**Zircaloy Fuel Cladding Collapse
Test Plan**

D. C. Hobson

MASTER

OAK RIDGE NATIONAL LABORATORY

OPERATED BY UNION CARBIDE CORPORATION FOR THE ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

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D. O. Hobson

AUGUST 1976

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UNION CARBIDE CORPORATION
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ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

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ABSTRACT

This test plan outlines the experimental philosophy and procedures for investigating the deformation behavior of Zircaloy fuel cladding under normal and near-normal reactor operating conditions. Such conditions impose compressive hoop and axial stresses on the cladding at temperatures that encompass the time-dependent or creep-strain regime. The purpose of the outlined study is to understand the deformation behavior of cladding under in- and out-of-reactor conditions so that mechanical properties correlations may be developed.

INTRODUCTION

An understanding of the behavior of light-water, power-reactor fuel cladding under normal¹ reactor operating conditions is important from several standpoints, including calculations of heat transfer from the fuel to the coolant and of stresses and strains in the cladding. Several computer programs have been developed to predict the behavior of cladding and, in particular, to calculate the change in ovality of an initially oval, closed-end, finite-length tube as a function of time, temperature, neutron flux, and uniform external pressure.

The purpose of this report is to outline our current thoughts on the subject of Zircaloy cladding creepdown and collapse. The planned experimentation will provide information to improve the mechanical properties data needed for various computer codes.

An extensive review has been performed on prior experimentation on cladding collapse, on theoretical work on the collapse of cylindrical bodies, and on the anisotropy of Zircaloy in general.

¹The term "normal" is defined as the operation of the reactor under design conditions [nominally approximately 760°F (371°C) cladding temperature and approximately 1800 to 2200 psi (12.4 to 15.2 MPa) external pressure] and includes temperature variations and changes in fuel pellet geometry and spacing over the lifetime of the fuel element.

The effects of creep collapse, both in- and out-of-reactor, are at present somewhat unknown quantities. This is especially true with regard to creep rate. Very little information presently exists on this subject. In fact, unless prior specimen history is available any mechanical properties data are of limited value in developing correlations.

It is apparent that tubing deformation is both a geometrical and a mechanical property phenomenon. Geometrically, the tubing dimensions [0.430 in. OD by 0.025 in. wall (10.92 × 0.64 mm)] and, very importantly, the unsupported length of the tubing [up to 4 in. (102 mm)] significantly affect the magnitude and distribution of the stresses induced in the tubing. The strength properties of the material determine the behavior in response to these forces. If these properties are anisotropic, the behavior of the tubing is further complicated by the need to consider stress states of the tubing as a function of its geometry.

Another geometric factor of direct importance to the present problem is found in the situation where a pellet-to-pellet gap exists and the tubing is not supported over part of its length, thereby affecting the length-to-diameter ratio and, consequently, the stress states and the collapse behavior of the tubing. It is reasonable to assume that the directions of the stresses in the tube wall will not change during collapse — at least in the early stages of the process. The magnitudes of those stresses will change, however, as will the associated stress ratios. While it is pointless to speculate on the specific forms that the deformation would take (this will be determined experimentally), it is important to note that a single tube will have a number of different stress states present during collapse or creepdown. Each of these stress states will interact with the specimen material to cause strain, either by yielding and plastic flow or by creep. In an isotropic material, these strains could be fairly predictable and, indeed, a large volume of literature exists on the multiaxial stress-strain behavior of the more isotropic materials. The anisotropic behavior of Zircaloy, however, adds a further complication to the discussion. This metallurgical variable, in which the mechanical properties are functions of the degree of preferred orientation (texture) and the direction and sense of the applied stress,

relative to the particular texture, certainly modifies and could even negate many of the observations and conclusions concerning tubing-collapse behavior described by various investigators and based on tests of more isotropic materials.

Since the experimental program addressed by this document is already under way, some aspects are less conjectural than others. This is especially true of the test parameters related to collapse. This will be discussed later in this report.

BACKGROUND

To aid in the appreciation of the complexity of the tubing collapse phenomenon the results of a fairly comprehensive literature survey will be reported

Mechanical Behavior of Zircaloy

The anisotropic character of Zircaloy has been known for years, primarily for its effect on mechanical properties. It was pointed out by Picklesimer² that "... it has not been recognized that the mildest anisotropy of mechanical properties obtainable in these materials is much more severe than the maximum anisotropy that can be produced in cubic metals." This statement was made in 1963 following a study of the effects of fabrication variables on the anisotropy of strain behavior and mechanical properties of Zircaloy-2 plate material.^{3,4} The three above-cited references represent perhaps the first exposition of the mechanical characteristics of Zircaloy in a context that appreciated

²M. L. Picklesimer, *A Preliminary Examination of the Formation and Utilization of Texture and Anisotropy in Zircaloy-2*, ORNL-TM-460, p. 2 (Feb. 28, 1963).

³P. L. Rittenhouse and M. L. Picklesimer, *Metallurgy of Zircaloy-2 Part 1. The Effects of Fabrication Variables on the Anisotropy of Mechanical Properties*, ORNL-2944 (Oct. 13, 1960).

⁴P. L. Rittenhouse and M. L. Picklesimer, *Metallurgy of Zircaloy-2, Part 2. The Effects of Fabrication Variables on the Preferred Orientation and Anisotropy of Strain Behavior*, ORNL-2948 (Jan. 11, 1961).

both the drawbacks and advantages of anisotropy. A later report,⁵ edited by Woods of Bettis Atomic Power Laboratory (BAPL), discussed various properties of Zircaloy-4 tubing and acknowledged the effect of texture on uniaxial and biaxial strength. A continuing set of reports from BAPL, from 1967 through 1973, have examined and discussed deformation and collapse phenomena in Zircaloy cladding from both experimental and theoretical bases. These reports will now be examined chronologically before other concurrent reports are reviewed. The earliest of these⁶ considered approximate methods for analyzing the effects of external pressure on the deformation of Zircaloy cladding. The author considered inelastic and creep collapse, ovality, diametral creep, local buckling, and axial wrinkling. Among the simplifying assumptions that were made was that the tube was long and thin walled. Most of the report deals with collapse as a geometric instability problem, with time-dependent (creep) behavior included in a short section toward the end. The author states "... it is questionable whether tube shrinkage can be predicted quantitatively with any real accuracy." The subject of diametral buckling of short tubes was handled on a lower limit basis related to long-tube calculations. Some comparisons with experimental results are given for long-tube buckling, but these were inconclusive from an anisotropic property standpoint.

A second BAPL report⁷ considered the effect of neutron flux on the deformation behavior of Zircaloy cladding. A computer program, Flux Induced Creep (FLIC), was reported capable of describing the in-reactor deformation characteristics of Zircaloy. Unfortunately, the effects of anisotropy were not included, although the extension of FLIC to include anisotropy was stated to be feasible.

⁵C. R. Woods, (ed.), *Properties of Zircaloy-4 Tubing*, WAPD-TM-585, (December 1966).

⁶D. S. Griffin, *Deformation and Collapse of Fuel Rod Cladding Due to External Pressure*, WAPD-TM-591 (January 1967).

⁷E. Duncombe et al., *Prediction of the In-Reactor Deformation of Zircaloy Cladding for Oxide Fuel Rods*, WAPD-TM-808 (L) (December 1969).

The next BAPL report discussed the development of a computer program (BUSHL) for calculating the inelastic buckling of shells of revolution under external pressure and axial compression.⁸ According to the author -- "The Reuss equations of plasticity combined with Hill's anisotropic theory of plasticity ... are used to determine the stress-strain relations." However, the anisotropic theory of plasticity developed by Hill was pointed out by Bogue⁹ as not being sufficiently general to handle the anisotropy of Zircaloy. For example, the Hill theory, a generalization of the von Mises yield criterion for isotropic materials, does not address the fact that Zircaloy usually possesses compressive and tensile yield strengths of unequal magnitude.² In fact, the Hill theory requires those yield strengths to be equal. So, even though it was stated by Thurman⁸ that BUSHL was developed primarily for the buckling collapse of Zircaloy-clad oxide fuel rods, the program appears to reflect inadequately the inherent mechanical behavior of Zircaloy.

Two companion documents^{10,11} related to the in-reactor length and diameter changes of Zircaloy-clad fuel rods were published in 1973 by BAPL. These will not be discussed here except to acknowledge their use of contractile strain ratios in the CYGRO computer program used to calculate strains. These ratios are directly related to the effects of texture on the strain behavior of the material. Unfortunately, the effects of temperature cannot be characterized from the results given in this reference.

⁸A. L. Thurman, *BUSHL - A Computer Program for the Inelastic Buckling of Shells of Revolution Under External Pressure and Axial Compression*, WAPD-TM-890 (March 1971).

