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Multirod Burst Test Program Quarterly Progress Report for July—September 1976

R. H. Chapman

Prepared for the U.S. Nuclear Regulatory Commission
Office of Nuclear Regulatory Research
Under Interagency Agreements ERDA 40-551-75 and 40-552-75

OAK RIDGE NATIONAL LABORATORY
OPERATED BY UNION CARBIDE CORPORATION FOR THE ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

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FROM: R. H. Chapman

SUBJECT: Errors in Report

Please make the following changes in your copy of subject report:

Page 26, first sentence: Change the word "unavailable" to "unavoidable."

Page 31, top line: Change "unheated" to "heated."

R. H. Chapman (MRS)

R. H. Chapman

RHC:cjf

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MULTIROD BURST TEST PROGRAM QUARTERLY PROGRESS REPORT FOR JULY—SEPTEMBER 1976

R. H. Chapman

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NOTICE: This document contains information of a preliminary nature. It is subject to revision or correction and therefore does not represent a final report.

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PREFACE

The Multirod Burst Test (MRBT) program is being conducted in the Engineering Technology Division of Oak Ridge National Laboratory for the Nuclear Regulatory Commission, Office of Nuclear Regulatory Research (NRC/ONRR); Dr. M. L. Picklesimer is the project manager for that organization.

Previously published MRBT progress reports are listed below.

1. *Quarterly Progress Report on Reactor Safety Programs Sponsored by the Division of Reactor Safety Research for July—September 1974*, ORNL/TM-4729, Vol. I, pp. 70—72.

2. *Quarterly Progress Report on Reactor Safety Programs Sponsored by the NRC Division of Reactor Safety Research for October—December 1974*, ORNL/TM-4805, Vol. I, pp. 102—10.

3. *Quarterly Progress Report on Reactor Safety Programs Sponsored by the NRC Division of Reactor Safety Research for January—March 1975*, ORNL/TM-4914, Vol. I, pp. 78—104.

4. *Quarterly Progress Report on Reactor Safety Programs Sponsored by the NRC Division of Reactor Safety Research for April—June 1975*, ORNL/TM-5021, Vol. I, pp. 76—98.

5. R. H. Chapman, *Multirod Burst Test Program Quarterly Progress Report for July—September 1975*, ORNL/TM-5154.

6. R. H. Chapman, *Multirod Burst Test Program Quarterly Progress Report for October—December 1975*, ORNL/NUREG/TM-10.

7. R. H. Chapman, *Multirod Burst Test Program Quarterly Progress Report for January—March 1976*, ORNL/NUREG/TM-36.

8. R. H. Chapman, *Multirod Burst Test Program Quarterly Progress Report for April—June 1976*, ORNL/NUREG/TM-74 (in publication).

SUMMARY

Battelle Columbus Laboratories performed additional tensile tests on specimens from each lot of the special Zircaloy tubing purchased for use in the NRC cladding research programs. These tests were conducted to verify the data provided by the tubing manufacturer as being representative of the material in the as-received condition. As anticipated, the BCL data are in substantial agreement with the manufacturer's data.

Two simulators were fabricated and tested with room-temperature gas volumes about four times greater than normally used to explore the effect of this parameter while keeping the other test parameters essentially the same as in comparable tests with normal volumes. Due to the method used to increase the gas volume, the additional volume was largely unheated during the tests and the thermodynamic effects may have been mitigated somewhat. The pressure increase during the tests was less than that in the comparable low-gas-volume tests due to the external gas volume being unheated and to compressibility factors. Altogether, the effect of the increased volume was not appreciable in these two tests. A greater influence would be expected if the increased volume were heated more effectively and might be more pronounced at higher test temperatures where oxidation effects are more important.

Two burst tests were conducted at significantly higher pressures to permit extrapolation of our earlier test results with greater certainty. The burst pressures in these tests were on the order of 19,100 kPa (2770 psi), compared to the range of 1440 kPa (2088 psi) for the earlier tests. In one of the tests at very high pressures (SR-15), the tube split on each end of the burst, indicating the violence of the failure; this is the first time we have observed this behavior. An equation based on a least-squares fit to our earlier data underestimated the burst temperature of SR-15 by 37°C (67°F) and of SR-19 by 9°C (16°F).

An order of lower seal glands for fuel pin simulators was received and tested; they satisfied the purchase order requirements and will be used in the first 4 × 4 bundle tests. Additional glands were ordered for the second and third bundles. Prototype glands of alternative designs provided by two other manufacturers were received for test and evaluation;

all the glands from one manufacturer failed the evaluation tests, while those from the other manufacturer showed promise and will be given further evaluation.

The effect of cold work on thermocouple accuracy was evaluated and found to be acceptably small for our requirements.

An attempt to fabricate fuel simulators with a different lot of BN powder introduced a new problem as the result of the larger BN particle size. The larger particles caused the concentricity of the heating element to be out of tolerance, and use of this powder was discontinued.

The powder, having the proper BN particle size distribution, was successfully processed to remove the magnetic contaminants. The first four simulators fabricated with the reprocessed powder showed unacceptably low insulation resistance between the heating element and the simulator sheath. This was traced to moisture contamination in the BN (that occurred during handling and filling of the powder) and to small metallic shavings that were scraped off the electrical lead-in terminals during the filling and tamping operations. These problems were eliminated by improved fabrication procedures and controls. As a result of these fabrication difficulties, delivery of the first 20 simulators (for use in 4 × 4 bundle 1) will be delayed.

Extensive failure analyses conducted on fuel simulators that failed in our high-temperature burst tests showed that the failures were caused by high temperature (in the range of melting), pressure buildup from BN reactions, and/or improper machining of the grooves in the sheath. Little can be done to relieve the first two factors since they are basically material characteristics. The influence of the third factor can and will be alleviated by more careful machining and inspection.

Plans were made to resume fabrication and installation of test equipment for the multirod tests. This work, temporarily stopped in January, will start again in October; the facility is scheduled for completion by March 1, 1977.

1. INTRODUCTION

R. H. Chapman

The objectives of this program are to delineate the deformation behavior of unirradiated Zircaloy cladding under conditions postulated for a loss-of-coolant accident (LOCA) and to provide a data base to facilitate assessment of the magnitude and distribution of geometrical changes in the fuel rod cladding in a multirod array and of the extent of flow channel blockage that might result. Data are obtained from single- and multirod experiments that include possible effects of rod-to-rod interactions on ballooning and rupture behavior; a tentative test matrix was given in a previous report.[1] Although the test matrix includes testing large bundle arrays, these will be held in abeyance until a definite need, based on the results of the smaller test arrays, is established. Also, tests with boiling-water reactor (BWR) cladding will be deferred until completion of the pressurized-water (PWR) cladding tests.

Internally pressurized, unirradiated Zircaloy tubes containing tubular electrically heated fuel simulators (to simulate nuclear fuel pellet heating) are tested to failure in a low-pressure, superheated-steam environment. These assemblies are heated over a 915-mm (36-in.) length at a constant rate of approximately 28°C/sec (50°F/sec); differential pressures range from about 700 to 14,000 kPa (100–2000 psi), corresponding to approximate rupture temperatures from 1200 to 750°C (2192–1292°F). In addition to measurements of cladding surface temperature and internal pressure during the transient tests, data will be obtained on pre- and posttest flow resistance (for the multirod arrays) and on deformation, rupture strain, and channel blockage (as measured by sectioning of tubes and tube bundles).

An initial series of tests, identified by the PS prefix, was conducted to develop and perfect test procedures, to evaluate and improve fuel pin simulator and test equipment performance, and to serve as scoping tests for guidance in the subsequent tests with simulators that include all the desired design features. It was anticipated that five or six prototype simulator tests would be adequate for these purposes; however, unforeseen difficulties with fabrication and characterization of fuel simulators necessitated additional testing to aid resolution of the fuel simulator manufacturing problems and to improve our nondestructive test and evaluation techniques. We have concluded testing of prototype simulators for the time being; a total of 19 such tests were conducted. The results of these tests were summarized in a previous report.[1]

Based on the experience gained from the PS series of tests, it was concluded that the present generation of fuel simulators is acceptable for the near-term requirements of the test program. However, use of this generation of fuel simulators imposes limitations on the quantity and quality of local temperature measurements that are needed to determine rod-to-rod interactions in bundle tests.

Upon conclusion of the PS series of tests, a second series of tests, identified by an SR prefix, was initiated. In general, the simulators used in this series employ all the desired design features. Results for the first group of the SR series of tests (eight) were reported previously.[1] Within the high temperature limits [$\lesssim$1150°C ($\sim$2100°F)] permitted by the present generation of fuel simulators, these tests covered the entire range of the test matrix.

The results of five tests in an argon environment and two additional tests in steam were reported last quarter.[2] During this report period, four additional tests were conducted in a steam environment. Two of these were conducted with simulators that incorporated about four times the gas volume normally used, and the other two were conducted at very high pressures (outside the range of the test matrix) in response to a special request of NRC/RSR. This report summarizes the preliminary results of the tests conducted this quarter and presents the status of our development activities.

2. PROGRAM PLANS AND ANALYSIS

2.1 Programmatic Activities

R. H. Chapman

One of the design objectives of the fuel pin simulators used in this test program was to approximate the gas volume and distribution in a full-length [3.66-m (12.0-ft)] fuel rod in the belief that cladding deformation in the tests would be more closely related to that expected in the nuclear fuel rods. This belief is predicated on the premise that deformation is directly related to the gas stored energy. Although competing design considerations precluded meeting the gas volume and distribution objective, we were able to approach the net volume consideration in that the simulators having all the design features have a net free volume[2] of about 45 cm^3 (2.75 $in.^3$) at room temperature, which is about 50 to 60% greater than the design objective.

Two simulators with gas volumes about four times greater than the standard volume were tested during this report period to investigate the effect of this parameter on cladding deformation. The results of these tests are discussed in Section 2.2.

Also in response to a request of NRC/RSR, two simulators were tested at a much higher pressure than specified[1] in the test matrix to obtain data to permit greater confidence in extrapolating our early test results. Certain system modifications and safety reviews were required to conduct the tests in a safe and reliable manner. The results of these tests are discussed in a subsequent section.

Battelle Columbus Laboratories (BCL) performed tensile tests on a tube from each lot of the special Zircaloy tubing[3] procured for use in the various NRC research programs as a check on the manufacturer's data supplied with the tubing. As reported,[3] difficulties were encountered in check tests performed by Argonne National Laboratory (ANL) and the results were suspected to be erroneous. Table 2.1 compares the three sets of data at the two temperatures for which data were required by the purchase order specifications.[3] As seen from the tabulations, the BCL data are in substantial agreement with the manufacturer's (Sandvik) data. Also, since

Table 2.1. Comparison of tensile properties of Zircaloy tubing

Tube lot	Temperature [°C (°F)]	Sandvik tests (before rerounding)		Sandvik tests (after rerounding)		BCL tests (as received)		ANL test (as received)	
				Ultimate tensile stress					
		MPa	psi	MPa	psi	MPa	psi	MPa	psi
7FD11	21 (70)	736 728	106,700 105,600	NA	NA	737 741	106,900 107,520	678	98,300
7FD12	21 (70)	729 739	105,700 107,200	723 757	104,900 109,800	760 763 759	110,190 110,660 110,030	655	95,000
7FD11	385 (725)	415 420	60,200 60,900	NA	NA	429 429	62,250 62,250	364	52,800
7FD12	385 (725)	411 417	59,600 60,500	427 439	61,900 63,600	447 449 438	64,760 65,080 63,500	361	52,400
				0.2% yield stress					
7FD11	21 (70)	563 561	81,600 81,400	NA	NA	557 553	80,800 80,170	421	61,100
7FD12	21 (70)	547 558	79,300 81,000	530 545	76,900 79,000	570 565 559	82,690 81,900 81,110	441	64,600
7FD11	385 (725)	308 318	44,700 46,100	NA	NA	332 334	48,100 48,410	288	41,800
7FD12	385 (725)	321 328	46,500 47,600	312 325	45,300 47,100	352 340 338	51,090 49,360 49,040	270	39,200
				Elongation					
		% in 50.8 mm (2 in.)		% in 50.8 mm (2 in.)		% in 50.8 mm (2 in.)		% in 25.4 mm (1 in.)	
7FD11	21 (70)	21 21		NA		23.7 22.4		24	
7FD12	21 (70)	22 21		21 19		20.3 22.5 20.3		16	
7FD11	385 (725)	22 25		NA		18.5 19.2		22	
7FD12	385 (725)	23 23		26 21		18.2 19.7 23.1		7	

replicate tests were conducted by BCL, the results appear more reliable than the single test results provided by ANL and hence should be regarded as representative values for the as-received tubing.

The BCL tests were conducted in accordance with the requirements in ASTM Standard E8-69 for tensile testing of tubing with the exception that the specimens were gripped at the internal bullet shoulder rather than below the shoulder as required by the standard. This should not affect the test results. The specimen gage length was 50.8 mm (2 in.), and a strain rate of 0.005/min was used up to the yield stress and then increased to 0.025/min to the point of failure.

It was reported[3] that lot 7FD12 was rerounded to remove excess ovality; the manufacturer concluded that the properties of this lot were not affected as determined from the limited tests conducted in his laboratory. The BCL data appear to indicate that the rerounding operation introduced some additional work hardening in this lot of tubing.

Preliminary results of our single-rod tests were incorporated in a paper[4] presented at an international meeting convened to review the status of research related to LWR fuel element behavior under accident conditions. Several research laboratories were visited in conjunction with this meeting to assess the status of similar research under way at those laboratories. In particular, work in progress at the Karlsruhe Nuclear Research Center is closely related to our programmatic objectives, and it is encouraging that their preliminary results[5] are in substantial agreement with our findings.

Although we did not present a summary of our activities at the NRC Fourth Water Reactor Safety Research Information Meeting, the significant highlights were included in an overview paper.[6]

A report[7] on the infrared methods used to evaluate the performance and to characterize the electrically heated fuel simulators was completed and forwarded to the Reproduction Department for printing and distribution. The report describes the components of the system and the errors contributed by each and the procedures developed to facilitate evaluation of fuel simulator performance. This technique is uniquely suited to the detection of anomalies in the thermal performance of simulators since it reflects the dynamic behavior of the total assembly.

A report[8] was published that describes the development, construction, and early testing and evaluation of an apparatus for spot welding sheathed thermocouples to the inside of small-diameter tubes at precise locations. Although the apparatus was developed specifically for attaching thermocouples to the inside of the Zircaloy tubes used in this test program, it has potential for use in many applications with other combinations of materials.

