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**Quarterly Progress Report on the
Creepdown and Collapse of Zircaloy Fuel
Cladding Program Sponsored by the NRC
Division of Reactor Safety Research
for October-December 1975**

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MASTER

OAK RIDGE NATIONAL LABORATORY

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

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QUARTERLY PROGRESS REPORT ON THE CREEPDOWN AND COLLAPSE
OF ZIRCALOY FUEL CLADDING PROGRAM SPONSORED BY THE
NRC DIVISION OF REACTOR SAFETY RESEARCH
FOR OCTOBER-DECEMBER 1975

D. O. Hobson

Work performed by Union Carbide Corporation for the
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SUMMARY

The creepdown and collapse study on Zircaloy fuel cladding is concerned with the deformation behavior of cladding under normal and near-normal reactor operating conditions. Efforts this past quarter have continued on two phases of the program: (1) collapse testing and (2) development and fabrication of deformation-monitoring equipment.

Sufficient collapse testing has been done to begin the analysis of the test data. It is apparent that all three of the independent variables used in this study (pellet-to-pellet gap, pellet-to-cladding gap, and temperature) play major roles in the collapse phenomenon. Tentative trends are presented but they constitute an insufficient basis for the quantitative formulation of a collapse model at this time.

The instrumentation for deformation monitoring has been developed and provision has been made for automatic control of the data gathering system and for protection of the monitoring coils from damage caused by collapse of the specimen tube.

Work performed by Union Carbide Corporation for the U.S. Nuclear Regulatory Commission under interagency agreements 40-551-75 and 40-552-75.

CREEPDOWN AND COLLAPSE OF ZIRCALOY FUEL CLADDING

D. O. Hobson

Metals and Ceramics Division

INTRODUCTION

The purpose of this study continues to be the determination of the deformation behavior of Zircaloy fuel cladding under normal and near-normal reactor operating conditions. The previous report in this series¹ provided background information on the various tasks in this study. The present report will be confined to two aspects of the study: the results of collapse testing of tubing and the status of the eddy-current, deformation-monitoring equipment to be used for the creep-collapse experiment.

A tentative set of curves are presented based on a small number of data points. These curves should be examined with the clear understanding that they represent trends in collapse behavior and have insufficient basis to be considered a model at this time.

DISCUSSION OF COLLAPSE TESTS

A sequence of collapse tests has been completed and the results are tabulated in Table 1 and will be discussed later. The test matrix, which contained test temperature, pellet-to-cladding gap, and pellet-to-pellet gap as independent variables, was originally designed to allow statistical evaluation of the cladding behavior. It is now evident that the collapse response of the cladding is too complex for immediate statistical treatment, and more testing and analysis will be required before the phenomenon is understood. It was initially conjectured that, of the three independent variables, temperature would be the most important and pellet-to-cladding gap the least important in determining

¹D. O. Hobson, *Quarterly Progress Report on the Creepdown and Collapse of Zircaloy Fuel Cladding Program Sponsored by the NRC Division of Reactor Safety Research for July-September 1975*, ORNL-TM-5149.

Table 1. Results of Collapse Tests Based on Statistically-Designed Test Matrix

Mandrel Number	Pellet-to-Cladding Gap		Pellet-to-Pellet Gap		Test Temperature		Collapse Pressure		Number of Lobes	Average Ovality	
	(in.)	(mm)	(in.)	(mm)	(°F)	(°C)	(psi)	(MPa)		(in.)	(mm)
42	0.0046	0.117	0.8	20.32	700	371	4080 ^a	28.1		0.005	0.127
40	0.006	0.152	0.4	10.16	650	343	4000 ^a	27.6		0.009	0.229
38	0.006	0.152	0.4	10.16	750?	399?	4100 ^a	28.3		0.004	0.102
38R	0.006	0.152	0.4	10.16	800	427	<4100	<28.3	4	0.009	0.229
41	0.006	0.152	1.2	30.48	650	343	3940	27.2	2	0.006	0.152
39	0.006	0.152	1.2	30.48	715?	379?	4000	27.6	3	0.006	0.152
12	0.008	0.203	0.127	3.23	700	371	4000 ^a	27.6 ^e		0.007	0.178
36	0.008	0.203	0.8	20.32	616	324	4020	27.7	3	0.013	0.330
19	0.008	0.203	0.8	20.32	700	371	4100 ^a	28.3 ^e		0.008	0.203
19R	0.008	0.203	0.8	20.32	784	418	3630	25.0	3	0.011	0.279
20	0.008	0.203	0.8	20.32	700	371	4100 ^a	28.3 ^a		0.010	0.254
21	0.008	0.203	0.8	20.32	700	371	<4100	<28.3	3	?	
22	0.008	0.203	0.8	20.32	640?	338?	4100 ^a	28.3 ^a		0.013	0.330
22R	0.008	0.203	0.8	20.32	700	371	4000 ^a	27.6 ^a		0.015	0.381
23	0.008	0.203	0.8	20.32	700	371	3950	27.2	3	0.014	0.356
24	0.008	0.203	0.8	20.32	700	371	3750	25.9	3	0.013	0.330
25	0.008	0.203	0.8	20.32	700	371	4100	28.3	3	0.011	0.279
30	0.008	0.203	1.47	37.34	700?	371?	4090 ^{a?}	28.2		0.005	0.127
30R	0.008	0.203	1.47	37.34	700	371	3425	23.6	2	0.007	0.178
6	0.008	0.203	0.8	20.32	784?	418?	3900?	26.9	3	0.009	0.229
4	0.010	0.254	0.4	10.16	650	343	4050 ^a	27.9		0.013	0.330
2	0.010	0.254	0.4	10.16	750?	399?	4100 ^a	28.3 ^a		0.008	0.203
2R	0.010	0.254	0.4	10.16	800	427	<4000	<27.6	4	0.018	0.457
5	0.010	0.254	1.2	30.48	650	343	3540	24.4	2	0.011	0.279
3	0.010	0.254	1.2	30.48	750?	399?	3700	25.5	2	0.008	0.203
1	0.0114	0.290	0.8	20.32	700	371	3750	25.9	3	0.013	0.330