⁹D. C. Bogue, *The Yield Stress and Plastic Strain Theory for Anisotropic Materials*, ORNL-TM-1869 (July 1967).

¹⁰D. A. Mertz et al., *In-Pile Length Changes of Cladding and Fuel Stacks of Zircaloy-Clad Oxide Fuel Rods*, WAPD-TM-1166 (1) (October 1973).

¹¹R. C. Hoffman et al., *In-Pile Diameter Changes of Zircaloy-Clad Oxide Fuel Rods*, WAPD-TM-1167 (1) (October 1973).

Finally, two documents were published on cladding collapse^{12,13} that are directly related to the present studies. The first of these dealt with both the in- and out-of-reactor collapse of short unsupported lengths of Zircaloy-4 cladding under external pressure. Test parameters included tubing fabrication method, unsupported length, diameter-to-wall thickness ratio, pressure, and irradiation environment. The out-of-reactor tests were run at 700°F and time-of-collapse was monitored by an instrumented ceramic ring that fractured at the instant of collapse. The in-reactor tests were similarly instrumented and were apparently tested at 655-660°F. The BUSHL code⁶ was used to analyze and compare the test results; while bearing in mind the limitations of BUSHL discussed earlier, one finds that Mertz and co-workers¹⁰ concluded that BUSHL was "not inconsistent" and that "... BUSHL predictions bound the test data...." In the other work,¹² the applicability of BUSHL is somewhat ambiguous. (The present study of creepdown and collapse will differ from the BAPL study in that continuous monitoring of collapse strain will be performed during testing rather than just the determination of collapse time. This is an important difference because both rate-of-collapse and collapse geometry, not considered by McCabe and co-workers,¹² are parameters that affect fuel-rod performance.)

McCabe¹³ discussed ovality, collapse, and axial wrinkling of Zircaloy cladding as a function of external pressure, pellet-cladding gap, cladding dimensions, and cladding material heat treatment. Test conditions were such that both "instantaneous" and creep collapse could be achieved. Results of analyses using a GACL code were reported by Thurman.¹⁴ This code used isochronous stress-strain curves, apparently generated by the PLIC code,⁷ to predict creep collapse and axial wrinkling. The agreement

¹²E. A. McCabe, Jr., et al., *Short Tube Collapse of Zircaloy-Clad Oxide Fuel Rods Under External Pressure*, WAPD-TM-1173 (L) (November 1973).

¹³E. A. McCabe, Jr., *Ovality, Collapse and Axial Wrinkling of the Cladding on Zircaloy Clad Oxide Fuel Rods*, WAPD-TM-1174 (L) (November 1973).

¹⁴A. L. Thurman, *GACL3 - A Computer Program for the Inelastic Large-Deflection Stress Analysis of a Thin Plate or Axially Symmetric Shell with Pressure Loading and Deflection Restraints*, WAPD-TM-791 (June 1969).

with experiment was not good and was thought to be due "... to the uncertainty of the creep data used because of the high stress state of the tests." The use of isochronous stress-strain curves was also thought to be inadequate. McCabe¹³ postulates that a time-dependent relationship of creep-stress strain and cladding deformation would be needed to improve the predictive ability of the analysis. It was stated earlier in this report that the FLIC code does not address anisotropy adequately. It is possible that the stress state of the cladding is also not adequately modeled by CAPL.

Returning to earlier concurrent reports of interest to this study one finds that, in 1966, two papers were presented at an Electrochemical Society symposium that reviewed the state of knowledge of the anisotropy and mechanical properties of Zircaloy-2. The first of these, by Picklesimer,¹⁵ concerned the causes of anisotropy (preferred orientation, deformation systems) and illustrated many of the effects anisotropy can have on mechanical properties. In the paper he discussed studies, criteria, and theories needed to better understand the behavior of Zircaloy. He concluded with a statement that has direct applicability to the present study of cladding collapse:

Finally, new and adequate theories must be developed of the stress-strain behavior of anisotropic metals in multiaxial stress systems, for both elastic and plastic strains. In such theories, the general case must be for metals with no symmetry of properties so that, mathematically, the behavior of cubic metals would become essentially a special case, and the behavior of cph metals an intermediate case. The theories must allow the stress-strain behavior to be dependent on the sign of the stress (tensile or compressive), the crystallographic texture, the change in deformation systems with temperature and strain rate, and on the multiaxial stress configuration.

¹⁵M. L. Picklesimer, "Deformation, Creep, and Fracture in Alpha-Zirconium Alloys," *Electrochem. Technol.* 4(7-8): 289-300 (July-August 1966).

In effect, he states the case for a generalization of Hill's theory of yielding and its application to the complex stress state present during cladding collapse.

The second paper, by Rittenhouse and Picklesimer¹⁶ delineates the anisotropic characteristics of Zircaloy sheet material with emphasis on yield and strain behavior. One of the conclusions reached in this study is again of direct concern to the problem of cladding collapse because it points out the role of compressive strain in the complete description of anisotropic behavior:

The variation of mechanical properties in the rolling plane cannot be taken as a true measure of the anisotropy of plastic properties. Complete evaluation of mechanical anisotropy must include consideration of behavior in tension and compression in the three principal plate directions.

A number of papers on the creep of Zircaloy, both in- and out-of-reactor, have been published by U.S., English, and Canadian workers.¹⁷⁻²⁹

¹⁶P. L. Rittenhouse and M. L. Picklesimer, "Research on the Mechanical Anisotropy of Zircaloy-2," *Electron. Technol.* 4(7-8): 322-29 (July-August 1966).

¹⁷V. Fidleris, "The Effect of Texture and Strain Aging on Creep of Zircaloy-2," pp. 1-17 in *Application Related Phenomena in Zirconium and Its Alloys*, Spec. Tech. Publ. 458, American Society for Testing and Materials, Philadelphia, 1968.

¹⁸E. F. Ibrahim, "In-Reactor Creep of Zirconium-Alloy Tubes and Its Correlation with Uniaxial Data," pp. 18-36 in *Application Related Phenomena in Zirconium and Its Alloys*, Spec. Tech. Publ. 458, American Society for Testing and Materials, Philadelphia, 1968.

¹⁹B. Watkins and D. S. Wood, "The Significance of Irradiation-Induced Creep on Reactor Performance of a Zircaloy-2 Pressure Tube," pp. 226-49 in *Application Related Phenomena in Zirconium and Its Alloys*, Spec. Tech. Publ. 458, American Society for Testing and Materials, Philadelphia, 1968.

²⁰V. Fidleris, "Uniaxial In-Reactor Creep of Zirconium Alloys," *J. Nucl. Mater.* 26(1): 51-76 (1968).

²¹P. A. Ross-Ross and C.E.L. Hunt, "The In-Reactor Creep of Cold Worked Zircaloy-2 and Zirconium-2.5 wt % Niobium Pressure Tubes," *J. Nucl. Mater.* 26(1): 2-17 (1968).

²²G. R. Piercy, "Mechanisms for the In-Reactor Creep of Zirconium

These studies, while contributing greatly to a knowledge of the effects of both uniaxial and biaxial tensile stresses on annealed and lightly cold-worked Zircaloy sheet and tubing in- and out-of-reactor, without exception, fail to address the conditions of importance to the present study. Those conditions are:

1. uniaxial and biaxial *compressive* loading,
2. *small* length-to-diameter ratios (pellet-to-pellet gaps), and
3. the 70% *cold-worked* plus *stress-relieved* condition.

Unfortunately, the studies^{30,12,13,23} that consider cladding collapse do so either with tubing length-to-diameter (L/D) ratios greater than 6, which makes them inapplicable to the present concern, or do not adequately monitor collapse strains during testing.

As stated earlier the anisotropy of Zircaloy has not been adequately taken into account in any of the considerations of mechanical properties in the compression-compression stress state — the state under which the cladding operates in the reactor. Such a state, at stress levels where

Alloys," *J. Nucl. Mater.* 26(1): 18-50 (1968).

²³G. F. Slattery, "The Prediction of Collapse Pressures for Anisotropic Zircaloy-2 Tubing Using Tensile Stress/Strain Data," *J. Inst. Met.* 96: 267-73 (1968).

²⁴D. A. Howl and B. Moore, "Prediction of Creep Collapse Pressures and Times for Nuclear Fuel Cladding," *J. Br. Nucl. Energy Soc.* 8: 103-08 (April 1969).

²⁵E. R. Gilbert, "In-Reactor Creep of Reactor Materials," *React. Technol.* 14(3): 258-85 (1971).

²⁶J. Schroeder and M. J. Holicky, "Continuum — Mechanics and Micro-Mechanisms for In-Reactor Creep of Zirconium Alloys," *J. Nucl. Mater.* 39: 27-34 (1971).