2.2 Tests on Simulators with Large Gas Volumes

R. H. Chapman G. Hofmann*

The net gas volume of the test simulator, being a measure of the stored energy, is expected to have an influence on cladding deformation. Since the simulators used to obtain the Hobson[9] burst test data had significant gas volumes, the large deformations observed in those tests may be partially attributed to this parameter. During this reporting period, we assembled and tested two simulators with gas volumes about four times greater than normally used to explore the effect of this parameter while keeping the other parameters essentially the same.

To obtain the increased volume, we modified the test simulators by attaching a small external plenum, constructed of tubing and pipe fittings, to the upper seal gland. A nominal 6.5-mm (0.25-in.) tube was welded to the side of the gland to provide ready and relatively unrestricted access of the external volume to that provided in the voids inside the simulator. It should be noted that the gas contained in the external volume was essentially unheated during the test transient and hence the thermodynamic effect of the increased gas volume may have been mitigated somewhat. The results of these tests are discussed and compared below with comparable tests from simulators having the normal gas volume.

As will be evident in the discussion of the test results for simulators with high gas volumes, the effect of the increased gas volume was not appreciable in these two tests. The influence would be expected to be much greater if the simulator design were such as to cause the total gas volume to be heated effectively. Also, the effect of increased gas volume might be more pronounced at higher temperatures, so that oxidation effects would become more important. Further tests are contemplated to explore the gas volume parameter in greater detail.

Results of SR-16

Test conditions for SR-16 were selected to permit direct comparison with PS-10. The same fuel simulator was used in each of the tests to

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*On assignment from Karlsruhe Nuclear Research Center.

facilitate comparison of the posttest deformation profiles. Table 2.2 compares pertinent test conditions and results for the two tests.

Table 2.2. Comparison of SR-16 and PS-10 test results

	Test SR-16	Test PS-10
Fuel simulator No.	2828005	2828005
Room-temperature gas volume, cm^3	159.2	35.9
Environment	Steam	Steam
Initial temperature, °C	345	352
Initial pressure, kPa	6500	6440
Maximum pressure, kPa	6580	6830
Burst pressure, kPa	6420	6000
Burst temperature, °C	880	901
Burst strain, %	15	20

As indicated in the table, the maximum pressure attained in the large-volume test (SR-16) was about 330 kPa (48 psi) lower and the burst pressure was 420 kPa (61 psi) higher than those for PS-10. This is shown graphically in Fig. 2.1, which depicts "quick-look" pressure-time traces for the tests on an expanded scale to illustrate the detailed behavior in test SR-16. A representative temperature plot is also included for each test. The higher burst pressure of SR-16, compared to PS-10, is consistent with the lower burst temperature.

The axial distributions of the average circumferential elongation are compared for the two tests in Fig. 2.2; the pretest infrared characterization of the fuel simulator is also shown for reference. The burst locations in the two tests were essentially the same and were in the region of a relatively uniform (axially) high temperature as inferred from the infrared scan. The fuel simulator used in these tests is known to have a strong circumferential temperature gradient in the region of the bursts, and the circumferential position of the bursts corresponded to the maximum temperature

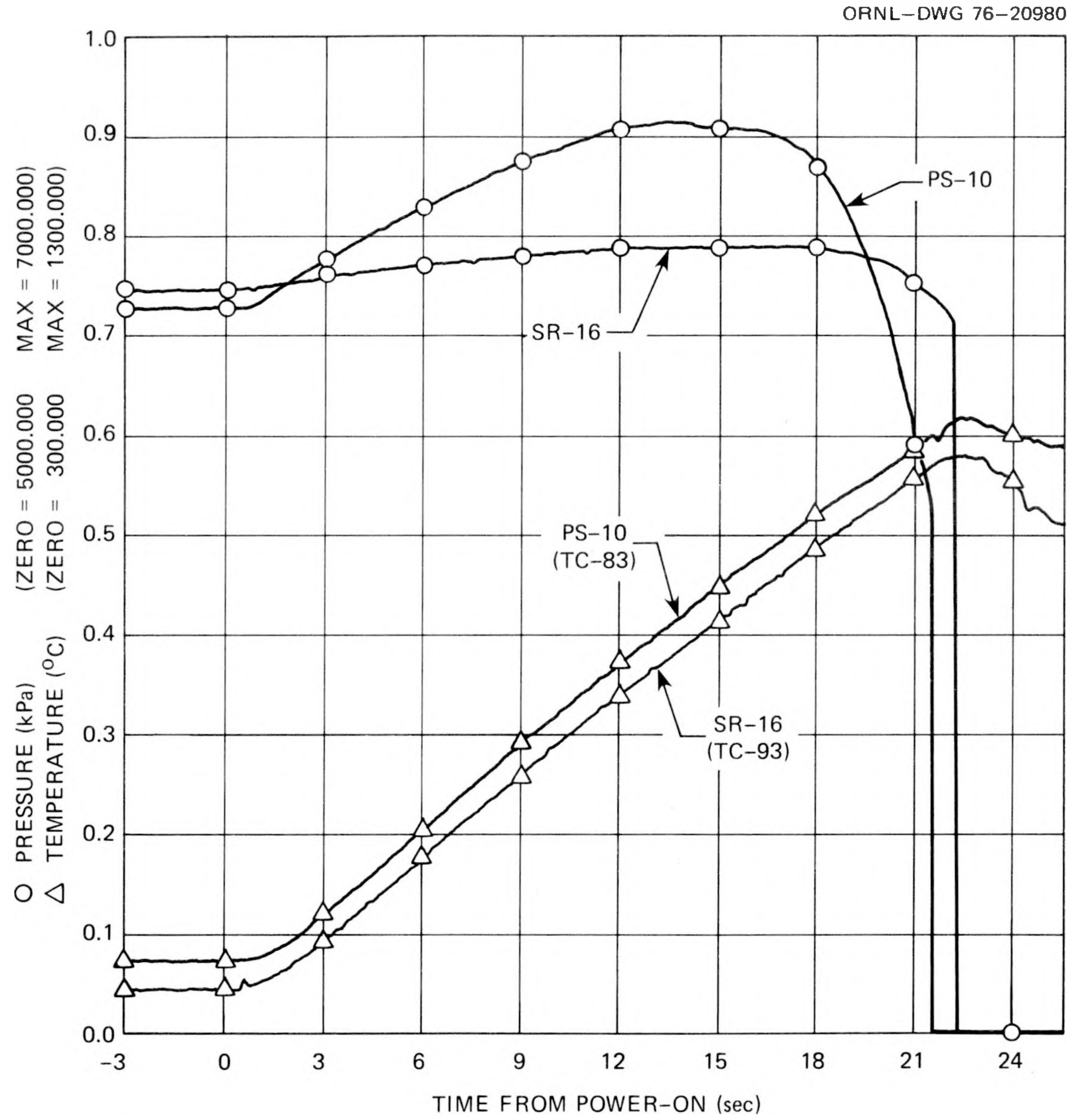

Fig. 2.1. Comparison of pressure and temperature transients for SR-16 and PS-10.

location in the simulator. As indicated in the figure, deformations in the two tests were essentially the same throughout the heated length of the cladding, although that for test PS-10 was slightly higher. This is attributed to the higher pressure loading over a significant time interval during the high-temperature portion of the test. The additional (external) unheated gas volume in SR-16 presumably permitted greater compression of the gas and minimized the pressure increase relative to that in PS-10.

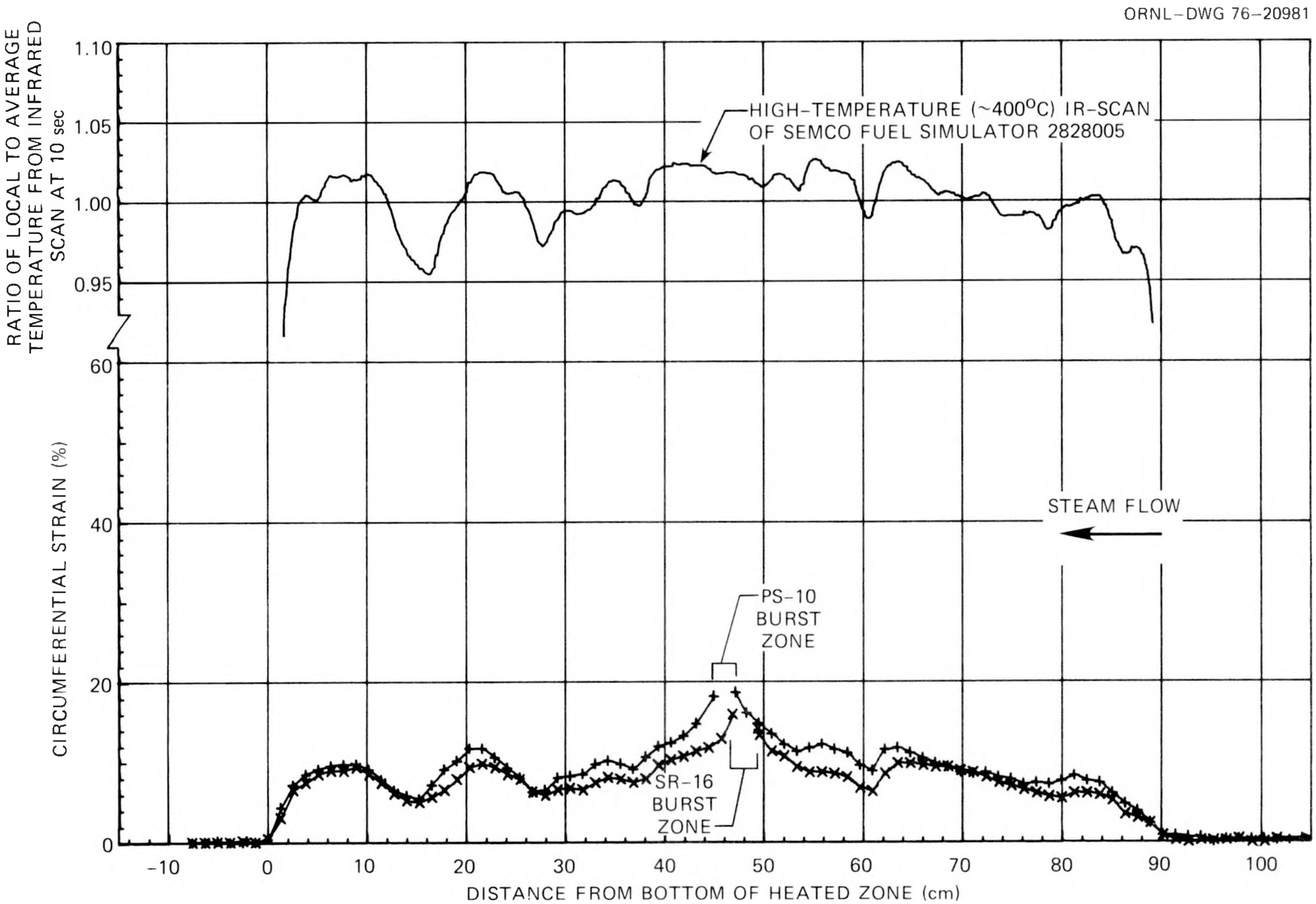

Fig. 2.2. Deformation profiles for SR-16 and PS-10.

Results of SR-18

Test conditions for SR-18 were selected to permit direct comparison with PS-19; the same fuel simulator was used in each of these tests (as well as in the SR-16 and PS-10 tests) to facilitate comparison of the post-test deformation profiles. Table 2.3 compares pertinent test conditions and results for the two tests.

Table 2.3. Comparison of SR-18 and PS-19 test results

	Test SR-18	Test PS-19
Fuel simulator No.	2828005	2828005
Room-temperature gas volume, cm^3	154.6	37.4
Environment	Steam	Steam
Initial temperature, °C	344	358
Initial pressure, kPa	2590	2590
Maximum pressure, kPa	2630	2820
Burst pressure, kPa	2590	2590
Burst temperature, °C	968	959
Burst strain, %	22	28

As indicated in the table, the initial and burst pressures were the same in each of the two tests. The burst temperatures were nominally the same; the difference indicated by the tabulated values may be the result of our defining the burst temperature as the maximum measured (without regard to the location of measurement with respect to the burst) value at the time of failure or it may be due to normal scatter in the data or small errors in the measured values.

As expected from the results of the earlier high-gas-volume test (SR-16), the pressure in SR-18 increased to a lower value than that in PS-19. This behavior is shown in Fig. 2.3, which depicts "quick-look" pressure traces on an expanded scale to show the relative effects. A representative temperature trace from each of the tests is also shown. As

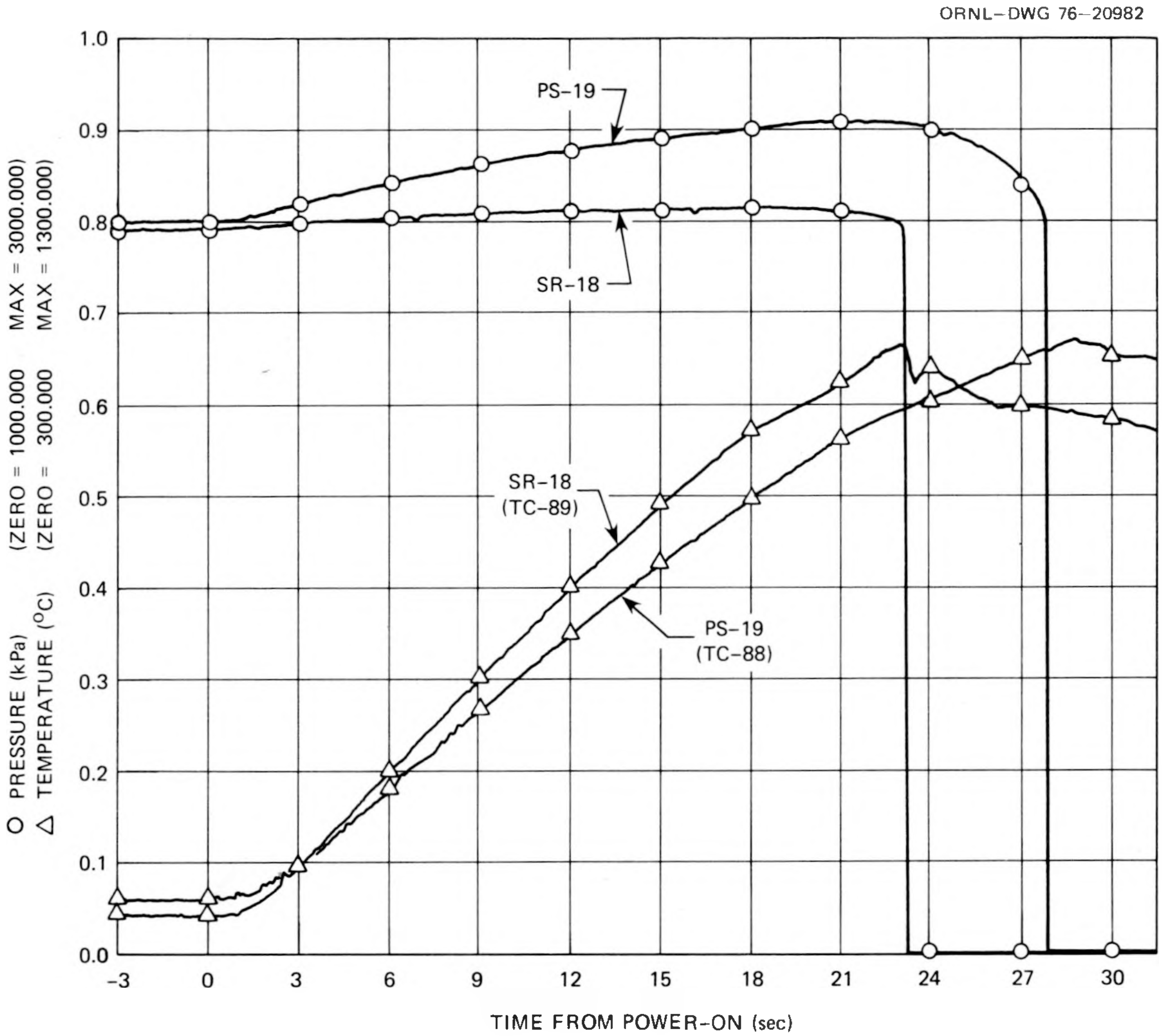

Fig. 2.3. Comparison of pressure and temperature transients for SR-18 and PS-19.

evident from the figure, the heatup rate of SR-18 was somewhat higher [∿30°C/sec vs ∿25°C/sec (54°F/sec vs 45°F/sec)] than that for PS-19, and hence the time to failure was about 4.5 sec less. The appearance of the tubes reflected this difference in that PS-19 showed evidence of more cracking in the thin film of oxide that developed during the increased exposure time.

