (CSR)

FIGURE C-3



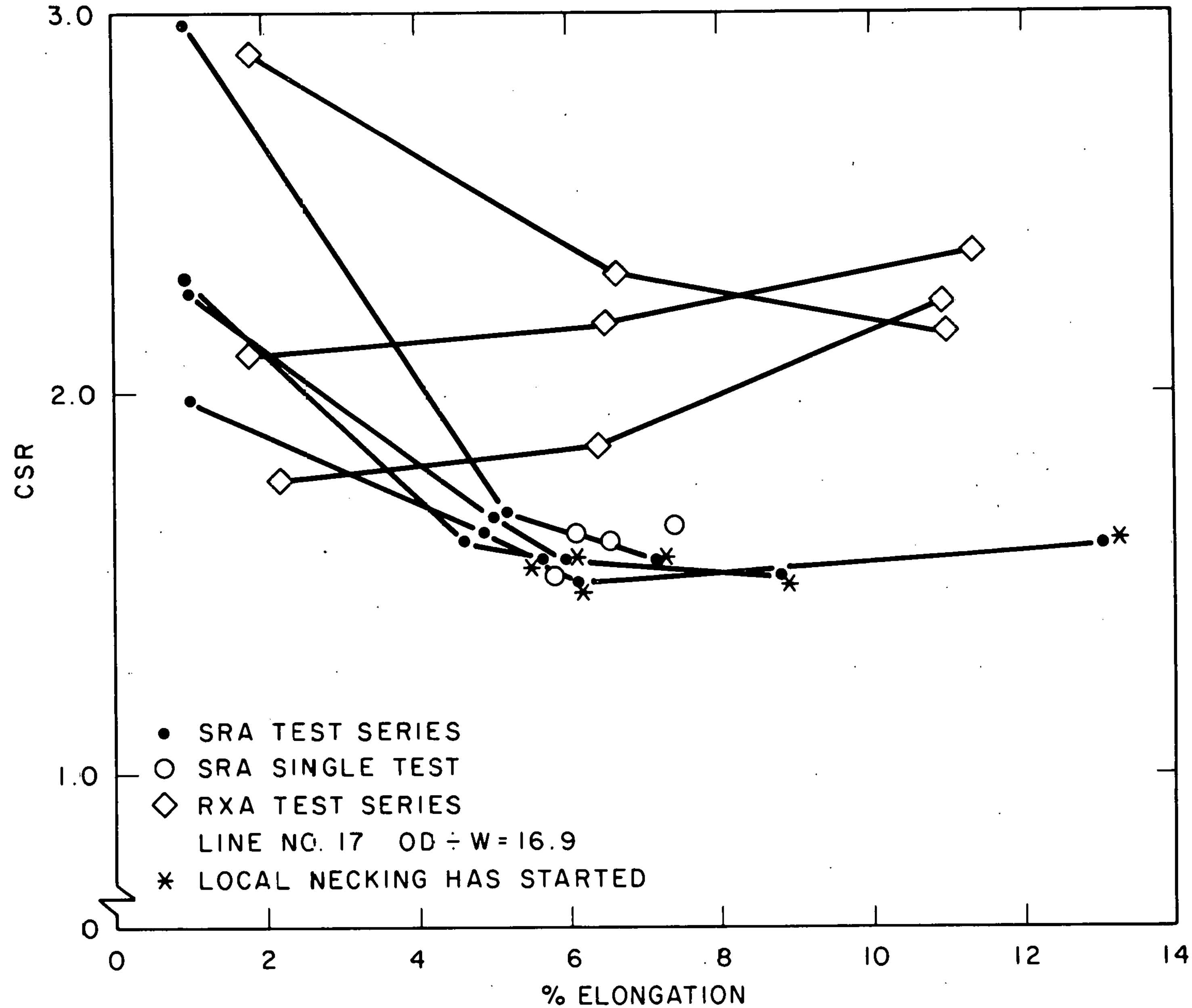
CSR VS % ELONGATION IN 0.250" OD SRA TUBING

FIGURE C-4

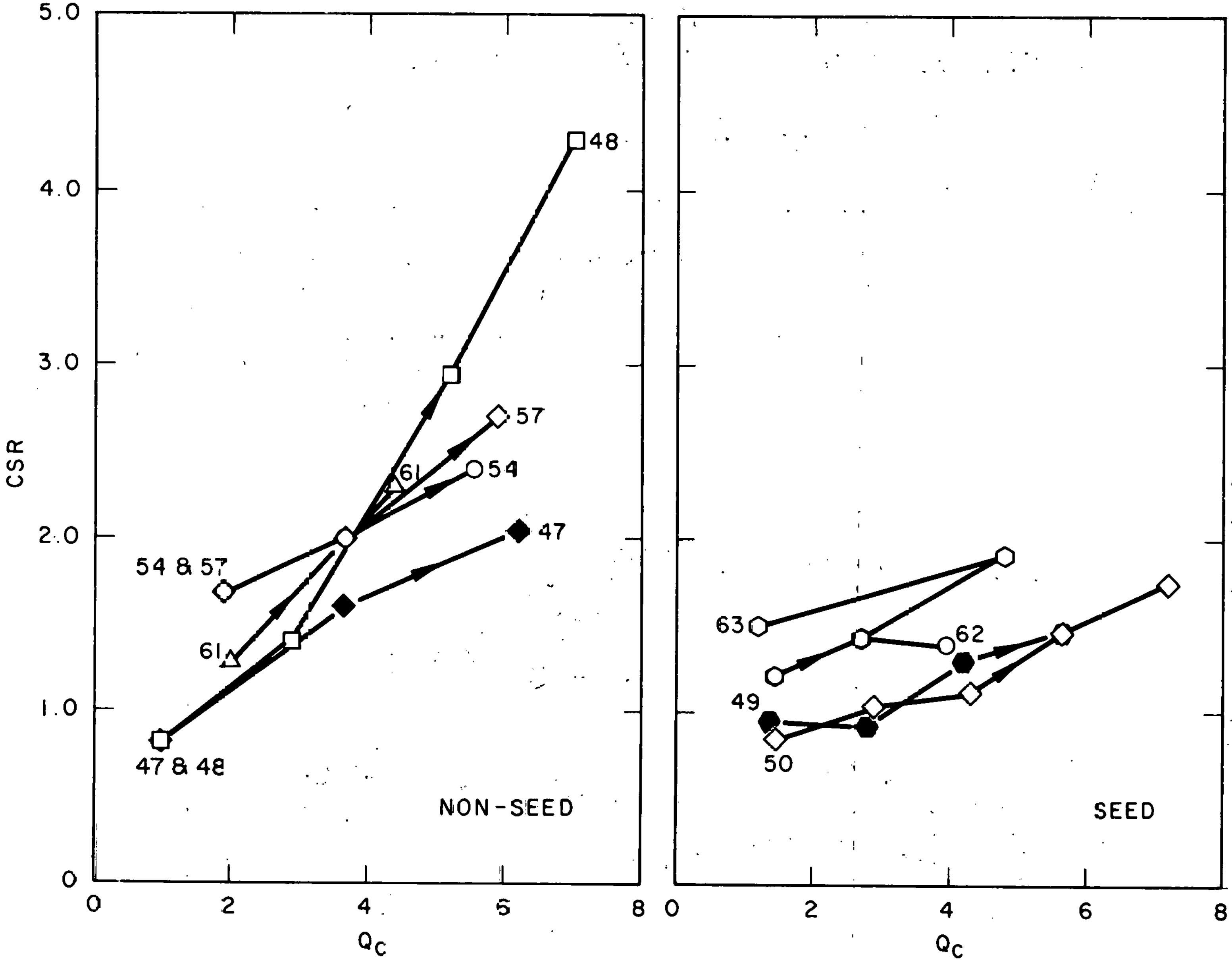


CSR VS % ELONGATION IN 0.250" OD RXA TUBING

FIGURE C-5

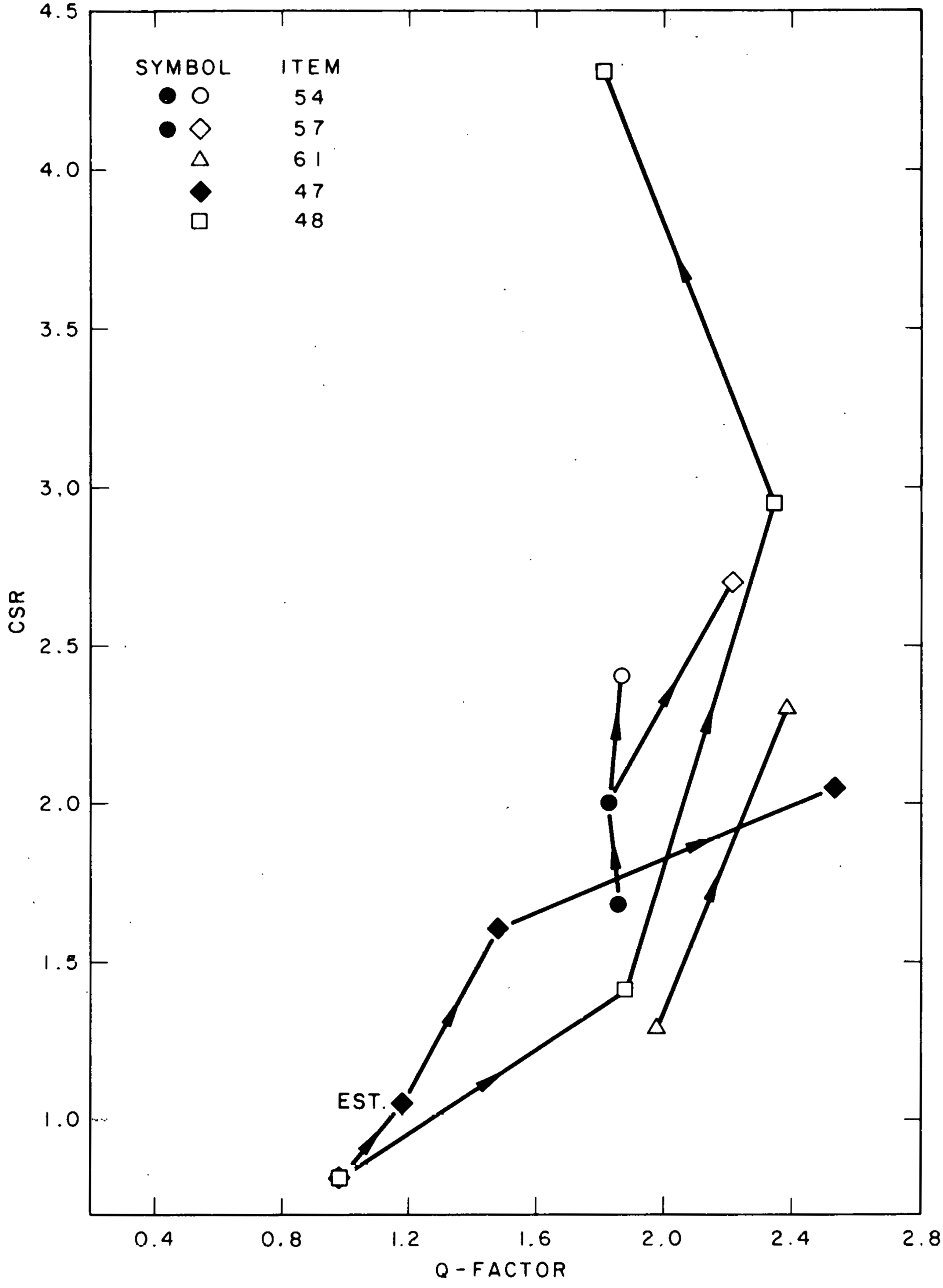


CSR VS % ELONGATION IN 0.627" OD TUBING
FIGURE C-6



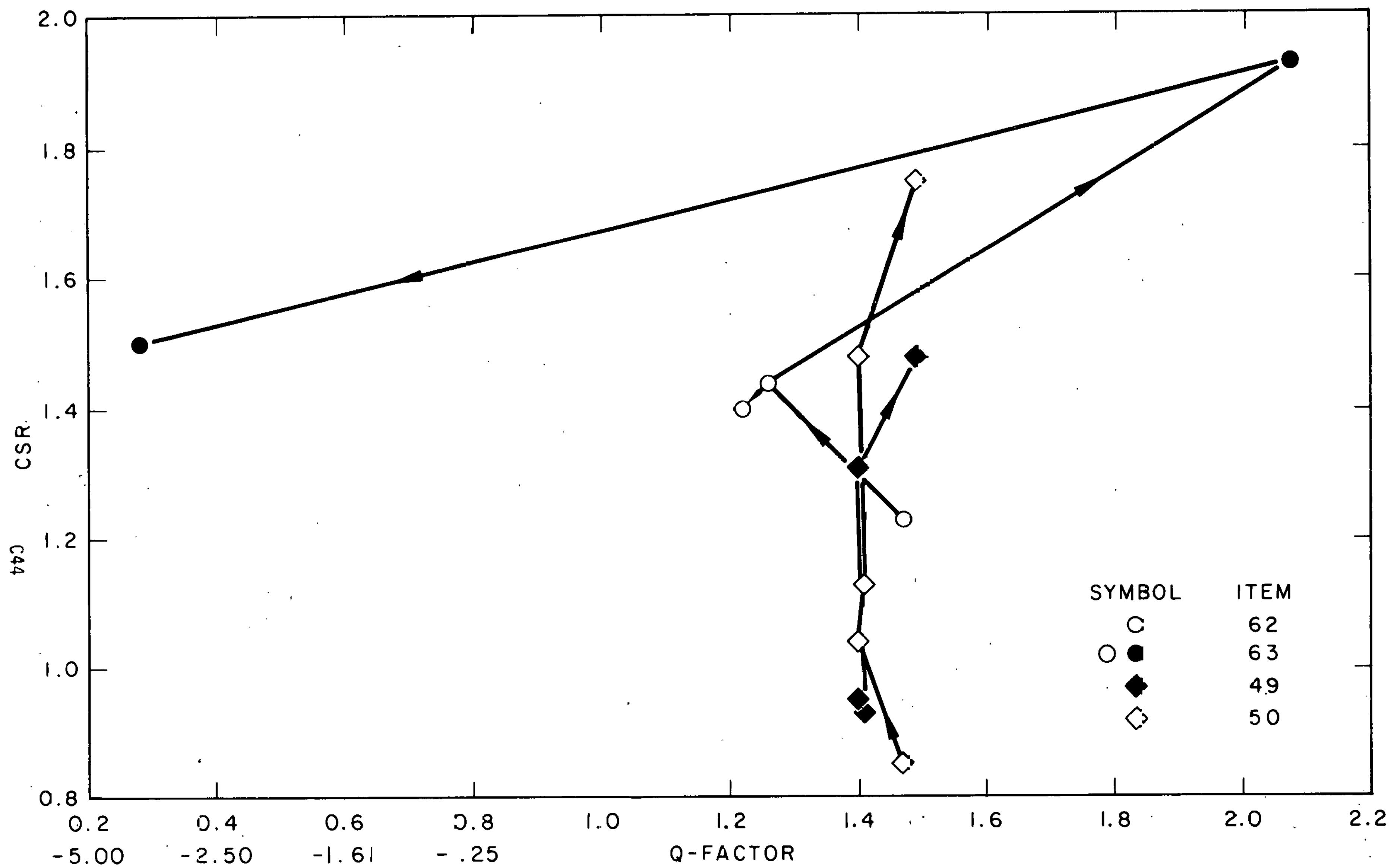
CUMULATIVE EFFECT OF REDUCTIONS ($Q_C = \Sigma Q$) ON TEXTURE (CSR)

FIGURE C-7



SEQUENTIAL EFFECT OF REDUCTIONS (Q-FACTOR) ON TEXTURE (CSR) IN NON-SEED RXA TUBING TABLE C-13

FIGURE C-8



SEQUENTIAL EFFECT OF REDUCTIONS (Q-FACTOR) ON TEXTURE (CSR) IN SEED RXA TUBING-TABLE C-13

FIGURE C-9

APPENDIX D

FURNACE AND LOAD DEPTH QUALIFICATION

I. INTRODUCTION

It was necessary to qualify the heat treating facility to assure that the required thermal treatment was obtained, since the desired microstructural and mechanical properties of Zircaloy tubing are temperature sensitive.

Experiments were performed to prove that all tubes in a given furnace run received the required heat treatment. The experiments supported the calculations of time in furnace, time at temperature, and load depth limits, required to assure proper heat treatment for all tubes within established limits for time at temperature as well as total time in hot zone. Another series of experiments established the length of the uniform hot zone in the furnace and, therefore, established the maximum length of tube permitted and the position of that tube within the furnace. These experiments are discussed in the following sections.

II. FURNACE QUALIFICATION

A. Load Limit and Heat Treatment

Heat Treatment	Run No. 1 (RXA)	Run No. 2 (SRA)
Furnace Temperature	1200 to 1250°F	900°F to 950°F
Load Depth (inch)	4	5

B. Load Description

Tubing Size	.425" O.D. x .025" Wall x 32 ft long
Tubing Condition	Cleaned and etched surface finish
Tubing Alloy	Zircaloy-4

C. Furnace Basket Loading

For each run, the furnace basket (thoroughly oxidized and approximately 14 in. wide x 7 in. deep x 33 ft long) was loaded to the depths noted above, with the load axially centered in the basket and therefore centered in the furnace hot zone when the loaded basket was moved into the hot zone. Care was exercised in assembling the load such that the maximum number of tubes was loaded into the space available. An optimum packing fraction of 0.907 was attempted (close-packed triangular pitch array), but since some of the tubing was not totally straight, a somewhat lower fraction resulted. However, a packing fraction exceeding .785 was maintained. A close-packed square pitch array has a 0.785 packing fraction.

D. Required Minimum Heat Treatment

As pointed out in Appendix A, the desired characteristics for seed tubing was achieved by a recrystallization heat treatment of at least 2 hours at 1100°F. It was also noted that the desired properties of the stress relieved tubes for the blanket and reflector tubes could be achieved by a heat treatment of at least 2 hours above 850°F (or 13 minutes at 900°F).

E. Thermocouple Locations

Three thermocouples (calibrated at 400°F, 550°F, 800°F, 1000°F, 1100°F, and 1200°F) were placed at the following positions within the load of tubing. See Figure A-3 of Attachment A for schematic of load in the vacuum furnace basket. A sketch of the thermocouple positions in the load cross section is included in Figures D-1 and D-2.