²⁷D. S. Wood and B. Watkins, "A Creep Limit Approach to the Design of Zircaloy-2 Reactor Pressure Tubes at 275°C," *J. Nucl. Mater.* 41: 327-40 (1971).

²⁸D. O. Pickman, "Properties of Zircaloy Cladding," *Nucl. Eng. Des.* 21(2): 212-36 (1972).

²⁹E. F. Ibrahim, "In-Reactor Tubular Creep of Zircaloy-2 at 260 to 300°C," *J. Nucl. Mater.* 46: 169-82 (1973).

³⁰D. S. Griffin, *Deformation and Collapse of Fuel Rod Cladding Due to External Pressure*, WAPD-TM-591 (January 1967).

yielding can occur or where the creep rate is high, is very difficult to achieve experimentally. Dressler et al.,³¹ reported tests of Zircaloy fuel element cladding performed at room temperature to determine the yield strength in all four quadrants of the plane-stress yield locus and they stated that "... the observed strong anisotropy was not caused by any effect other than the variation of the biaxial state of stress." This statement was occasioned by the very weak biaxial yield strengths found in the negative tangential stress portions of the yield locus, corresponding to external pressurization. It is entirely possible, however, that a collapse phenomenon (perhaps elastic) was operative in the test. The single yield locus, corresponding to a single texture, does not provide sufficient information for evaluation. Further investigation of the deformation characteristics of cladding material, with special emphasis on the prevention of collapse before plastic yielding, is necessary before the yield behavior of the cladding can truly be quantified.

Although the test procedures necessary for the determination of the biaxial behavior of tubing may seem unrelated to the problem of fuel cladding collapse and creepdown and may seem overly fundamental in approach, it cannot be emphasized too strongly that Zircaloy is vastly different from any other reactor structural material in its mechanical behavior. Its strength properties vary with stress direction, ratio of stresses, and crystallographic preferred orientation so that for the same combination of stresses, two different tubing specimens of identical geometry but with dissimilar fabrication history could behave quite differently. Generally, the works referenced in this report acknowledge that Zircaloy is anisotropic and then treat the material as being isotropic, or at least orthotropic, in its behavior. Such procedures are not necessarily either conservative or nonconservative. They do, however, beg the questions of correlating the mechanical properties behavior of Zircaloy. This simply means that when fuel cladding collapse occurs, no one can presently be

³¹G. Dressler et al., "Determination of Complete Plane Stress Yield Loci of Zircaloy Tubing," pp. 92-103 in *Zirconium in Nuclear Applications, Spec. Tech. Publ. 551*, American Society for Testing and Materials, Philadelphia, 1974.

quantitatively certain what the collapse mechanism was. One can only treat the symptoms, without any real understanding of the phenomena involved.

The test procedures necessary to determine the multiaxial behavior of Zircaloy require a testing machine capable of precisely regulating, through appropriate servo valving and controllers, hydraulically- or mechanically-actuated forces on the test specimen in various combinations and levels and the capability to monitor accurately the strains induced in the specimen. While the region of greatest interest to the collapse study is, of course, the compression-compression quadrant of the biaxial stress field, any attempt to correlate yield or strain behavior (through continuum mechanics, yield loci, texture coefficients, etc.) with stress field must necessarily consider all four quadrants of biaxial stress space. It is of interest to consider three sets of experimental results from multiaxial testing to obtain an understanding of the kind of information obtainable and to see some of the ambiguities that presently exist on the subject.

Unpublished data by Rittenhouse³² illustrate the 0.2% offset yield behavior of Zircaloy-2 tubing with two different textures. These sets of tubes were tested in three of the four quadrants of the biaxial stress field - the compression-compression quadrant was not investigated. The first texture (material 1) had basal poles concentrated at six times random within $\pm 15^\circ$ of the radial direction of the tubing. The second texture (material 2) had basal poles concentrated at 6 1/2 times random within $\pm 20^\circ$ of the tangential direction. The experimental results are shown in Fig. 1. The effects of the different textures are immediately evident upon examination of the curves drawn through the data points. The material with the basal-poles-radial texture exhibits a yield locus that extends far out into quadrant I, the tension-tension stress state. Without going into detail concerning the deformation mechanisms that govern the stress-strain behavior of the material, it can be stated that

³²P. L. Rittenhouse, unpublished data, private communication to the author.

Fig. 1. Plane-Stress Yield Loci for Annealed Zircaloy-2 Tubing.
(P. L. Rittenhouse, unpublished data, private communication to the author.)

the biaxial tensile stresses require a wall-thinning strain to take place in the specimen. It is known³³ that compression along the basal pole direction is more difficult to effect than along other crystallographic directions, and this is what is required by the combination of texture and stress state for material 1 in quadrant I. Conversely, material 2, with basal poles strongly aligned in the tangential direction should be weaker when subjected to balanced biaxial tensile stresses. Indeed, this is seen in Fig. 1. By the argument presented for material 1, material 2 should be highly resistant to a compressive stress in the tangential direction, since this would involve compressive strain parallel to the basal pole concentration. If one extends the curve for material 2 to the negative tangential stress axis, the intersection could well be at stress values around -100 ksi (-689 MPa), thereby supporting the argument.

³³M. L. Picklesimer, *A Preliminary Examination of the Formation and Utilization of Texture and Anisotropy in Zircaloy-2*, ORNL-TM-460 (Feb. 28, 1963).

It should again be emphasized that no data exist on the materials discussed above tested in quadrant III, the compression-compression stress state.

While the Rittenhouse work did not investigate yield behavior in the compression-compression quadrant for the annealed Zircaloy-2 material, recent work in Germany by Dressler et al.³¹ (mentioned earlier) examined Zircaloy-4 specimens that had almost identical textures to those of material 1 in the Rittenhouse work. The Zircaloy-4 tubing specimens were tested in all four quadrants. The results are shown in Fig. 2 drawn to the same scale and orientation as Fig. 1 for comparison. The most obvious feature of Dressler's results is the almost constant value of compressive tangential yield stress; a stress that is apparently independent of the magnitude and sign of the axial stress. It was discussed earlier that this behavior might be attributed to elastic collapse and, therefore, might not represent true yielding behavior. Other differences between the results in the two figures may be attributable to the fact that the Rittenhouse material was fully annealed, while the Dressler material was stress relieved. Obviously the two sets of data leave a question unanswered about the behavior of Zircaloy-2 or -4 in the compression-compression quadrant, the quadrant that contains the stress state to which fuel element cladding is subjected in the reactor.

A recent publication concerning texture strengthening of a Ti-6Zr-4V alloy³⁴ is an excellent example of the behavior that might be expected from Zircaloy under biaxial loading. (It is very surprising that zirconium and its alloys are not mentioned in the background discussion of that article, since the anisotropy inherent in Zircaloy is at least as strong as the examples given.) The texture of one material, A, is a direct analog of the texture found in Zircaloy tubing that has undergone a high ratio of wall thinning to diametral reduction during the latter stages of fabrication and is analogous to the Rittenhouse material 1 and the Dressler material discussed earlier. The basal pole $\langle 0001 \rangle$ directions are concentrated $\sim 22^\circ$

³⁴W.A.W. Lowden and W. B. Hutchinson, "Texture Strengthening and Strength Differential in Titanium-6Al-4V," *Met. Trans.* 6A: 441-48 (March 1975).

Fig. 2. Plane-Stress Yield Locus for Zircaloy-4. (G. Dressler et al., "Determination of Complete Plane Stress Yield Loci of Zircaloy Tubing," pp. 92-103 in *Zirconium in Nuclear Applications, Spec. Tech. Publ. 551*, American Society for Testing and Materials, Philadelphia, 1974.)

on each side of the sheet normal toward the transverse directions - the analogous tubing directions would be the radial and tangential directions, respectively. The texture of material B is, in a sense, the "opposite" texture from that of material A - the basal poles are located approximately 90° from their position in the A material. This is equivalent to the Ritterhouse material 2. In each case there are no basal poles situated anywhere near the sheet rolling (equivalent to tubing axial) direction. The effects of these two textures on the yield loci at equivalent strains are shown in Fig. 3, reproduced directly from the work of Lowden and Hutchinson. The dashed ellipses represent the 0.2% yield stress calculated from the isotropic von Mises yield criterion. It is unreasonable to expect that the mechanical behavior of the titanium alloy would be quantitatively analogous to the behavior to be found in Zircaloy of the same texture because different deformation mechanisms are operative. Both zirconium and titanium have essentially the same c/a ratios (~ 1.59), but they differ in both number and type of deformation systems (both slip and twinning systems). Without going into the details of these differences,

Fig. 3. Yield Loci for Materials A and B. Reprinted from M.A.W. Lowden and W. B. Hutchinson, "Texture Strengthening and Strength Differential in Titanium-6Al-4V," *Met. Trans.*, 6A: 441-48 (March 1975).

it is sufficient at this time to simply state that the anisotropy found in the titanium alloy should be at least as strong in Zircaloy with the same texture.