The axial distribution of the circumferential elongation is compared for the two tests in Fig. 2.4, along with the pretest infrared characterization of the fuel simulator for comparison. As evident in the figure, the

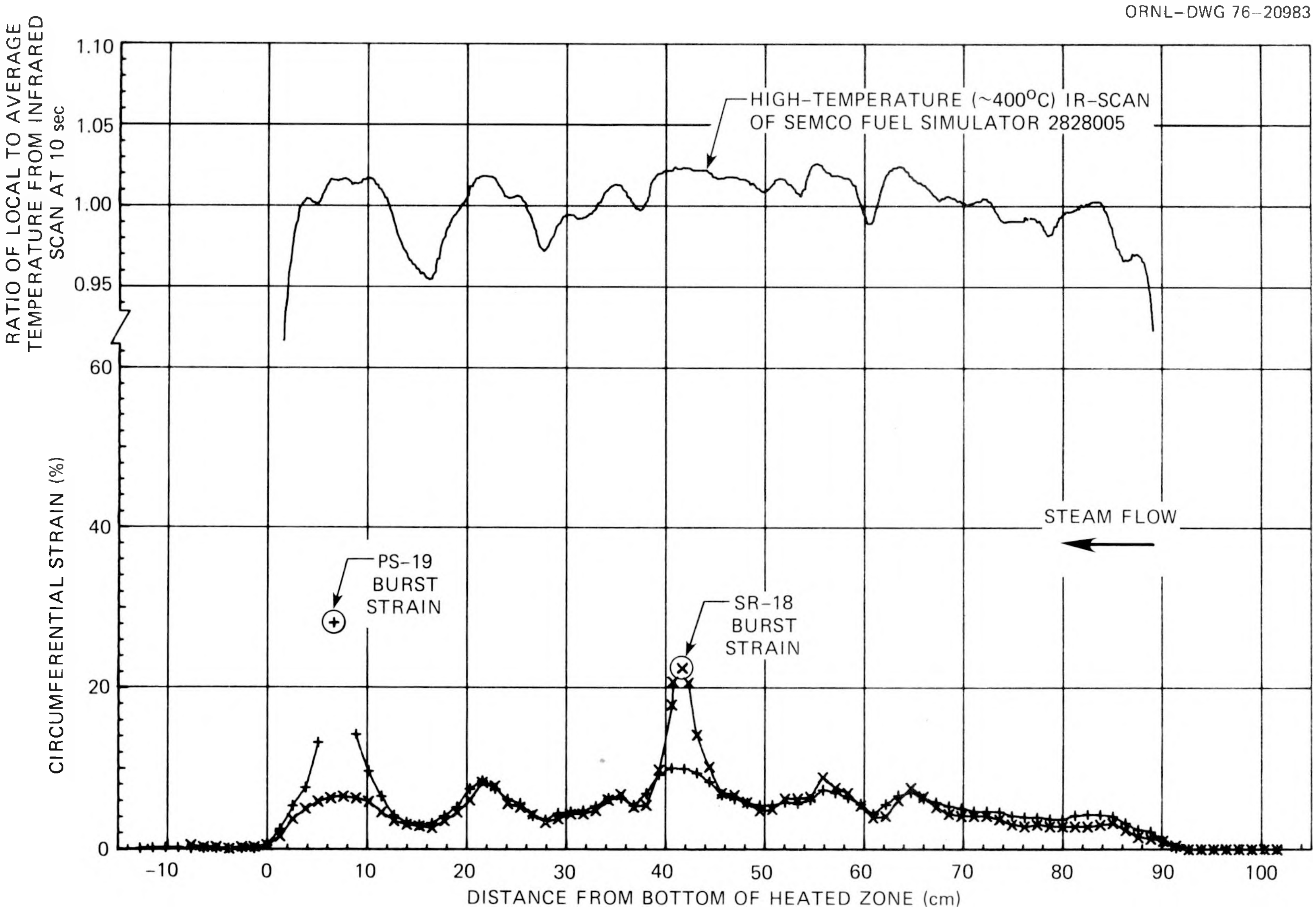

Fig. 2.4. Deformation profiles for SR-18 and PS-19.

deformation was virtually the same along the heated portion of the two simulators. SR-18 burst in the general vicinity of bursts for other tests with this fuel simulator, whereas PS-19 burst in a hot zone near the lower end of the heated length.[1] Comparing Fig. 2.4 with Fig. 2.2, the generalized deformation in the higher temperature (lower pressure) tests (i.e., SR-18 and PS-19) is somewhat less than that in the lower temperature tests, as would be expected by the lower pressure loading. The burst strains in the high-temperature tests seem to reflect greater differences, perhaps due to superplasticity or oxidation effects.

2.3 Burst Tests at Very High Pressure

R. H. Chapman G. Hofmann*

The test matrix[1] specified testing simulators at pressure levels up to about 14,000 kPa (∿2000 psi) and extrapolating the data to higher pressure levels. During this report period, we were requested by NRC to conduct two single-rod burst tests at a much higher pressure to permit extrapolation of our data with greater certainty; the results of these tests are discussed below.

In order to conduct the tests, it was necessary to improve the pressure capability of the test equipment and to substitute transducers with higher pressures than the ones we normally use to obtain the pressure vs time data. The transducer used was of the same type (same manufacturer) and had essentially the same response characteristics as the normal one. After the system was modified, a safety check was performed to demonstrate the integrity of the equipment for operation at the anticipated pressure level.

Results of SR-15 and SR-19

Table 2.4 summarizes the test conditions and results of these high-pressure tests. The burst temperature given in the table for SR-15 was obtained from a thermocouple (TC-91) located axially at the midpoint of the burst and about 10° around the tube periphery from the opening; hence, the

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*On assignment from Karlsruhe Nuclear Research Center.

Table 2.4. Comparison of SR-15 and SR-19 test results

	Test SR-15	Test SR-19
Fuel simulator No.	2828005	2828031
Room-temperature gas volume, cm^3	38.9	35.2
Environment	Steam	Steam
Initial temperature, °C	342	335
Initial pressure, kPa	20,350	19,970
Maximum pressure, kPa	21,280	20,830
Burst pressure, kPa	19,150	19,040
Burst temperature, °C	714	688
Burst strain, %	14	16

burst temperature is considered to be accurate. A thermocouple (TC-92) located 180° around the tube at this axial location indicated a temperature of 655°C at the time of burst, thus showing a significant circumferential temperature gradient in the burst zone. This gradient existed throughout the test transient. Figure 2.5, a posttest radiograph of the portion of the simulator that includes the burst, shows clearly the displacement of the fuel simulator to the hot side, creating a small gas gap on this side and a large gap on the relatively cold side. This behavior was discussed in a previous report[1] and has been actually photographed, using a radiographic technique, by Karlsruhe researchers during the transient.[5]

The axial distribution of the circumferential elongation for SR-15 is plotted in Fig. 2.6, along with the pretest infrared characterization of the fuel simulator for reference. As indicated in the figure, the generalized deformation is rather uniform along the length, although it does reflect the general shape of the characterization scan.

The extent of the failure is shown in Fig. 2.7. As evident in the photographs, the tube split at each end of the burst. The split portions are typical shear-type failures, with the failure line being approximately 45° to a radial line through the split. This was the first time we have observed this behavior.

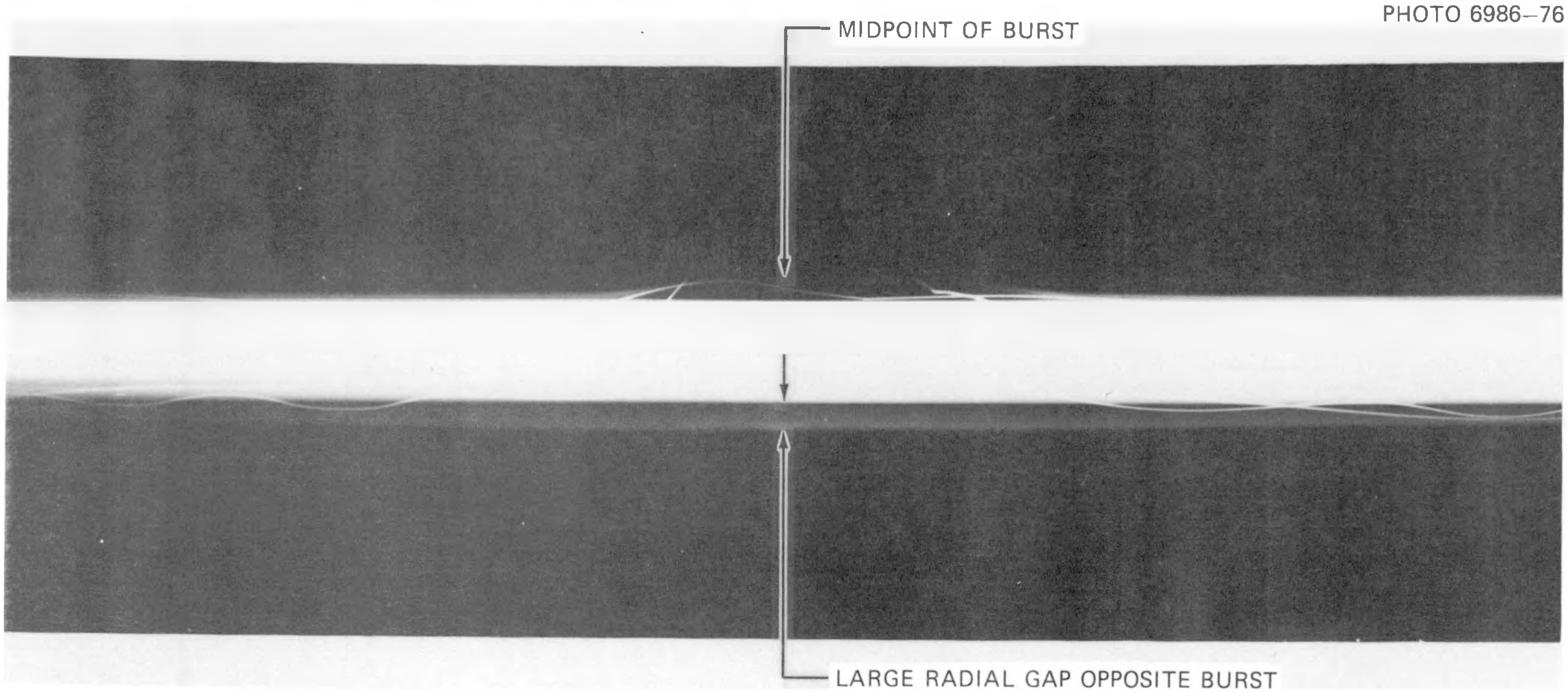

Fig. 2.5. Posttest radiograph of SR-15 showing displacement of the fuel simulator to the burst side of the tube and a large radial gap on the side opposite the burst.