T/C No.	Transverse Position	Axial Position Within Load
A	Top layer, outside tube	4" to 6" into near end* of tube
B	Center of load, middle tube in middle layer	At mid-length of center tube in center layer
C	Bottom layer, outside tube on side opposite T/C No. A	4" to 6" from far end of tube*

*Far end is defined as the point of entrance of the load into the hot zone. The far end is adjacent to the evacuation and vacuum cooling chamber. The load monitoring thermocouples entered the furnace from the near end.

F. Qualification Procedure

1. The loaded basket was placed in the cold zone of the furnace and evacuated to the standard operating pressure range, i.e., less than one micron of mercury.

2. The basket was moved into the hot zone and the monitoring thermocouples were inserted into the guide tubes placed in the load at the locations noted in II.E. above. The technique for inserting the three thermocouples through the furnace wall and along the guide tubes without developing air leaks was the major obstacle to be overcome in developing the ability to monitor temperatures within each load of tubes. An autographic record was made of the temperature of the three thermocouples and of the vacuum gage readings. Figures D-1 and D-2 illustrate the convergence of the tube temperatures at the three thermocouple locations during the qualiication experiments performed for recrystallization and stress relief heat treatments, respectively. Figure D-2 is typical of all the curves obtained when the tubes are at room temperature when

loaded into the furnace. The first hour of Figure D-1 is abnormal in that the load was still warm when that experiment was started.

3. Additional experiments were run duplicating the furnace and load cycles described above, except that while the three thermocouples were located in the same transverse position noted in II.E. they were positioned in the same transverse plane as thermocouple B at the mid-length of the load. The time versus temperature curves generated by the three thermocouples duplicated those developed with T/Cs A & C at the end positions.

G. Results

1. These experiments provided the support data needed to confirm the initial calculations and to establish the heat treatment parameters for the operation of WTD furnace #430-32 to achieve the required heat treatment for each tube in the furnace load as described in Section II.D.

2. The central tubes reached 1200°F after 3 hours in the furnace during the recrystallization. Furnace time was set at 5 to 6 hours to assure at least 2 hours at 1200°F for all tubes.

3. In the stress relief run, the central tube reached 900°F in 4-1/2 hours. Furnace time was set at 6 ± 1/2 hours to assure a minimum of one hour at 900°F for all tubes.

4. The load sizes and furnace operation parameters established to achieve the required heat treatment are summarized in the following table.

Heat Treatment	Nominal Furnace Temperature	Maximum Load Depth	Time in Furnace at Nominal Temperature
Recrystallize	1225°F	4 inch	5 to 6 hours
Stress Relief	925°F	5 inch*	5-1/2 to 6-1/2 hours

*This limit was later relaxed to 5-1/4 inch to permit entering one more layer of reflector tube during heat treatment since that layer barely exceeded the 5 inch limit.

III. LOAD LENGTH VERSUS UNIFORM TEMPERATURE

A. Requirement

In addition to qualifying the furnace times and temperatures, it was necessary to define the length of uniform heat zone. This zone defined the maximum tube length that could be permitted and the proper location of the tubes in furnace to assure a proper heat treatment throughout the load.

B. Experimental Procedure

1. These experiments duplicated those described in Section II for temperature, load size, and transverse position of the thermocouples. The exception was that thermocouple B was inserted through the load and extended beyond the end of the load by some 6 inches.

2. After the load had reached a stable uniform temperature as indicated by the thermocouples A & C and the results of previous experiments, thermocouple B was drawn stepwise through the load and held at each step for two minutes to stabilize. Then the temperature at that location was recorded.

3. This incremental advance, followed by a two minute stabilization period prior to recording, was continued through the length of the load. Six inch increments were used in the first and last 2-foot sections of the load. The remaining measurements were taken at one-foot intervals.

C. Results

1. Typical plots of the temperature along the centerline of the load and the position of that reading with respect to the load, the basket, and the furnace are shown in Figures D-3 for a recrystallization heat treatment and in Figure D-4 for a stress-relief heat treatment.

2. Data on the traverse of B thermocouple in the recrystallization run illustrated in Figure D-3 ranged from a low of 1247°F near the mid-length to a high of 1261°F at the end of the basket for a 14°F range, well within the 50°F range permitted by the limits listed in Section II.A. but with a mid-range temperature of 1254°F indicating a bias between the furnace control thermocouple and the load thermocouple.

3. Data on the traverse of thermocouple B in the stress relief anneal heat treatment experiment, illustrated by the temperature profile shown in Figure D-4, shows a temperature range laong the center of the load from a maximum of 957°F at the near end to a minimum of 943°F near the mid-length of the load. This 14°F range is also well within the 50°F range permitted by the limits listed in Section II.A. Here again a control bias was evident.

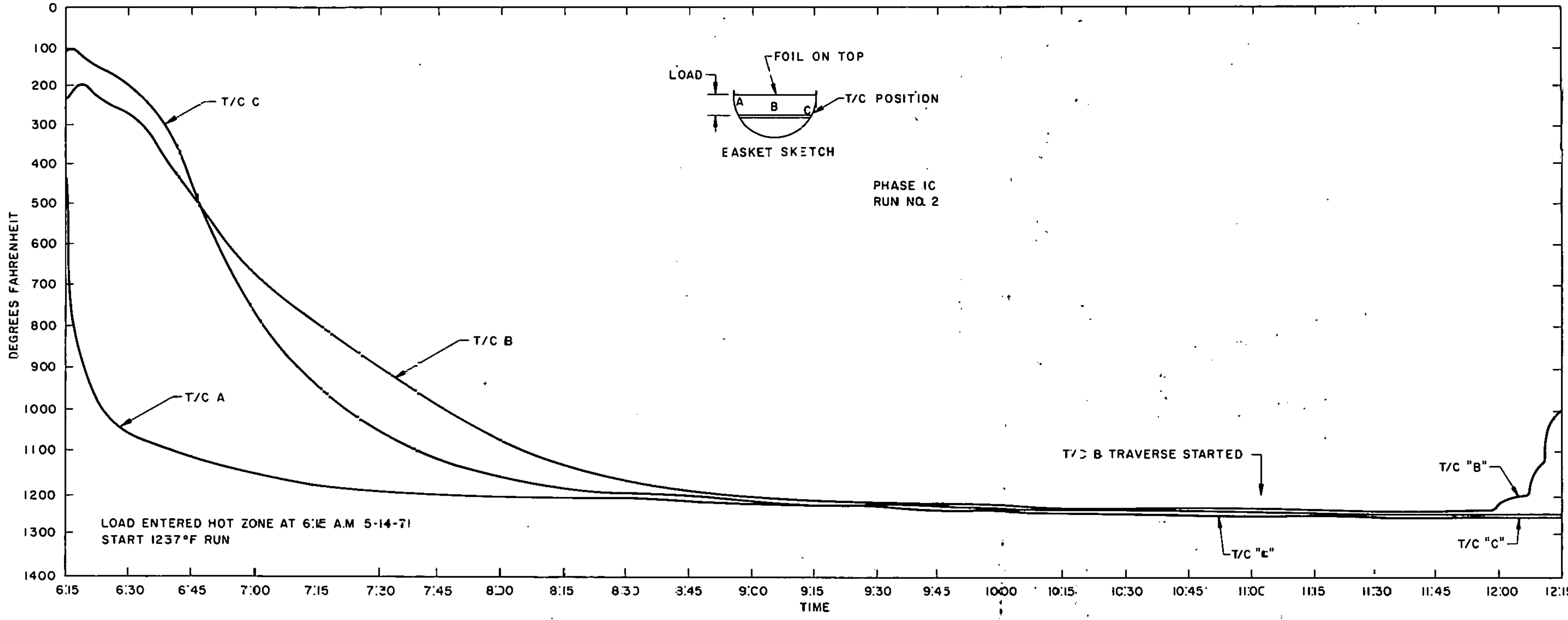
4. The limits of the uniform hot zone of the furnace were defined and all final heat treatment loads had to be positioned within the defined uniform hot zone.

IV. OVERALL RESULTS

A. A specific heat treatment furnace (WTD #430-32) was approved for use in the final heat treatment of tubes produced for LWBR fuel rod cladding after demonstrating that the prescribed heat treatment could be achieved with the load and within the limits discussed above when the load was positioned within the "uniform hot zone" of that furnace.

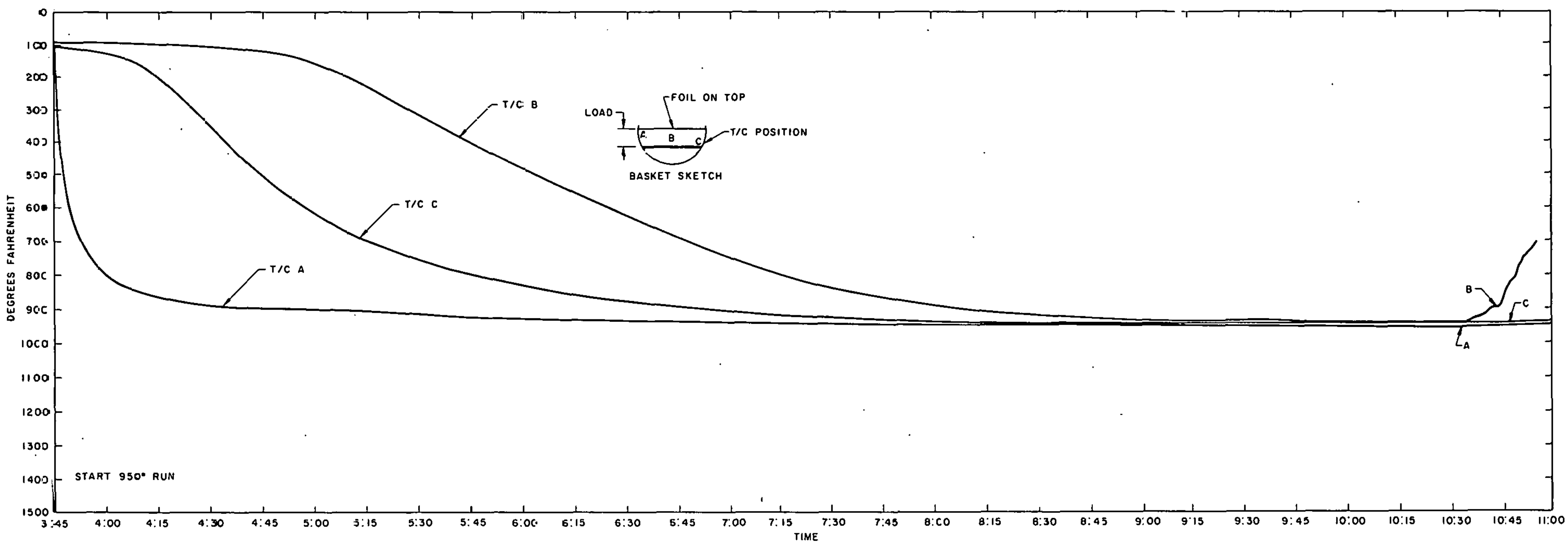
B. The relation between the monitor thermocouples in the load and the furnace control thermocouples was established defining the bias between the control and the load. Thus, the set-point for the furnace to achieve a given load temperature was established, further minimizing the potential for load temperatures outside the desired range.

C. The correlation between load time in hot zone and the thermal experience of the outermost and intermost tube in the load permitted selection of parameters for the operation of the furnace which would assure that all tubes in the load received the required heat treatment.

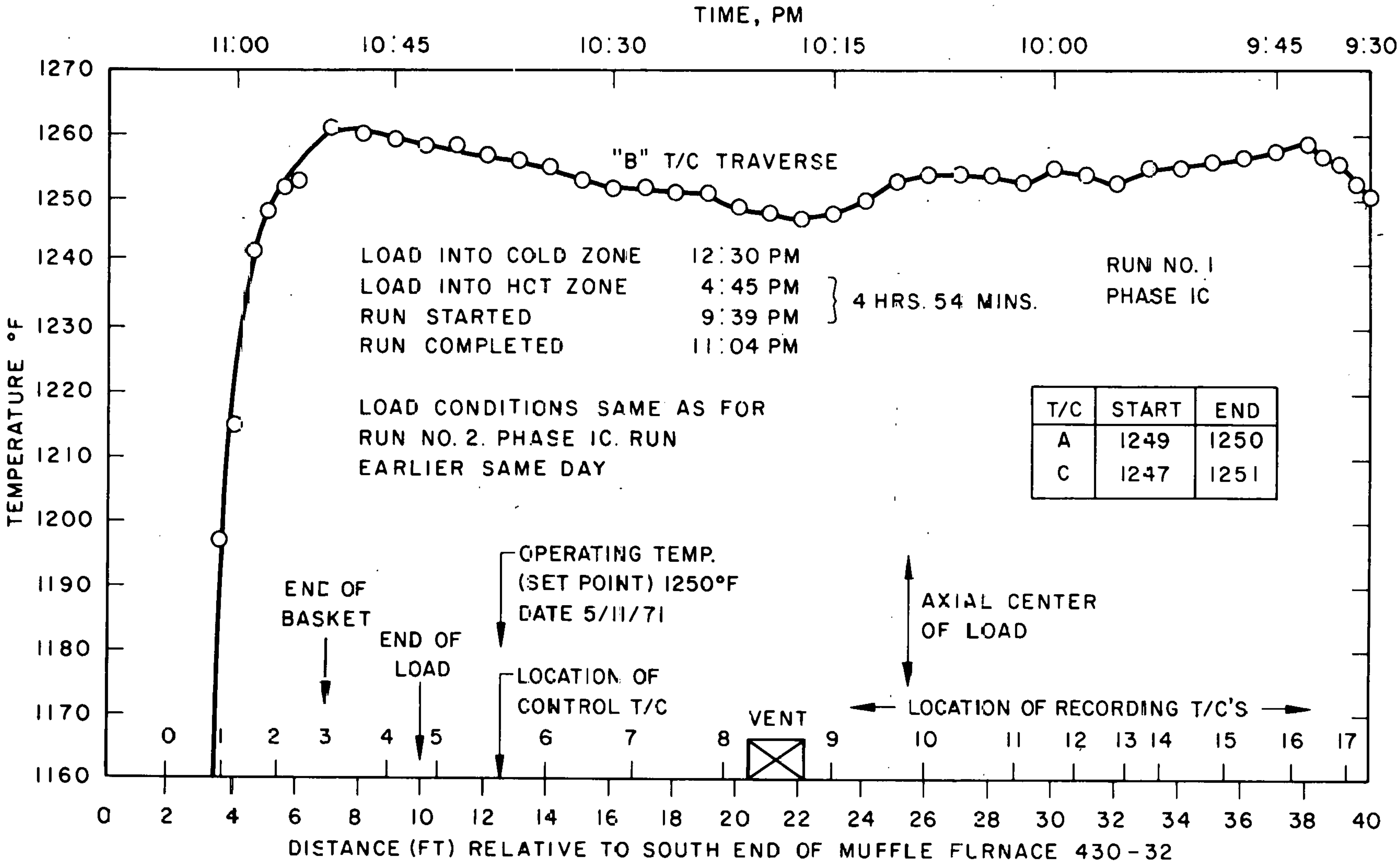


TIME-TEMPERATURE PROFILE OF START OF A 1237°F RECRYSTALLIZATION ANNEAL OF ZIRCALOY-4 TUBES

FIGURE D-1

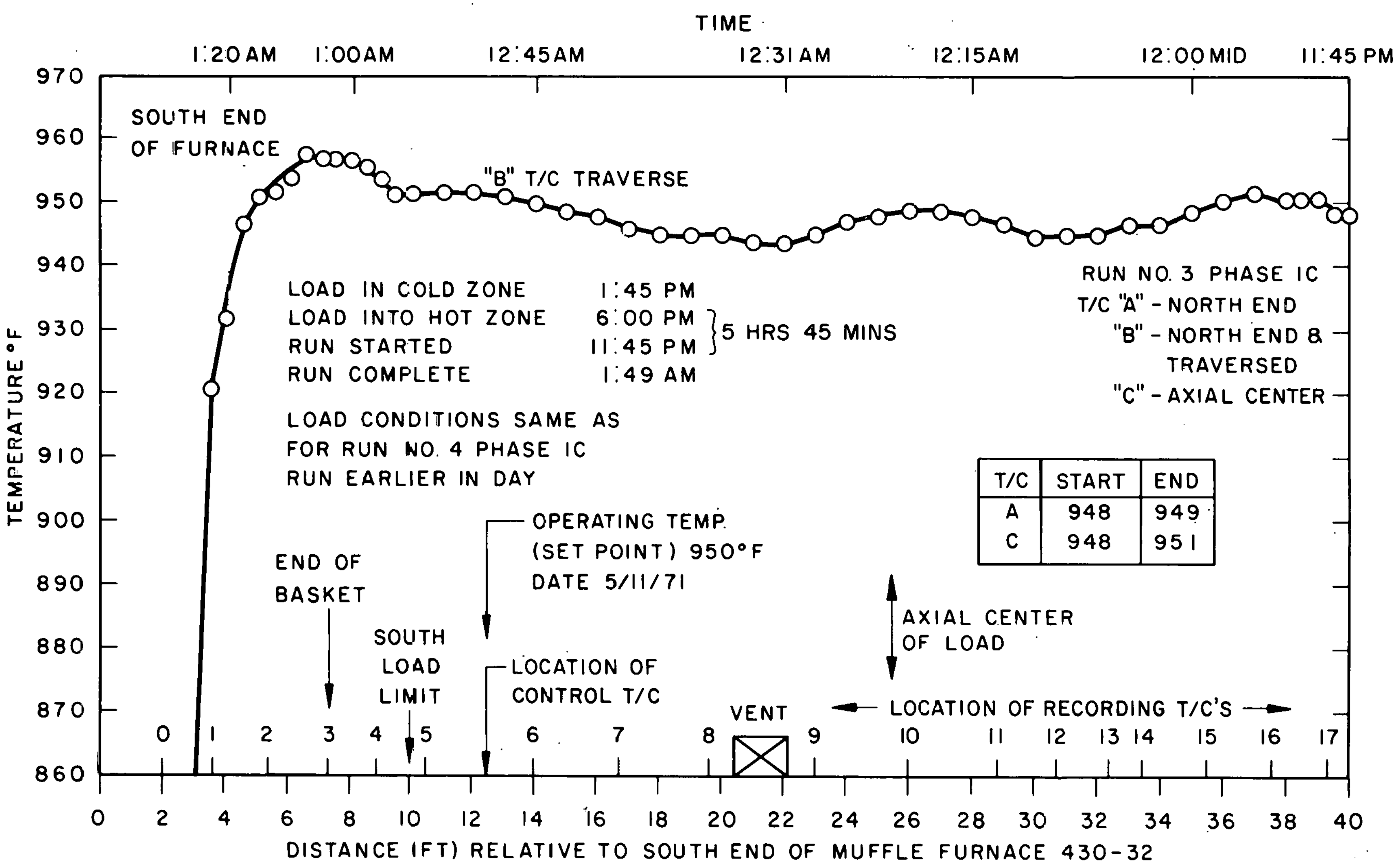


TIME - TEMPERATURE PROFILE OF START OF 950°F
STRESS RELIEF ANNEAL OF ZIRCALOY-4 TUBES
FIGURE D-2



TEMPERATURE PROFILE OF AXIAL CENTERLINE OF LOAD OF ZIRCALOY-4 TUBES DURING A 1237°F RECRYSTALLIZATION ANNEAL

FIGURE D-3



TEMPERATURE PROFILE OF AXIAL CENTERLINE OF LOAD OF ZIRCALOY-4 TUBES DURING A 950°F STRESS RELIEF ANNEAL

FIGURE D-4

APPENDIX E

DEVELOPMENT OF A THERMAL TECHNIQUE TO DETERMINE THE LEVEL OF POST-ANNEAL COLD WORK (PACW) IN RECRYSTALLIZE ANNEALED ZIRCALOY-4 TUBING

I. INTRODUCTION

Under conditions of external pressure at elevated temperatures, the free-standing life or time-to-collapse of Zircaloy-4 cladding is highly sensitive to low levels of residual cold work. Therefore, during manufacture of LWBR tubing, it was necessary to establish controls to minimize induced cold work following final heat treatment.

