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Evaluating Strength and Ductility of Irradiated Zircaloy Task 5

Quarterly Progress Report April — June 1979

Prepared by L.M. Lowry, A.J. Markworth, J.S. Perrin, M.P. Landow

Battelle-Columbus Laboratories

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PREVIOUS REPORTS

Table of reports previously distributed for the program "Evaluating Strength and Ductility of Irradiated Zircaloy".

Report Number	Reporting Period
Letter Report of January 2, 1975	October-December 1974
Letter Report of April 18, 1975	January-March 1975
BMI-1935	April-June 1975
BMI-1938	July-September 1975
BMI-1942	October-December 1975
BMI-NUREG-1948	January-March 1976
BMI-NUREG-1956	April-June 1976
BMI-NUREG-1961	July-September 1976
BMI-NUREG-1967	October-December 1976
BMI-NUREG-1971	January-March 1977
BMI-NUREG-1976	April-June 1977
BMI-NUREG-1985	July-September 1977
NUREG/CR-0026 BMI-1992	October-December 1977
NUREG/CR-0085 BMI-2000	January-March 1978
NUREG/CR-0582 BMI-2007	April-June 1978
NUREG/CR-0981 BMI-2020	July- December 1978
NUREG/CR-0982 BMI-2034	January-March 1979

ABSTRACT

The Lot 4 material (Oconee I, Three Cycle) was received, visually examined and gamma scanned. The four rods were Babcock and Wilcox (B&W) fuel rods irradiated in the Oconee I reactor, sectioned at B&W, and shipped to Battelle Columbus Laboratories (BCL) in the shipping cask BCL-4. Specimens for tensile, expanding mandrel, tube-burst, and transient heating burst tests were prepared from the Lot 4 rods.

Burst tests were conducted using unirradiated Oconee I archive fuel rod cladding material. Additional burst tests were conducted using Lot 2 (Oconee I, One Cycle) irradiated Zircaloy fuel rod cladding. Also burst tests were conducted using Lot 3 (Oconee I, Two Cycle) Zircaloy fuel rod cladding. A comparison of Oconee I archive, one cycle, and two cycle tube-burst test results is included. The yield and ultimate burst stress increased with fluence and decreased with increased test temperature as expected. The yield and ultimate burst stress also increased with increased strain rate. For both transient and isothermal annealed tube-burst specimens tested at a temperature of 371 C and a strain rate of 0.004/min, the yield and ultimate burst stress was almost constant from 482 to 621 C and both yield and ultimate stress decreased sharply above 704 C.

The uniform strain was constant with fluence below 427 C and lower (3% strain)for unirradiated archive material as compared to the irradiated one and two cycle (both about 4.5% strain). The total strain did not decrease appreciably after one cycle (15%) but dropped to 5% after the second cycle. Both uniform and total strains decreased with increased strain rate and appear to converge at about 0.05/min after two cycles of irradiation. Both uniform and total strain increased for tube-burst specimens transient annealed at 28 C/sec and both were constant for specimens transient annealed at 5.6 C/sec. The transient annealed tube-burst specimens were tested at a temperature of 371 C and a strain rate of 0.004/min.

The uniform and total strains increased for one cycle irradiated tube-burst specimens isothermally annealed for one minute or less. The total strain decreased appreciably (50%) when the specimen was isothermally annealed at 593 C for 10 minutes. A similar decrease was observed for a two cycle tube-burst specimen isothermally annealed at 704 C for one minute. These decreases occur because of annealing recovery, recrystallization and grain growth which are both temperature and time dependent.

Modeling studies are continued using a number of constitutive equations fitted to the BCL tensile data using a nonlinear-regression-analysis computer code developed at Battelle and based on the Marquardt algorithm.

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FOREWORD

This work is part of the Division of Reactor Safety Research/Fuel Behavior Branch's program being performed at a number of sites throughout the country on Zircaloy fuel cladding performance during various postulated reactor transients and accidents. The data available on the mechanical properties of irradiated Zircaloy cladding as functions of irradiation level, texture, temperature, and condition of loading are not sufficient to permit predictions of cladding performance to the level of accuracy desired. They do not permit prediction of the onset of plastic instability, definition of strain to failure at relatively low temperatures, or estimates of the response to multiaxial stresses during temperature transients. In addition, the data available on irradiated Zircaloy show considerably greater scatter than that available on unirradiated material. A body of data must be obtained under carefully designed experimental conditions if a statistically valid data base is to be made available for code development.

STRENGTH AND DUCTILITY OF IRRADIATED ZIRCALOY

PROGRAM OBJECTIVE

The objective of the program is to establish a mechanical-property data base that can be used to predict the performance of Zircaloy cladding under various postulated off-normal, transient, and accident conditions in a power reactor.

PROGRAM APPROACH

The mechanical properties of irradiated Zircaloy are to be determined under uniaxial and biaxial stress conditions for the purpose of simulating the loading and stress conditions encountered by cladding under postulated off-normal, transient, and accident conditions. Cladding of various textures are to be obtained for the tests from spent commercial fuel rods irradiated to various burnup levels.

The cladding will be subjected to detailed examination in order to establish pretest characteristics. As-irradiated strength and ductility characteristics from room temperature to 480 C (900 F) and at strain rates in the range 0.001 to 2/min will be evaluated by tests that include tensile, burst, and expanding mandrel. The annealing of irradiation damage will be evaluated under both isothermal and transient heating conditions to temperatures of 700 C (1300 F). Transient heating burst tests will be conducted at temperatures to 1355 C (2400 F) to evaluate cladding behavior under simulated LOCA conditions.

PROGRAM PROGRESS

Material for scoping and preliminary mechanical testing of Zircaloy cladding was supplied by one spent fuel rod irradiated in the Point Beach reactor. Zircaloy cladding from spent fuel rods irradiated in the H.B. Robinson and Oconee I reactors provided the material for subsequent mechanical testing. The fuel rods from the H.B. Robinson reactor were designated Lot 1, the Oconee I reactor one cycle rods were Lot 2, Oconee I reactor two cycle rods were Lot 3 and the Oconee I reactor three cycle rods were designated Lot 4. Postirradiation characterization including visual examinations, gamma scanning, profilometry, and in some cases eddy current testing was performed on the irradiated fuel rods.