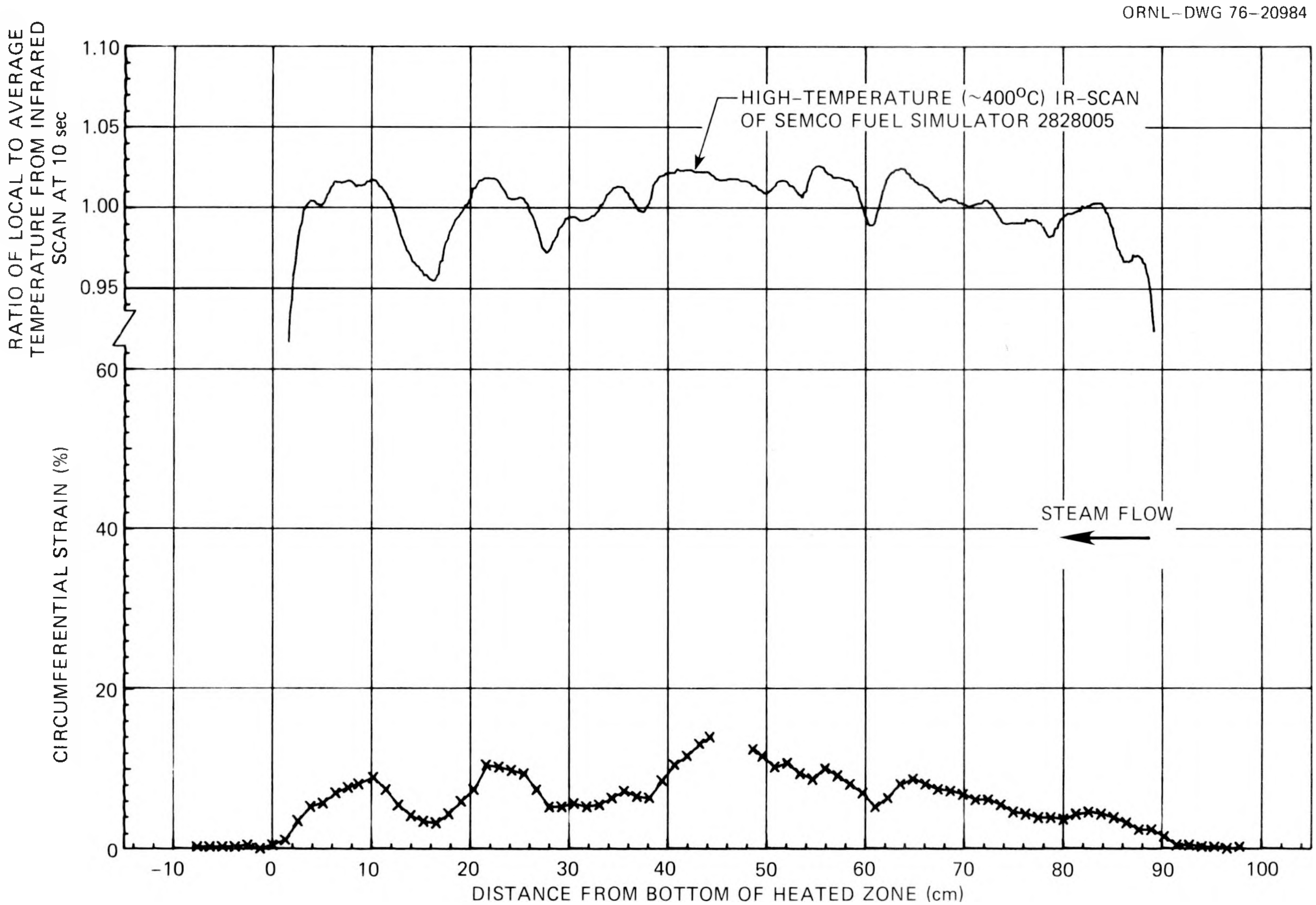

Fig. 2.6. Deformation profile of SR-15.

PHOTO 6987–76

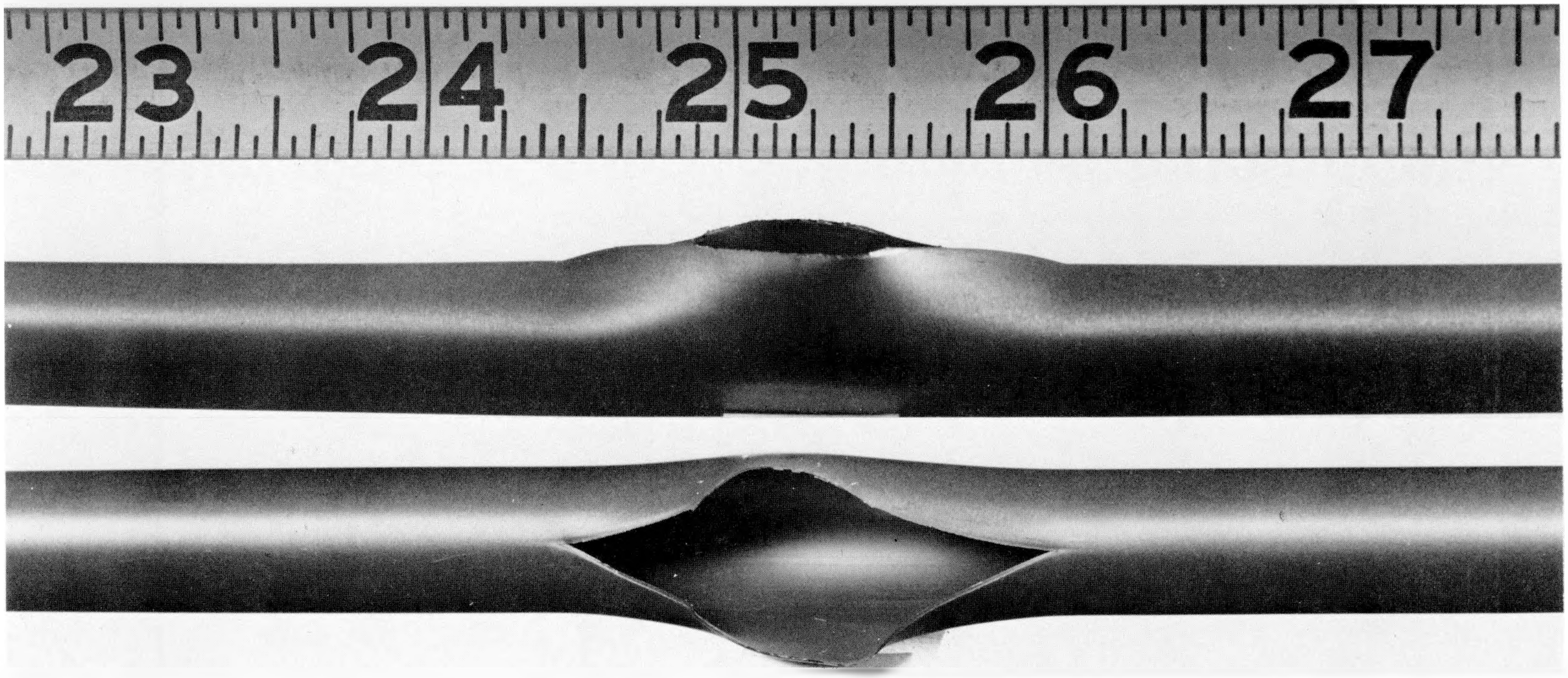

Fig. 2.7. Rupture in SR-15 showing splitting of tube at ends of burst.

The burst temperature given in Table 2.4 for SR-19 was obtained from a thermocouple (TC-86) located 27.5 cm (10.8 in.) below the burst point and may not be an accurate measure of the temperature in the vicinity of the failure. Comparing the burst pressure for SR-19 with that for SR-15, for which the burst temperature is believed to be very reliable, the burst temperature for SR-19 would be expected to be 15 to 20°C (27 to 36°F) higher than the value given in the table, which was obtained from the thermocouple that read highest.

Figure 2.8 is a plot of the axial distribution of the circumferential elongation of SR-19, along with the pretest infrared characterization of the fuel simulator for reference. It should be noted that the axial temperature distribution of the fuel simulator, as inferred from the infrared scan, is very uniform. (Thermocouple TC-86 was located at the 26.4-cm position, which is very near the peak temperature shown in the infrared scan.) The temperature uniformity is reflected by the uniformity in the deformation profile.

Photographs of the burst are shown in Fig. 2.9. Contrary to the behavior in SR-15, the tube did not split at the ends of the burst. In fact, the failure was similar to that for SR-7, which burst at a much lower pressure [14,440 kPa (2094 psi) compared to 19,040 kPa (2761 psi) for SR-19].

Both SR-15 and SR-19 burst at higher temperatures than would be expected from an extrapolation of our earlier data. A least-squares fit to the earlier data was presented[4] in the form of

$$T = 3921 - 0.0131P - \frac{10000P}{219 + 3.33P} ,$$

where T is burst temperature (°C) and P is burst pressure (kPa). Using the burst pressures given in Table 2.4, the equation predicts a burst temperature of 677°C for SR-15 and 679°C for SR-19.

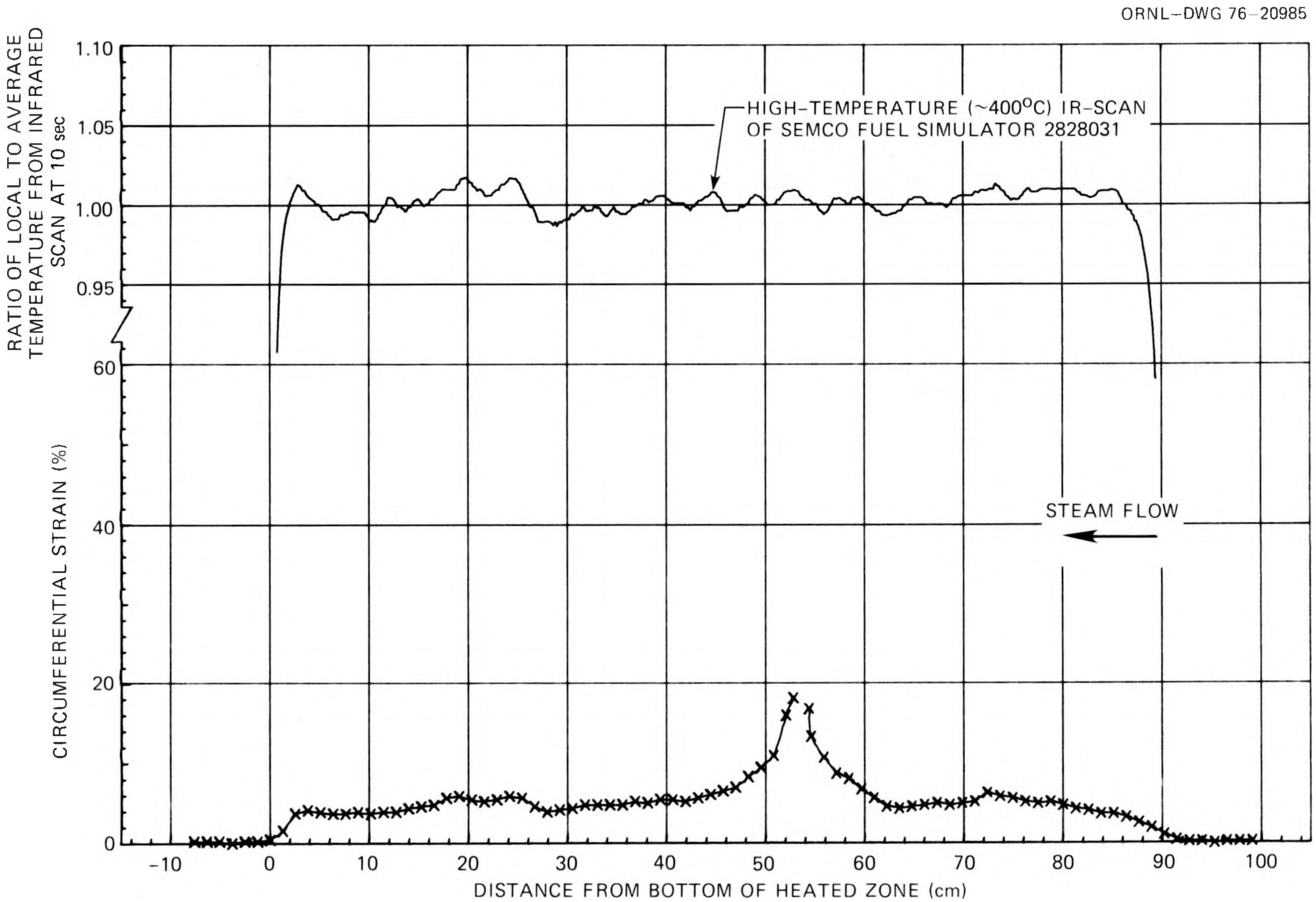

Fig. 2.8. Deformation profile of SR-19.

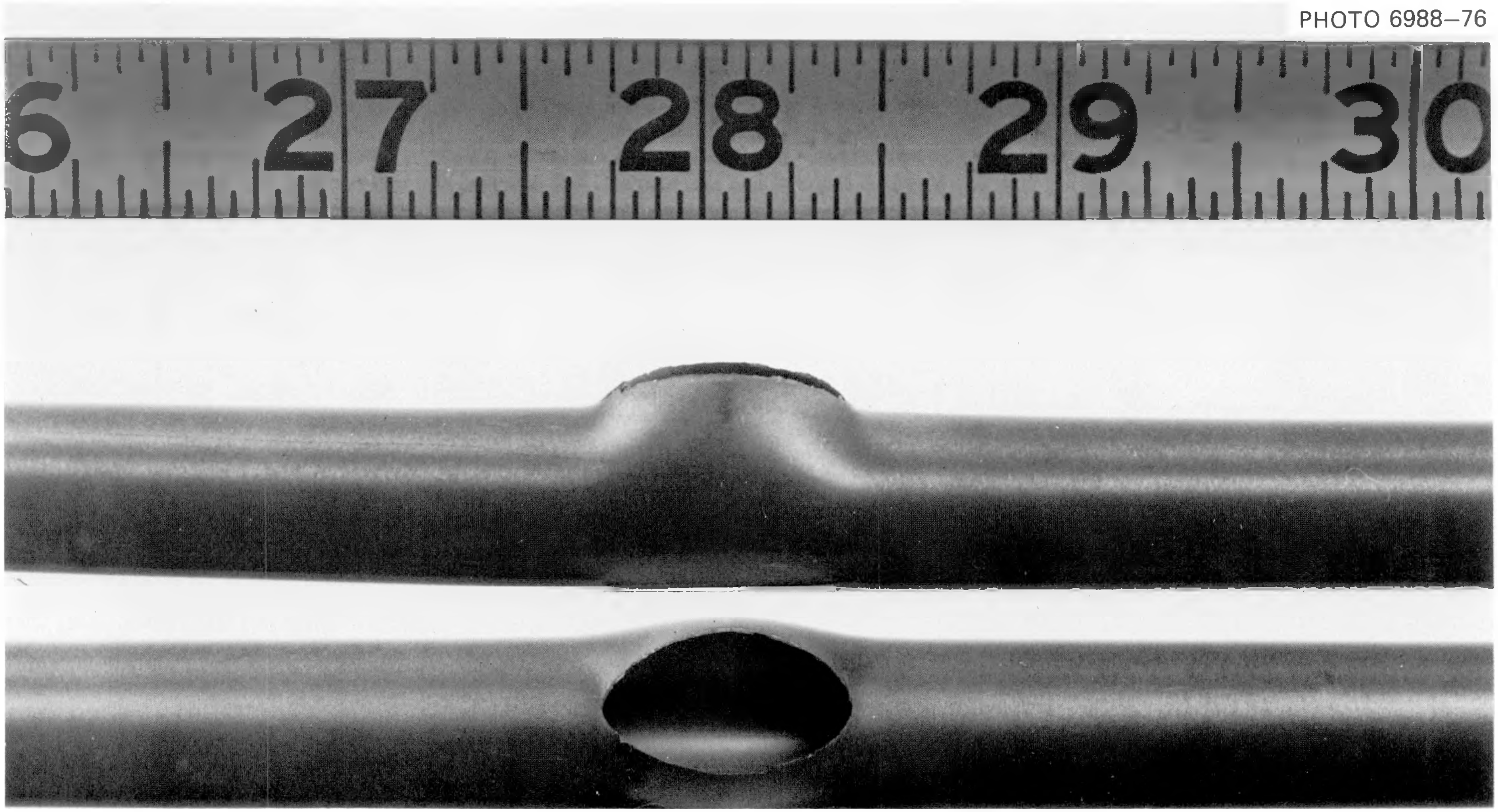

Fig. 2.9. Burst in SR-19.