Controls were applied to both recrystallize annealed seed tubing and stress relief annealed blanket and reflector tubing in two areas in the following manner:

(a) Handling procedures were implemented to prevent local plastic deformation during inspection and transfer operations; e.g., improper tube support can result in excessive bending and formation of "kinks."

(b) Tube straightening parameters were introduced to limit induced cold work to 3 percent maximum. These parameters included restrictions in tube offset and number of passes as well as roll clearances to avoid tube "pinching."

Process controls were implemented to assure that all processing and inspection procedures were closely followed, and a special test was developed for recrystallize annealed seed tubing for added assurance that the 3 percent maximum cold work limit had not been exceeded. This test, designated as the Post-Anneal Cold Work (PACW) test, is based on the strain-sensitive grain growth behavior of recrystallize annealed Zircaloy-4.

Whereas normal grain growth occurs by reduction of stored grain-boundary surface energy, grain growth can also occur by inducing strain energy into the crystal lattice through cold work. During thermal treatment, the boundaries between grains migrate, causing one grain to increase in size at the expense of another grain, which shrinks and finally disappears. Since grains greater than fifty times the size of the original grains can result, the term exaggerated grain growth (EGG) has been applied.

At levels of cold work below approximately 3%, normal recrystallization occurs. Above that level of cold work, a few grains receive sufficient strain energy to permit boundary migration, and the resultant new grain size can be quite large (greater than 0.020 inch diameter, where 0.020 inch is equivalent to ASTM grain size "00"). As the level of cold work increases, the number of grains susceptible to strain-induced boundary movement is increased, with boundary movement occurring faster in those regions where the distortion has been greatest. The resultant new grains are smaller than at the lower cold work levels, assuming the same thermal treatment, primarily due to the larger number of new grains in the same volume and to the impingement of the newly grown grains upon each other. The upper limit to the level of cold work that will result in EGG is approximately 10%, since greater deformation will result in normal recrystallization.

Parameters for the seed PACW test were determined by uniaxially straining samples of recrystallize annealed Zircaloy-4 tubing to the 3 percent axial strain (= 3% axial elongation) level and then evaluating the EGG response by heat treating at various combinations of time and temperature. A heat-treatment cycle was selected for the PACW test such that the presence of EGG indicated a minimum of 3 percent cold work, whereas the absence of EGG indicated less than the 3 percent cold worked level. Additional cold work levels, ranging from 1.0 to 3.7 percent, were also included as part of the investigation to more closely define the relationship between cold work and EGG.

The EGG study was primarily directed to the establishment of PACW test parameters for recrystallize annealed seed tubing. Both of the blanket sizes and the reflector size tubing for LWBR were manufactured with a stress-relief anneal as the final heat treatment and, therefore, were not susceptible to the EGG phenomenon. However, a small quantity of recrystallize annealed blanket tubing was available from a previous procurement effort, and some limited PACW-EGG experimentation was performed for additional information.

II. MATERIAL

Two Zircaloy-4 tubing sizes were used in the study, 0.283" O.D. x 0.019" wall thickness (the nominal LWBR seed size was later changed to 0.311" O.D. x 0.024" wall thickness), and 0.574" O.D. x 0.032" wall thickness (the nominal LWBR standard blanket size was later changed to 0.576" O.D. x 0.030" wall thickness). The tubing was received in the recrystallize-annealed-plus-straightened condition from the vendor, and the test samples were given a second recrystallization anneal at Bettis (1200 ± 20°F for 5 ± 1/4 hours in vacuum) to eliminate any strain induced by the straightening operation.

Tubing fabrication history and chemistry are given in Table E-1. The microstructures after the second recrystallization for both sizes of tubing prior to the start of these experiments are presented in Figure E-1.

III. EXPERIMENTAL PROCEDURE

Recrystallize annealed Zircaloy-4 tube specimens were uniaxially strained by tensile testing and subsequently heat treated at various combinations of time and temperature. The resultant microstructures were then evaluated for the presence of exaggerated grain growth (EGG). The following details identify the specific experimental techniques:

A. Tube specimens, twenty-four inch long, were circumferentially scribed in 3/4" increments.

B. Each specimen was uniaxially strained at room temperature at a uniform strain rate of 0.05 ± 0.005 inches per inch of gage length per minute to axial elongations ranging from 1.0% to 3.7%. Note Tables E-2 through E-5 for the actual elongation obtained.

C. Individual axial elongation (E_A) calculations were made for each 3/4" section from length measurements. At these low levels of strain the elongation is approximately equal to the true strain as shown by the following equation.

$$E_A = \frac{L_f - L_o}{L_o} \approx \ln\left(\frac{L_f}{L_o}\right)$$

where

L_f = Length after straining

L_o = Length before straining

D. The 24" long specimens were cut into individual 3/4" long sections using an abrasive saw. The tube clamping device used during cutting was covered with a soft material to avoid surface abrasions, which could potentially impart sufficient local surface strain to initiate EGG during thermal treatment.

E. The 3/4" sections were encapsulated in Vycor tubes, backfilled with argon, sealed, and heat treated at temperature and time combinations noted in Tables E-2 through E-5. The encapsulated specimen was air cooled to room temperature. A minimum of two sections was used for each heat treatment condition.

F. Each 3/4" section was cut in half (longitudinally), mounted, polished and evaluated for EGG at 50X under polarized light. A minimum of 30 fields (15 fields per each of two longitudinal sections) per specimen was evaluated. Each field covered an area of 0.035 inch x 0.035 inch on the polished surface of the metallographic mount.

G. To aid in quantitative evaluation of the test specimen the metallograph or miroscope was fitted with an overaly grid (0.035 inch square) subdivided in to 100 squares at 0.0035 inch on a side. The relative severity of the grain growth in each specimen was determined by counting the total number of grid segments (0.0035" square) which contained an exaggerated grain.

IV. RESULTS AND DISCUSSION

A. Blanket Tubing (0.574" O.D. x 0.032" Wall)

Sensitivity to EGG in the range of 2.3% to 3.7% elongation (axial strain) was detected at 1450°F, and a series of heat treatments were performed at various time intervals. EGG results are given in Table E-2 and Figure E-2. At 2.3% strain, the response to grain coarsening is quite slow. Even after an eight hour treatment, only 30% coarsening has occurred. As the axial strain is increased, however, the coarse grain growth phenomenon becomes progressively more pronounced, until at 3.7% elongation almost complete grain coarsening has occurred after two hours. The metallographic data supporting the 1450°F curves of Figure E-2 are summarized in Table E-2, and are presented in photomicrographs in Figures E-3 through E-6 which illustrate the time-transformation function. Two strain levels are shown in each figure.

As illustrated in Figures E-3 through E-6, the resultant grain size of the newly grown grains is a function of the number of new grains formed. The following comparison of grain sizes at various strain levels shows a consistent trend toward smaller grain size as the strain level is increased. Heat treatment times were selected where grain growth was considered essentially complete, or nearly complete in the case of the lower strain levels.

Elongation	Time at 1450°F	% Grain Coarsening	Photomicrograph	ASTM Grain Size
2.5%	16 hrs.	77.6	Fig. E-3i	>00 to 1
2.7%	8 hrs.	82.3	Fig. E-4d	00 to 1.5
2.9%	8 hrs.	99.8	Fig. E-4h	00 to 2
3.0%	8 hrs.	99.9	Fig. E-5d	0.5 to 2
3.2%	4 hrs.	100.	Fig. E-5h	1.5 to 4
3.7%	4 hrs.	100.	Fig. E-6h	2 to 5

The variation in EGG response to temperature fluctuations around the nominal 1450°F heat treatment temperature was determined at two temperature levels, 1435°F and 1465°F. The grain coarsening results at these strain levels are also presented in Table E-2 and plotted in Figures E-7 and E-8. These data show the rate of formation of new grains increases with higher heat treatment temperature. The effects of time and temperature on the development of a coarse grain microstructure are illustrated in Figures E-9, E-10, and E-11 for specimens with axial strains of 2.5%, 3.0%, and 3.5%, respectively. The trade-off of time and temperature is evident in these three sets of photomicrographs.

The curves of EGG vs time for specimens with three levels of axial strain in Figure E-7 for transformation temperatures of 1435°F and 1465°F bracket the 1450°F curves of Figure E-2 for three selected axial strains (2.5%, 3.0%, and 3.6%).

Where Figures E-2 and E-7 plot percent EGG versus time for a family of strains at a given transformation temperature, Figure E-8 is a plot of percent EGG versus temperature for a family of exposure times at three strain levels. Figure E-8 is a graphic plot of the information illustrated by the photomicrographs in Figures E-9, E-10, and E-11.

Investigation of the use of the EGG phenomenon to detect strains less than 2.3% were initiated at 1450°F but the response was too sluggish. Several experiments were performed at 1475°F using specimens with

1.0%, 1.5% and 2.0% axial strain. The results of these experiments are shown in the curves of Figure E-12 which were plotted from the data presented in Table E-3.

B. Seed Tubing (.283" O.D. x 0.019" Wall)

Sensitivity to EGG at 3 percent strain was detected at 1375°F, and a series of heat treatments were performed at various time intervals in the 2.3 percent to 3.4 percent range. EGG results are given in Table E-4 and Figure E-13. At 2.3%, the EGG response is quite slow; even after an eight hour heat treatment, only 28% coarsening has occurred. As the strain level increases, however, the EGG phenomenon becomes progressively more pronounced, until in the 3.0 to 3.5% strain range complete coarsening occurs within four hours. The photomicrographs in the bottom section of Figure E-14 illustrate the changes noted in Table E-4 and Figure E-13. Based on these results, a PACW test was established for seed tubing at 1375°F for one hour and was incorporated as part of the tubing specification. This test required that samples (2.5" long) representative of three straightened tubes from each final recrystallization anneal furnace lot be heat treated at the sensitizing temperature (1375°F) and subsequently evaluated for the presence of coarse grains (ASTM 7 or coarser). EGG of 10% or more was designated as indicative of a cold work level above 3% strain.

As the 2.3% strain curve in Figure E-13 indicates, the 1375°F tests did not produce EGG at reasonable times below the 2.3% strain level. Additional testing was performed at 1475°F to determine if strains in the 1% to 2% range could be detected in recrystallized annealed seed tubes using the EGG phenomenon. The results of the tests at 1475°F are shown in the photomicrographs at the top of Figure E-14 and the test data are shown in Table E-5 and in the curves of Figure E-15. The 1475°F results showed that strains as low as 1% could be detected at 1475°F using the EGG phenomenon. The 1475°F test for EGG was not used, since the residual strain limit for seed tubes was set at 3.0% maximum. The increased EGG response with increasing exposure time was evident at both temperatures.

Additional data were obtained to show the variations in EGG with time for minor changes in temperature (± 15°F) about the nominal test temperature. Grain coarsening sensitivity as a function of temperature was determined for the strain range of 2.3 to 3.4% at 1460°F and 1490°F (nominal = 1475°F) and at 1360°F and 1390°F (nominal = 1375°) for the 1.0 to 2.1% strain range. The results are given in Tables E-4 and E-5 and shown in Figure E-16. All responses were consistent and, at a given strain level, displayed increased grain coarsening with increased temperature.

While the percent EGG is plotted against time at temperature in Figures E-13, E-15, and E-16 using the data in Table E-4 and E-5, the same data are presented in Figures E-17 and E-18 as percent EGG versus heat treat temperature for various times for axial strains ranging from 1.0% to 3.4%.

V. CONCLUSIONS

A. Recrystallize annealed Zircaloy-4 tubes exhibit the exaggerated grain growth phenomenon when specimens with axial strains in the range of 1 to 4% are exposed in vacuum to temperatures from 1360 to 1475°F.

B. The percent transformation from a fine grain to a coarse grain structure increases with time, temperature, strain level and the ASTM grain size number in the strained specimen.

C. The time to achieve a given percent transformation decreases with increasing temperature and decreases with increasing levels of strain prior to the vacuum heat treatment over the range of variables covered in this study.

D. Three percent strain can be reproducibly detected in fine grain seed tubing. Coarse grains in excess of 10% of the metallographic field inspected, following a heat treatment of one hour at 1375°F, indicates a strain in excess of 3%.

TABLE E-1

FABRICATION HISTORY AND CHEMICAL ANALYSIS OF
ZIRCALOY-4 TUBING

Fabrication History	Seed Tubing	Blanket Tubing
Tube Item No. from Table C-14	7	42
Size	.283" O.D. x .019" W	.574" O.D. x .032" W
Number of Tube Reducer Passes	3	3
% Area Reduction Last Pass	78	42
Final Heat Treatment (As Purchased)	1200 ± 20°F for 2±1/2 Hrs	1237 ± 37°F for 6±2 Hrs
Bettis Pre-Test Heat Treatment	1200 ± 20°F for 5±1/4 Hrs	1200 ± 20°F for 5±1/4 Hrs

Chemical Analysis	Seed Tubing	Blanket Tubing
Alloys (%)		
Sn	1.54	1.48
Fe	0.22	0.23
Cr	0.11	0.11
Ni	<0.004	<0.001
Impurities		
Al	<20	<20
B	<0.2	<0.2
C	98	109
Cd	<0.2	<0.2
Co	10	<10
Ca	<20	<20
Cu	<28	<20
Cl	<10	<10
H	22	11
Hf	<100	<100
Mg	<10	<10
Mn	<20	<20
Mo	<20	<20
N	32	32
O	1490	1280
Pb	<20	<20
Si	<32	<30
Ti	<20	<20
U	1.3	<1
U-235	0.01	<0.007
V	<20	<20
W	<50	<50

TABLE E-2

PERCENT GRAIN COARSENING* IN RECRYSTALLIZE ANNEALED
0.574" O.D. X 0.032" WALL
ZIRCALOY-4 TUBING AXIALLY ELONGATED FROM 2.3% to 3.7% AND SUBSEQUENTLY
HEAT TREATED FOR THE INDICATED TIME AT TEMPERATURE

Heat Treatment	Axial Elongation							
Temperature/Time	2.3%	2.5%	2.7%	2.9%	3.0%	3.2%	3.4%	3.7%
1435°F - 1/2 hr	--	--	--	--	--	--	--	0.6
1 hr	--	0	--	--	0.3	--	--	5.3
2 hrs	--	0.8**	--	--	7.9	--	--	78.2
4 hrs	--	2.2	--	--	19.2	--	--	--
8 hrs	--	16.0	--	--	85.1	--	--	--
1450°F - 1/2 hr	--	--	--	--	--	0.2	0.5	2.3
1 hr	--	0.8**	0.7	0.9	2.2	9.8	23.7	51.5
2 hrs	0.6	2.6	5.5	15.4	35.8	55.1	65.5	99.0
4 hrs	6.4	23.2	45.3	86.8	89.9	100	100	100
8 hrs	32.2	50.6	82.3	99.8	99.9	100	--	100
16 hrs	70.5	77.6	--	--	--	--	--	--
1465°F - 1/2 hr	--	--	--	--	--	--	--	4.3
1 hr	--	0.5**	--	--	4.2	--	--	99.8
2 hrs	--	4.3	--	--	49.7	--	--	100
4 hrs	--	22.1	--	--	90.9	--	--	--
8 hrs	--	63.1	--	--	99.1	--	--	--

* Reported values are averages based on a minimum of two specimens per heat treatment/elongation combination. Each was evaluated on the basis of two locations (180° apart) per specimen, 15 views per location.

** Percent grain coarsening for each test condition.

TABLE E-3

PERCENT GRAIN COARSENING* IN RECRYSTALLIZE ANNEALED
0.574" O.D. x 0.032" WALL
ZIRCALOY-4 TUBING AXIALLY ELONGATED FROM 1.0% to 2.0% AND SUBSEQUENTLY HEAT TREATED AT 1475°F FOR THE HOURS INDICATED

Heat Treatment Temperature/Time	Axial Strain or Elongation 1.0%	1.5%	2.0%
1475°F - 8 hrs	0.2**	8.5	61.0
16 hrs	3.2	38.8	97.7
24 hrs	8.4	79.1	100

* Reported values are averages based on minimum of two specimen per heat treatment/elongation combination. Each specimen was evaluated on the basis of two locations (180° apart) per specimen, and a minimum of 15 views per location.