Theories of Buckling and Collapse of Hollow Cylinders from a Mechanistic Standpoint

It is instructive to examine the background of the theories of the mechanics of tubing instability and collapse and to relate them to the experimental work that will be discussed later in this report.

Interest in the effects of external pressure on the deformation characteristics of cylinders and tubing was first demonstrated by Fairbairn³⁵ over 100 years ago. His work, performed with iron tubes, and work by Carman³⁶ in 1905, on brass tubes, demonstrated two aspects

³⁵W. Fairbairn, "The Resistance of Tubes to Collapse," *Phil. Trans.* 148: 389-413 (1858).

³⁶A. P. Carman, "Resistance of Tubes to Collapse," *Phys. Rev.* 21: 361-87 (December 1905).

of collapse that proved of great importance for later theory. These are (1) that the ratios of length to diameter and diameter to wall thickness are critical parameters in predicting collapse pressures and (2) that below a critical length-to-diameter ratio the number of lobes into which the cross section of the tube deforms increases in a regular manner with decreasing collapse length. It was not until 1914 that von Mises³⁷ developed a mathematical model for this behavior. This model, corrected in 1934 for a mathematical mistake,³⁸ relates the critical collapse pressure to length-to-diameter and wall thickness-to-diameter ratios, Young's modulus, Poisson's ratio, and n - the number of lobes that are formed. In addition to the equation for collapse under uniform radial loading discussed above, von Mises developed an equation for the critical collapse pressure for tubes externally pressurized to provide end loading as well as circumferential loading. There is some ambiguity concerning the date of this development. One form of the equation was given by Sander and Günther³⁹ in 1920 and was attributed to von Mises, while another form was given by von Mises⁴⁰ in 1929.

The three forms of the equation for critical collapse pressure taken from literature⁴¹ are shown below:

³⁷R. von Mises, "Der kritische Aussendruck zylindrischer Rohre," *Z.V.D.I.* 58(19): 750-55 (May 1914).

³⁸D. F. Windenburg and C. Trilling, "Collapse by Instability of Thin Cylindrical Shells Under External Pressure," *Trans. Am. Soc. Mech. Engrs.* 56: 819-25 (November 1934).

³⁹K. von Sanden and K. Günther, "Ueber das Festigkeitsproblem querversteifter Hohlzylinder unter gleichmässigem Aussendruck," *Werft Reederei* 10: 220 (1920).

⁴⁰R. von Mises, "Der kritische Aussendruck für allseits belastete zylindrische Rohre," *Fest. zum 70. Geburtstag von Prof. Dr. A. Stodola*, Zurich, 1929, pp. 418-30. Also: Translated by D. F. Windenburg, Rept. No. 366 of the U.S. Exp. Model Basin, Navy Yard, Washington, D. C., Aug. 1933.

⁴¹P. J. Pankaskie, *BUCKLE - An Analytical Computer Code for Calculating Creep Buckling of an Initially Oval Tube*, BNWL-1784 (May 1974).

$$\bar{P} = \left\{ \frac{\frac{E t}{n^2 R}}{\left[1 + \left(\frac{nL}{\pi R} \right)^2 \right]^2} + \frac{n^2}{12} \left[1 + \left(\frac{\pi R}{nL} \right)^2 \right]^2 \frac{\pi^2 E t^3}{(n^2 - 1) R^3} \right\} \frac{1}{1 + 0.5 \left(\frac{\pi R}{nL} \right)^2}, \quad (1)^{32}$$

and

$$P = \left[\frac{1}{3} \left\{ \left[n^2 + \left(\frac{\pi D}{2L} \right)^2 \right]^2 - 2\mu_1 n^2 + \mu_2 \left\{ \frac{2F}{1 - \mu^2} \left(\frac{t}{D} \right)^3 \right. \right. \right. \right. \\ \left. \left. \left. + \frac{2E \left(\frac{t}{D} \right)}{\left[n^2 \left(\frac{2L}{\pi D} \right)^2 + 1 \right]^2} \right\} \frac{1}{n^2 - 1 + 0.5 \left(\frac{\pi R}{2L} \right)^2} \right\} \right] \quad (2)^{40}$$

where

$$2\mu_1 = \{1 + (1 + \mu) \rho\} \{2 + (1 - \mu) \rho\}, \\ \mu_2 = (1 - \rho\mu) [1 + (1 + 2\mu) \rho - (1 - \mu^2) (1 + \frac{1 + \mu}{1 - \mu} \rho) \rho^2], \text{ and} \\ \rho = \frac{1}{n^2 \left(\frac{2L}{\pi D} \right)^2 + 1}.$$

$$P = \frac{E}{1 + 0.5 \left(\frac{\pi R}{nL} \right)^2} \left(\frac{c}{R} \right) \left\{ \frac{1}{n^2 \left[1 + \left(\frac{nL}{\pi R} \right)^2 \right]^2} + \frac{n^2 - 1}{12 (1 - \mu^2)} \left(\frac{t}{R} \right)^2 \left[1 + \frac{\pi R}{nL} \right]^2 \right\}. \quad (3)^{41}$$

In the above equations

- P = critical pressure,
- E = elastic modulus,
- R = radius of cylinder,
- L = unsupported length,
- n = number of nodes,
- t = wall thickness.

μ = Poisson's ratio,

$\nu = 1/\mu$,

D = diameter of cylinder, in.

Equations 1 and 2 are also referenced and discussed in later publications by Windenburg and Trilling³⁸ for Eq. (2) and Saunders and Windenburg⁴² for Eq. (1). Pankaskie⁴¹ also cites Saunders and Windenburg⁴² in his presentation of Eq. (3).

It is obvious that the time at which a tube collapses from external pressure is a function of several variables. Geometrically, and somewhat simplistically, any initial departure from perfect cross-sectional circularity will result in a tube with a propensity for further departure from circularity with increasing external pressure, temperature, and time. If an initially oval tube is loaded to a pressure below the critical collapse pressure and to a temperature within the creep range, and no supporting mandrel is used, a gradually increasing departure from circularity will be obtained. At some point a geometry will be reached that has associated with it a critical collapse pressure equal to the ambient pressure around the tube, and collapse will take place. The interrelationships among the several variables are complex and worthy of further conjecture.

From our review of the literature it is apparent that tubing deformation is both a geometrical and a mechanical-property phenomenon. Geometrically, the tubing dimensions and, very importantly, the unsupported length of the tubing determine the deformation behavior of the tubing. The strength properties of the material determine, of course, the ability of the tubing to resist deformation. If these properties are anisotropic, the behavior of the tubing is further complicated by the need to consider stress states of the tubing as a function of its geometry.

An indication of this problem can be found in Fig. 4, which illustrates the stress state of an infinitesimal element of the wall of a

⁴²H. E. Saunders and D. F. Windenburg, "Strength of Thin Cylindrical Shells Under External Pressure," *Trans. Am. Soc. Met. Engrs.* 53: 207-18 (December 1931).

closed-end tube subjected to uniform external pressure. The stresses and their directions are as defined in the figure, and correspond to those that would exist in an undeformed fuel cladding. If it is assumed that the cladding contains fuel pellets whose diameters are such that a small uniform pellet-to-cladding gap exists, then the geometry shown in Fig. 5

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Fig. 4. Stress State of a Simple, Externally-Pressurized, Sealed Tube.

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Fig. 5. Schematic of Fuel Rod Prior to Deformation.

will exist. (One assumes that the pellets can be represented by a one-piece mandrel of the appropriate diameter) If initial ovality exists in the tubing, the application of external pressure can cause an increased ovality as previously discussed. This elastic deformation, or some plastic deformation due to creep, can eventually cause line contact with the pellets. Once line contact is achieved, further deformation would probably take place by creep as shown in the sequence in Fig. 6. If one assumes that the initial cross-sectional shape of the tubing is

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Fig. 6. Possible Progressive Creepdown Configurations.

neither circular nor oval, but some irregular shape (low-amplitude wrinkles or undulations), one could conjecture a selective process by which a dominant shape emerges and then undergoes the process shown in Fig. 6. The importance of wall thickness variation must not be overlooked. Information found in a report of Corum^{4,3} on the collapse behavior of 8-in.-OD (203-mm) type 304 stainless steel tubes indicated an interaction between wall thickness variations and lack of circularity in influencing the deformation behavior of the tubing. In Fig. 22 of Corum's report he showed a series of diagrams that pointed out an interesting coincidence. This figure is reproduced as Fig. 7. Among the various curves depicted in the figure are those that represent "wall thickness deviations from nominal." If one locates the maximum wall

^{4,3}J. M. Corum, *An Investigation of the Instantaneous and Creep Buckling of Initially Out-of-Round Tubes Subjected to External Pressure*, ORNL-5299 (Jan. 16, 1963).