3. DEVELOPMENT AND PROCUREMENT

3.1 Sheathed Thermocouple Junction Development

K. R. Carr* J. L. Crowley

In all the tests conducted to date, the reported burst temperatures were measured values obtained from 0.25-mm-OD (0.010-in.) bare-wire, type S, thermocouples spot welded to the outside surface of the Zircaloy tubes. In a number of these tests, we also included 0.75-mm-OD (0.030-in.) sheathed thermocouples attached to corresponding positions on the inside surface of the Zircaloy tube to obtain comparisons of the indicated temperatures during the transient. The calibrated bare-wire thermocouples on the outside of the tube are considered to provide a very accurate measurement of the tube temperature. However, there is some question about the accuracy of the measurements obtained from the inner sheathed thermocouples due to their proximity to the electrically heated fuel simulator and to inadequate interfacial contact area between the thermocouple sheath and the Zircaloy tube. (The difference between the inner and outer tube surface temperatures is very small and may be considered negligible for the purposes of this comparison.)

The data accumulated thus far indicate appreciable differences in the temperatures indicated by the two types of thermocouples, ranging from a few degrees in some cases to as much as about 100°C (180°F) in others. Clearly, such differences are cause for concern since we anticipate the use of only the internal sheathed thermocouples for cladding temperature measurements in the simulators comprising a multirod test array. We developed a prototype tool, shown in Fig. 3.1, for preparing "duckbill" junctions on sheathed thermocouples to evaluate the performance of increased junction contact area relative to the bare-wire thermocouple and the normally used sheathed thermocouple junction. As shown in the figure, a thermocouple tip is deformed between two surfaces to produce a convex surface on one side and a concave surface on the other. The amount of thermocouple

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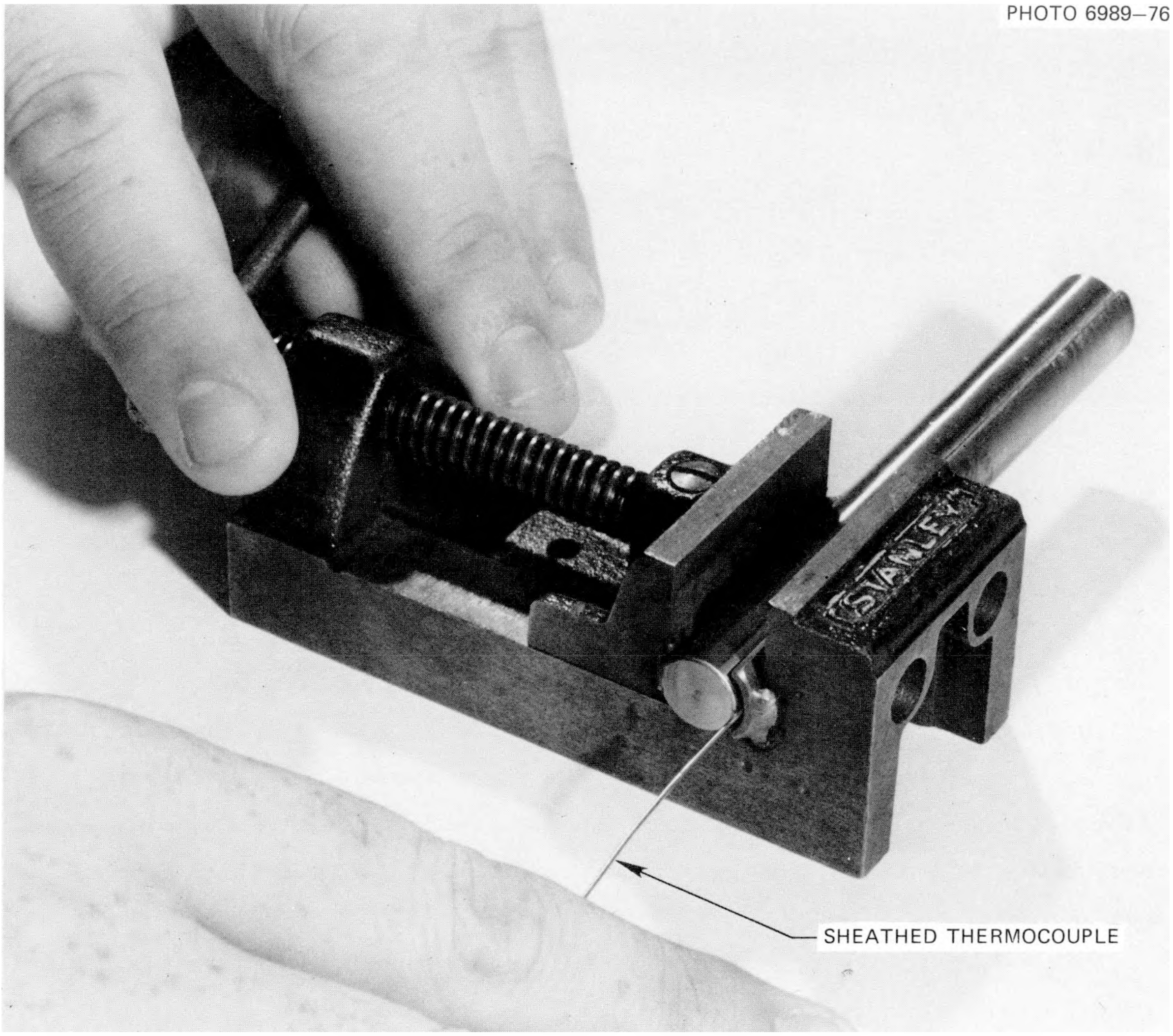

Fig. 3.1. Prototype tool for forming "duckbill" thermocouple junctions.

tip deformation can be controlled by micrometer measurements across the two members of the tool that contact the thermocouple. The contours of the tool are sized to produce an exact mating surface of the junction with the Zircaloy tube. Rounded edges are provided on the deformation tool to prevent damage to the thermocouple sheath. If this method of attachment offers appreciably increased accuracy of the temperature measurements, an improved deformation tool will be developed. For example, a tool based on a modification of a wire-terminal "crimp-on" tool would provide a fast and convenient way of forming thermocouple tips with uniformity from unit to unit.

A "duckbill" tip thermocouple with a grounded junction [0.762-mm-OD (0.030-in.) stainless steel sheath] was prepared and welded to the outside surface of the SR-18 Zircaloy tube. The spot-welding parameters (electrode lead length and W-sec settings) had to be changed significantly from those used previously to produce acceptable welds, indicating a significant difference between the electrical contact resistance at the interface for the normal rounded-tip and deformed-tip thermocouples. Straps of 0.0635-mm-thick (0.0025-in.) nickel were used to provide additional support; Fig. 3.2 shows the "duckbill" junction on the left; a typical type-S bare-wire sensor in the middle; and a typical 0.762-mm-OD (0.030-in.) stainless-steel-sheathed, insulated-junction unit on the right. The spacing between the bare-wire sensing junction and each of the other sensing junctions was 12.7 mm (0.5 in.).

A "quick-look" plot of the temperatures measured by the three thermocouples during the transient is given in Fig. 3.3. Assuming the actual temperature at the three measuring junctions is the same and is accurately measured by the bare-wire thermocouple, the figure shows that the "duckbill" junction has less error and faster response (as anticipated) than the insulated junction normally used on the inside thermocouples. For example, at 18 sec into the transient, the "duckbill" junction indicated a temperature 13°C (23.4°F) lower than the bare-wire junction, whereas the normal sheathed thermocouple indicated 61°C (110°F) lower. Some of these differences may be associated with actual variations in the local temperatures, but we believe that the main difference is attributed to the increased contact area present in the "duckbill" junction.

We plan to continue evaluating various types of thermocouple junctions in future single-rod tests in an effort to improve the accuracy of the internal sheathed thermocouples.

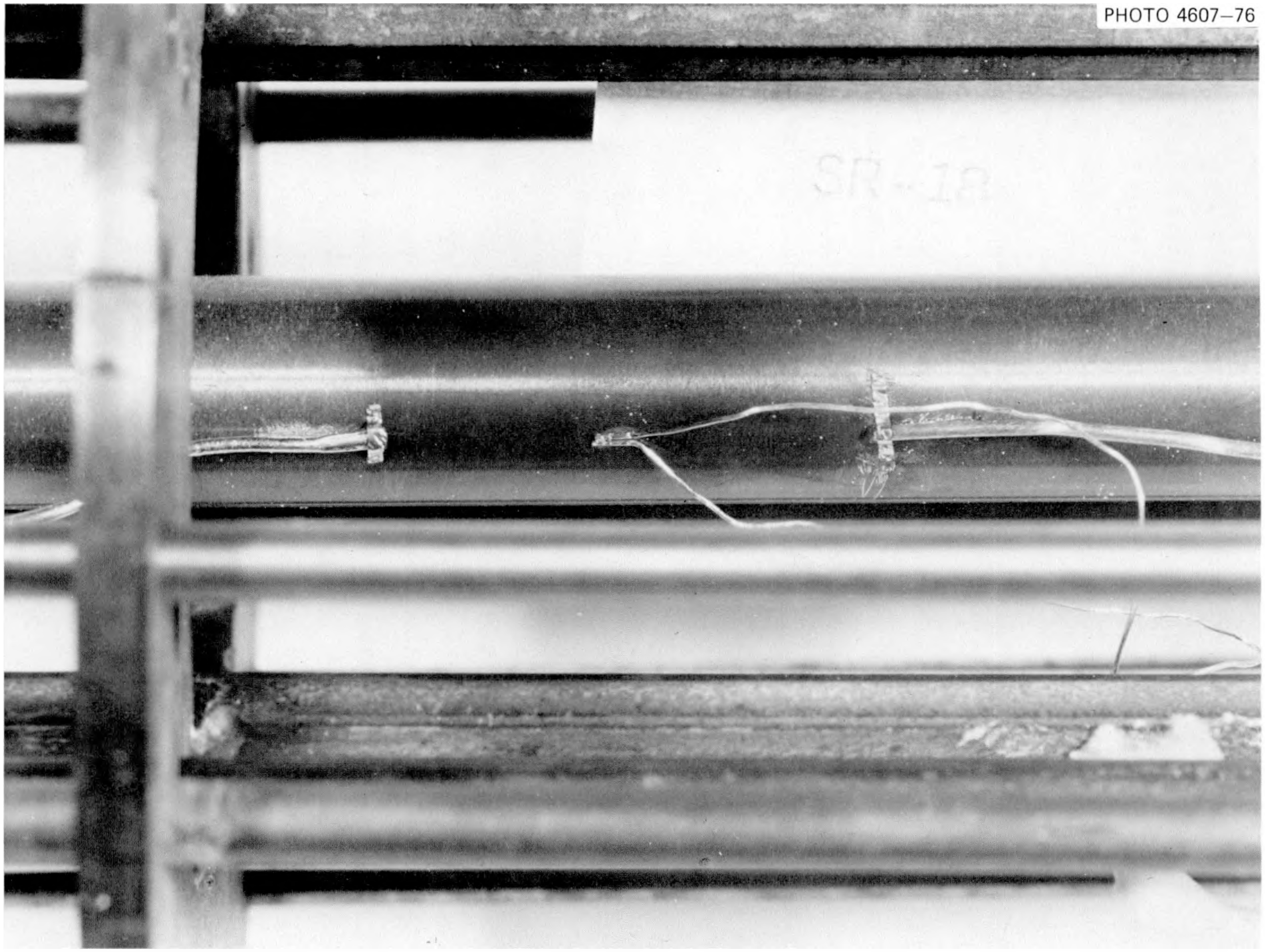

Fig. 3.2. Installation of thermocouples for comparison of responses in test SR-18. The spacing between sensing junctions is ∿13 mm (0.5 in.).

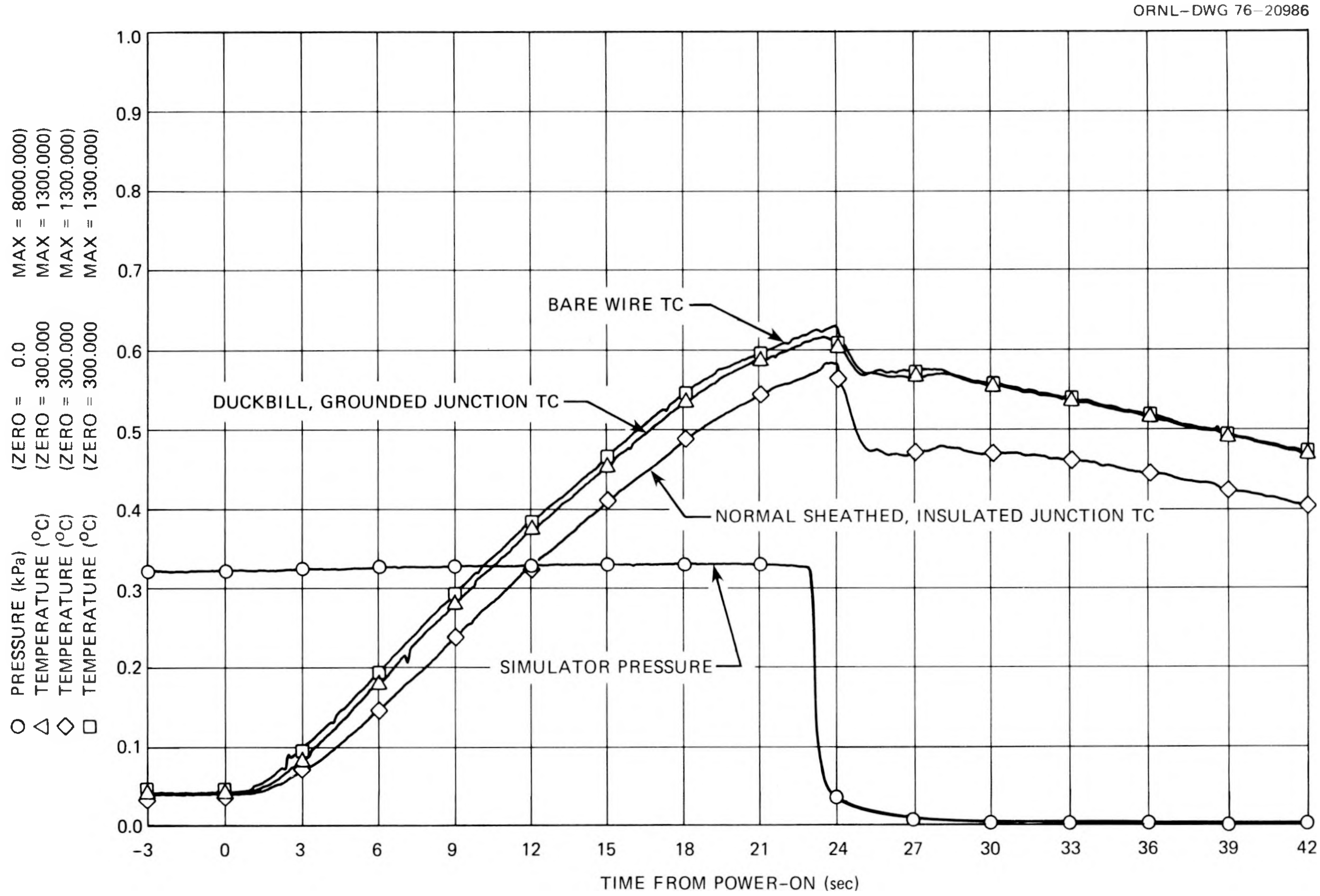

Fig. 3.3. Comparison of thermocouple indications for SR-18.