** Percent grain coarsening for each test condition.

TABLE E-4

PERCENT GRAIN COARSENING* IN RECRYSTALLIZE ANNEALED
0.283" O.D. x 0.019" WALL
ZIRCALOY-4 TUBING AXIALLY ELONGATED FROM 2.3% TO 3.4% AND SUBSEQUENTLY
HEAT TREATED FOR THE INDICATED TIME AT TEMPERATURE

Heat Treatment	Axial Elongation					
Temperature/Time	2.3%	2.5%	2.7%	3.0%	3.2%	3.4%
1360°F - 1 hr	--	--	--	1.7	--	2.1
2 hrs	--	3.3**	--	7.6	--	4.0
4 hrs	--	8.3	--	74.9	--	95.0
1375°F - 1/2 hr	--	--	--	--	--	4.1
1 hr		0.4	0.5	3.2	31.9	45.0
2 hrs	1.8**	4.3	10.4	31.4	65.8	77.0
4 hrs	--	52.9	93.9	99.7	100	100
8 hrs	28.3	100	--	--	--	--
1390°F - 1 hr	--	0.6**	--	9.6	--	--
2 hrs	--	16.7	--	56.9	--	--
4 hrs	--	61.7	--	99.0	--	--

* Reported values are averages based on two specimens minimum per heat treatment/elongation combination, each specimen evaluated on the basis of two locations (180° apart) per specimen, 15 views per location.

** Percent grain coarsening for each test condition.

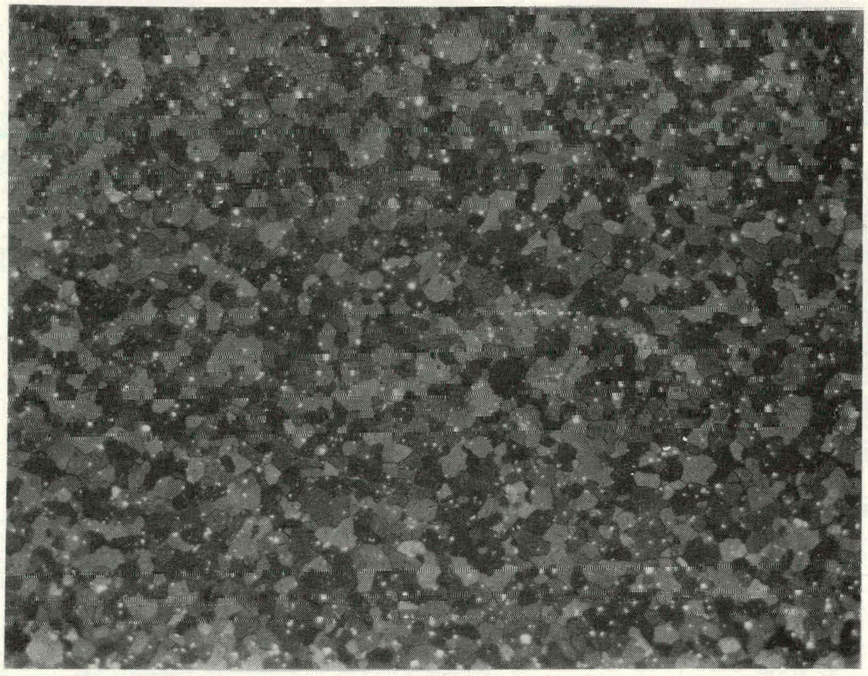
TABLE E-5

PERCENT GRAIN COARSENING* IN RECRYSTALLIZE ANNEALED
0.283" O.D. x 0.019" WALL
ZIRCALOY-4 TUBING AXIALLY ELONGATED FROM 1.0% to 2.0% AND SUBSEQUENTLY
HEAT TREATED FOR THE INDICATED TIME AT TEMPERATURE

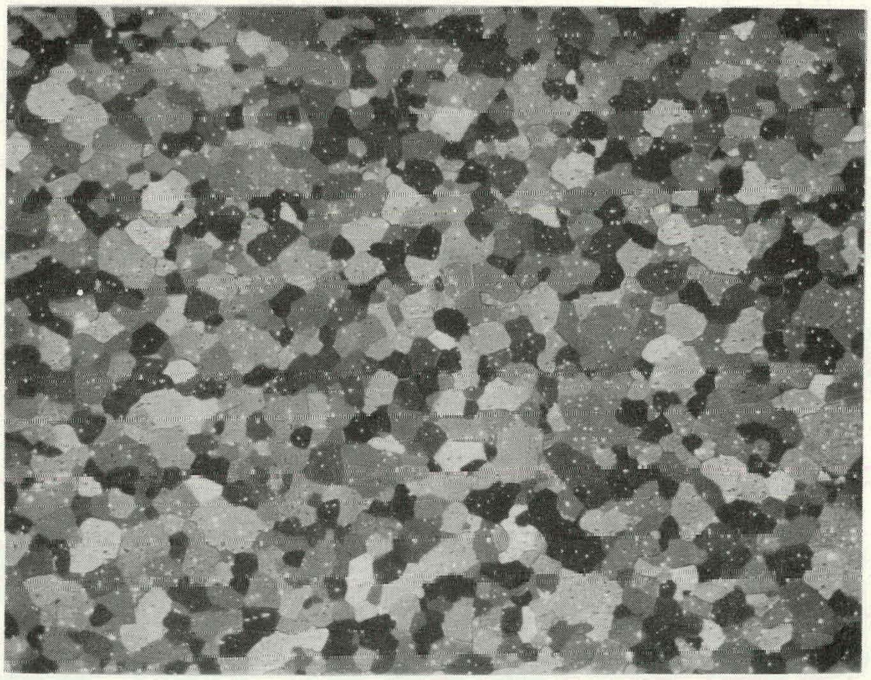
Heat Treatment	Axial Elongation			
Temperature/Time	1.0%	1.5%	1.8%	2.0%
1460°F - 1 hr	--	--	--	1.2
2 hrs	--	5.7**	--	73.3
4 hrs	9.1	83.3	--	98.7
1475°F - 1/2 hr	--	--	2.7	--
1 hr	--	13.6**	33.7	71.4
2 hrs	1.8	41.9	83.3	96.3
3 hrs	--	90.9	99.9	--
4 hrs	44.9	95.0	100	100
8 hrs	99.2	100	--	--
16 hrs	--	100	--	--
1490°F - 1 hr	0	9.1**	--	93.8
2 hrs	16.6	72.1	--	96.4
4 hrs	--	100	--	--

* Reported values are averages based on two specimens minimum per heat treatment/elongation combination. Each specimen evaluated on the basis of two locations (180° apart) per specimen, 15 views per location.

** Percent grain coarsening for each test condition.



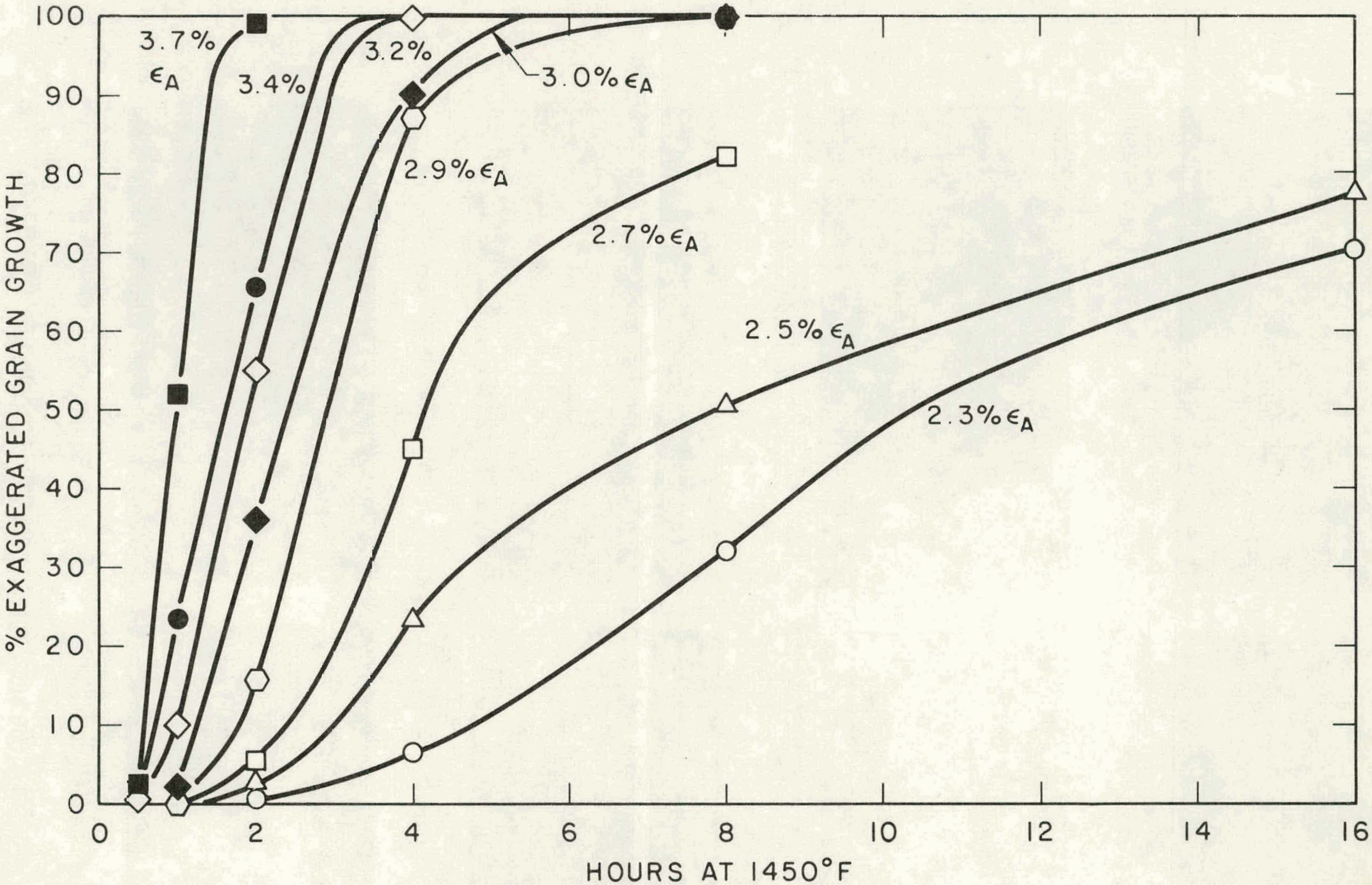
Seed Size (0.283" O.D. x 0.019" Wall)



Blanket Size (0.574" I.D. x 0.032" Wall)

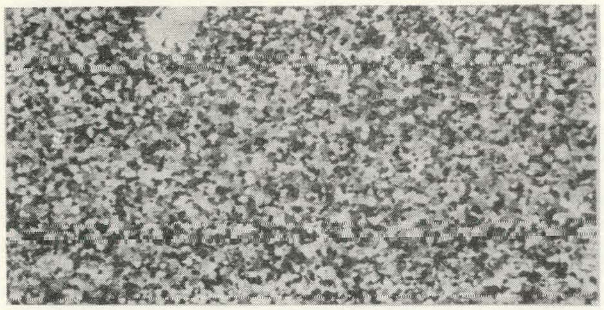
Microstructure of Zircaloy-4 Tubing Samples After the Second Recrystallization Heat Treatment. Both Transverse, Polarized Light 250X

Figure E-1

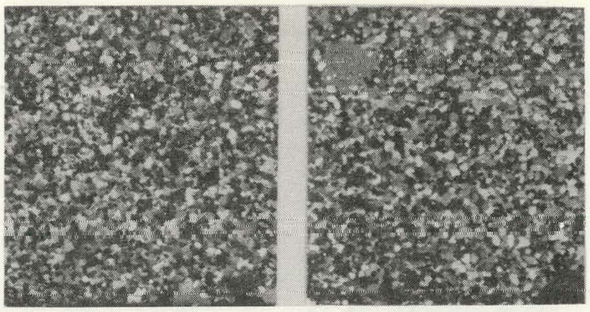


EFFECT OF TIME AT 1450°F ON EXAGGERATED GRAIN GROWTH IN RECRYSTALLIZE ANNEALED 0.574" OD X 0.032" WALL ZIRCALOY-4 TUBING AXIALLY STRAINED AT THE INDICATED LEVELS

FIGURE E-2

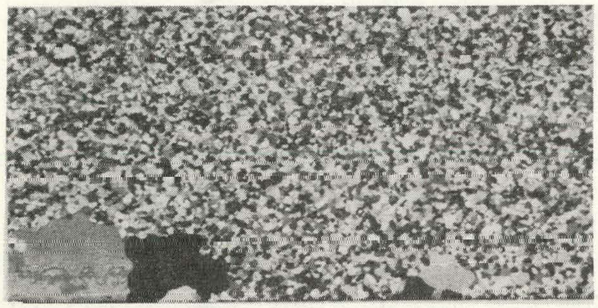


a. 1450 °F / 2 HRS 2.3 % ϵ_A
0.6 % GRAIN COARSENING

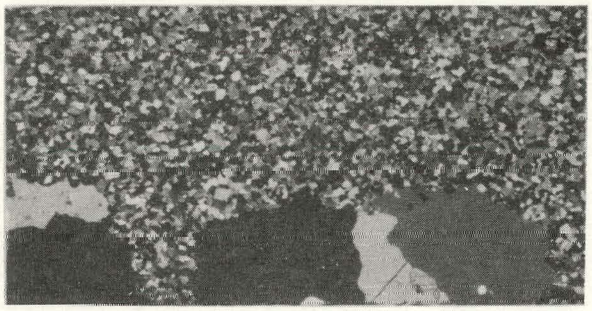


e. 1450°F/1HR 2.5% ϵ_A
0.8% GRAIN COARSENING

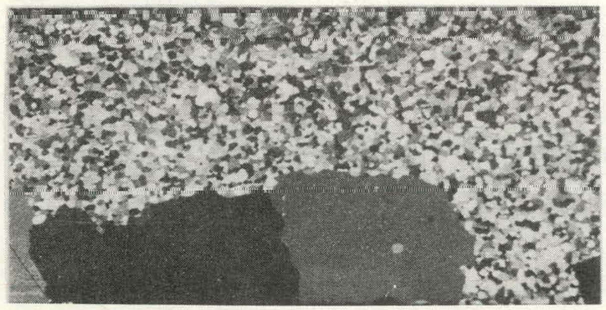
f. 1450°F/2HRS 2.5% ϵ_A
2.6% GRAIN COARSENING



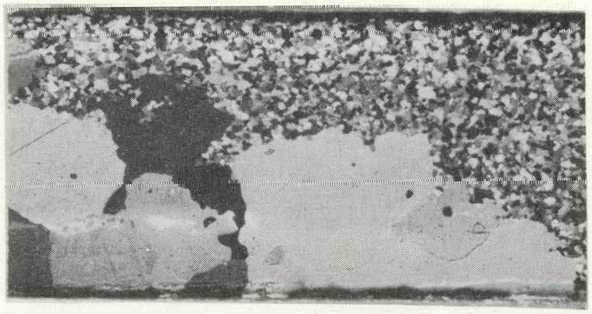
b. 1450 °F / 4 HRS 2.3 % ϵ_A
6.4 % GRAIN COARSENING



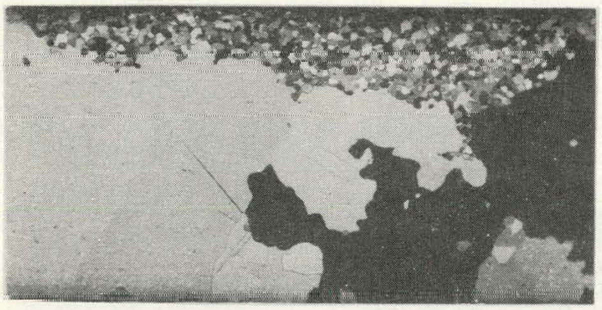
g. 1450°F/4HRS 2.5% ϵ_A
23.2 % GRAIN COARSENING



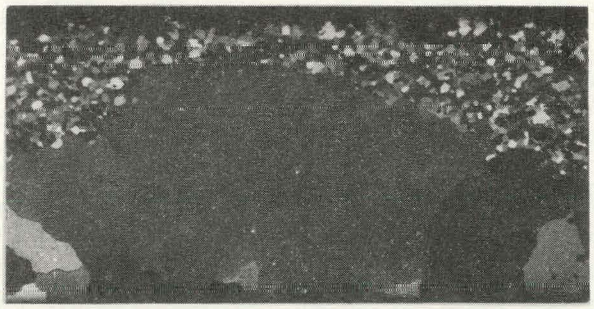
c. 1450 °F / 8 HRS 2.3 % ϵ_A
32.2 % GRAIN COARSENING



h. 1450°F/8HRS 2.5% ϵ_A
63.1 % GRAIN COARSENING



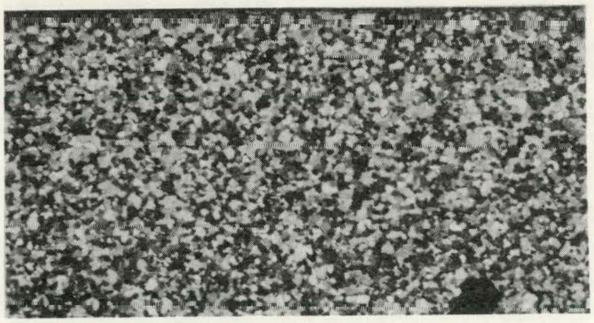
d. 1450°F / 16 HRS 2.3% ϵ_A
70.5 % GRAIN COARSENING



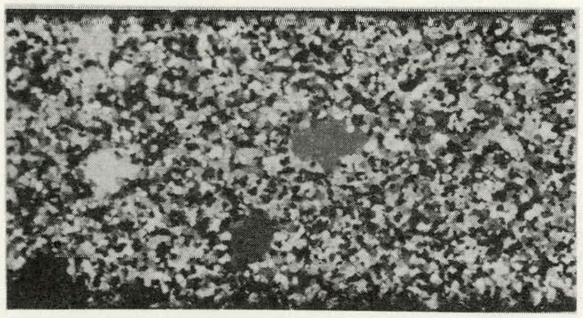
i 1450°F/16 HRS 2.5% ϵ_A
77.6 % GRAIN COARSENING

GRAIN COARSENING IN LONGITUDINAL SECTIONS OF RECRYSTALLIZE ANNEALED 0.574" OD X 0.032" WALL ZIRCALOY-4 TUBING STRAINED 2.3% AND 2.5% AND SUBSENQUENTLY HEAT TREATED AT 1450°F. POLARIZED LIGHT, 50X