Fig. 7. Cross Sections of a Large-Diameter Stainless Steel Tube at Various Sections of Creepdown. Reprinted from J. M. Corum, *An Investigation of the Instantaneous and Creep Buckling of Initially Out-of-Round Tubes Subjected to External Pressure*, ORNL-3299 (Jan. 16, 1963).

thickness for each cross section and then examines the curves that represent deviation from circularity, one finds that common points of essentially zero radius change (during the tests) fall close to those points of maximum wall thickness. The zero radius change is, admittedly, measured from a curve that represents initial deviation from circularity and it is obvious that this represents a coincidental situation. Figure 8 illustrates the pattern that seems to exist - a $\pm 11-12^\circ$ variation of zero radius change from maximum wall thickness. The point to be made is that the above discussion shows some of the geometrical factors that may be important in the collapse problem.

Fig. 8. Relationship of Nodes of Zero Radius Change to Maximum Wall Thickness.

PROPOSED EXPERIMENTATION

The first part of this report has reviewed numerous investigative and analytical efforts by others for applicability of existing theory and results to the case of Zircaloy fuel cladding collapse. Having found

that much information is presently lacking, it is only appropriate to attempt a constructive solution to the problems created by that lack. Concisely stated, the problems exist because the anisotropy of Zircaloy has not been fully recognized as the important property that can strongly influence fuel-cladding behavior, and the tests that have been run do not simulate the conditions that exist in fuel element cladding under conditions of external pressurization, with or without a fuel pellet gap. The experimentation to be described below will address these problems and should, when implemented, provide some of the answers that are presently unavailable.

Before the proposed experiments are described, the experimental variables will be discussed in detail. The test program appropriately breaks down into two major study divisions: Out-of-reactor collapse and creep collapse and the in-reactor determination of creepdown rates and times to collapse.

Both the collapse tests and the creepdown tests involve the application of external pressure to the specimen at various levels of temperatures. The magnitude of the pressure and whether it is ramped at continually increasing levels or held at a constant value differentiates between the two types of tests.

The results already obtained on the collapse tests will be discussed later and, therefore, the test matrix for those tests will not be given here. It should be mentioned that the original matrix for those tests was completed, but it required three times the number of originally scheduled tests to satisfactorily define the cladding behavior.

The creepdown tests, to be conducted at constant pressure and temperature, will require a lower level of pressurization than did the collapse test. The development of a test matrix for the creepdown tests is difficult at this point because the analogous high-strain-rate test data are not available. In uniaxial tensile and creep testing, one is able to plot stress versus strain rate for the tensile data, extrapolate to lower stress values, and estimate the strain rates that will be obtained. A scoping test was run with an uninstrumented specimen with a 4 in. (102 mm) unsupported length at nominal values of 660°F (349°C) and 3600 psi (17.9 MPa) for 70 hr followed by 94 hr at 740°F (393°C), and the same pressure at which time collapse occurred.

Based on this result, the following tests, shown in Table 1, will be performed. This matrix is considered highly preliminary and subject to change as data are accumulated.

Table 1. Preliminary Creepdown Test Matrix

Test	Temperature		Pressure	
	(°F)	(°C)	(psi)	(MPa)
CD-1	750	399	2500	17.2
CD-2	750	399	2300	15.9
CD-3	700	371	2800	19.3
CD-4	700	371	2600	17.9
CD-5	800	427	2200	15.2
CD-6	800	427	2000	12.8

The information on both creepdown rates and collapse times from these tests will allow the formulation of a more complete statistical matrix. The tests listed in Table 1 should all be short term - lasting from ~50 to ~200 hr. The longer term tests will require careful choices of pressure levels relative to test temperature to produce creepdown rates and collapse times within the desired ranges.

Collapse Study

Experimentation to study the collapse behavior of Zircaloy fuel cladding is essentially complete, with the exception of certain additional tests we feel are necessary to explore and either prove or disprove an unexpected form of collapse behavior we have observed.

To date the collapse studies have involved the external pressurization of tubing specimens to effect deformation and collapse over a short time interval. The tubes were pressurized at a relatively constant rapid rate [~ 50 psi/sec (0.35 MPa/sec)] until collapse occurred. The variables that are considered in this study are:

A. Independent Variables

1. Temperature [600–800°F (316–427°C) – centered on the normal reactor operating temperature of the cladding]
2. Pellet-to-pellet gap [0.4–4 in. (10.2–101.6 mm)]
3. Original cladding gap [0.005–0.011 in. (0.13–0.28 mm)]

B. Dependent Variables

1. Pressure differential (ΔP) across wall at collapse
2. Diametral strain
3. Strain geometry (buckling, wrinkling, lobe formation, ovality)

C. Covariate Variables

1. Tubing dimensions
 - a. Diameter
 - b. Wall thickness
 - c. Wall-thickness variation
 - d. Ovality
2. Texture

The independent variables, those that are directly controllable during testing, are shown in Sect. A. While the effects of temperature would be expected to be fairly straightforward, the effects of the other independent variables are more subtle. The pellet-to-pellet gap variable is important in determining the collapse geometry of the cladding – see Eqs. (1), (2), and (3). Under conditions of relatively rapid collapse, where creep effects are less important, the pellet-to-pellet gap spacing has a large influence on the number of lobes formed during collapse and on the amount of bending (over pellet edges) necessary for the cladding to be able to deform into the gap. The cladding gap (i.e., the clearance between the pellets and the cladding) is important because its size determines the distance the cladding can deform before it becomes supported by the pellets. For instance, with a large cladding gap, appreciable ovality occurs before pellet-cladding contact is made. This ovality strongly affects further collapse of the cladding into a pellet-to-pellet gap.

The dependent variables, shown in Sect. B, should provide the necessary strain, strain-rate, and geometry information for describing cladding collapse. Obviously, the pressure differential across the

cladding wall produces the deformation in the wall and the magnitude of the deformation is directly related to temperature, cladding dimensions, and other variables. In addition to collapse pressure, diametral strain and strain geometry are the most important information to be obtained in this part of the study.

The covariate variables offer, as their name implies, little opportunity for experimental investigation. Yet their magnitudes and types are extremely important to the analysis of the data to be obtained in this investigation, since they determine to a large degree the forces necessary to deform the cladding and the types of deformation mechanisms that will operate. All of the covariate variables will be well characterized in the study.

Creepdown Study

This portion of the experimentation contains many of the same variables as the collapse study. The exceptions are, as shown below, the substitution of constant pressure differential across the cladding wall for the pressurization rate as an independent variable and the substitution of collapse time for pressure differential as a dependent variable. The variables associated with creepdown of Zircaloy cladding are:

A. Independent Variables

1. Temperature [600-800°F (316-427°C)]
2. Pressure differential across wall (ΔP) [up to 3500 psi (24.1 MPa)]
3. Pellet-to-pellet gap [0.4-4.0 in. (10.2-101.6 mm)]

B. Dependent Variables

1. Collapse time
2. Diametral strain
3. Diametral strain rate
4. Strain geometry

C. Covariate Variables

1. Tubing dimensions
 - a. Diameter
 - b. Wall thickness

- c. Wall-thickness variation
 - d. Ovality
2. Texture

Since these tests will require longer times to run than the collapse tests, the measurement of strain rate is of prime importance. Special care will be required in such measurements and in temperature control to obtain the required precision.

In-Reactor Experiments

The in-reactor tests will determine the rate of cladding creepdown under essentially the same ranges of temperature, external pressure, pellet-to-pellet gap and pellet-to-cladding gap used in the out-of-reactor tests. It is anticipated that neutron flux will have a substantial effect on this rate. The same care and sophistication of measurement used for the out-of-reactor experiment will be required, with the additional problems of gamma heating, heat transfer adjustments and smaller experimental space requirements being anticipated and accounted for.

EXPERIMENTAL PROCEDURE

The experimental procedures to be used in this study require the use of high-pressure autoclave equipment to provide the requisite external pressurization of the specimens and the development and use of strain monitoring equipment capable of detecting cladding deformation under the high temperature and pressure environment of the tests.

Pressurizing Equipment

The tests are being run in a high pressure autoclave pit. The services to the pit include electricity, water, compressed air, and helium. The compressed air service is used to power a booster pump to fill the autoclave with helium at pressures greater than the available bottle pressure. A vacuum pump is available to evacuate the autoclave prior to pressurization. The autoclave is heated by a large resistance

furnace and the temperature is controlled by a standard temperature controller and by a safety cutoff switch in such a manner that accidental overheating of the autoclave cannot happen. All control and monitoring equipment used during the high-pressure portion of the tests is located outside the pit because of safety considerations.