Specimens were prepared for tensile, tube-burst, and expanding mandrel test to evaluate the as-irradiated mechanical properties (temperature and strain rate dependence) of the H.B. Robinson (Lot 1) and Oconee I (Lot 2) cladding. Tests have been completed and the results reported in BMI-NUREG-1961, -1967, -1976, -1985, NUREG/CR-0026 BMI-1992, NUREG/CR-0085 BMI-2000, and NUREG/CR-0582 BMI-2007. Isothermal bend tests to evaluate the as-irradiated properties of the Lot 1 and Lot 2 cladding material have also been completed and reported (NUREG/CR-0085, BMI 2000). Further bend testing was cancelled because little information relating to cladding ductility was produced. Tensile, tube-burst, and expanding mandrel specimens annealed under transient and isothermal conditions were tested at 371 C to determine the mechanical properties and annealing kinetics of Lot 1 and Lot 2 cladding materials.

The annealing tests have been completed and the data evaluated for Lots 1 and 2 material. The results have been reported in BMI-NUREG-1961, -1967, -1971, -1976, and -1985, NUREG/CR-0026 BMI-1992, NUREG/CR-0085 BMI-2000, and report BMI-2007. Additional evaluation of the expanding-mandrel test results on Lot 1 fuel rod cladding also has been performed and reported in NUREG/CR-0085 BMI-2000.

Specimens were prepared for transient heating burst (THB) tests from both Lot 1 and Lot 2 spent-fuel cladding and testing has completed. The results of the THB tests conducted on Lot 1 material were reported in NUREG/CR-0026 BMI-1992 and the results of the THB tests conducted on Lot 2 material were reported in NUREG/CR-0085 BMI-2000. Additional THB tests conducted on Lot 2 material have been completed and the results presented in the report, BMI-2007. The evaluation of the THB test results has been completed for Lot 1 and 2 cladding material.

The analysis of mechanical properties data for tensile, tube-burst and expanding mandrel specimens annealed under isothermal and transient conditions and subsequently tested at 270 C is in progress. Results of earlier analyses were reported in BMI-NUREG-1985, NUREG/CR-0026 BMI-1992, NUREG/CR-0085 BMI-2000, and in the report BMI-2007.

Metallographic examination of cladding samples from the as-irradiated fuel rods and selected tensile, burst and expanding mandrel specimens from Lot 1 and Lot 2 materials has also been completed.

Tensile and expanding mandel tests using both as-received and anealed archive material for the Oconee I reactor were completed with the tests results being contained in NUREG/CR-0982 BMI-2034.

Cladding for Lot 3 fuel rod material (Oconee I, Two Cycle) was recieved and characterized at the Battelle Hot Cells (See NUREG/CR-0085, BMI-2006). The cladding from Lot 3 fuel rods has been sectioned, defueled, and specimens prepared. Tensile test results of Lot 3 material in the as-received condition and tested as a function of temperature and strain rate are contained in NUREG/CR-0982, BMI-2034.

Oconee I, three cycle (Lot 4) fuel rods were received during this reporting period. Limited characterization of these rods is underway.

Mechanical properties tests for the Lot 3 fuel rod cladding material has been completed. The results of the tensile and expanding mandel tests were reported in NUREG/CR-0982, BMI-2034 and the tube-burst test results are contained in this report.

MATERIAL RECEIPT AND CHARACTERIZATION

The Lot 4 (Oconee I, Three Cycle) spent fuel rods were received at the Battelle hot cells to provide Zircaloy cladding for use in this program. This lot, consisting of four rods, was provided by B&W and was irradiated in the Oconee I reactor for three fuel cycles. The fuel burnup for these rods is estimated to be 26,000 MWD/T.

The fuel rods were previously subjected to visual examination, gamma scanning, profilometry, eddy current testing, and fission gas recovery at the B&W hot cells. Also, due to the licensing problems of the large shipping casks, these rods were sectioned into approximately four equal lengths of 38 inches by B&W and shipped to the BCL Hot Laboratories in shipping cask BCL-4. Upon receipt of these material at BCL, additional limited characterization of each rod section was performed in order to evaluate the condition of the as-received material. These tests included viaual examination and gamma scanning.

After the nondestructive evaluation of the rods was completed, test specimen sectioning diagrams were prepared for use in sectioning tensile, expanding mandrel, tube-burst, and transient heating burst specimens. The fuel rods were then marked, sectioned, defueled, and the cladding prepared for the next phase of the Lot 4 material testing and evaluation.

BURST TESTS

Burst Tests were conducted using unirradiated Oconee I archive fuel rod cladding material. Additional burst tests were conducted using irradiated Oconee I, one cycle (Lot 2) Zircaloy fuel rod cladding. The Lot 2 material was tested in the as-irradiated condition at selected temperatures and strain rates. Transient and isothermal annealed specimens of Lot 2 material were also burst tested. Previous Lot 2 burst test data was reported in NUREG/CR-0085, BMI-2000.

During this period, burst tests were also conducted using irradiated Oconee I, two cycle (Lot 3) Zircaloy fuel rod cladding. The Lot 3 material was tested in the as-irradiated condition at selected temperatures and strain rates. Transient and isothermal annealed specimens of Lot 3 material were also burst tested.

Archive Material

Because very little Oconee I archive material remained, only four burst tests were conducted. Single tests were conducted at temperatures of 316 C and 427 C and two tests at a temperature of 371 C; the strain rate was 0.004/min for all tests. The results of these tests are tabulated in Table 1 and plotted in Figures 1 and 2.

Lot 2 (Oconee I, One Cycle) Material

Earlier reported burst data for Lot 2 material (NUREG/CR-0085, BMI-2000) is listed in Table 1 along with the data generated during this reporting period. These data are for the tube burst tests for unirradiated archive fuel rod cladding as a function of temperature and for irradiated Lot 2 fuel rod cladding as a function of temperature and strain rate. The burst yield and ultimate (engineering) stress are plotted versus temperature in Figures 1 and 3. The uniform and total burst (engineering) strain are plotted versus temperature in Figures 2 and 3.