^aMaximum pressure - no collapse.

collapse behavior. It is now felt that the order of importance could probably be reversed, with pellet-to-cladding gap strongly influencing cladding behavior in an as-yet-undetermined manner.

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 the 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 will have 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 deg 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 the number of lobes, it is certain that a truly elastic collapse was not obtained.
7. When the external pressure is released, the tube elastically springs away from the mandrel, reestablishing a slight pellet-to-cladding gap.

Steps 4 and 5, in the foregoing scenario, are important because the presence of a simulated pellet-to-cladding gap prevents an orderly

analysis of the cladding deformation. If there were no such gap (i.e., zero clearance) then the cladding would be completely supported at the edges of the mandrel on each side of the simulated pellet-to-pellet gap, and there would be little tendency for a plastically-deformed ridge to form along the tube prior to collapse. The complete circumferential support at each end of the pellet-to-pellet gap would lend more meaning to the use of the von Mises collapse equation for determining the number of collapse lobes.

The data presented in Table 1 are the result of a multiparameter study and are difficult to interpret without recourse to three-dimensional 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

$$P_{\text{crit}} = kE\left(\frac{t}{D}\right)^3, \quad (1)$$

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 1, modified from the literature,² shows a series of curves that represent values of k calculated by 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 simply supported, (2) the

²R. G. Sturm, *A Study of the Collapsing Pressure of Thin-Walled Cylinders*, Bull. 329, Engineering Experiment Station, University of Illinois, 1941.

Fig. 1. 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.

value of Poisson's ratio ($\mu = 0.30$) may not be applicable to this material, and (3) the collapse may not be totally elastic. However, the curves do describe the experimentally observed collapse geometries 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. 1 to represent this ratio. The arrows at the bottom of the graph represent the various simulated pellet-to-pellet gaps used in this study. Reference to Table 1, in conjunction with this figure, shows that the collapse geometry generally follows the prediction of the curves as far as number of lobes is concerned. It can also be noted that the intersections of the L/R values for the collapse specimens (with pellet-to-pellet gaps between 0.4 and 1.47) 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. Figure 2 is a semilogarithmic plot of the most precise data in Table 1. The data points for which either the test temperature or the collapse pressure were in question were omitted, except for tests 2R and 38R. A data point for an 800°F (427°C) test that was run without a mandrel was added to the data set. It should be emphasized that the curves in Fig. 2 are tentative and represent the first step in formulating a model for the collapse behavior of the particular tubing used in these experiments. The curves would approximate straight lines in a log-log plot, thereby fulfilling the relationship discussed above.

Fig. 2. Graph of Collapse Pressure as a Function of Temperature, Pellet-to-Pellet Gap and Pellet-to-Cladding Gap. Curves are tentative trend indications.

Three assumptions were made in drawing the curves: collapse pressure should decrease with (1) increasing pellet-to-pellet gap,

(2) increasing pellet-to-cladding gap, and (3) increasing test temperature. The curves in Fig. 2 were positioned by eye to fit the above assumptions and to avoid obvious physical contradictions. Obviously, there are too few data to allow any statistical curve fitting. Additional tests are presently being made to fill in missing data and as a first check on the model assumption.

Table 1 contains a column labeled "Average Ovality." The values in that column represent the average values of the differences between maximum and minimum diameters, taken at a number of axial positions between the collapsed section and the end-plug sections of each tube. The most important observation is that ovality was present, after testing, in all specimens — even those that did not collapse. This forms the basis for the fourth step in the collapse scenario discussed earlier.

The apparent moduli of elasticity, calculated from Eq. (1), the tubing geometry, and the observed collapse pressure are found to be quite low compared to the literature values. This is another indication that the collapse mechanism is not totally elastic and that the use of tangent moduli (if appropriate stress-strain curves could be obtained) would be more appropriate.

Discussion of Eddy-Current Deformation-Monitoring Equipment and Instrumentation

Both the deformation-measuring equipment and the instrumentation to control and monitor that equipment have been improved during the past quarter. Modifications have been made in the coil holders for better stability 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).

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 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 to be described 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 developed and are completing 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 3 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 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.

Fig. 3. Block Diagram of Deformation-Monitoring Instrumentation.

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 signals to control 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.

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 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.

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