Three autoclaves are available for this study. Two of the vessels have internal dimensions of 2 1/16 in. (52.4 mm)-ID by 32 in. (813 mm) long and the other vessel is 3 5/16-in. (84.1 mm)-ID by 10 in. long. Stress analyses have shown that all three vessels can safely withstand the most severe combination of test conditions anticipated - 800°F (427°C) and 4300 psi (29.6 MPa). The autoclave bodies are manufactured of type 304 stainless steel and the caps are carbon steel. The autoclave head has been redesigned to accept multilead compression fittings for the various electrical connections to the strain-measuring devices and to the thermocouples. Stress analyses of the new head design show it also to be acceptable for the test conditions.

Strain-Measurement Instrumentation

The remote strain measurements necessary for the success of this study represent a difficult experimental task. In order to define the strain behavior of the cladding as a function of the variables discussed earlier, one must be able to monitor strain continuously as the cladding deforms. This must be done with the specimen inside an autoclave vessel at high temperature and pressure. We have developed a device for monitoring deformation based on an eddy-current system that measures the distance (lift-off) between a coil and a flat-plate follower that is spring-loaded against the specimen surface. Prototype coils have shown the ability to measure reproducibly from zero to 0.060-in. (1.52 mm) lift-off at room temperature. We presently intend to limit the coil range to approximately ± 0.020 in. (0.51 mm) of travel and we expect to know the probe position to approximately ± 0.0005 in. (0.013 mm) over that range.

It is anticipated that a minimum of 20 coils will be used per test to measure radial displacements of the specimen surface. From these

measurements and from post-test examination of the specimen it should be possible to follow the deformation history of the specimen.

Both the deformation-measuring equipment and the instrumentation to control and monitor that equipment have been continually improved. Modifications have been made in the coil holders for better response to both thermal and pressure cycling. Earlier designs had problems with the coil assemblies breaking loose from their lavite holders during pressure and temperature cycling. Design modifications have produced coils and holders that have withstood repeated cycling to 800°F (427°C) and repeated cycling from atmospheric pressure to 4300 psig (29.6 MPa), at 800°F (427°C). These are shown in Figs. 9 and 10. Several dimensional modifications have been made to decrease the overall size of the monitoring system.

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Fig. 9. Prototype Eddy-Current Coils Used to Determine Coil Characteristics as a Function of Temperature and Pressure.

One problem that has been addressed in depth is how to prevent damage to the coils and interference with the specimen tube when the tube collapses during testing. Space limitations within the autoclave limit the amount of travel available to the monitoring probes. If a probe should happen to be positioned on one of the lobes that forms during collapse, it would have insufficient travel to allow the lobe to form. It would be driven back into its monitoring coil, probably

Fig. 10. Overall View of Coil Assembly and Leads.

breaking the coil holder and possibly preventing free expansion of the lobe. It was decided to prevent this occurrence by electronic means. This will be described below.

The equipment was developed primarily to monitor the creep deformation of Zircaloy cladding. Such use requires that a probe-position reading be made by each coil at uniform time intervals for total times that could approach several thousand hours. We have completed an automated system, controlled by a microcomputer, that can monitor 24 coils, including a reference coil, and record the deformation values at preselected intervals. Figure 11 is a block diagram of the existing circuitry.

The oscillator and power amplifier supply a 2 MHz sinusoidal signal to all 24 coils. The impedance of each coil (and therefore the voltage developed across the coil) is affected by the spacing between the coil and the probe.

The analog multiplexer, controlled by the microcomputer, passes the 2 MHz signal that is developed across the coil to a differential amplifier. This module amplifies the difference between that signal and a signal from the reference coil. The two coils are in the same environment and should have similar drift characteristics. The difference signal is converted to a direct-current voltage and, on command from the microcomputer, is converted to a digital signal. This signal is then

Fig. 11. Schematic Diagram of Eddy-Current Instrument.

read into the microcomputer through a parallel-interface integrated circuit and converted into actual displacement by the microcomputer. The displacement and the channel number are recorded by the printer and the multiplexer is switched to the next channel. The data can be recorded on a teletype and punched paper tape if desired.

The microcomputer uses an Intel 8080A central processing unit, an 8228 system controller, and has both a read-only memory (for program storage and a random-access memory for read-write capability). The computer provides all of the needed control signals to operate the multiplexer, the analog-to-digital converter, the printer, the teletype, and the paper tape punch. The system can operate in several different run and calibrate modes, as controlled by the front panel switches or by the clock. A photograph of the instrumentation is shown in Fig. 12.

It was mentioned earlier that it is desirable to prevent damage to the coil equipment and interference with the tube deformation during collapse. This can be done by programming the computer to sense when any probe has reached the limit of its travel or other preselected distance. At that limit, the system will send a series of signals to

Fig. 12. Eddy-Current Instrument.

automatically terminate the high-pressure supply and vent the autoclave. The furnace can also be cooled if desired. At this point the coil assemblies can be removed and the test restarted to determine the time to final collapse. The total travel of a probe will be approximately 0.020 in. (0.51 mm). This could allow up to 0.080 in. (2.03 mm) ovality (difference between maximum and minimum diameters at a given axial position) to be monitored before the system is automatically shut down.

The instrumentation discussed above has been developed by C. V. Dodd and L. D. Chitwood of the Nondestructive Testing Group of this division.

At this writing it is unresolved whether the in-reactor creepdown tests will be conducted in the Oak Ridge Research Reactor (ORR) at ORNL or in the test reactor at RCN-Petten in the Netherlands. This does not pose a large problem because the reactors are quite similar, with only minor modifications of test equipment being required to fit either reactor.

We have developed a preliminary design, shown in Fig. 13, for use in heat transfer calculations and for the determinations of space requirements within the reactor core. The test system is designed to operate at maximum temperatures and pressures of 800°F (427°C) and 3500 psig (24.1 MPa). It is presently unresolved whether heating or cooling of the specimen will be needed. The present design calls for the interior of the specimen to be filled with Nak for uniformity of temperature.

TEST MATERIAL

A large lot of specially fabricated Zircaloy-4 tubing was ordered from Sandvik Speciality Metals Company for use as a uniform test material for all testing conducted for the light-water-reactor safety program. Sandvik carefully preserved the identification of each tube as it passed through the various fabrication steps so that any effects of fabrication variation could be identified. A continuing program of tubing characterization is under way.

Dimensional Measurements

The geometrical shape of the tubing to be used for creepdown and collapse testing is of great importance. Wall thickness variations and ovality have a direct effect on the deformation behavior of the tubing. Ninety pieces of Zircaloy-4 tubing were taken from the large order of Sandvik tubing received at ORNL for the reactor safety programs. Non-destructive testing (NDT) information in the form of plots of wall thickness and outside and inside diameters were also received for each of the ninety tubes. The NDT data were taken in a spiral trace [1/4-in. (6.25-mm) pitch] along each tube length and the amplitude of the trace over a single cycle furnished a direct measure of the dimensional variation around the circumference at, essentially, an axial position of the tube. The position of the trace relative to the chart gave the absolute value of the dimension in question.

The ninety sets of charts were examined for amounts of variation in diameter and wall thickness and the maximum values of each are shown in Table 2. It should be emphasized that the values given in the table represent maxima, and these maxima usually occurred as isolated, random areas of high-amplitude signal scattered along the axial direction of the tubes. The number of such areas varied from tube to tube. It is of further interest to note the differences in amounts of variation between the first and second halves of the lot. The tube numbers represent the sequence in which the tubes were fabricated. The tubes of the second half were sent through a straightening operation twice to correct excess ovality. The tubing then met purchase specifications on dimensional tolerances.

Note the high degree of uniformity of the tubes in the first half compared to the tubes in the second half. This distribution of variation is useful in this program because tubes with high uniformity are available for use in investigating the effects of test variables such as temperature and pressure. However, tubes with varying amounts of ovality are also available and can be used to investigate the effects of ovality itself on the deformation characteristics of the tubing.