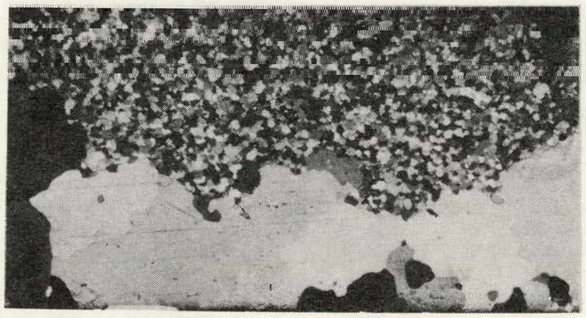
FIGURE E-3



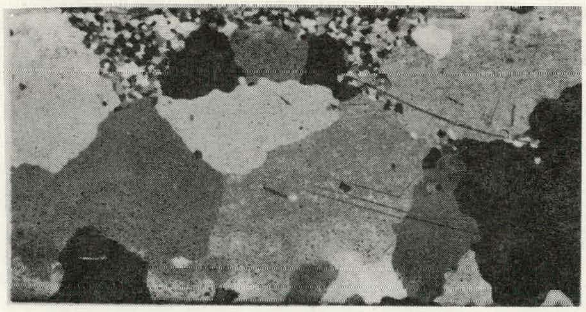
a. 1450°F/1HR 2.7 % ϵ_A
0.7 % GRAIN COARSENING



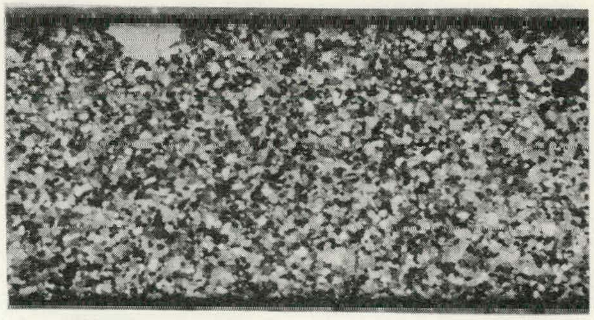
b. 1450°F/2HRS 2.7 % ϵ_A
5.5 % GRAIN COARSENING



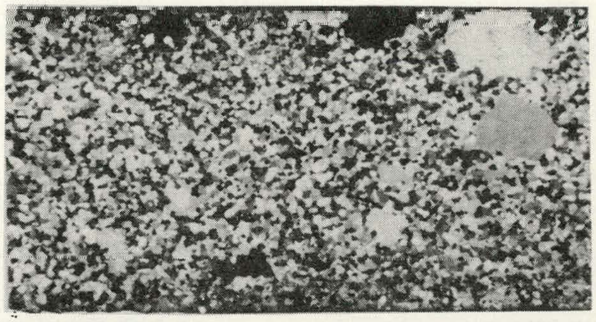
c. 1450°F/4HRS 2.7 % ϵ_A
45.3 % GRAIN COARSENING



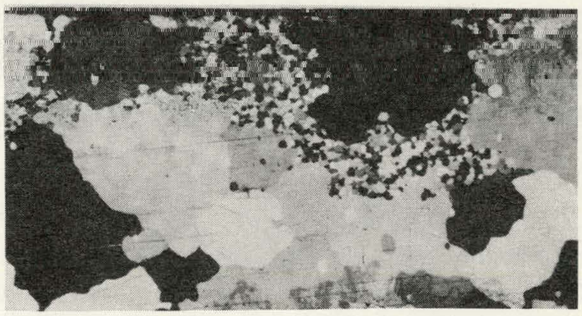
d. 1450°F/8HRS 2.7 % ϵ_A
82.3 % GRAIN COARSENING



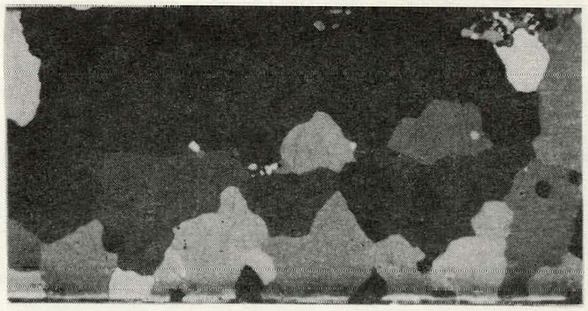
e. 1450°F/1HR 2.9 % ϵ_A
0.9 % GRAIN COARSENING



f. 1450°F/2HRS 2.9 % ϵ_A
15.4 % GRAIN COARSENING



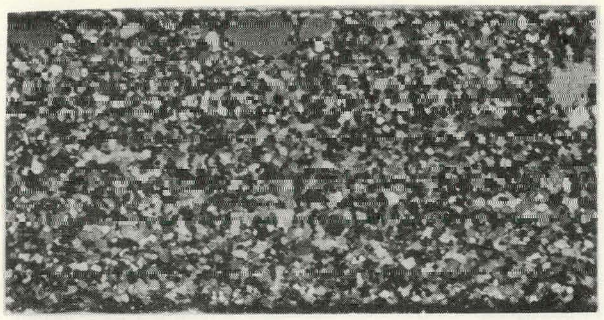
g. 1450°F/4HRS 2.9 % ϵ_A
86.8 % GRAIN COARSENING



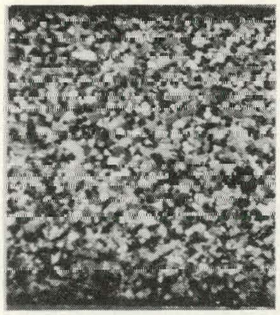
h. 1450°F/8HRS 2.9 % ϵ_A
99.8 % GRAIN COARSENING

GRAIN COARSENING IN LONGITUDINAL SECTIONS OF RECRYSTALLIZE ANNEALED 0.574"OD X 0.032" WALL ZIRCALOY-4 TUBING STRAINED 2.7% AND 2.9% AND SUBSEQUENTLY HEAT TREATED AT 1450°F. POLARIZED LIGHT, 50X

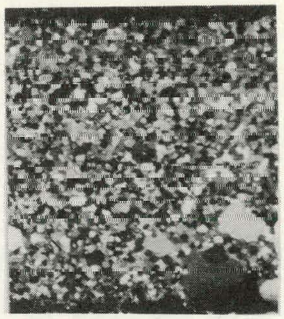
FIGURE E-4



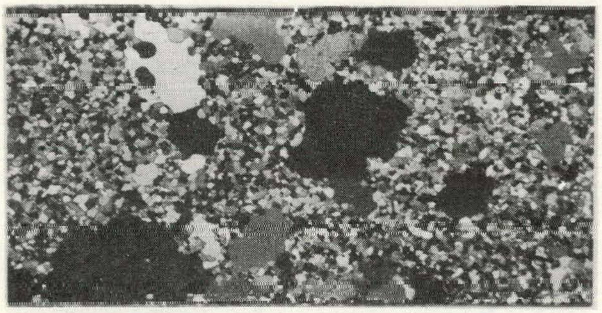
a. 1450°F/1 HR 3.0% ϵ_A
2.2% GRAIN COARSENING



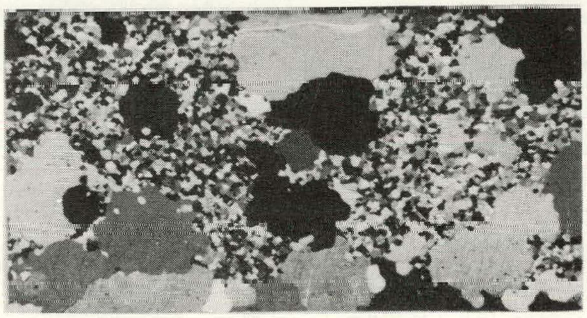
e. 1450°F/1/2 HR 3.2% ϵ_A
0.2% GRAIN COARSENING



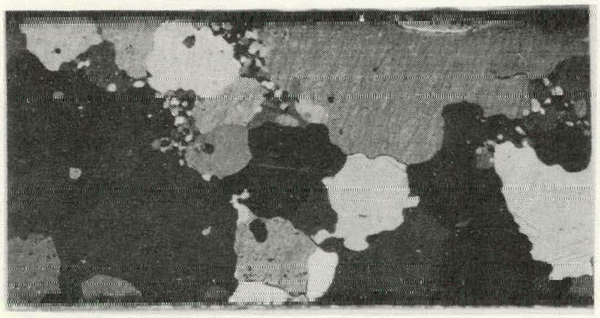
f. 1450°F/1 HR 3.2% ϵ_A
9.8% GRAIN COARSENING



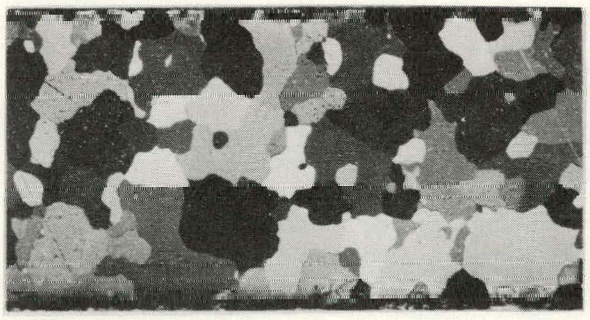
b. 1450°F/2 HRS 3.0% ϵ_A
35.8% GRAIN COARSENING



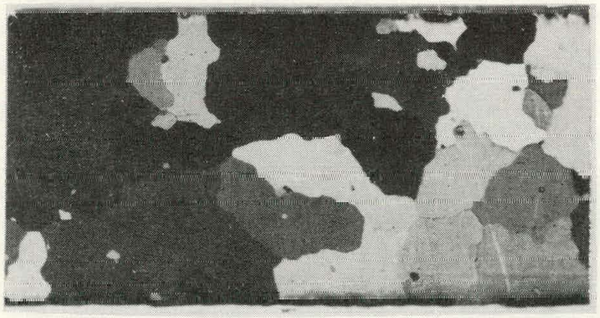
g. 1450°F/2 HRS 3.2% ϵ_A
55.1% GRAIN COARSENING



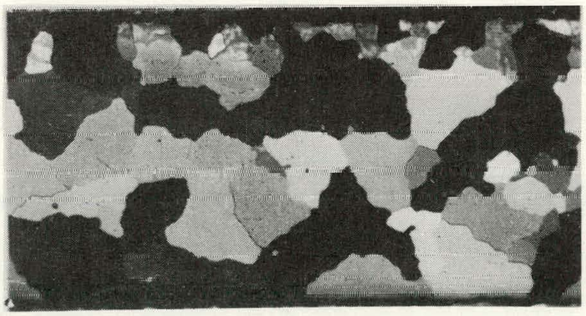
c. 1450°F/4 HRS 3.0% ϵ_A
89.9% GRAIN COARSENING



h. 1450°F/4 HRS 3.2% ϵ_A
100% GRAIN COARSENING



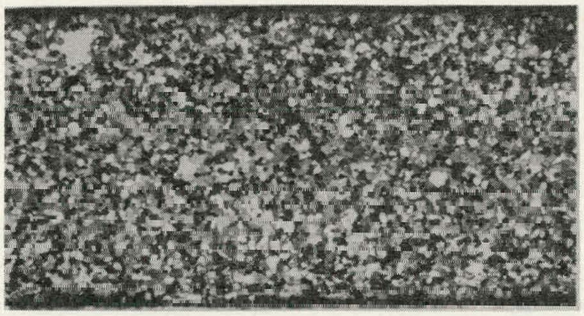
d. 1450°F/8 HRS 3.0% ϵ_A
99.9% GRAIN COARSENING



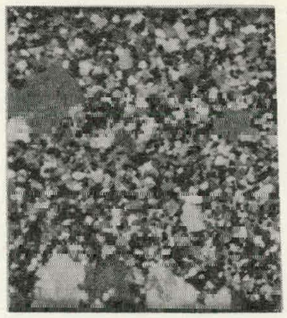
i. 1450°F/8 HRS 3.2% ϵ_A
100% GRAIN COARSENING

GRAIN COARSENING IN LONGITUDINAL SECTIONS OF RECRYSTALLIZE ANNEALED 0.574" OD X 0.032" WALL ZIRCALOY-4 TUBING STRAINED 3.0% AND 3.2% AND SUBSEQUENTLY HEAT TREATED AT 1450°F. POLARIZED LIGHT, 50X

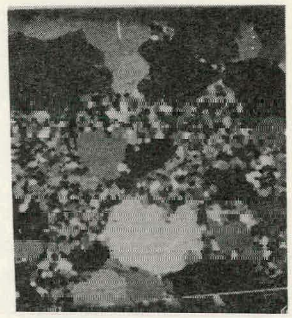
FIGURE E-5



a. 1450°F/1/2 HR 3.4% ϵ_A
0.5% GRAIN COARSENING

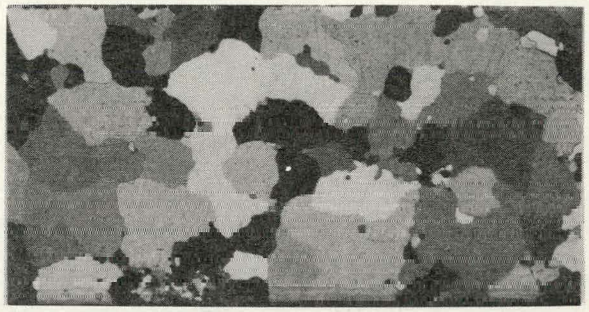


e. 1450°F/1/2 HR 3.7% ϵ_A
4.3% GRAIN COARSENING

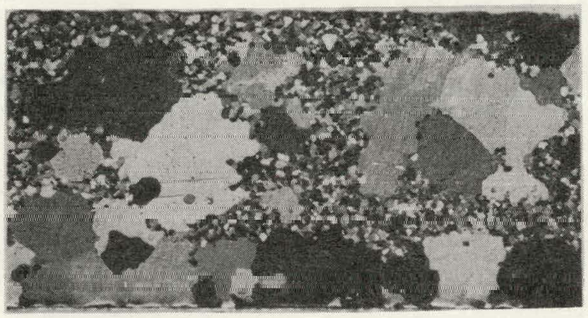


f. 1450°F/1 HR 3.7% ϵ_A
51.5% GRAIN COARSENING

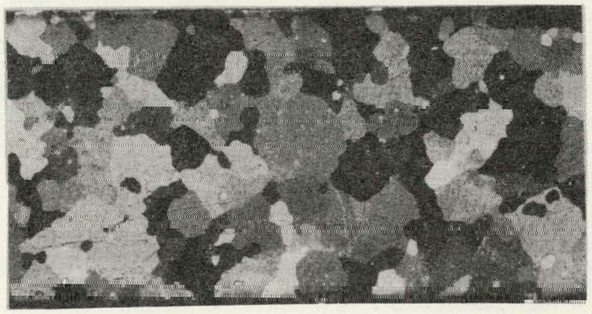
b. 1450°F/1 HR 3.4% ϵ_A
23.7% GRAIN COARSENING



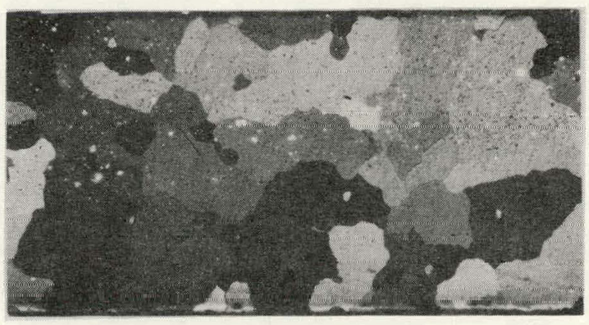
g. 1450°F/2 HRS 3.7% ϵ_A
99.0% GRAIN COARSENING