Also reported in NUREG/CR-0085, BMI-2000 was burst data for Lot 2 material as a function of strain rate (independent variable) and the test results are reproduced here in Table 1. The burst yield and ultimate burst (engineering) stress are plotted versus strain rate in Figure 4. The uniform and total burst (engineering) strain are plotted versus strain rate in Figure 5.

TABLE 1. TUBE BURST TEST RESULTS FOR IRRADIATED OCONEE I (ONE CYCLE) ZIRCALOY FUEL ROD CLADDING AS A FUNCTION OF TEMPERATURE AND STRAIN RATE

Specimen Number	Test Temperature C	Strain Rate /Min	STRESS Yield MPa	STRESS Ultimate MPa	STRESS Failure MPa	STRAIN Uniform Percent	STRAIN Total Percent
3*	316	0.004	499	565	560	2.7	9.2
2*	371	0.004	439	498	493	2.6	9.6
34020*	371	0.004	410	476	456	2.6	10.0
1*	427	0.004	330	419	406	3.2	15.4
47104-27	260	0.004	596	688	688	2.4	6.4
47101-2	260	0.004	732	797	797	1.8	5.7
47104-19	316	0.004	622	664	664	2.4	4.5
47101-7	316	0.004	622	687	687	1.8	4.0
47104-28	371	0.004	537	610	610	2.7	6.8
47104-2	427	0.004	420	525	495	4.7	18.0
47104-22	371	0.001	493	595	564	2.7	8.1
47118-4	371	0.035	679	725	725	2.3	2.5

* Unirradiated Archive Specimens.

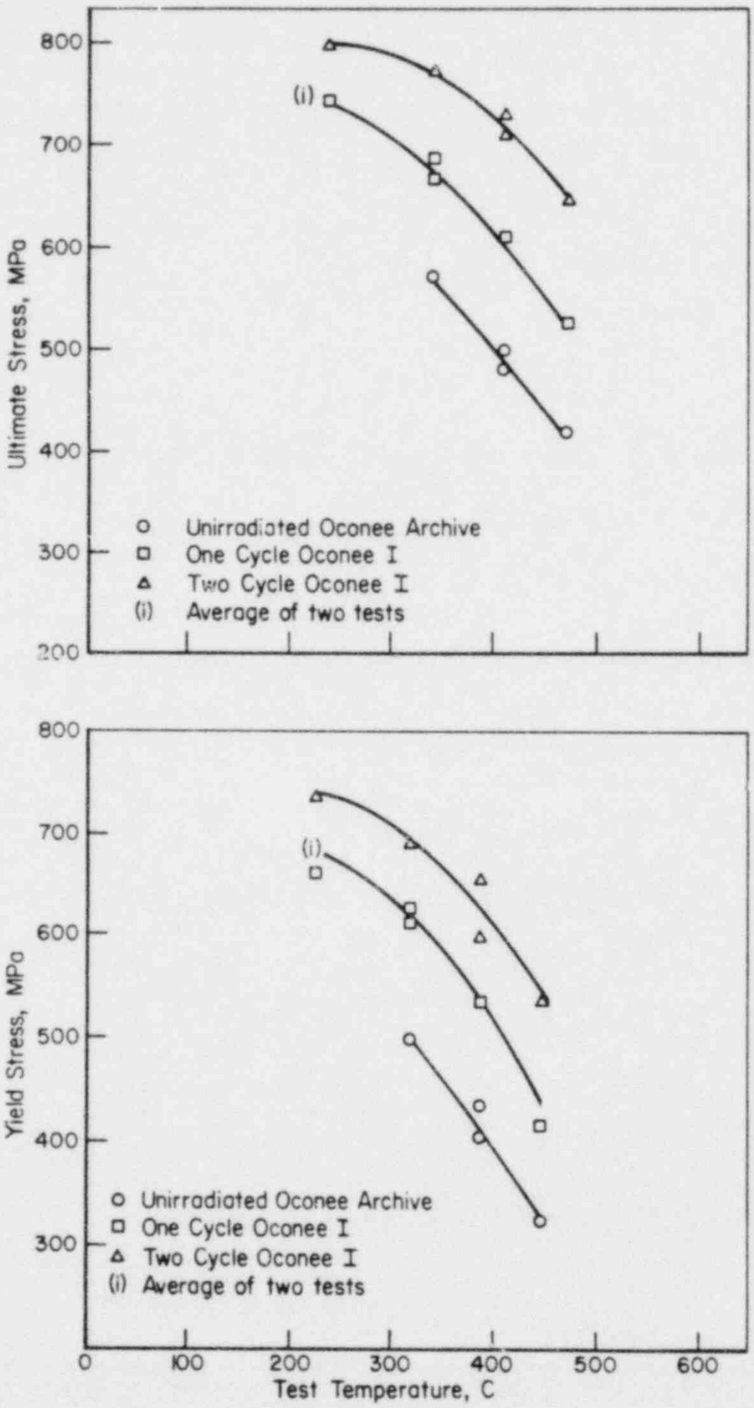

FIGURE 1. ENGINEERING BURST ULTIMATE AND YIELD STRESS FOR IRRADIATED OCONEE I ZIRCALOY FUEL ROD CLADDING AS A FUNCTION OF TEMPERATURE. Strain Rate 0.004/min.