Table 2. Maximum Dimensional Variations in
As-Received Zircaloy Tubing

Lot 7FD11				Lot 7FD12			
Tube Number	Variations, in. ($\times 10^3$) ^a			Tube Number	Variations, in. ($\times 10^3$)		
	Diameter		Wall Thickness		Diameter		Wall Thickness
	Outer	Inner			Outer	Inner	
11	0.7	0.7	0.4	654	1.2	1.3	1.4
20	1.0	1.1	0.6	666	1.4	1.5	1.0
30	0.8	0.9	1.2	680	1.8	2.0	1.4
43	0.5	0.6	0.8	693	1.2	1.3	1.0
56	0.5	0.6	0.6	705	1.6	1.6	0.8
68	0.4	0.4	0.6	719	0.8	0.9	1.4
81	0.5	0.6	1.6	732	1.0	1.1	0.8
94	0.5	0.5	1.0	745	0.5	0.5	1.2
106	0.4	0.4	0.8	758	0.6	0.7	1.4
122	0.5	0.5	0.8	771	0.9	1.0	1.2
139	0.5	0.6	1.4	783	1.0	1.1	1.0
150	0.7	0.7	1.4	796	1.7	1.8	0.4
164	0.4	0.4	1.0	817	0.5	0.7	1.4
178	0.6	0.5	1.2	829	0.8	0.9	1.6
191	0.6	0.7	1.2	841	1.4	1.4	1.6
204	0.6	0.6	0.6	853	0.5	0.5	1.2
216	0.5	0.5	0.6	865	1.4	1.8	1.0
229	0.4	0.5	0.6	880	1.8	2.0	0.8
242	0.5	0.4	1.0	906	1.1	1.1	0.8
254	0.4	0.4	0.8	918	1.2	1.3	1.4
269	0.4	0.5	1.0	929	0.5	0.6	0.6
282	0.4	0.4	1.6	942	0.6	0.6	1.2
296	0.4	0.4	1.0	966	2.8	2.9	0.6
308	0.5	0.6	1.2	978	2.0	1.8	0.6
323	0.4	0.5	1.2	990	1.5	1.4	1.2
335	0.4	0.4	1.2	1003	1.0	1.2	0.6
346	0.4	0.5	1.2	1016	2.3	2.5	1.4
360	0.5	0.6	1.2	1040	2.2	2.5	1.2
372	0.4	0.5	1.4	1052	1.1	1.2	0.8
385	0.6	0.7	1.0	1064	1.3	1.4	0.8
397	0.4	0.5	1.0	1076	1.6	1.5	1.0
414	0.6	0.6	1.2	1088	1.4	1.4	0.8
428	0.9	1.0	0.6	1100	1.8	1.8	0.6
444	0.4	0.4	1.2	1112	2.1	2.3	0.6
458	0.4	0.4	0.8	1138	1.2	1.5	0.6
470	0.5	0.5	0.4	1162	2.0	2.1	0.8
482	0.5	0.6	1.0	1186	1.6	1.7	0.8
495	0.5	0.5	1.0	1198	1.5	1.8	1.0
508	0.6	0.5	1.4	1210	1.5	1.7	0.6
523	0.6	0.6	1.0	1234	1.2	1.5	1.4
550	0.6	0.7	1.4	1252	0.8	0.9	1.0
564	0.6	0.7	1.6	1277	2.3	2.4	1.2
578	0.6	0.6	0.6	1297	1.6	1.6	1.2
600	0.6	0.7	1.2	1316	2.0	2.4	1.0
624	0.6	0.6	1.2	1326	1.5	1.6	1.6

^a Multiply tabulated values by 0.0254 to obtain equivalent values in mm.

Both inside and outside diameters exhibited the trend shown in Table 2. Wall thickness variation was found to be small and fairly constant in magnitude, indicating that the diametral variations were due to ovality and not to wall thickness variation.

Texture Measurements

X-ray texture specimens were machined from the wall of tube 759 from the second half of the tubing lot. Machining and chemical thinning were done to expose sections of the wall at positions 0.0035, 0.0105, and 0.0185 in. (0.0889, 0.267, and 0.470 mm) from the outer surface of the tubing. The Shultz method was used to determine the $\{0002\}$, $\{10\bar{1}0\}$, and $\{11\bar{2}0\}$ pole figures for each position. The resultant textures were typical of those expected from tubing fabricated according to present-day commercial practice. The $\{0002\}$, or basal pole figure, showed peaks distributed approximately 30° on each side of the radial direction, toward the tangential directions. The textures were similar at all three wall-thickness positions indicating little texture variation through the wall. The $\{10\bar{1}0\}$ and $\{11\bar{2}0\}$ pole figures confirmed the information shown by the basal pole figure. These results will be compared to information gained from similar texture determinations to be made on tubing from other positions in the fabrication sequence.

EXPECTED RESULTS OF THIS STUDY

The present study is in three parts. The first part will produce information concerning the short-term elastic and plastic behavior of Zircaloy cladding under conditions of external pressure and will provide information on ovality effects and on stress states during tube collapse. The second part will use such information as a very necessary foundation upon which to build an understanding of creepdown behavior. The interaction between collapse and creepdown involves a somewhat subtle overlapping of phenomena. Initial loading of a specimen can cause (through elastic strain) an increase in a preexisting ovality. Creep strain can cause a further increase in ovality until, at a critical point, the

specimen geometry is such that the external pressure becomes the collapse pressure for a given pellet-to-pellet gap. Superimposed upon these deformation phenomena is the need to know the effect of the changing stress state as the tubing deforms into the pellet-to-pellet gap and over the edges of the pellets. Multiaxial tests to determine both yield and strain loci will be necessary to obtain quantitative information on such behavior. Finally, the third part of the present study involves the behavior of Zircaloy in the nuclear environment to which the cladding will be subjected. Studies^{44,45} have shown that ten-fold increases in creep rate can be obtained for specimens exposed to fast neutron fluxes as compared to out-of-reactor tests. Such behavior must be characterized relative to the tests in parts one and two.

Since the major portion of the study will be performed on a single lot of tubing, the effects of texture on behavior will not be demonstrated. Instead, that single lot will be studied in detail to develop correlations among the dependent variables with respect to the independent variables. It is expected that these correlations will enable one to predict, for a given temperature, external pressure, and pellet gap, both how and when the cladding will deform. From the strain-rate data obtained in this study, it is expected that the long-time creepdown behavior of cladding into a pellet-to-pellet gap will also become predictable. The strength and deformation behavior of the reference tubing can be made applicable to other lots of tubing through the multiaxial testing of the yield and flow behavior of specimens of other tubing of different textures and fabrication histories and through correlation of those results with the reference tubing.

Finally, the end result of the present study will be to provide input into the several computer codes for materials behavior.

⁴⁴B. Watkins and D. S. Wood, "The Significance of Irradiation-Induced Creep on Reactor Performance of a Zircaloy-2 Pressure Tube," pp. 226-49 in *Applications-Related Phenomena in Zirconium and Its Alloys*, Spec. Tech. Publ. 458. American Society for Testing and Materials, Philadelphia, 1968.

⁴⁵V. Fidleris, "Uniaxial In-Reactor Creep of Zirconium Alloys," *J. Nucl. Mater.* 26(1): 51-76 (1968).

RESULTS TO DATE

As stated earlier, the major work on the collapse behavior of the Zircaloy cladding is complete. The collapse tests were initially conceived in the form of a test matrix that involved the variables discussed previously in this document. It became apparent during the testing that the collapse phenomenon was more complicated than first believed.

A total of almost 90 collapse tests have been run on tubes with minimum initial ovality. These include the early tests which turned out to be, in effect, equipment checkout runs. A number of these were run with argon gas as the pressurizing medium (causing spurious temperature readings) and were not sufficiently instrumented to detect the instant of collapse. In addition, eight runs were made in which the tube collapsed into four lobes without causing the instrumentation to signal that collapse had occurred. None of the above test results could be used with any degree of confidence. There were also a number of tubes that did not collapse during testing, even at the maximum pressure of the test apparatus.

Thirty tests were run that produced what we consider accurate information, i.e. with specimen temperature and collapse pressures known with confidence. Data from these tests are listed in Table 3. The effect of the independent variables on collapse pressure is better shown graphically, as will be done later. The most important results shown in Table 3 concern the average ovality of each tube following testing, the effect of hardness, and the interaction of pellet-to-pellet and pellet-to-cladding gaps. The ovality was measured, on each side of the tube, away from the unsupported test section, and as a function of the plastic strain that occurred in the region where the pellet-to-cladding gap existed. The ovality was also found regardless of whether or not the tube collapsed into the gap, indicating that the deformation down onto the mandrel was inelastic in character.