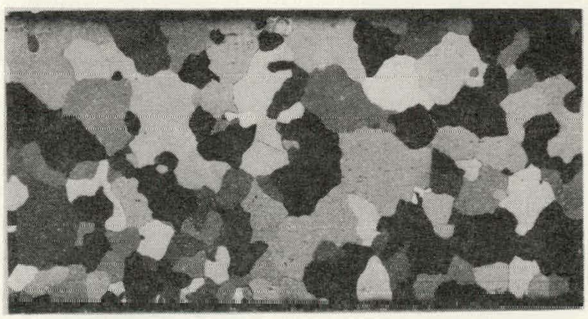
c. 1450°F/2 HRS 3.4% ϵ_A
65.5% GRAIN COARSENING



h. 1450°F/4 HRS 3.7% ϵ_A
100% GRAIN COARSENING



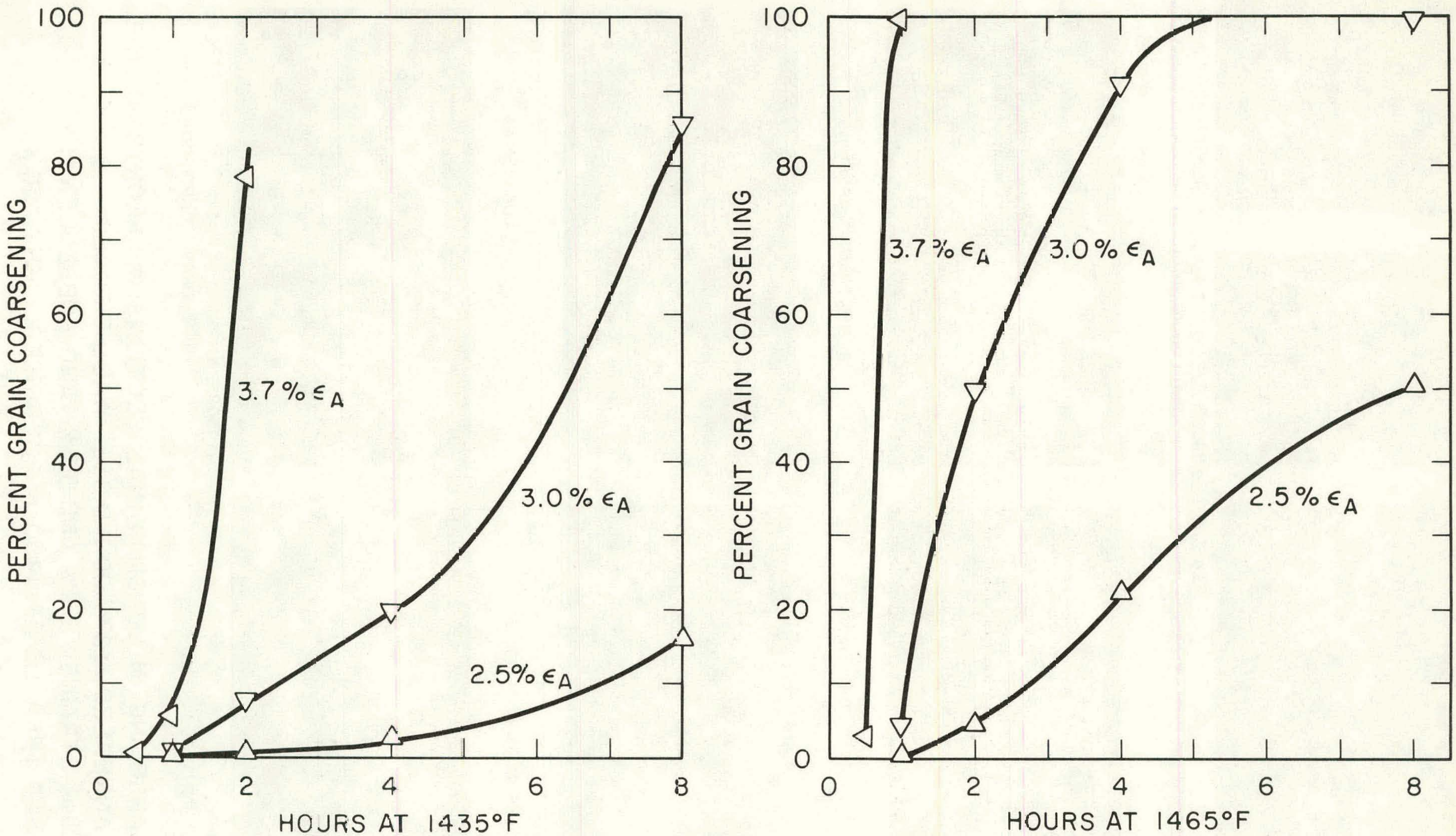
d. 1450°F/4 HRS 3.4% ϵ_A
100% GRAIN COARSENING



i. 1450°F/8 HRS 3.7% ϵ_A
100% GRAIN COARSENING

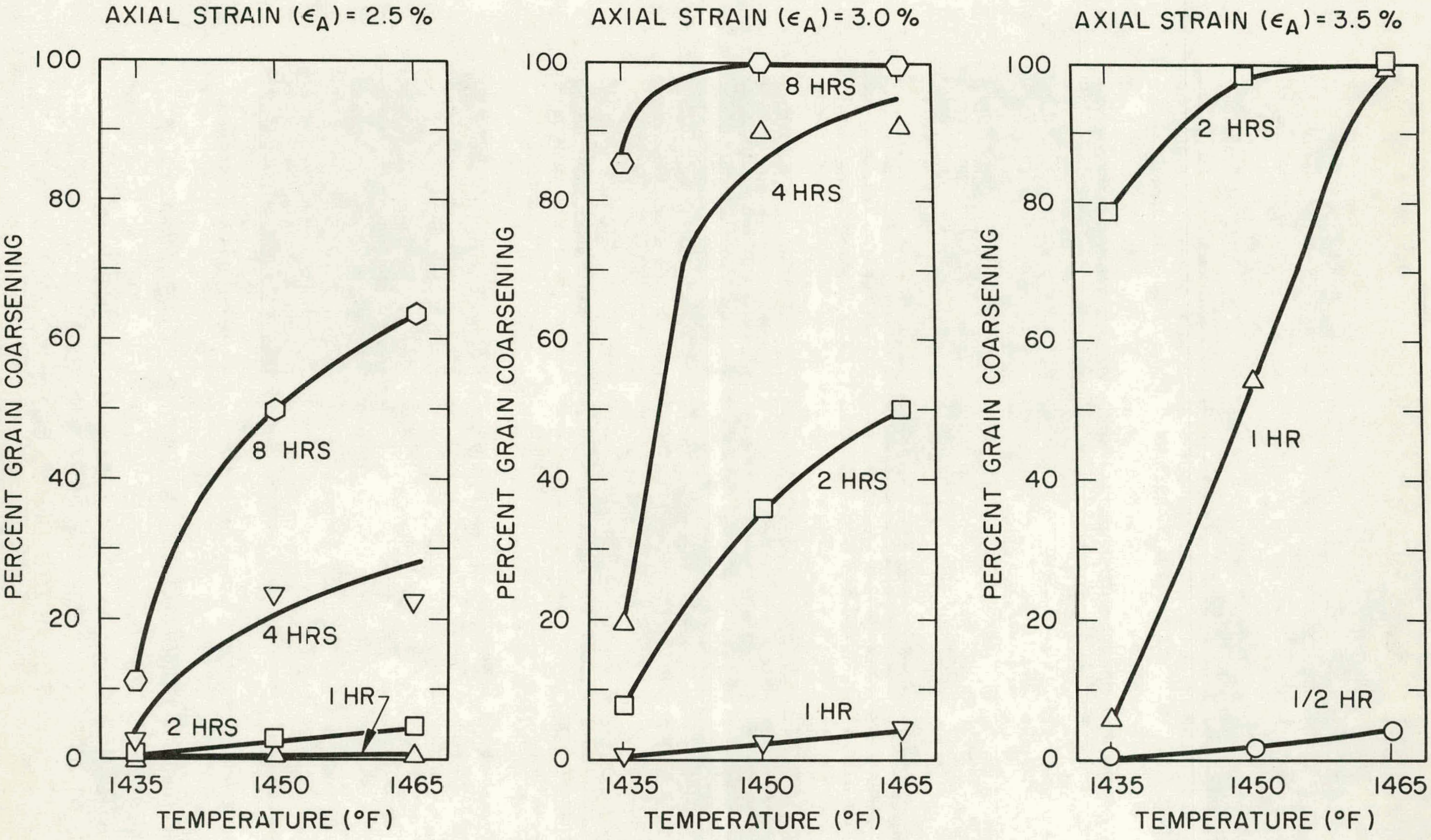
GRAIN COARSENING IN LONGITUDINAL SECTIONS OF RECRYSTALLIZE ANNEALED 0.574" OD X 0.032" WALL ZIRCALOY-4 TUBING STRAINED 3.4% AND 3.7% AND SUBSEQUENTLY HEAT TREATED AT 1450°F. POLARIZED LIGHT, 50 X

FIGURE E-6



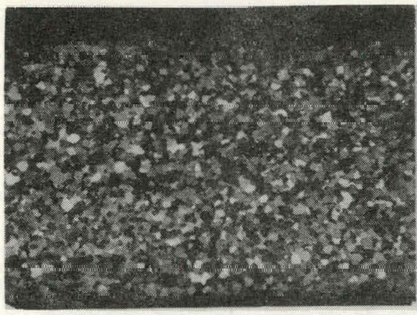
EFFECT OF TIME AT HEAT TREATMENT TEMPERATURE (1435°F AND 1465°F) ON GRAIN COARSENING IN RECRYSTALLIZE ANNEALED 0.574 "O D X 0.032" WALL ZIRCALOY-4 TUBING AXIALLY STRAINED AT THE INDICATED LEVELS (ϵ_A)

FIGURE E-7

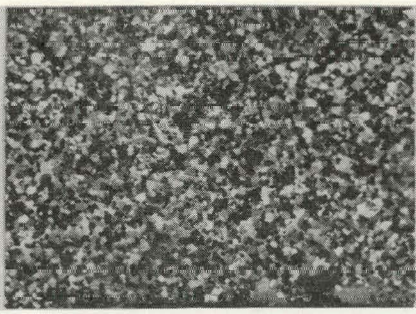


EFFECT OF HEAT TREATMENT TEMPERATURE ON GRAIN COARSENING IN RECRYSTALLIZE ANNEALED 0.574" OD X 0.032" WALL ZIRCALOY-4 TUBING AXIALLY STRAINED AT THE INDICATED LEVELS

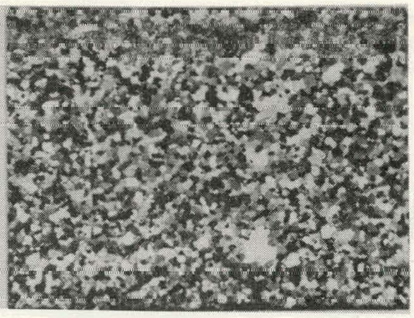
FIGURE E-8



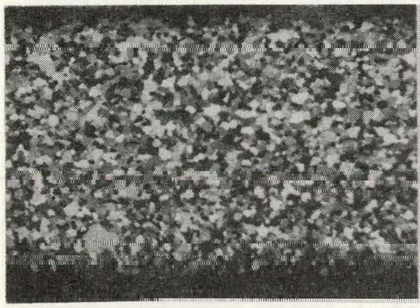
a. HEAT TREATED AT 1435°F/1 HR
0% GRAIN COARSENING



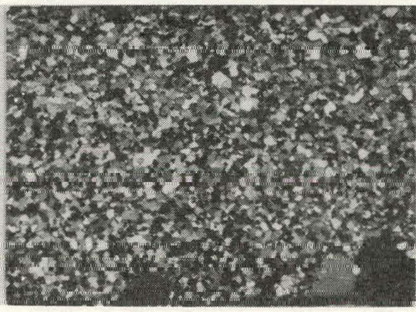
e. HEAT TREATED AT 1450°F/1HR
0.8% GRAIN COARSENING



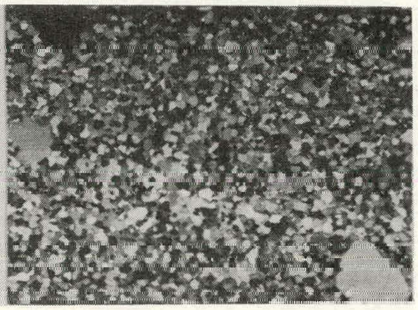
i. HEAT TREATED AT 1465°F/1HR
0.5% GRAIN COARSENING



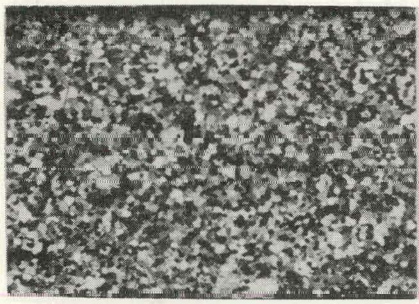
b. HEAT TREATED AT 1435°F/2 HRS
0.8% GRAIN COARSENING



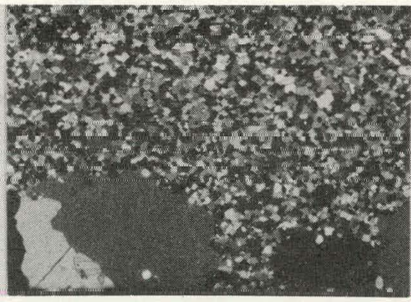
f. HEAT TREATED AT 1450°F/ 2 HRS
2.6% GRAIN COARSENING



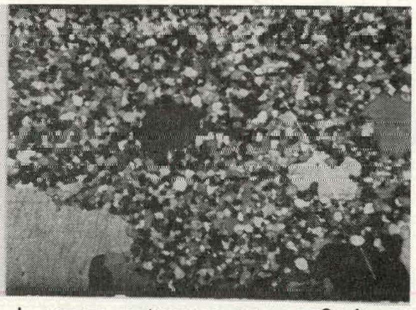
j. HEAT TREATED AT 1465°F/2HRS
4.3% GRAIN COARSENING



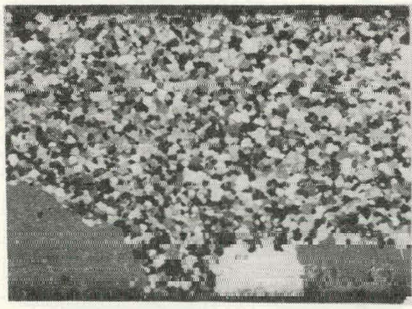
c. HEAT TREATED AT 1435°F/4 HRS
2.2% GRAIN COARSENING



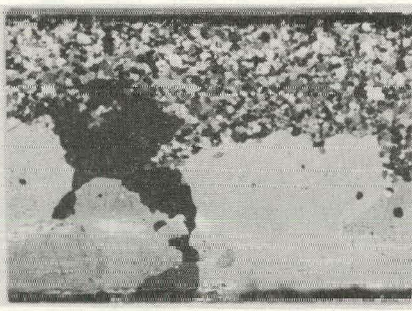
g. HEAT TREATED AT 1450°F/4 HRS
23.2% GRAIN COARSENING



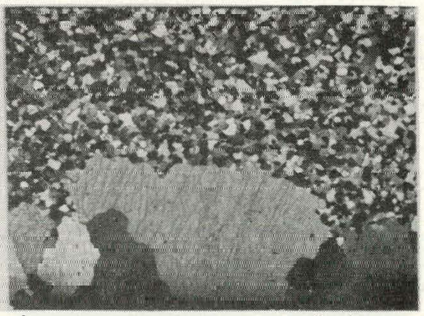
k. HEAT TREATED AT 1465°F/4 HRS
22.1% GRAIN COARSENING



d. HEAT TREATED AT 1435°F/8 HRS
16% GRAIN COARSENING



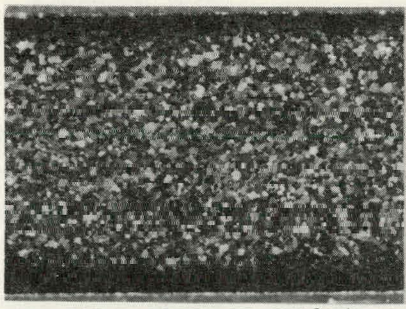
h. HEAT TREATED AT 1450°F/8 HRS
63.1% GRAIN COARSENING



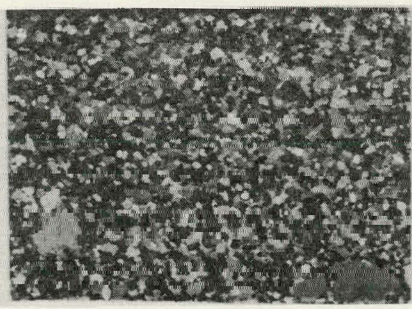
l. HEAT TREATED AT 1465°F/8 HRS
50.6% GRAIN COARSENING

GRAIN COARSENING IN LONGITUDINAL SECTIONS OF RECRYSTALLIZE ANNEALED 0.574" OD X 0.032" WALL ZIRCALOY-4 TUBING STRAINED 2.5% AXIALLY AND SUBSEQUENTLY HEAT TREATED AT VARIOUS TEMPERATURE/TIME COMBINATIONS. POLARIZED LIGHT, 50X

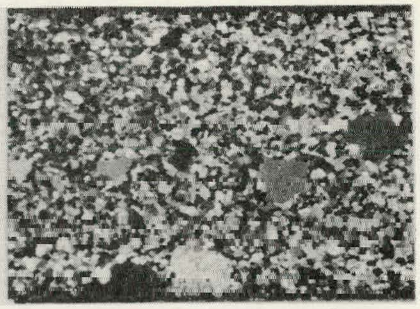
FIGURE E-9



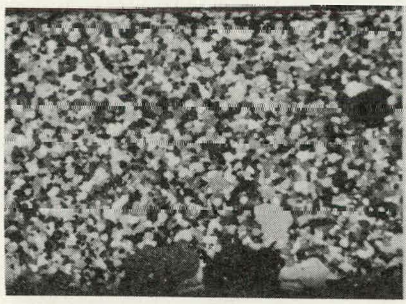
a. HEAT TREATED AT 1435°F/1 HR
0.3% GRAIN COARSENING



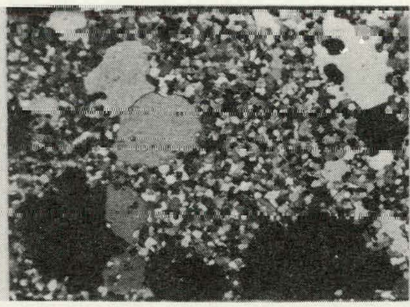
e. HEAT TREATED AT 1450°F/1 HR
2.2% GRAIN COARSENING



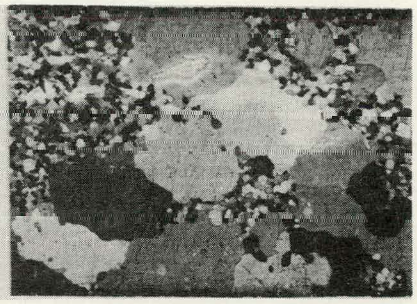
i. HEAT TREATED AT 1465°F/1 HR
4.2% GRAIN COARSENING



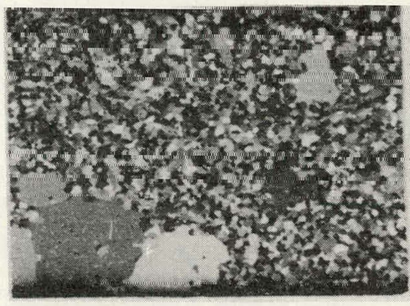
b. HEAT TREATED AT 1435°F/2 HRS
7.9% GRAIN COARSENING



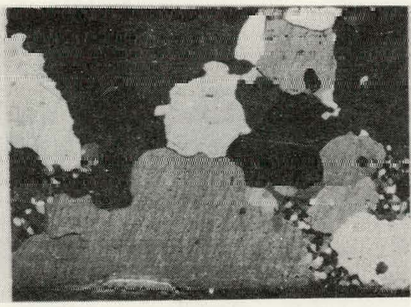
f. HEAT TREATED AT 1450°F/2 HRS
35.8% GRAIN COARSENING



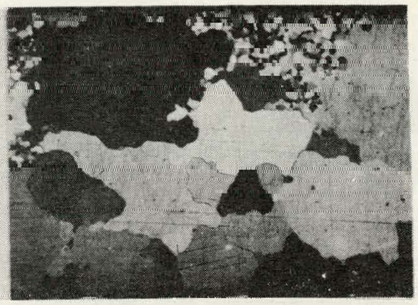
j. HEAT TREATED AT 1465°F/2 HRS
49.7% GRAIN COARSENING