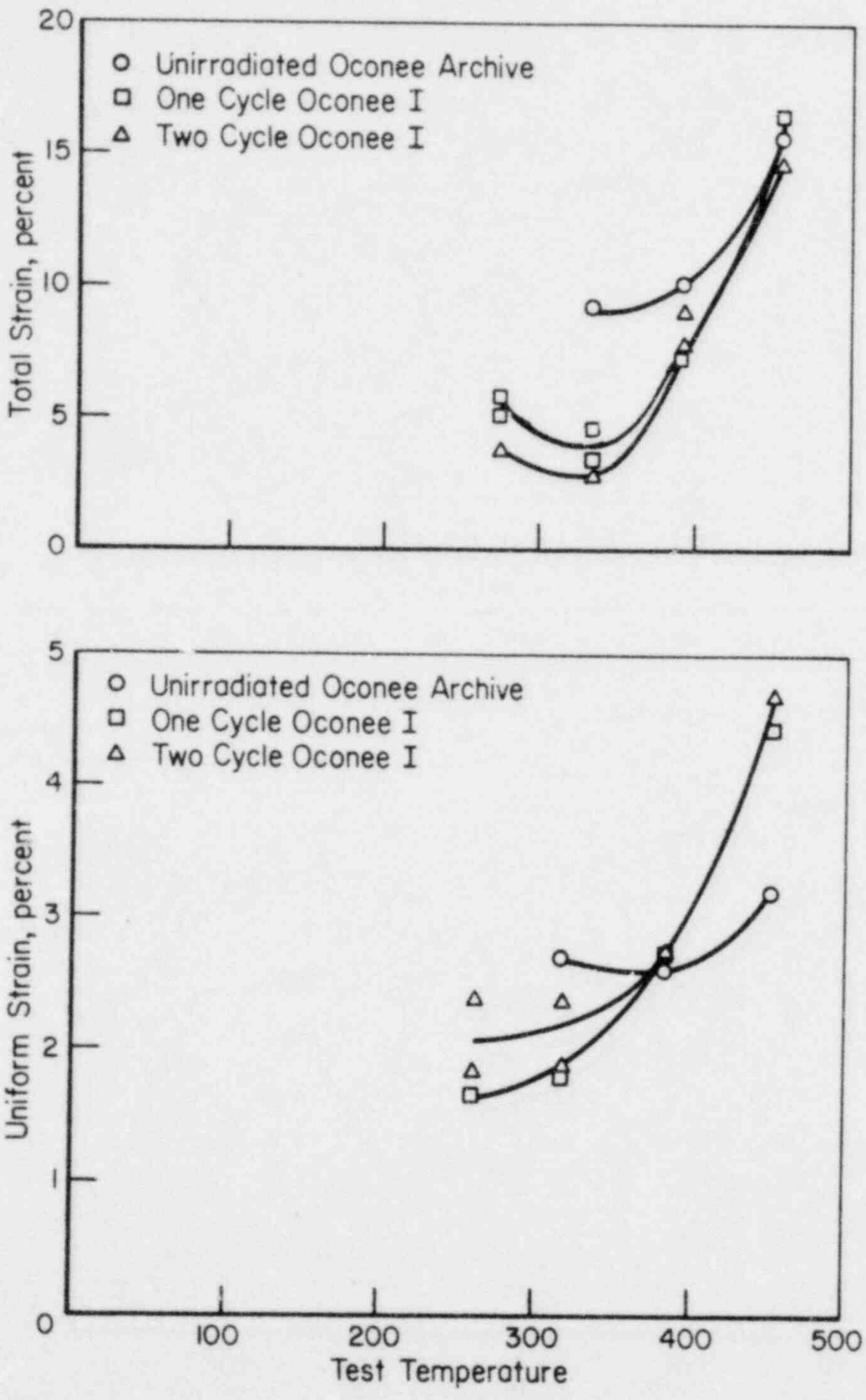

FIGURE 2. ENGINEERING UNIFORM AND TOTAL BURST STRAIN FOR IRRADIATED OCONEE I ZIRCALOY FUEL ROD CLADDING AS A FUNCTION OF TEMPERATURE. Strain Rate 0.004/min.