3.2 Effects of Cold Work on Thermocouple Accuracy

T. G. Kollie*

During fabrication and assembly of the instrumented test simulators and bundles, some cold working of the thermocouples is unavailable. Since cold working causes emf changes in the thermocouple outputs (which appear as temperature measurement errors), the Inhomogeneity Test Facility[10] (ITF) was used to investigate these effects. Sample thermocouples [0.25-mm-diam (0.010-in.) bare-wire, type S, and 0.71-mm-diam (0.028-in.) 310 stainless-steel-sheathed, type K] were cold worked to amounts believed typical of what might be introduced during installation of the thermocouples in the test assemblies.

The error in the type S thermocouples due to cold work was essentially linear with percent elongation of the thermoelements, yielding an error of —0.7% for a 15% elongation. The error was twice as large in the Pt—10% Rh thermoelement as in the platinum thermoelement and was eliminated by heat treatment for 2 hr at 350°C (662°F) but was unaffected after 2 hr at 250°C (482°F). Since 350°C (662°F) is below the recrystallization temperature of both thermoelements, recovery (i.e., the first stage of annealing out defects caused by cold work) was the mechanism responsible for removing the errors. Because the effects are removed by heating, the maximum temperature measurement error due to a 15% elongation in a type S thermocouple was estimated as —1.4°C (2.5°F) when used in the 350°C (662°F) steam atmosphere of the MRBT tests.

During the insertion of the bare-wire, type S thermoelements in Al_2O_3 insulators, the thermoelements are often bent inadvertently because of binding of the thermoelements in the holes of the insulators. Several 90° bends in a Pt—10% Rh thermoelement caused a —0.15% change in its thermal emf, which is the same error introduced by 4% elongation in a straight length of the wire.

Using the present stock of the as-received type S, bare-wire thermocouple material without prior heat treatment (to remove the cold work introduced during spooling and handling by the manufacturer) introduces a —1.4°C (2.5°F) temperature-measurement error.

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*Instrumentation and Controls Division.

Errors in the sheathed, type K thermocouples due to cold working were linear with the tensile force applied to the sheath: a −0.42% error for a force of 133 N (30 lb_f) with a threshold of 73.3 N (16.5 lb_f). The thermocouple broke at an applied tensile force of 173 N (39 lb_f), a force that can be easily applied during assembly. The effects of heat treatment on the error were distorted by the formation of an ordered crystal lattice[10] in the positive thermoelement above 300°C (572°F), which introduced positive errors in the thermocouple emf; however, the maximum temperature measurement error in the MRBT tests resulting from cold working these sheathed type K thermocouples was estimated as −1.7°C (3.1°F). These results may be extended to other size sheaths by equating the tensile stress, rather than the tensile force, in the thermocouple sheaths.

The cold work introduced in the thermoelements by straightening of the sheathed thermocouple assembly during passage through a tube straightener was found to be negligibly small.

3.3 Thermocouple Calibration

T. G. Kollie*

The third 4 × 4 test bundle will be specially instrumented with 0.25-mm-diam (0.010-in.) bare-wire, type S thermocouples attached to the outside of the Zircaloy tubes for accurate determination of the temperature profiles in the test assembly. These thermocouples were procured with 1.5-mm-OD (0.060-in.) stainless steel sheaths over the entire length (for electrical isolation and mechanical protection) except for about 20 cm (∿8 in.) of exposed thermoelements for making the hot junctions on the Zircaloy tubes. A hermetic seal was developed[2] and applied to assemblies at the point where the thermoelements exit the sheath.

A standard grounded hot junction was fabricated on two assemblies on which the bare-wire thermoelements broke during application of the hermetic seal, and preliminary calibrations were performed to obtain an indication of the quality of the thermocouples. A detailed calibration to 1300°C (2372°F) will be performed in FY-77 on a random sampling of the assemblies

*Instrumentation and Controls Division.

with the hermetic seals in place. Only the bare-wire thermoelements will be heated to the calibration temperature, with the sheathed part of the assemblies being maintained below 350°C (662°F).

The preliminary calibration data are given in Table 3.1. The data were repeatable on heating and cooling and were in excellent agreement at 388 and 691°C (730 and 1276°F), but the calibrations at 996°C (1825°F) differed [2.3°C (4.1°F)] by more than the precision of the technique [∿±0.2°C (0.4°F)]. These calibrations show that the thermoelements were contaminated during manufacturing because type S thermoelectric wire should be within ±0.25% of the standard curve; the errors shown in Table 3.1 are a factor of about 4 higher than this tolerance. High-temperature calibrations[2] for tantalum-sheathed, type S thermocouples from another manufacturer also showed significant deviations from the standard. However, decalibration of the thermoelements appears to be the same for the two assemblies tested and was not affected by heating to 1000°C (1832°F). The maximum temperature of the sheathed part of the thermocouples during use is to be only about 350°C (662°F).

Table 3.1. Preliminary calibration data of special stainless-steel-sheathed, type S thermocouples

Temperature (°C)	Error (°C)		Error (°C)	
	Assembly 1	Assembly 2	Assembly 1	Assembly 2
388	−3.5	−3.7	−0.89	−0.93
691	−6.3	−6.7	−0.90	−0.96
996	−7.3	−9.6	−0.73	−0.96
690	−5.8	−6.3	−0.92	−0.91
389	−3.7	−4.1	−0.92	−1.05

3.4 Lower End Seal of Fuel Pin Simulator

J. L. Crowley

As discussed in the previous report,[2] the simpler of two types of seal glands provided by Ceramaseal Corporation showed promise for use in the bundle fuel pin simulators. During this quarter, 20 more seals of this type were received and tested; all were accepted as meeting the purchase order requirements and will be used in the first bundle assembly. Some single-rod tests with these seals will be conducted next quarter to prove the design under test conditions. Additional glands were ordered for the second and third 4 × 4 bundles.

Six glands were received for test and evaluation from each of two manufacturers as possible alternatives for the Ceramaseal gland. Glands from one of the manufacturers (Astro Seal, Inc.) failed the simple bench tests and further effort with this design concept will be abandoned. Glands from the other manufacturer (Ceradyne, Inc.) appear promising and will be evaluated further.

3.5 Fuel Simulator Development and Procurement

W. E. Baucum   R. W. McCulloch

Fuel simulator procurement

As was reported last quarter,[2] the lot (No. 345) of BN supplied to SEMCO for fabricating MRBT fuel simulators was found to contain a small amount of iron and iron boride (30 ppm of iron). Another lot (No. 5), which was found to contain a smaller amount of contaminants (6 ppm of iron), was sent to SEMCO to use in the fabrication of the fuel simulators while the first lot of powder was being reprocessed to remove the foreign particles. SEMCO fabricated three simulators with powder from this lot of material, but inspection showed them to have above tolerance eccentricity of the heating element. SEMCO blamed this problem on the larger particle size of this powder and thus production was halted.

Meanwhile, several different attempts were being made to purify the lot 345 powder and one finally succeeded. Powder which had been purified by a magnetic separation process at Magnetics Engineering Associates, Cambridge, Mass., was tested by chemical and radiographic analysis and by evaluation of electrical conductivity cells (similar to fuel simulators). These tests and evaluations showed the powder to be purer than any previously used. This purified powder was sent to SEMCO; two simulators were fabricated with this powder, and both showed low insulation resistance. With ORNL assistance, this new problem was traced to the presence of moisture in the BN (which occurred during the handling and filling at SEMCO) and to metal chips scraped off the lead-in terminals during filling. These have been corrected by improved fabrication procedures and controls, and the last two simulators shipped to ORNL and two others ready to be shipped have acceptable insulation resistances.

Of the two simulators received at ORNL, one showed an excellent infrared scan, while the other showed an acceptable, though marginal, scan. SEMCO has indicated that it will now attempt to supply 20 simulators by Dec. 1, 1976, but Jan. 1, 1977, is probably a more realistic estimate.

Problems of vendor employee instability continue to plague efforts to procure fuel simulators for the MRBT program. For example, since this order was placed with SEMCO, both the responsible engineer and the manager have on two occasions left the company to accept other employment. This situation has caused a great deal of delay and confusion.

Simulator failure analysis

As was mentioned in an earlier report,[1] posttest visual examination of fuel simulators (2828007 and 2828013A) used in two high-temperature tests (PS-18 and SR-1, respectively) revealed cracks in the bottom of the thermocouple grooves machined in the sheaths of the simulators. More recent single-rod tests have yielded two additional fuel simulators, 2828016 and 2828017, with similar cracks. Results of a detailed metallurgical examination of fuel simulator 2828013A have been previously described,[1] and similar information is now available for simulators 2828007, 2828016, and 2828017. Also, the unheated portion of 2828013A was further examined to determine whether the variations in groove depth from one side to the other were due to machining or to distortions incurred during the test cycle. It was found that the variation in the unheated area corresponds quite well to that of the unheated area, thus indicating that the grooves were improperly machined; an example of this can be seen in Fig. 3.4. This was undoubtedly an important factor in determining the point of melting and cracking of the groove base in this simulator during the test.

Fuel simulator 2828007 was used in test PS-18, in which the maximum Zircaloy temperature was measured as 1171°C (2138°F); from other data it was estimated that the maximum fuel simulator sheath temperature was in the range of 1320 to 1370°C (2408 to 2498°F). Metallurgical examination of the fuel simulator showed that all cracks were intergranular, with evidence of melting, and that three of the four cracks occurred in the sheath weld seam area. Figure 3.5 shows one such crack which occurred at the tube weld–base metal interface (the material in the groove is plasma sprayed Ta and ZrO_2 and remnants of the melted thermocouple sheath); Fig. 3.6 shows melting at the base of the groove in the center of the tube seam weld, and Fig. 3.7

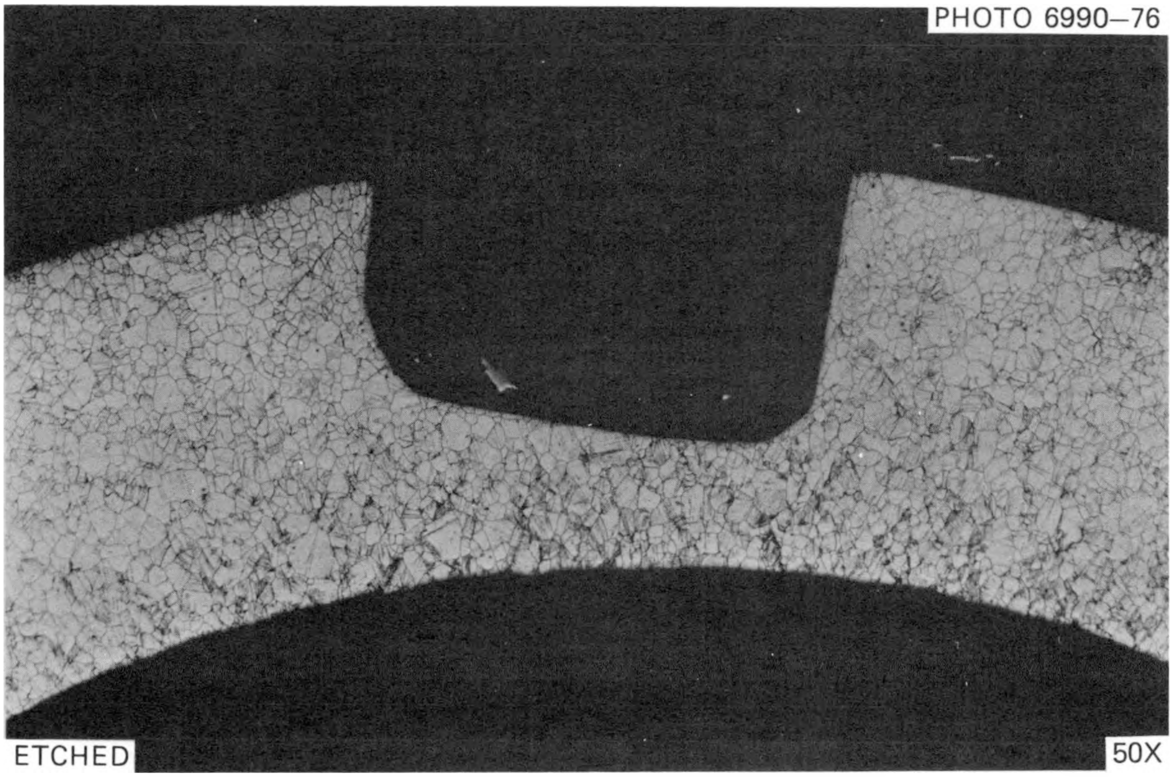

Fig. 3.4. Groove 4 of unheated region of fuel simulator 2828013A showing off-center machining of groove. (Etched; 50×).