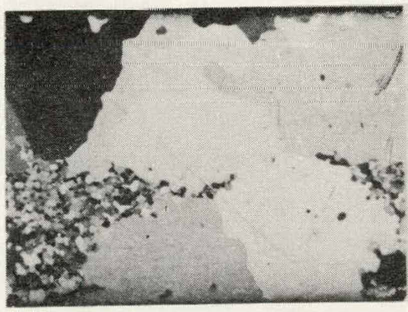
c. HEAT TREATED AT 1435°F/4 HRS
19.2% GRAIN COARSENING



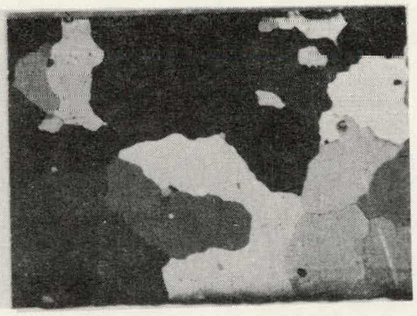
g. HEAT TREATED AT 1450°F/4 HRS
89.9% GRAIN COARSENING



k. HEAT TREATED AT 1465°F/4 HRS
90.9% GRAIN COARSENING



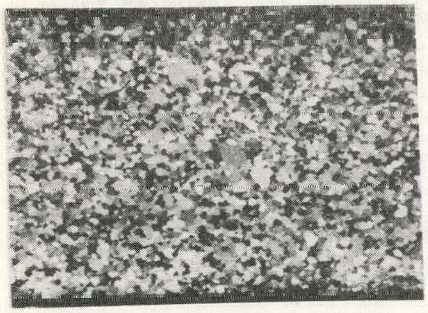
d. HEAT TREATED AT 1435°F/8 HRS
85.1% GRAIN COARSENING



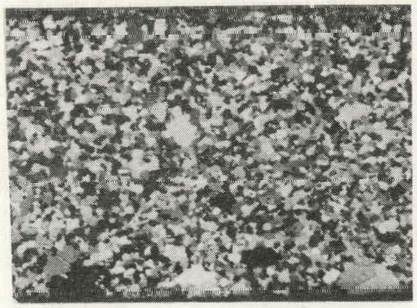
h. HEAT TREATED AT 1450°F/8 HRS
99.9% GRAIN COARSENING

GRAIN COARSENING IN LONGITUDINAL SECTIONS OF RECRYSTALLIZE ANNEALED 0.574" OD X 0.032" WALL ZIRCALOY-4 TUBING STRAINED 3.0% AXIALLY AND SUBSEQUENTLY HEAT TREATED AT VARIOUS TEMPERATURE/TIME COMBINATIONS. POLARIZED LIGHT, 50X

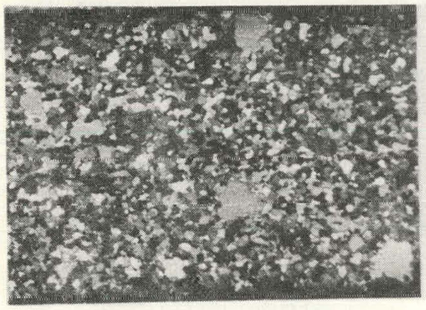
FIGURE E-10



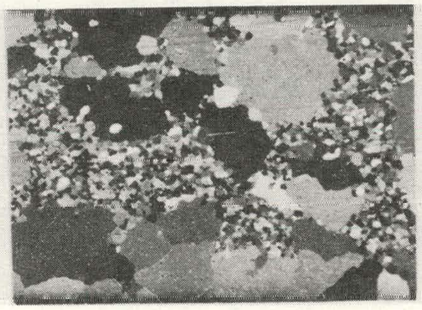
a. HEAT TREATED AT 1435°F/1/2 HR
0.6% GRAIN COARSENING



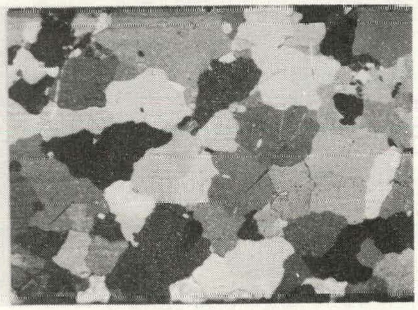
f. HEAT TREATED AT 1465°F/1/2 HR
2.3% GRAIN COARSENING



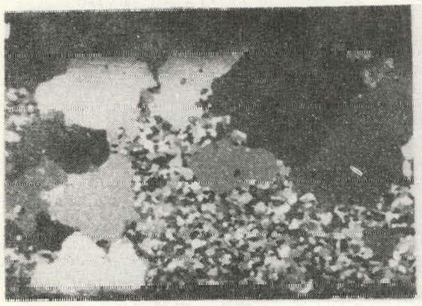
b. HEAT TREATED AT 1435°F/1 HR
5.3% GRAIN COARSENING



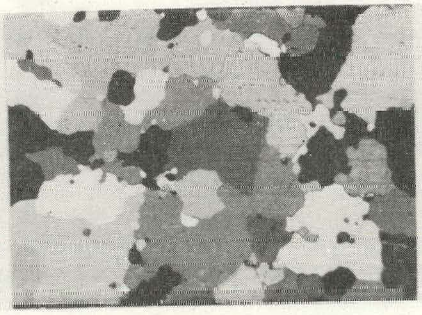
d. HEAT TREATED AT 1450°F/1 HR
51.5% GRAIN COARSENING



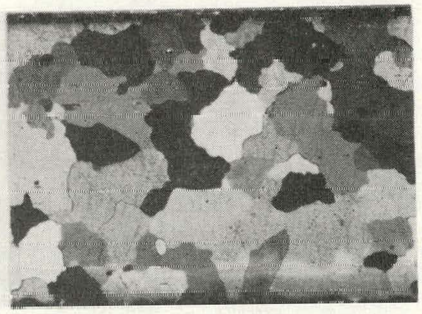
g. HEAT TREATED AT 1465°F/1 HR
99.8% GRAIN COARSENING



c. HEAT TREATED AT 1435°F/2 HRS
78.2% GRAIN COARSENING



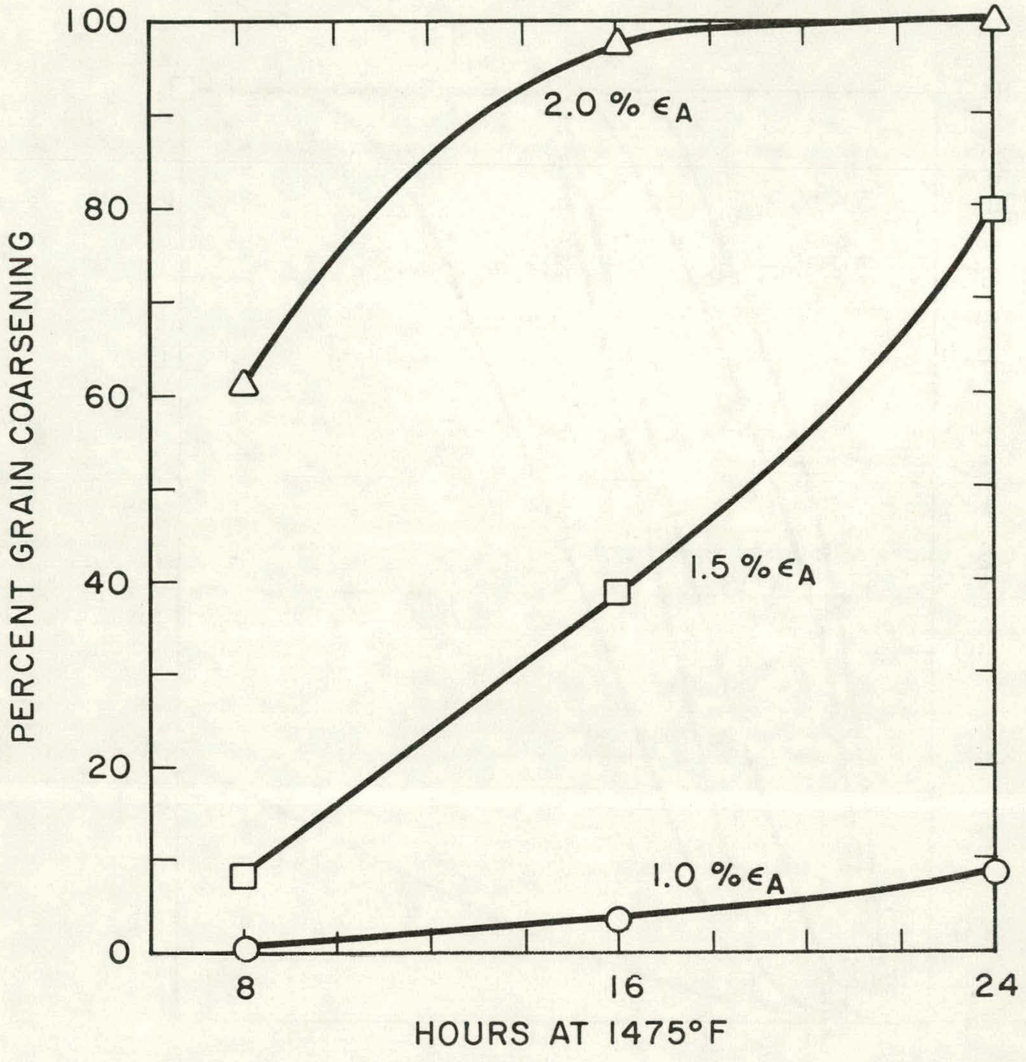
e. HEAT TREATED AT 1450°F/2 HRS
99.0% GRAIN COARSENING



h. HEAT TREATED AT 1465°F/2 HRS
100% GRAIN COARSENING

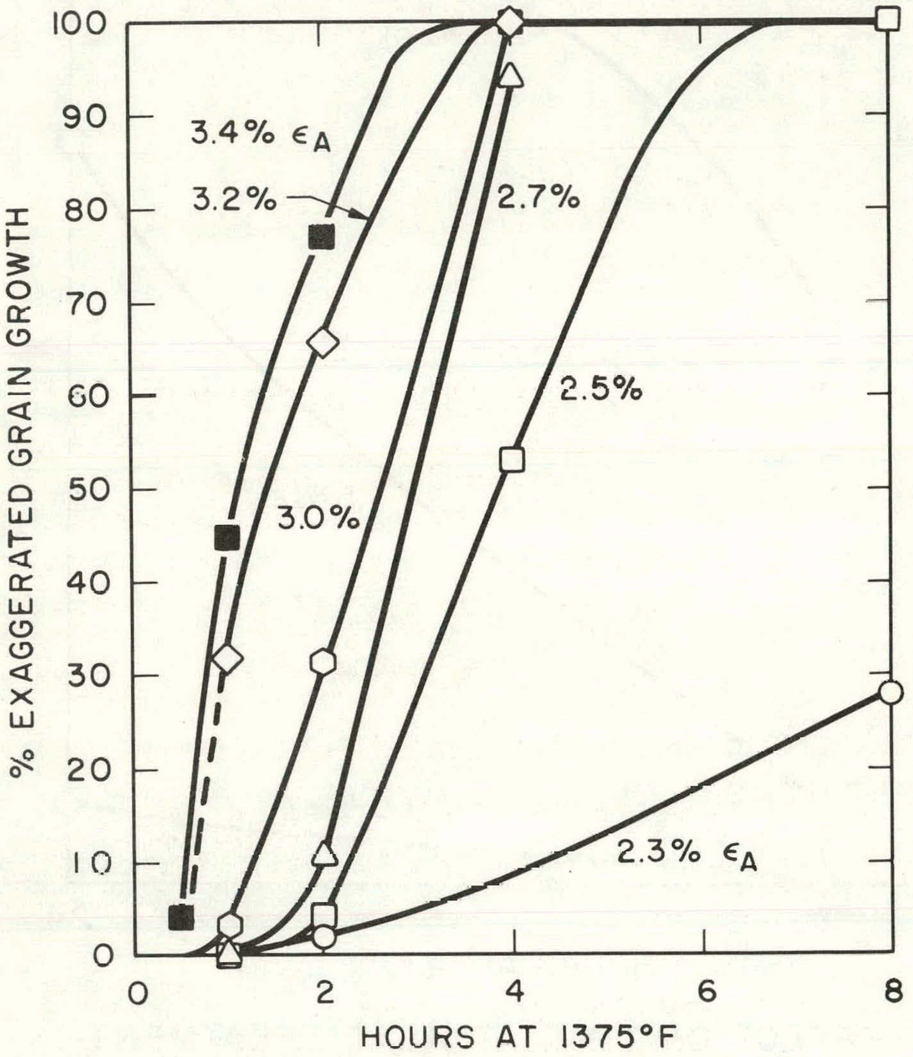
GRAIN COARSENING IN LONGITUDINAL SECTIONS OF RECRYSTALLIZE ANNEALED 0.574" OD X 0.032" WALL ZIRCALOY - 4 TUBING STRAINED 3.5% AXIALLY AND SUBSEQUENTLY HEAT TREATED AT VARIOUS TEMPERATURE/TIME COMBINATIONS. POLARIZED LIGHT, 50X

FIGURE E-11



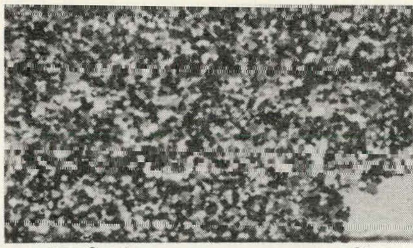
EFFECT OF TIME AT HEAT TREATMENT TEMPERATURE (1475 °F) ON GRAIN COARSENING IN RECRYSTALLIZE ANNEALED 0.574 " O D X 0.032 " WALL ZIRCALOY-4 TUBING AXIALLY STRAINED AT THE INDICATED LEVELS

FIGURE E-12

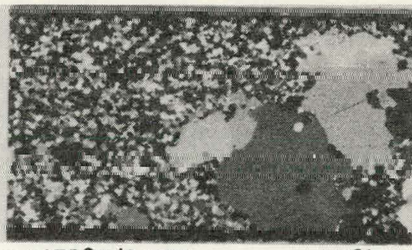


EFFECT OF TIME AT 1375°F ON GRAIN COURSENING IN RECRYSTALLIZE ANNEALED 0.283" OD X 0.019" WALL ZIRCALOY-4 TUBING AXIALLY STRAINED AT THE INDICATED LEVELS (ϵ_A)

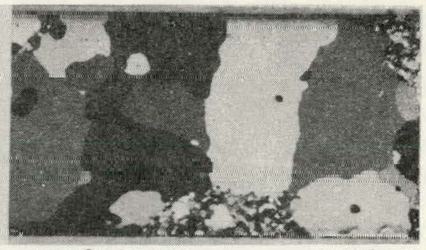
FIGURE E-13



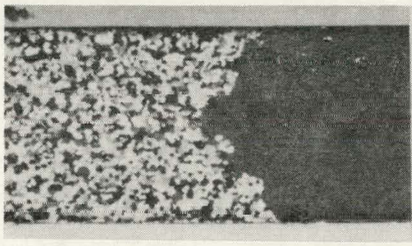
a. 1475°F/2 HRS 1.0% ϵ_A
1.8% GRAIN COARSENING



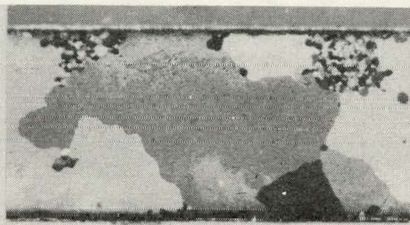
c. 1475°F/2 HRS 1.5% ϵ_A
41.9% GRAIN COARSENING



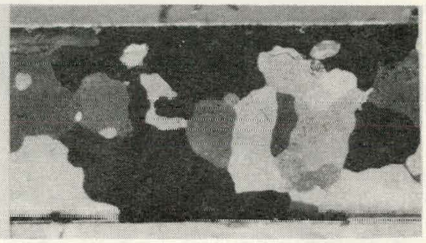
e. 1475°F/2 HRS 2.0% ϵ_A
96.3% GRAIN COARSENING



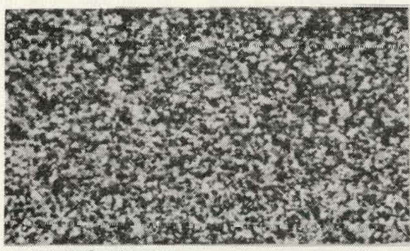
b. 1475°F/4 HRS 1.0% ϵ_A
44.9% GRAIN COARSENING



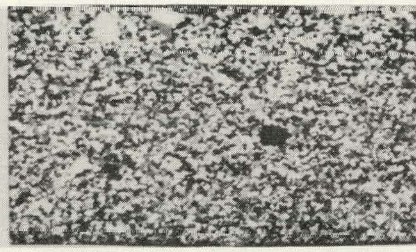
d. 1475°F/4 HRS 1.5% ϵ_A
95.0% GRAIN COARSENING



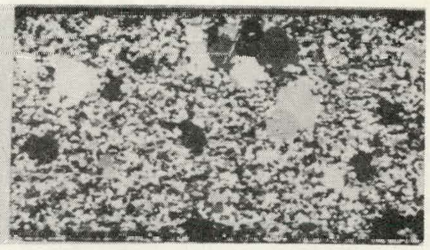
f. 1475°F/4 HRS 2.0% ϵ_A
100% GRAIN COARSENING



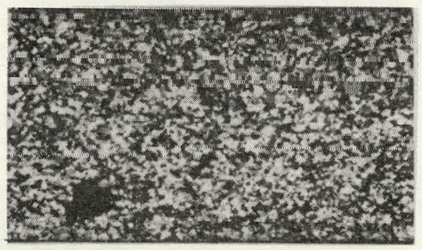
g. 1375°F/1 HR 2.5% ϵ_A
0.4% GRAIN COARSENING



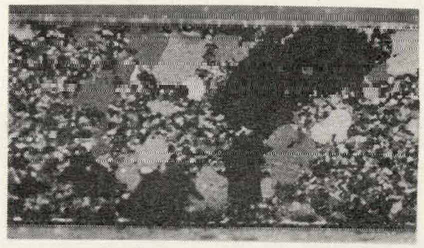
j. 1375°F/1 HR 3.0% ϵ_A
3.2% GRAIN COARSENING