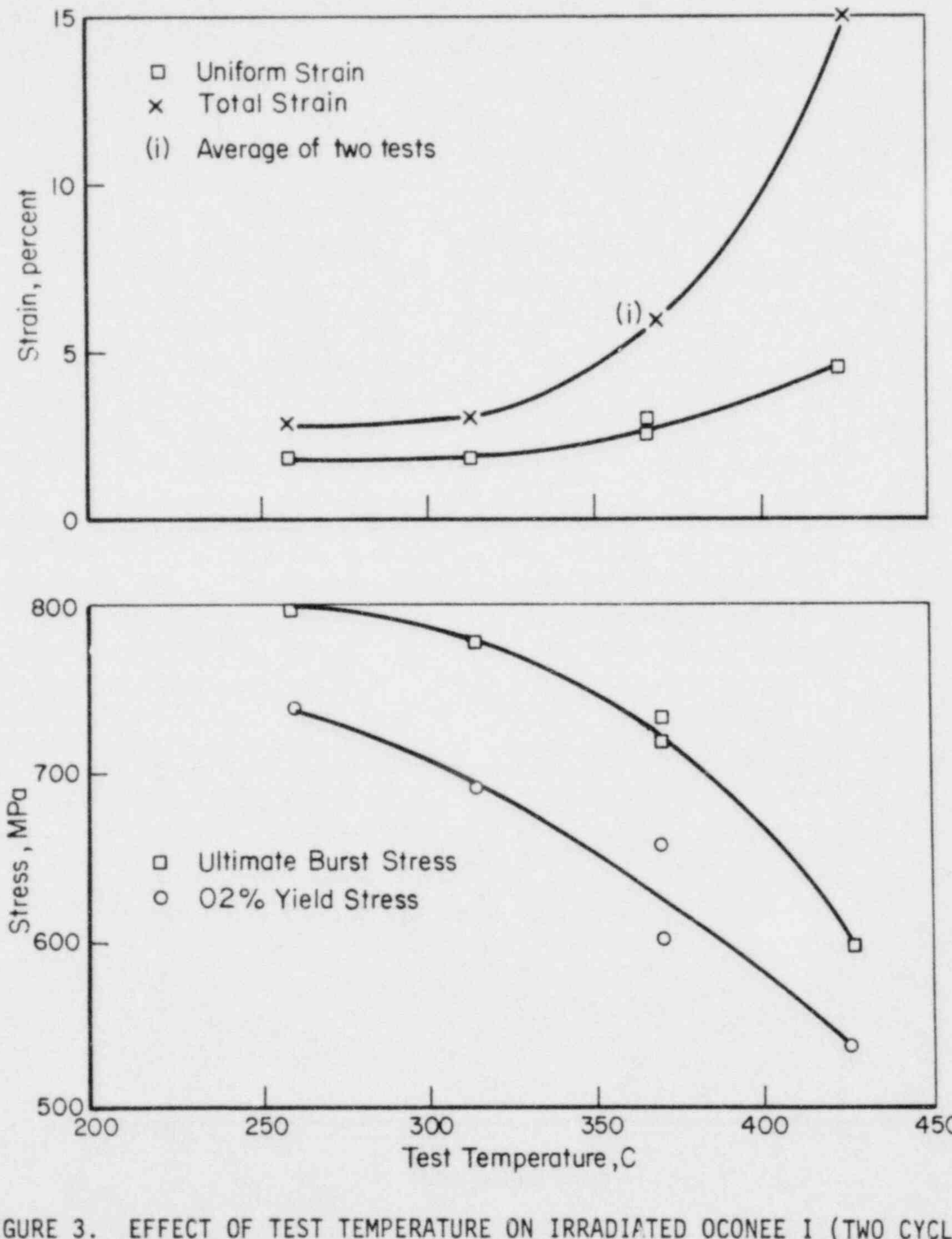

FIGURE 3. EFFECT OF TEST TEMPERATURE ON IRRADIATED OCONEE I (TWO CYCLE) FUEL ROD CLADDING BURST STRESS AND STRAIN (ENGINEERING). Strain Rate 0.004/min.

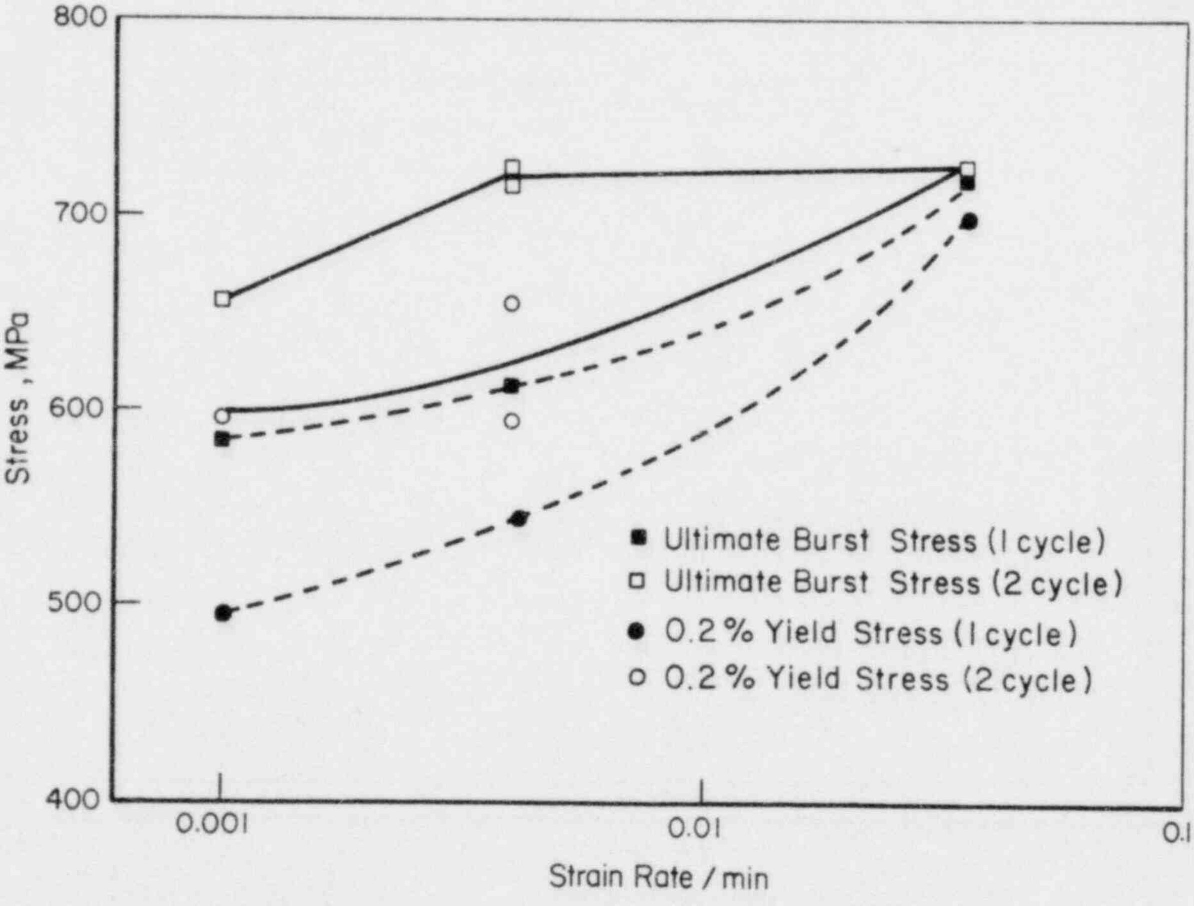

FIGURE 4. ENGINEERING BURST STRESS FOR IRRADIATED OCONEE I (ONE AND TWO CYCLE) FUEL ROD CLADDING AS A FUNCTION OF STRAIN RATE. Test Temperature 371C.