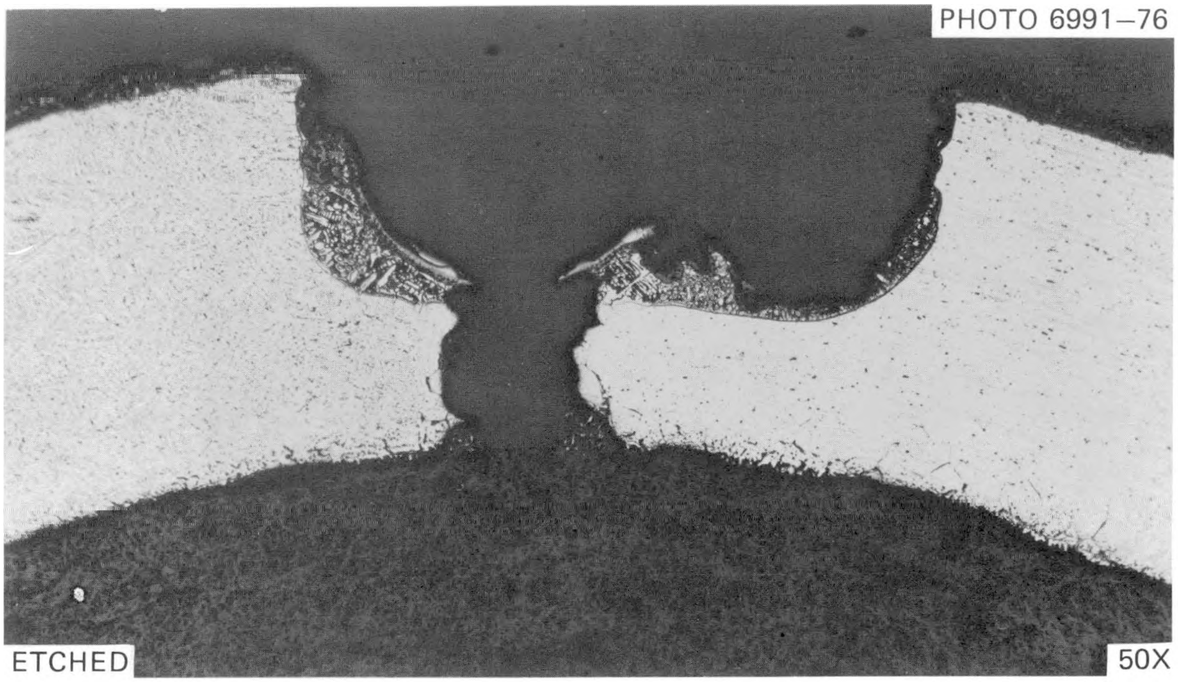

Fig. 3.5. Crack in groove 3 of fuel simulator 2828007. Remnants of melted thermocouple sheath are present in the groove.

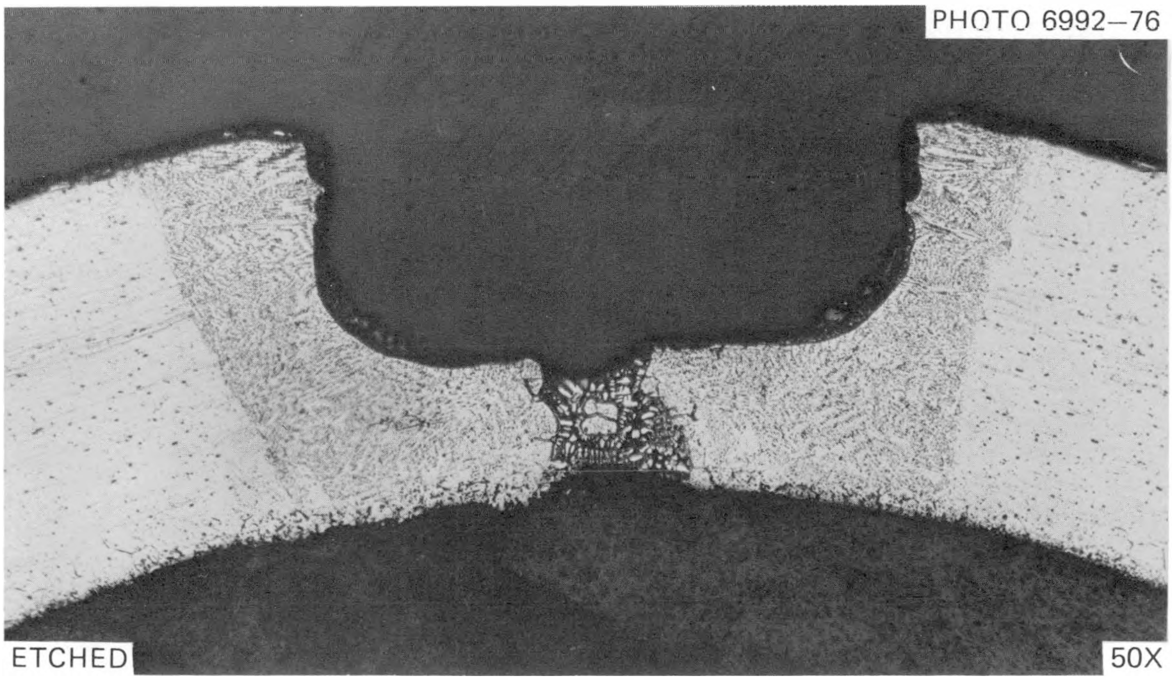

Fig. 3.6. Melting in groove 2 of fuel simulator 2828007. Note groove is centered in tube seam weld.

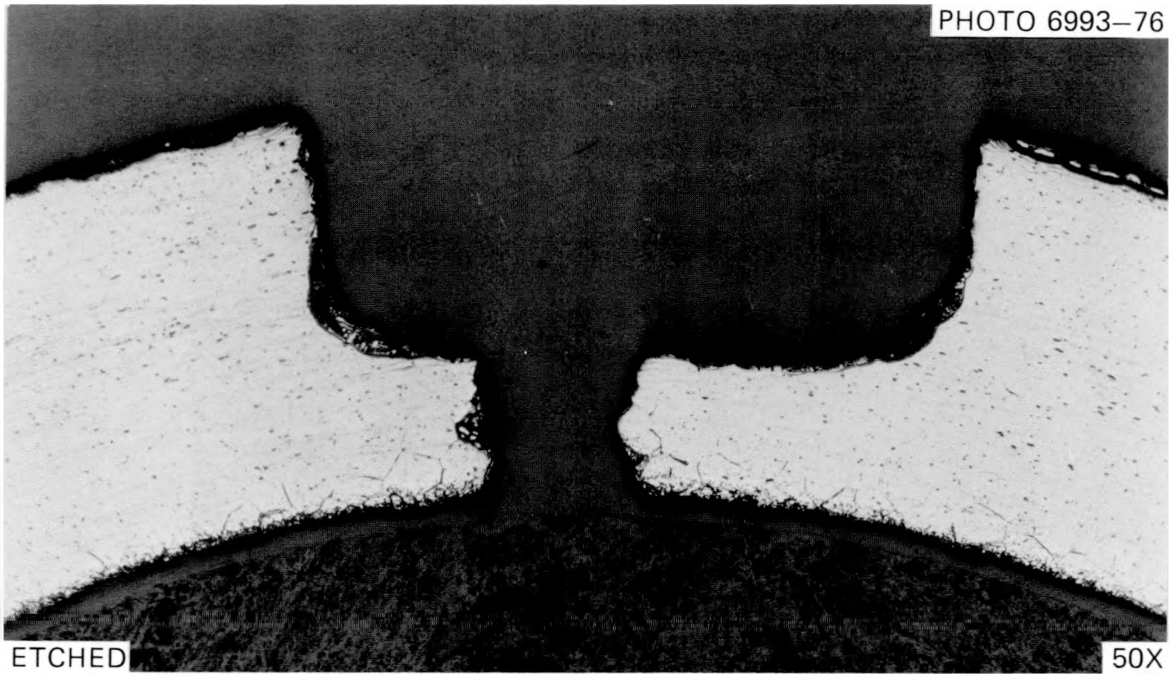

Fig. 3.7. Crack in groove 3 of fuel simulator 2828007 showing evidence of melting on left fracture surface.

shows a crack outside the tube seam weld. There is evidence in all three figures (3.5 to 3.7) of possible reactions at the BN-sheath interface. The high incidence of melting in the tube weld area may be explained by the fact that in an inhomogeneous weld, the material will begin melting at a temperature slightly below the temperature at which it commences in the base metal. No evidence of melting of the heating elements was seen. Figure 3.8, a section of the unheated area, indicates that the grooves were properly machined in this simulator.

Fuel simulator 2828016 (used in test SR-13) experienced a somewhat lower maximum temperature [1079°C (1976°F)] on the Zircaloy and approximately 1220 to 1270°C (2228 to 2318°F) on the sheath and showed three small cracks after testing. Figure 3.9 shows a section through the area of the crack, and Fig. 3.10 shows a magnified (and inverted) view of the crack. Considerable distortion can be seen in areas other than the cracked groove in Fig. 3.9. No evidence of melting is seen in Fig. 3.10, but there appears to be a reaction or diffusion layer on the fracture

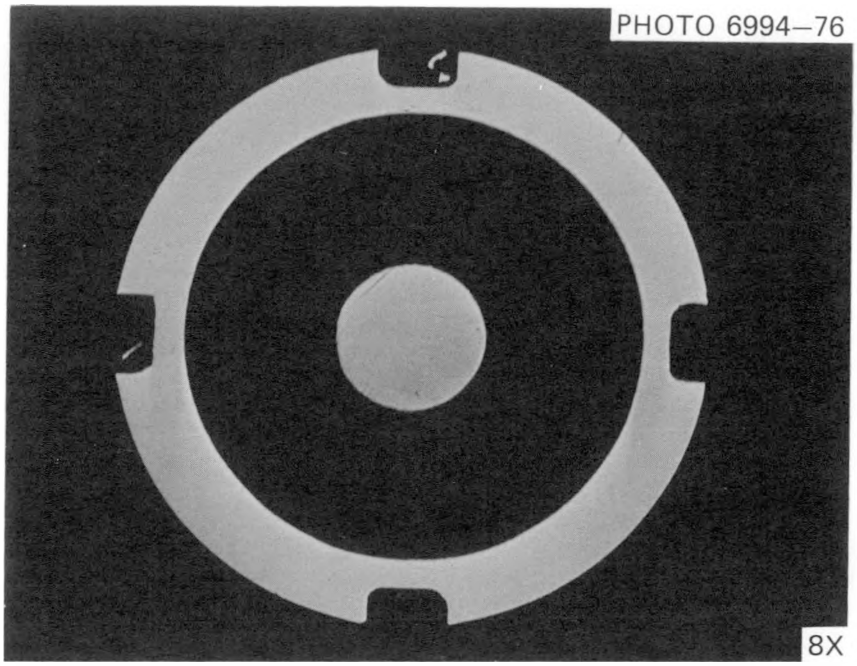

Fig. 3.8. Cross section of unheated region of fuel simulator 2828007 showing proper machining of grooves.

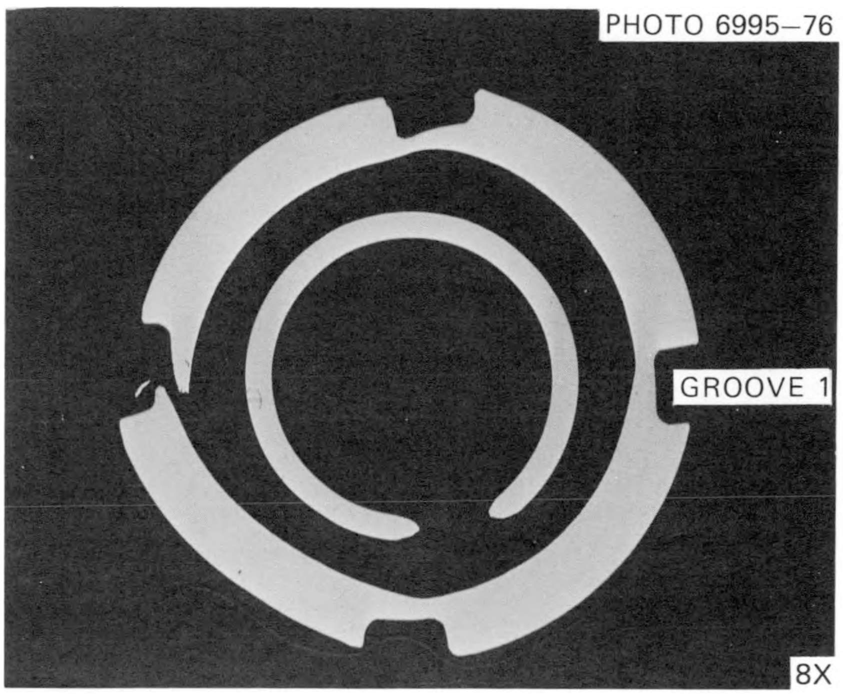

Fig. 3.9. Cross section of fuel simulator 2828016 showing crack in groove 3 and distorted shape.

Fig. 3.10. Magnified (and inverted) view of crack in groove 3 of fuel simulator 2828016. (Original reduced 5%)

surfaces. Figure 3.11 shows the cracked groove in the unheated area; all four grooves in this simulator appeared to be improperly machined.

Fuel simulator 2828017 (used in test SR-2) experienced a maximum sheath temperature of 1230 to 1280°C (2246 to 2336°F) and was found to be cracked after testing as shown in Fig. 3.12. Sections in the area of the crack are shown in Figs. 3.13 and 3.14. There is no evidence of melting, but there is a crack in the BN insulation layer. Figure 3.15 shows that the grooves were not properly machined. The evidence indicates that the failure was caused by a buildup of gas pressure near the heating element which was released at high temperature through the BN and the thin area of the sheath.