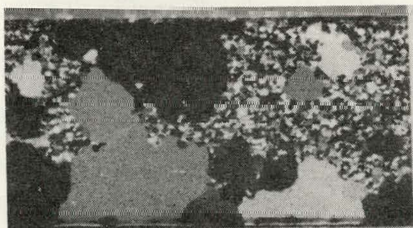
l. 1375°F/1 HR 3.4% ϵ_A
45% GRAIN COARSENING



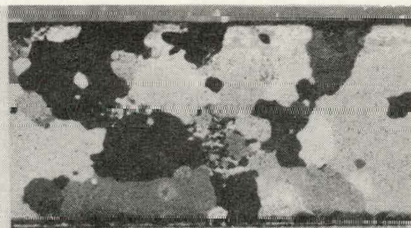
h. 1375°F/2 HRS 2.5% ϵ_A
4.3% GRAIN COARSENING



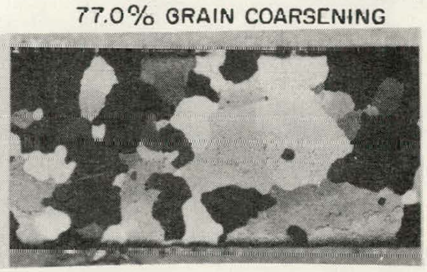
m. 1375°F/2 HRS 3.4% ϵ_A
77.0% GRAIN COARSENING



i. 1375°F/4 HRS 2.5% ϵ_A
52.9% GRAIN COARSENING



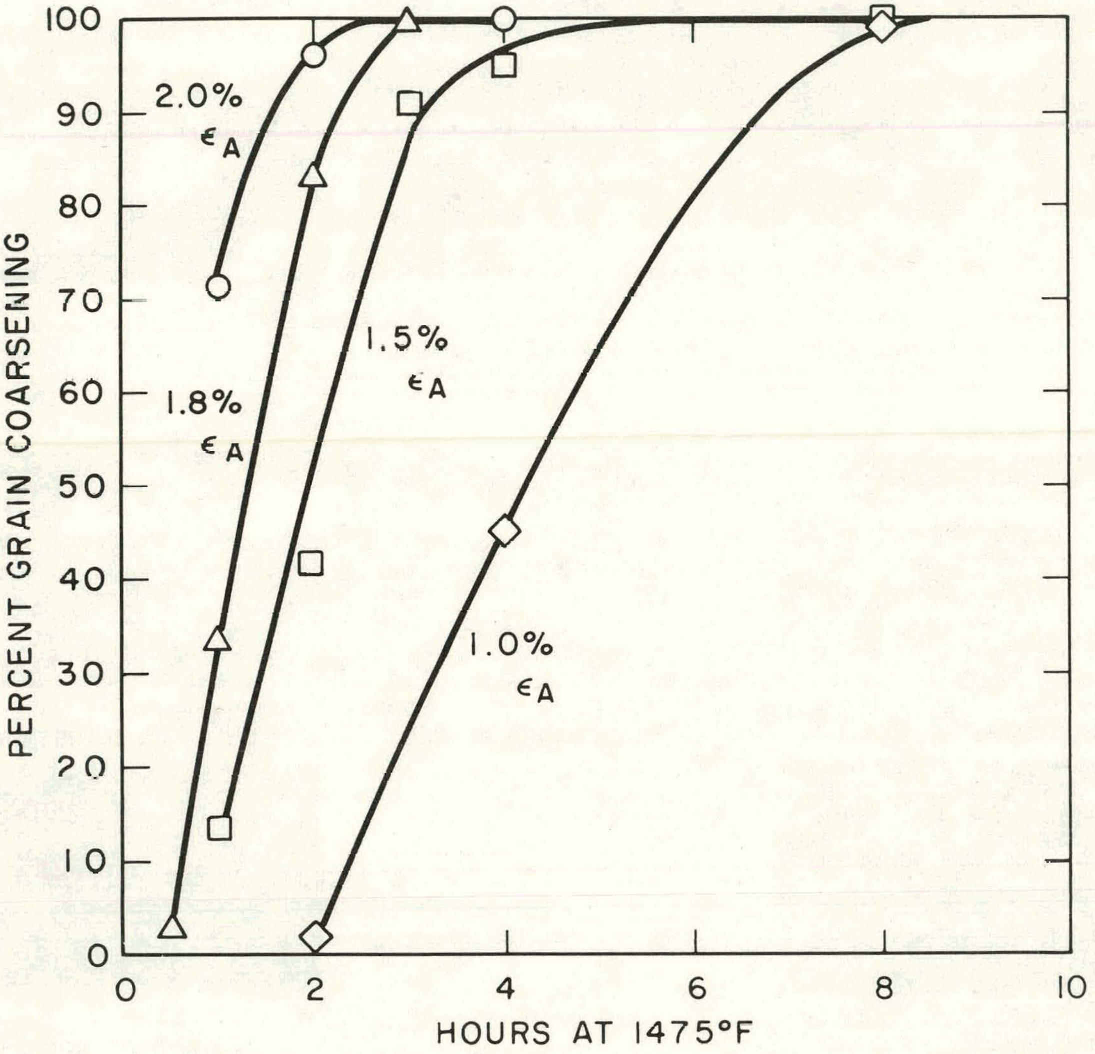
k. 1375°F/4 HRS 3.0% ϵ_A
99.7% GRAIN COARSENING



n. 1375°F/4 HRS 3.4% ϵ_A
100% GRAIN COARSENING

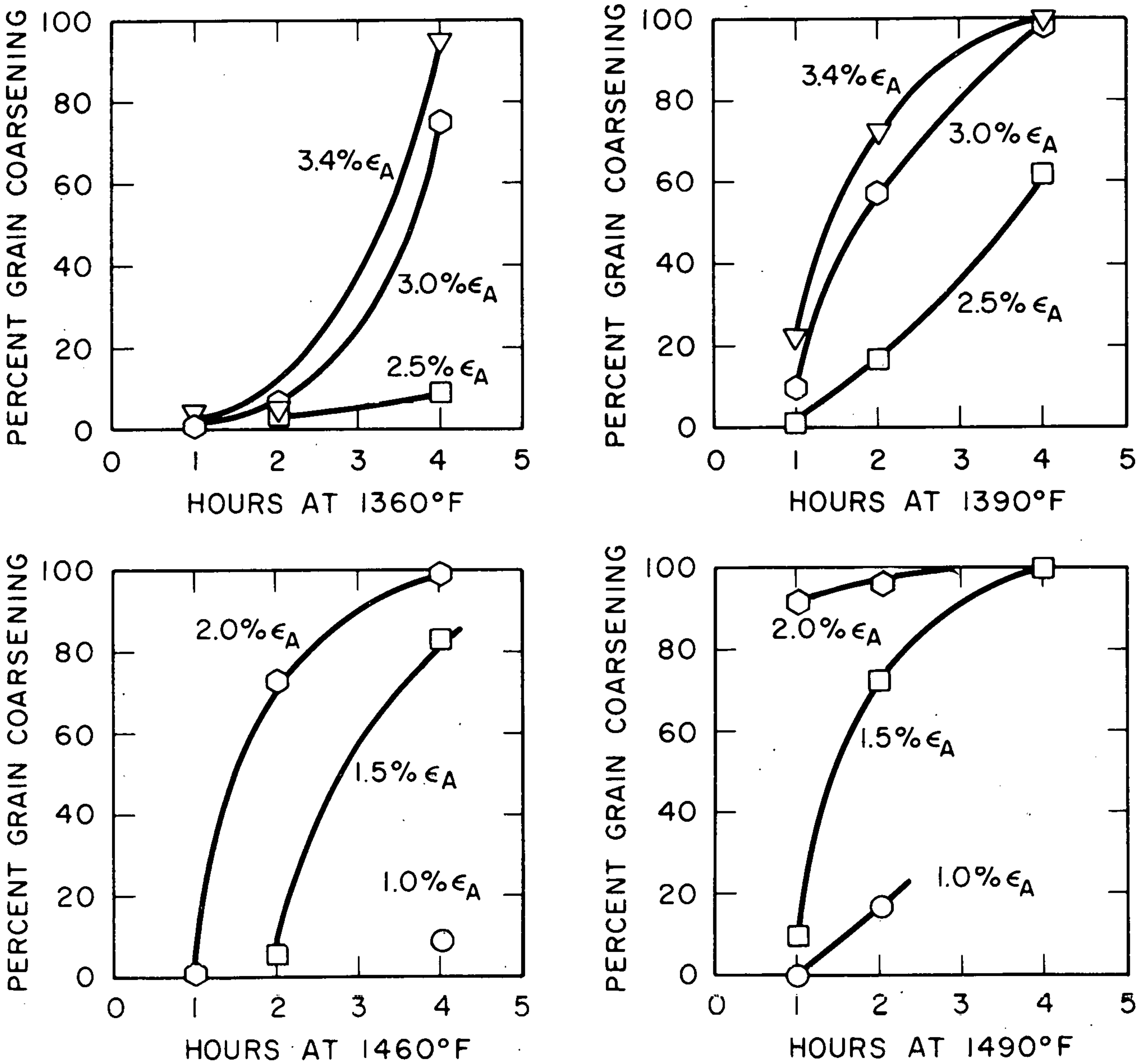
GRAIN COARSENING IN LONGITUDINAL SECTIONS OF RECRYSTALLIZE ANNEALED 0.283" OD X 0.019" WALL ZIRCALOY-4 TUBING AXIALLY STRAINED 1.0% TO 3.4% AND SUBSEQUENTLY HEAT TREATED AT THE SPECIFIED CONDITIONS. POLARIZED LIGHT, 50X

FIGURE E-14



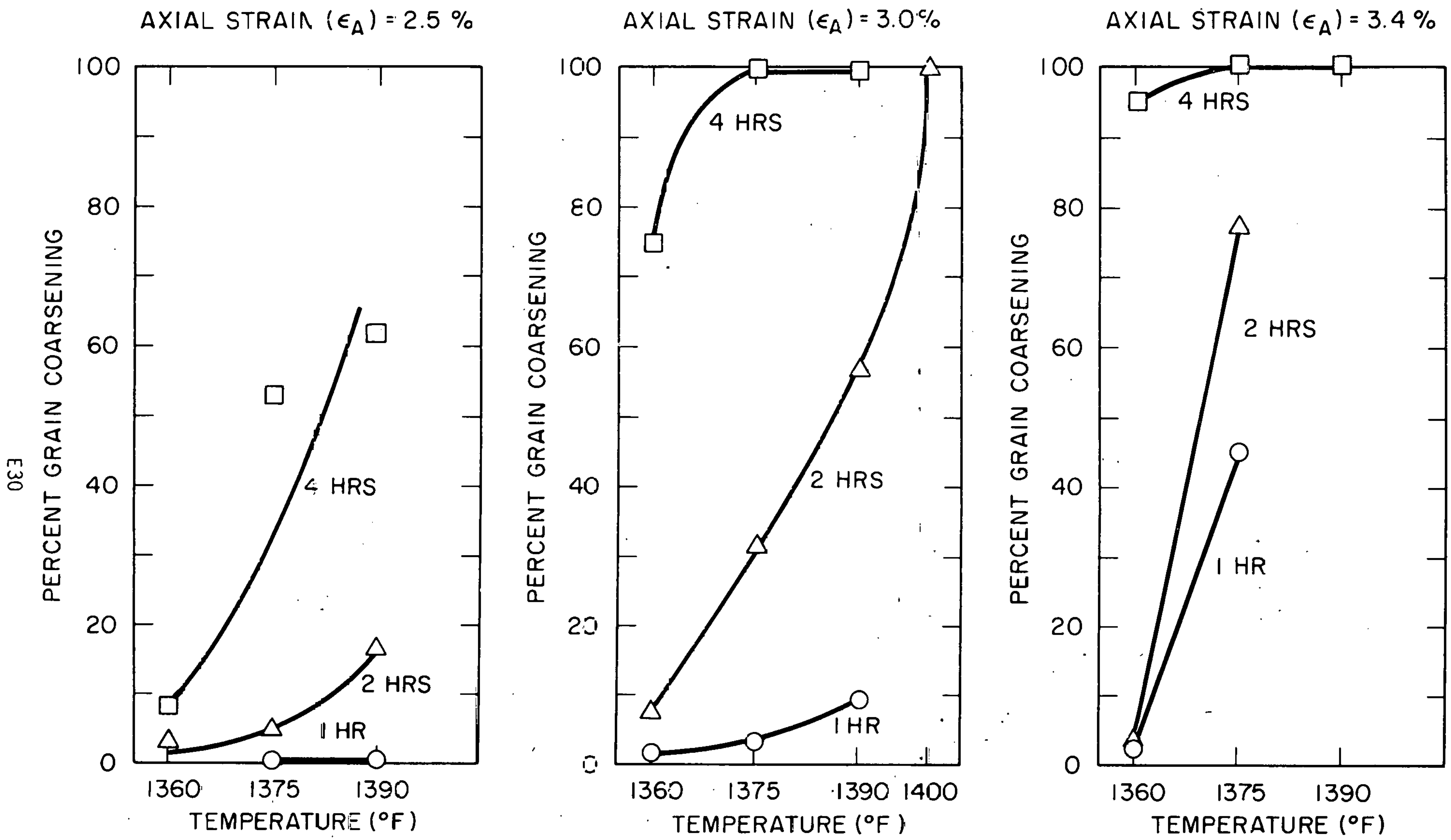
EFFECT OF TIME AT 1475°F ON GRAIN COARSENING IN RECRYSTALLIZE ANNEALED 0.283" OD X 0.019" WALL ZIRCALOY-4 TUBING AXIALLY STRAINED AT THE INDICATED LEVELS (ϵ_A)

FIGURE E-15



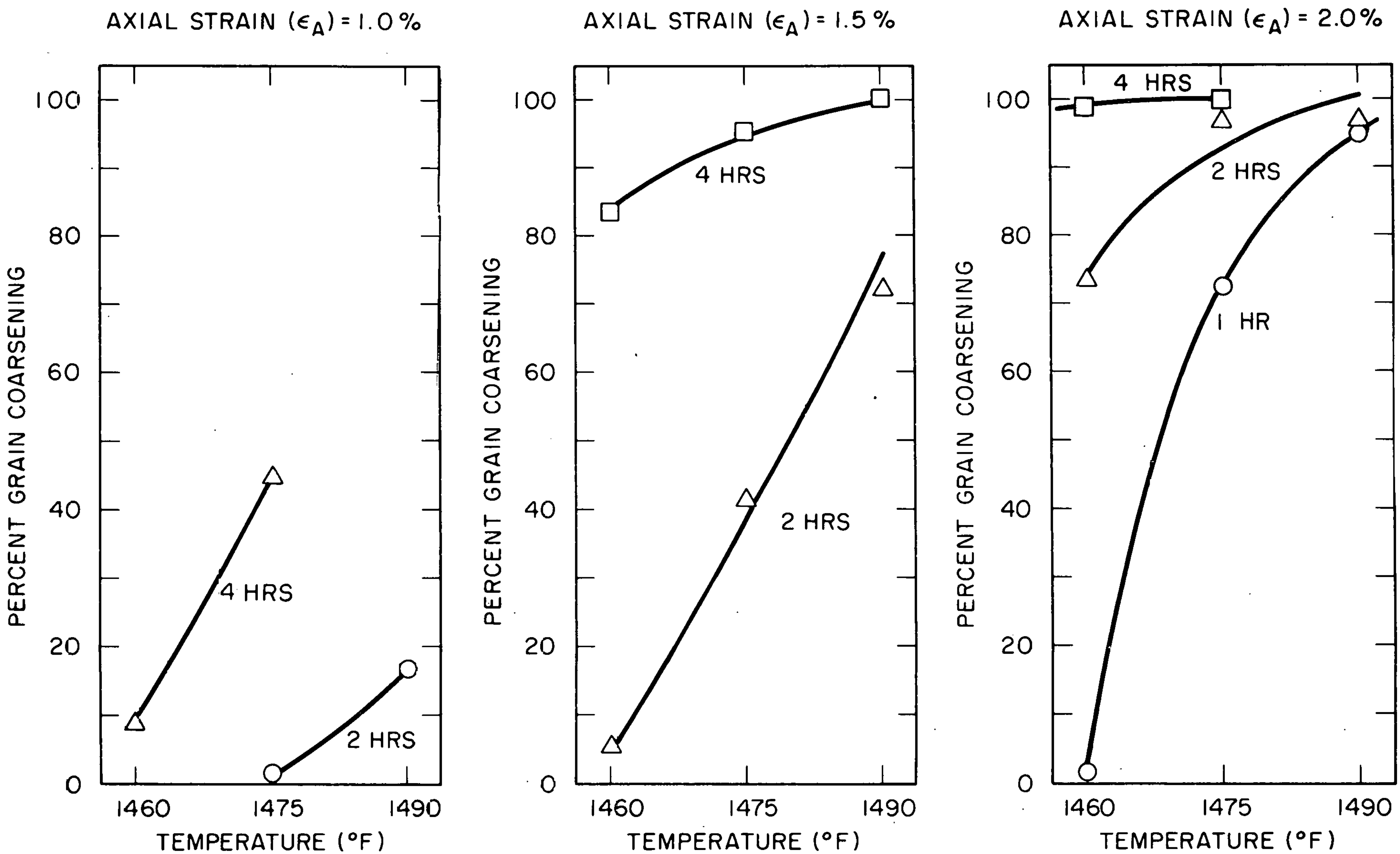
EFFECT OF TIME AT HEAT TREATMENT TEMPERATURE ON GRAIN COARSENING IN RECRYSTALLIZE ANNEALED 0.283" OD X 0.019" WALL ZIRCALOY-4 TUBING AXIALLY STRAINED AT THE INDICATED LEVELS(ϵ_A)

FIGURE E-16



EFFECT OF HEAT TREATMENT TEMPERATURE ON GRAIN COARSENING IN RECRYSTALLIZE ANNEALED 0.283" O D X 0.019" WALL ZIRCALOY-4 TUBING AXIALLY STRAINED AT THE INDICATED LEVELS

FIGURE E-17



EFFECT OF HEAT TREATMENT TEMPERATURE ON GRAIN COARSENING IN RECRYSTALLIZE ANNEALED 0.283" O D X 0.019" WALL ZIRCALOY-4 TUBING AXIALLY STRAINED AT THE INDICATED LEVELS

FIGURE E-18

☆U.S. GOVERNMENT PRINTING OFFICE: 1981/703-014/364