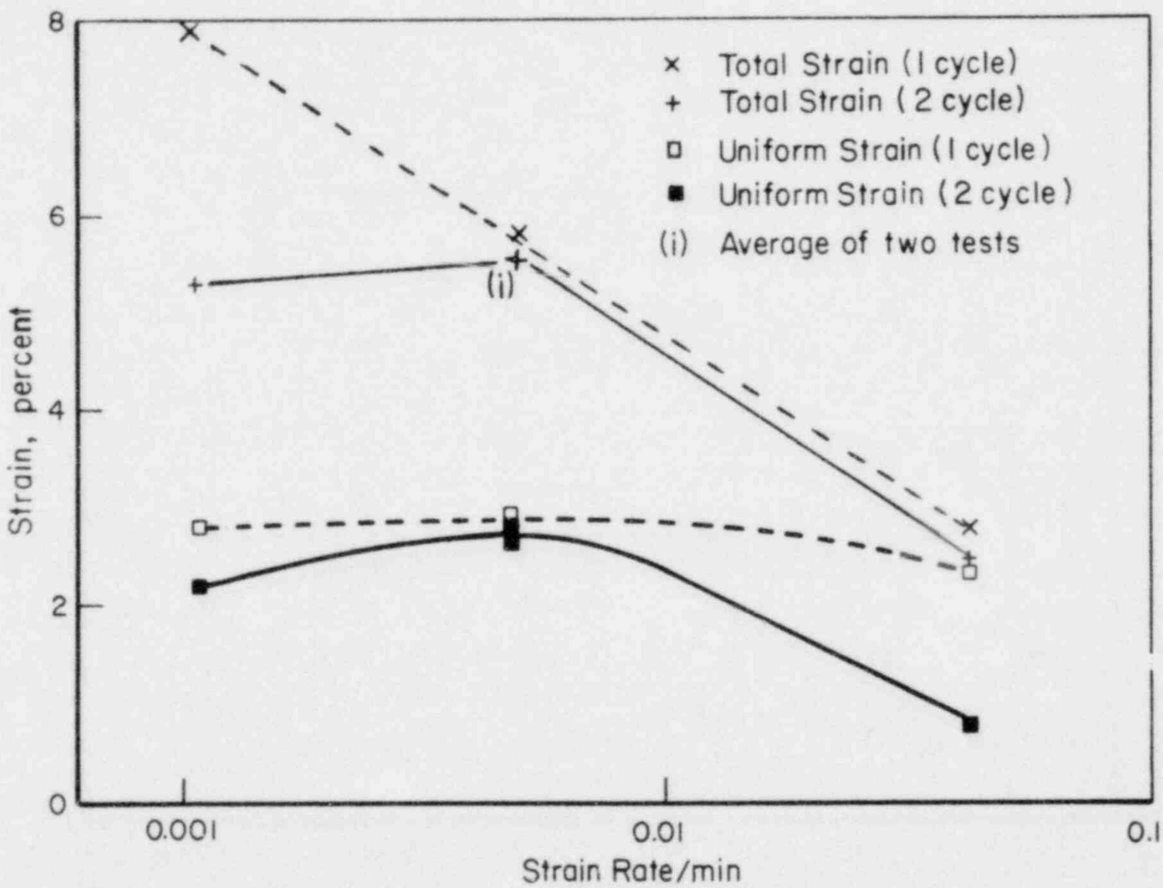

FIGURE 5. ENGINEERING BURST STRAIN FOR IRRADIATED OCONEE I (ONE AND TWO CYCLE) FUEL ROD CLADDING AS A FUNCTION OF STRAIN RATE. Test Temperature 371C.

The Lot 2 burst data for annealed specimens is tabulated in Table 2. Burst specimens were annealed under both transient and isothermal conditions. The specimens were transient annealed at both 28 and 5.6 C/sec heating rates. After transient annealing, each specimen was burst tested at a temperature of 371 C and at a strain rate of 0.004/min. The test results for Lot 2 material are plotted in Figure 6 as a function of a maximum temperature reached during the transient for specimens annealed at a heating rate of 28 C/sec. The test results for Lot 2 material are plotted in Figure 7 for specimens annealed at a heating rate of 5.6 C/sec. The isothermal anneal was accomplished by first heating the test specimen at a rate of 28 C/sec until the maximum temperature desired was reached. The specimen was then held at this maximum temperature for periods ranging from 1 to 60 minutes. The isothermal burst specimen test results are tabulated in Table 2 for Lot 2 material. After annealing, the burst tests were conducted at a temperature of 371 C and a strain rate of 0.004/min. The transient annealed specimen burst test results are plotted in Figures 8 through 11.

Lot 3 (Oconee I, Two Cycle) Material

During this reporting period, burst tests were conducted using the Lot 3 material. Burst tests using as-irradiated specimens were conducted at tests temperatures of 260, 316, 371 and 427 C to determine the effects of test temperature on the mechanical burst properties. The properties include 0.2% offset yield (engineering) burst stress, ultimate (engineering) burst stress, uniform (engineering) hoop strain, and total or failure (engineering) hoop strain. Burst tests using as-irradiated Lot 2 material were also run at strain rates of 0.001, 0.004 and 0.035/min. The tube burst test results for irradiated Oconee I, two cycle Zircaloy fuel rod cladding as a function of temperature and strain rate are tabulated in Table 3 and plotted in Figures 1 through 5.

The Lot 3 burst data for annealed specimens is tabulated in Table 4. Burst specimens were annealed under both transient and isothermal conditions. The specimens were transient annealed at both 28 and 5.6 C/sec heating rates. After transient annealing, each specimen was burst tested at a temperature of 371 C and a strain rate of 0.004/min. The test results for Lot 3 material are plotted in Figures 6 as a function of maximum temperature reached during the transient for specimens annealed at a heating rate of 28 C/sec. The test results for Lot 3 material are plotted in Figure 7 for specimens annealed at a heating rate of 5.6 C/sec. The isothermal anneal is described above. After annealing, the burst specimens were tested at a temperature of 371 C and at a strain rate of 0.004/min. The isothermal annealed specimen burst test results are also listed in Table 4 and are plotted in Figures 12 through 15.

TABLE 2. TUBE BURST TEST RESULTS FOR IRRADIATED OCONEE I (ONE CYCLE) ANNEALED ZIRCALOY FUEL ROD CLADDING. Test Temperature 371C; Strain Rate 0.004/min.

Specimen Number	Maximum Temperature C	Heating Rate C/sec	Holding Time Min	STRESS Yield MPa	STRESS Ultimate MPa	STRESS Failure MPa	STRAIN Uniform Percent	STRAIN Total Percent
				Transient Anneals				
47118-7	482	28	0	561	640	640	2.7	2.7
47118-17	538	28	0	556	621	619	2.6	2.9
47118-20	593	28	0	559	622	622	2.7	3.6
47118-22	621	28	0	557	627	627	2.5	4.0
47103-23	704	28	0	255	377	377	6.5	8.8
47101-8	816	28	0	250	376	371	7.2	16.0
47101-17	538	5.6	0	586	609	609	1.6	3.6
47101-12	593	5.6	0	554	587	587	2.1	5.0
47101-13	621	5.6	0	515	530	530	1.9	5.9
47010-8	621	5.6	0	254	371	367	6.6	11.8
47010-11	704	5.6	0	272	338	338	2.6	14.8
				Isothermal Anneals				
47010-13	538	28	1	537	600	576	1.7	5.7
47015-12	593	28	1	327	376	361	4.6	21.7
47015-14	621	28	1	256	326	326	3.2	6.7
47015-17	704	28	1	239	338	315	9.4	22.8
47015-3	538	28	15	339	383	378	2.7	12.4
47015-13	593	28	15	220	326	318	6.3	10.8
47015-12	482	28	60	505	543	539	2.4	5.0