The data presented in Table 3 are the result of a multiparameter study and are difficult to interpret without recourse to three-dimensional

**Table 3. Descriptions and Results of
Zircaloy Collapse Tests**

Specimen Number	Pellet-to-Pellet Gap		Diametral Pellet-to-Cladding Gap		Test Temperature		Room Temperature Nidwell Hardness (DPH)	Collapse Pressure		Post-Test Quality ^a	
	(in.)	(mm)	(in.)	(mm)	(°F)	(°C)		(psi)	(MPa)	(in.)	(mm)
1	-	101.6			800	427	230	4275	29.45		
2	-	101.6			600	316	218	4320	29.76		
3	-	101.6			700	371	220	4190	28.87		
4	-	101.6			800	427	217	3820	26.32		
5	-	101.6			600	316	187	3685	25.39		
6	-	101.6			700	371	188	3510	24.18		
7	-	101.6			800	427	196	3400	23.43		
8	-	101.6			600	316	179	3625	24.98		
9	-	101.6			700	371	184	3400	23.43		
10	-	101.6			800	427	187	3310	22.87		
11	1.47	37.3	0.008	0.20	600	316	185	3720	25.49		
12	1.47	37.3	0.008	0.20	700	371	195	3425	23.60	0.007	0.18
13	1.2	30.5	0.006	0.15	650	343	199	3960	27.15	0.008	0.15
14	1.2	30.5	0.008	0.20	650	343	192	3790	26.11		
15	1.2	30.5	0.010	0.25	650	343	193	3560	24.39	0.011	0.28
16	1.2	30.5	0.008	0.20	800	427	187	3510	24.18		
17	0.8	20.3	0.008	0.20	616	324	188	4300	29.67	0.014	0.36
18	0.8	20.3	0.008	0.20	700	371	194	4100	28.25	0.011	0.28
19	0.8	20.3	0.008	0.20	700	371	188	3750	25.94	0.013	0.33
20	0.8	20.3	0.008	0.20	700	371	193	3930	27.08		
21	0.8	20.3	0.0114	0.29	700	371	187	3750	25.84	0.013	0.33
22	0.4	10.2	0.005	0.13	800	427	187	4050	27.90		
23	3	76.2	0.008	0.20	700	371	224	4300	29.63		
24	2	50.8	0.008	0.20	700	371	228	4400	30.32		
25	3	76.2	0.008	0.20	600	427	227	4240	29.21		
26	2	50.8	0.008	0.20	800	427	223	4225	29.11		
27	3	76.2	0.008	0.20	800	427	226	4200	28.94		
28	2	50.8	0.008	0.20	700	371	188	3525	24.29		
29	3	76.2	0.008	0.20	600	316	187	3740	25.77		
30	2	50.8	0.008	0.20	800	427	189	3325	22.91		
31	3	76.2	0.008	0.20	700	371	190	3400	23.43		
32	3	76.2	0.008	0.20	800	427	187	3050	21.01		
33	2	50.8	0.008	0.20	600	316	186	3640	25.08		

^aPost-test ovality was found outside the collapse gage section for all tubes, including those that did not collapse. Ovalities up to 0.017 in. (0.43 mm) were found in uncollapsed tubes.

plots. In addition to the three independent variables (temperature, pellet-to-pellet gap, and pellet-to-cladding gap) there is also the factor of collapse geometry, which tends to prevent a simple relationship between collapse pressure and pellet-to-pellet gap. The von Mises collapse coefficient "k" is a proportionality factor in the equation

$$P_{\text{crit}} = kE \left(\frac{t}{D}\right)^3 \quad (4)$$

where

- P_{crit} = the critical collapse pressure,
- E = modulus of elasticity of the material,
- t = wall thickness of tube, and
- D = outside diameter of tube.

The relationship (strictly geometrical) between k , L/R (unsupported length divided by tube radius), and D/t is best shown graphically. Figure 14, modified from the literature,⁶ shows a series of curves that represent values of k calculated with the von Mises' equation for many combinations of tubing dimensions. The curves in this figure are not strictly applicable to the present collapse problem because (1) there is no reason to consider the specimen edges simple supported, (2) the value of Poisson's ratio ($\mu = 0.30$) is probably not applicable to this material, and (3) the collapse is almost certainly not totally elastic. However, the curves do describe the experimentally observed collapse geometrics and, with the above limitations in mind, will be used for a qualitative discussion of the collapse results.

The tubing used in this study has a D/t ratio of 17.2 and curves have been drawn on Fig. 14 to represent this ratio. The arrows at the bottom of the graph represent the various simulated pellet-to-pellet gaps used in this study. The collapse geometry generally followed the prediction of the curves as far as number of lobes is concerned. It can also be

⁶R. G. Sturm, *A Study of the Collapsing Pressure of Thin-Walled Cylinders*, Bull. 329, Engineering Experiment Station, University of Illinois, 1941.

Fig. 14. Graph of Collapse Coefficients Calculated by the von Mises Collapse Equation for Round Cylinders with Pressure on both the Sides and the Ends. Cylinder edges are assumed to be simply supported and $\mu = 0.30$. Graph is modified from: R. G. Sturm, *A Study of the Collapsing Pressure of Thin-Walled Cylinders*, Bull. 329, Engineering Experiment Station, University of Illinois, 1941.

noted that the intersections of the L/R values for the collapse specimens, with pellet-to-pellet gaps between 0.4 and 1.47 in. (10.2 and 37.3 mm) with the von Mises curves fall on a straight line. This coincidence allows one to assume a simple log-log relationship between L/R and k , and therefore, a similar relationship between L/R and collapse pressure. Also, since R is constant, L (the pellet-to-pellet gap) should bear that same relationship with collapse pressure — that is, log-log.

It has been found that the critical collapse pressure for this material is a function of room-temperature midwall hardness. It can be assumed, as a first approximation, that such hardnesses are proportional to strength. Various hardness levels were achieved in the material by short-time anneals at temperatures from 1000 to 1150°F (538–621°C).

These values ranged from approximately 238 DPH for the as-received, 80% cold worked, 930°F (500°C) stress-relieved material to approximately 180 DPH for the fully recrystallized material.

Preceding a more quantitative discussion, some qualitative discussion can be given on the observed collapse behavior of the test specimens in this study. Collapse appears to take place in several steps. The sequence of events can be inferred from observations of specimen behavior, starting with a hypothetical specimen at the test temperature and before external pressurization has been initiated. The specimen contains a mandrel to establish both a pellet-to-pellet and a pellet-to-cladding gap. These steps in the collapse phenomenon are as follows:

1. Pressure transient is initiated and tube begins its elastic response.
2. As pressure increases, the tube (with some slight initial ovality) becomes more oval.
3. As ovality increases, the tube contacts the mandrel and the simulated pellet-to-pellet gap becomes important (i.e., the tube no longer has an "infinite" unsupported length).
4. At this point, the outer fibers of the tube have probably yielded, since permanent deformations (ridges) have been found in tubes that did not collapse into the gap.
5. The tube is now supported along its length by the mandrel - except at the gap. It is probable that the edges of the gap provide support over 270-300° of the tube circumference.
6. Collapse occurs, with the plastically deformed ridge along the tube forming the predominant lobe of the collapse geometry. Although the collapse behavior seems to follow the von Mises criterion for a number of lobes, it is improbable that a truly elastic collapse was obtained.
7. When the external pressure is released, the tube elastically springs away from the mandrel, establishing a slight pellet-to-cladding gap.

It was stated earlier that the data in Table 3 are the result of a multiparameter study and are difficult to interpret without recourse

to three-dimensional graphs. The following figures, using both two- and three-dimensional plots, illustrate the interactions among those parameters — as far as can be interpreted from the still limited data base.

Figures 15, 16, and 17 illustrate the effects of temperature and hardness on the collapse pressure of the specimens. Included in the plots is information on pellet-to-pellet gap and pellet-to-cladding gap. The curves in the figures represent an estimate of the position of the data for the 4-in. (101.6-mm) pellet-to-pellet gap specimens. The curves are positioned with regard to the data for all four temperatures. Insufficient information is available to determine the curve positions for smaller gaps. Qualitatively, it is felt that decreasing pellet-to-pellet and pellet-to-cladding gaps cause an increase in collapse pressure, and this is shown, in general, by the data points.

Fig. 15. Collapse Pressure as a Function of Hardness, Pellet-to-Pellet Gap and Pellet-to-Cladding Gap at 600 and 650°F (316 and 343°C). Subscripted numbers represent pellet-to-pellet gap and numbers in parentheses represent pellet-to-cladding gap.

Fig. 16. Collapse Pressure as a Function of Hardness, Pellet-to-Pellet Gap and Pellet-to-Cladding Gap at 700°F (371°C). Subscripted numbers represent pellet-to-pellet gap and numbers in parentheses represent pellet-to-cladding gap.

Fig. 17. Collapse Pressure as a Function of Hardness, Pellet-to-Pellet Gap and Pellet-to-Cladding Gap at 800°F (427°C). Subscripted numbers represent pellet-to-pellet gap and numbers in parentheses represent pellet-to-cladding gap.

Figure 18 is a three-dimensional plot of the 800°F (427°C) data. The data points are drawn as if they fall on the curved surface. Their actual position may be slightly above or below the surface depending upon natural scatter of the data and on pellet-to-cladding gap values. For example, the data point that represents the collapse behavior of the specimen with a 0.4-in. (10.2 mm) pellet-to-pellet gap should lie above the surface since that specimen had a 0.005-in. (0.13 mm) pellet-to-cladding gap relative to the 0.8-in. (20-mm) gap represented by the surface.

Fig. 18. Three-Dimensional Graph of Collapse Pressure as a Function of Hardness and Pellet-to-Pellet Gap at 800°F (427°C).

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