Looking at the metallurgical data as a whole, the failures appear to be caused by three principal factors: (1) high temperature, which reduces the strength of the sheath material to the point that very small loads can

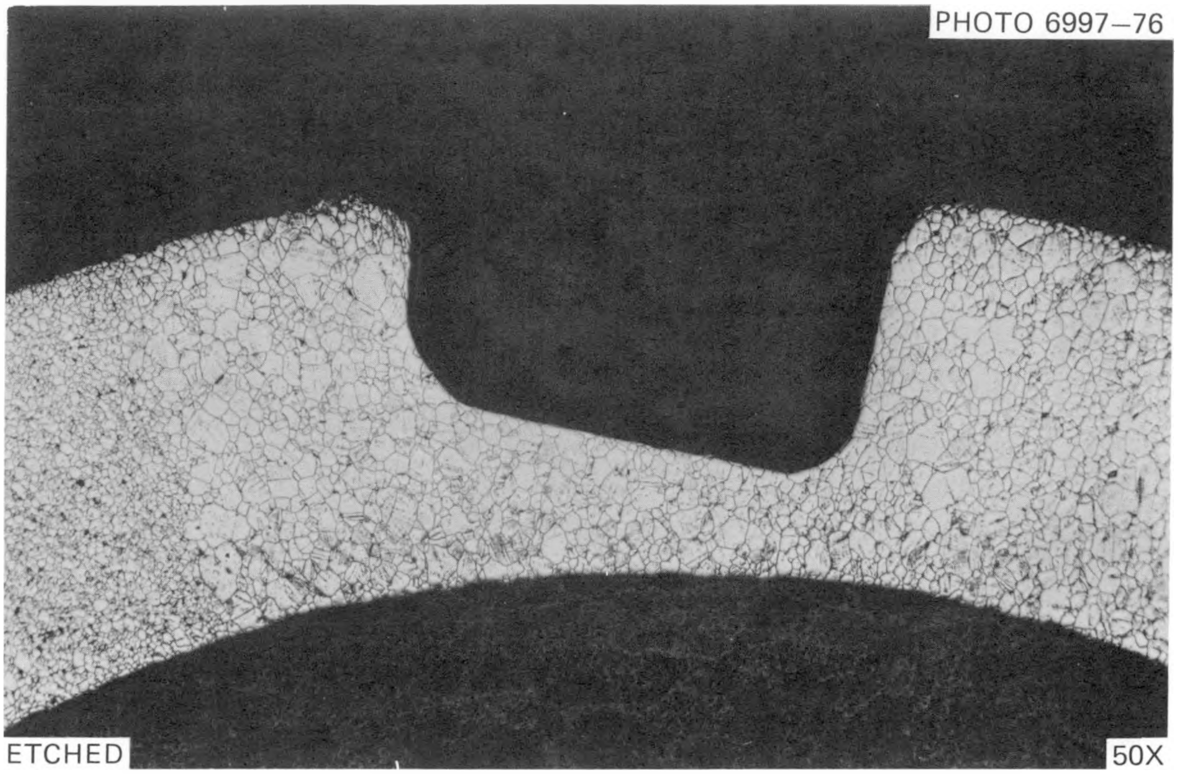

Fig. 3.11. Groove 3 in unheated region of fuel simulator 2828016 showing improper machining.

be sustained and which causes melting in some cases; (2) generation of internal gas pressures, which apparently arise from gas-producing reactions with the BN insulation material at very high temperature levels; and (3) improper machining of the grooves in the sheath, which results in very thin thicknesses at the base of the groove. Since the first two factors are basically material characteristics, there is little that can be done to mitigate their influence. The third factor can and will be eliminated by more careful machining and inspection.

Since the cracks have apparently not influenced test results and since it is anticipated that each fuel simulator can be used only once in a bundle test, it appears that the present simulator design is acceptable for tests in which the maximum Zircaloy temperature does not exceed 1170°C (2138°F). In this temperature range, the simulator sheath is at the

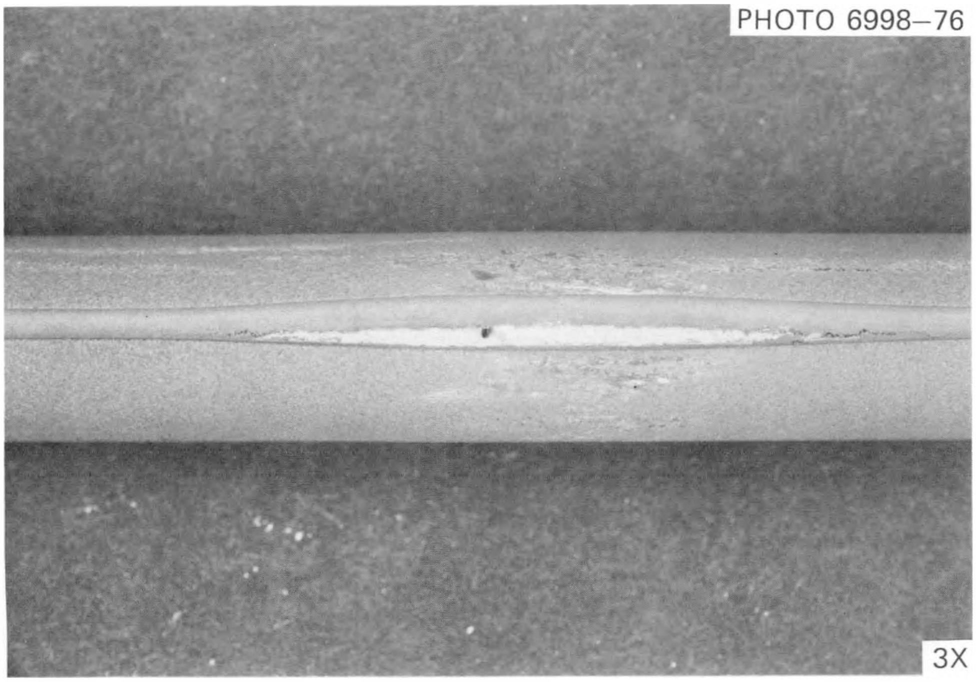

Fig. 3.12. Rupture in bottom of groove 3 of fuel simulator 2828017 showing evidence of pressure inside simulator contributed to failure.

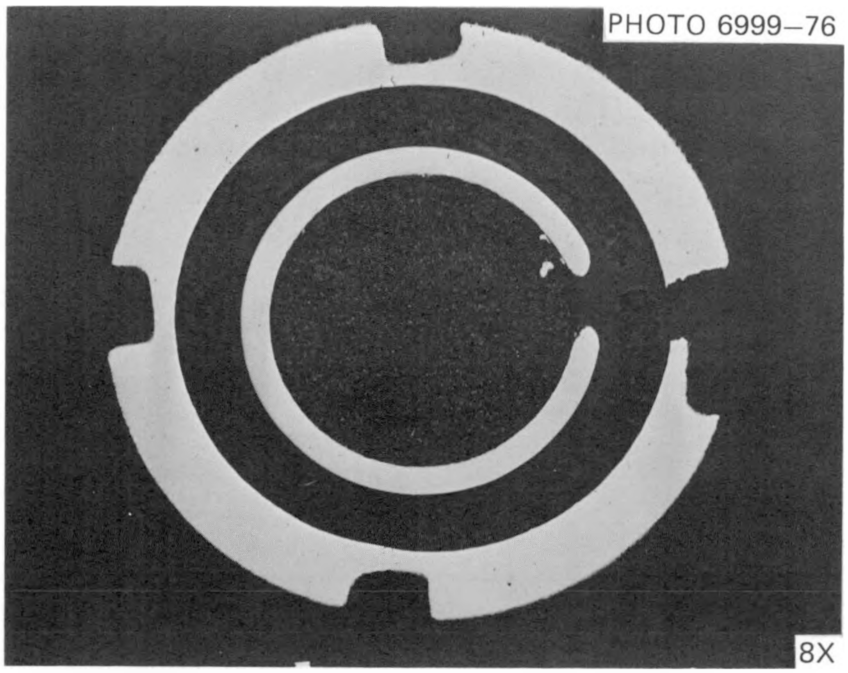

Fig. 3.13. Cross section of fuel simulator 2828017 showing crack in groove 3, cracked BN insulation, and sheath ovality.

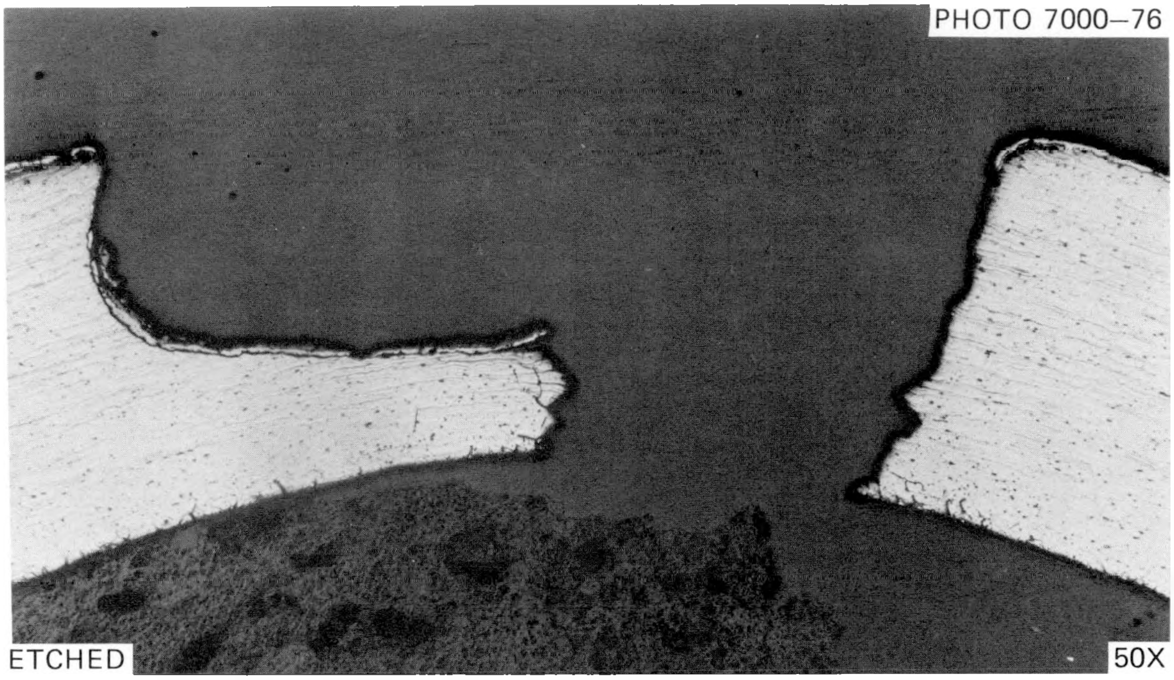

Fig. 3.14. Fracture in groove 3 of fuel simulator 2828017 showing absence of melting, evidence of tube-BN reaction at interface, and apparent intergranular fracture surface at thinnest position in base of groove.

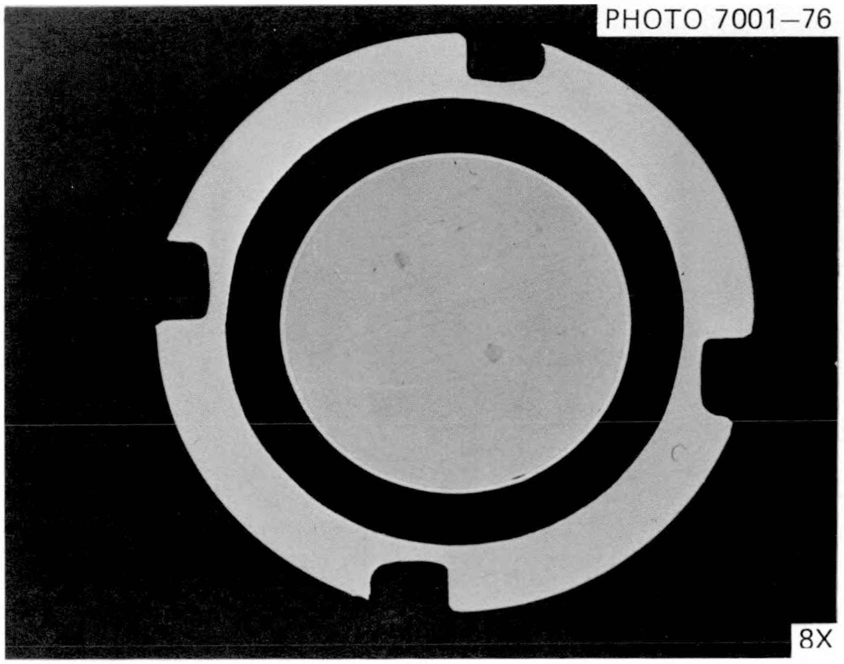

Fig. 3.15. Cross section from unheated region of fuel simulator 2828017 showing improper machining of grooves.

threshold of melting and thus significantly higher temperatures will likely cause catastrophic sheath blowout and electrical arcing. Therefore, a new fuel simulator design that uses materials with higher melting temperatures for the heating element and sheath (such as Pt—8% W element and Ta sheath) must be investigated to obtain higher Zircaloy tube temperatures.

4. DESIGN, FABRICATION, AND CONSTRUCTION

4.1 Data Acquisition and Analysis

K. R. Carr* K. J. Cross*

The multirod test facility will use the Computer-Controlled Data Acquisition System (CCDAS) provided for the Thermal-Hydraulic Test Facility (THTF), which is part of the Blowdown Heat Transfer (BDHT) program. While the CCDAS is quite adequate for MRBT requirements, a need has developed in the BDHT program for a significant increase in the number of data channels; a decision has been made to replace the existing PDP-8 system with a larger, faster system based on a 16-bit minicomputer. The new system uses a different concept for the software and will require rewriting the programs for acquisition and analysis of the data.

The new CCDAS is to be installed and checked out with minimum interference with the two test programs; the changeover is expected to be during the period January to March 1978, so as to permit completion of the first three 4 × 4 bundle tests before making the change.

The new CCDAS will require some wiring changes in the multirod test facility and additional hardware components to facilitate rapid switching of the CCDAS from the THTF to the MRBT facility with minimum checkout and verification of the data channels. This additional equipment will be installed during the period between the 4 × 4 and 8 × 8 bundle tests, when the test facility is being expanded to accommodate the larger test bundles.

4.2 Multirod Test Facility Construction

R. E. Bohanan J. L. Crowley

Plans were made to resume fabrication and installation of the test equipment on October 1. Materials were collected and transmitted to the shops for use in the assemblies. We expect to have the test facility constructed and checked out by March 1, 1977.

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5. OPERATIONS

J. L. Crowley

During this report period, two fuel pin simulators were fabricated (and tested) with gas volumes about four times greater than that usually contained in the simulators to explore the effect of this parameter on the deformation behavior of the cladding.

To obtain the increased volume, the test simulators were modified by attaching a small external plenum, constructed of tubing and pipe fittings, to the upper seal gland. A nominal 6.5-mm (0.25-in.) tube was welded to the side of the gland to provide ready and relatively unrestricted access of the external volume to that provided in the voids inside the simulator.

The results of these tests are discussed and compared in Section 2.2 with tests from simulators having the normal gas volume.

We were requested by NRC during this quarter to conduct two single-rod burst tests at a much higher pressure than used in any of our previous tests to permit extrapolation of our data with greater certainty; the results of the tests are discussed in Section 2.3.

In order to conduct the tests, it was necessary to improve the pressure capability of the test equipment and to substitute transducers with higher pressures than the ones we normally use to obtain the pressure vs time data. The transducer used was of the same type (same manufacturer) and had essentially the same response characteristics as the normal one. A special, high-pressure [20,700-kPa (3000-psig)] helium gas cylinder was borrowed from another test program to charge the simulators to the desired initial pressure for the tests. After the system was modified, a safety check was performed to demonstrate the integrity of the equipment for operation at the anticipated pressure level.

The system performed as expected during the tests, demonstrating once again the versatility and usefulness of this test facility for special test conditions.

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