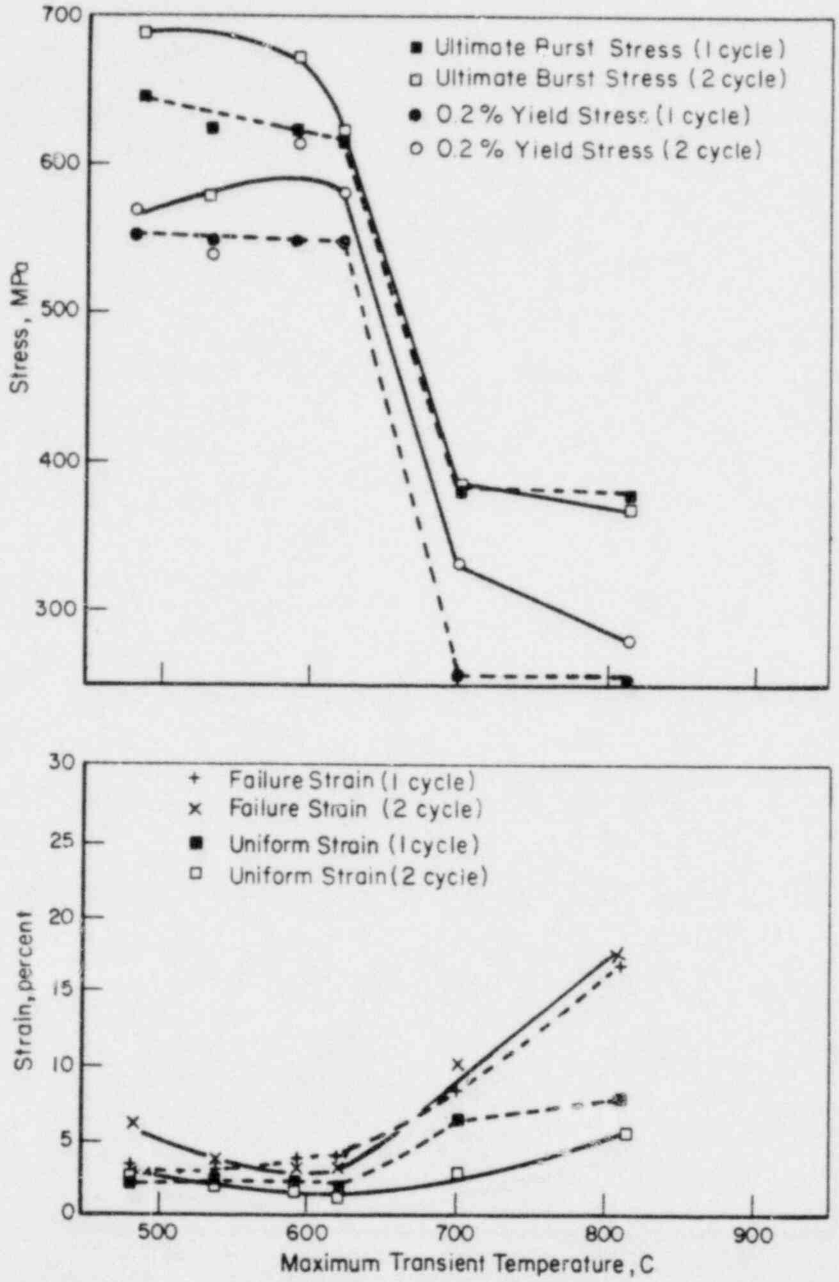

FIGURE 6. EFFECT OF MAXIMUM TEMPERATURE ACHIEVED IN TRANSIENT ON IRRADIATED OCONEE I (ONE AND TWO CYCLE) FUEL ROD CLADDING STRESS AND STRAIN AT A HEATING RATE OF 28C/SEC. Test Temperature 371C; Strain Rate 0.004/min.

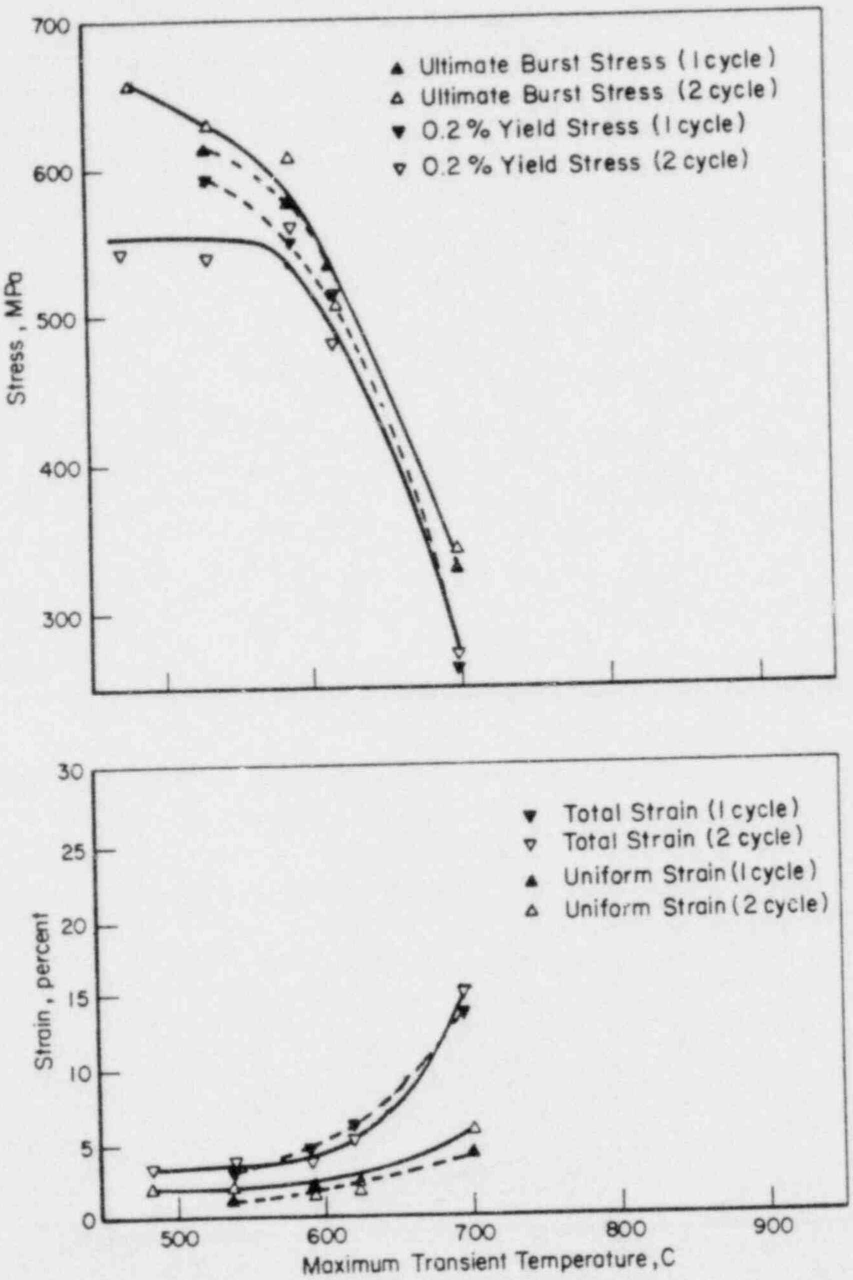

FIGURE 7. EFFECT OF MAXIMUM TEMPERATURE ACHIEVED IN TRANSIENT ON IRRADIATED OCONEE I (ONE AND TWO CYCLE) FUEL ROD CLADDING STRESS AND STRAIN AT A HEATING RATE OF 5.6C/SEC. Test Temperature, 371C; Strain Rate, 0.004/min.

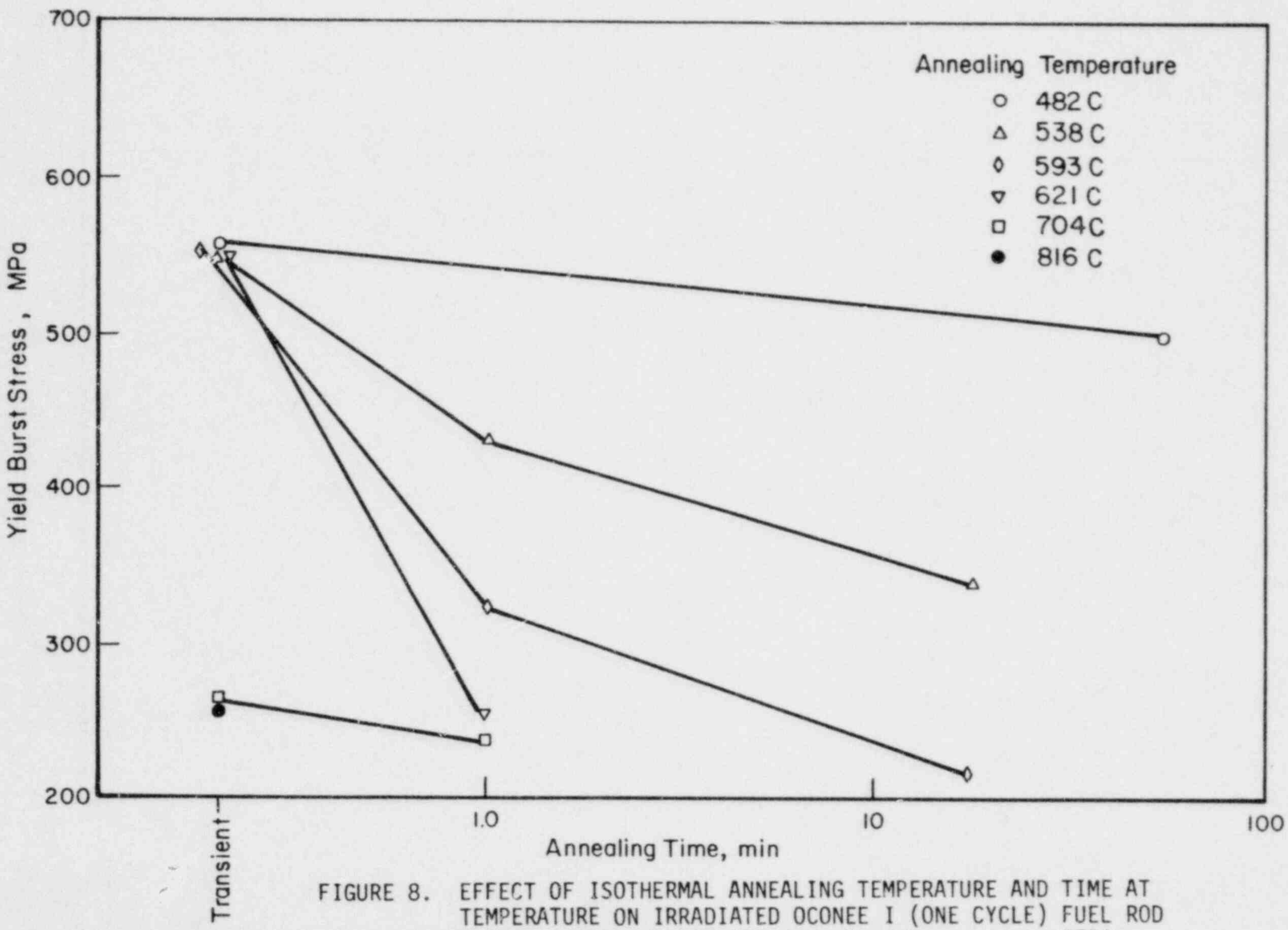

FIGURE 8. EFFECT OF ISOTHERMAL ANNEALING TEMPERATURE AND TIME AT TEMPERATURE ON IRRADIATED OCONEE I (ONE CYCLE) FUEL ROD CLADDING YIELD BURST STRESS. Test Temperature 371C; Strain Rate, 0.004/min.

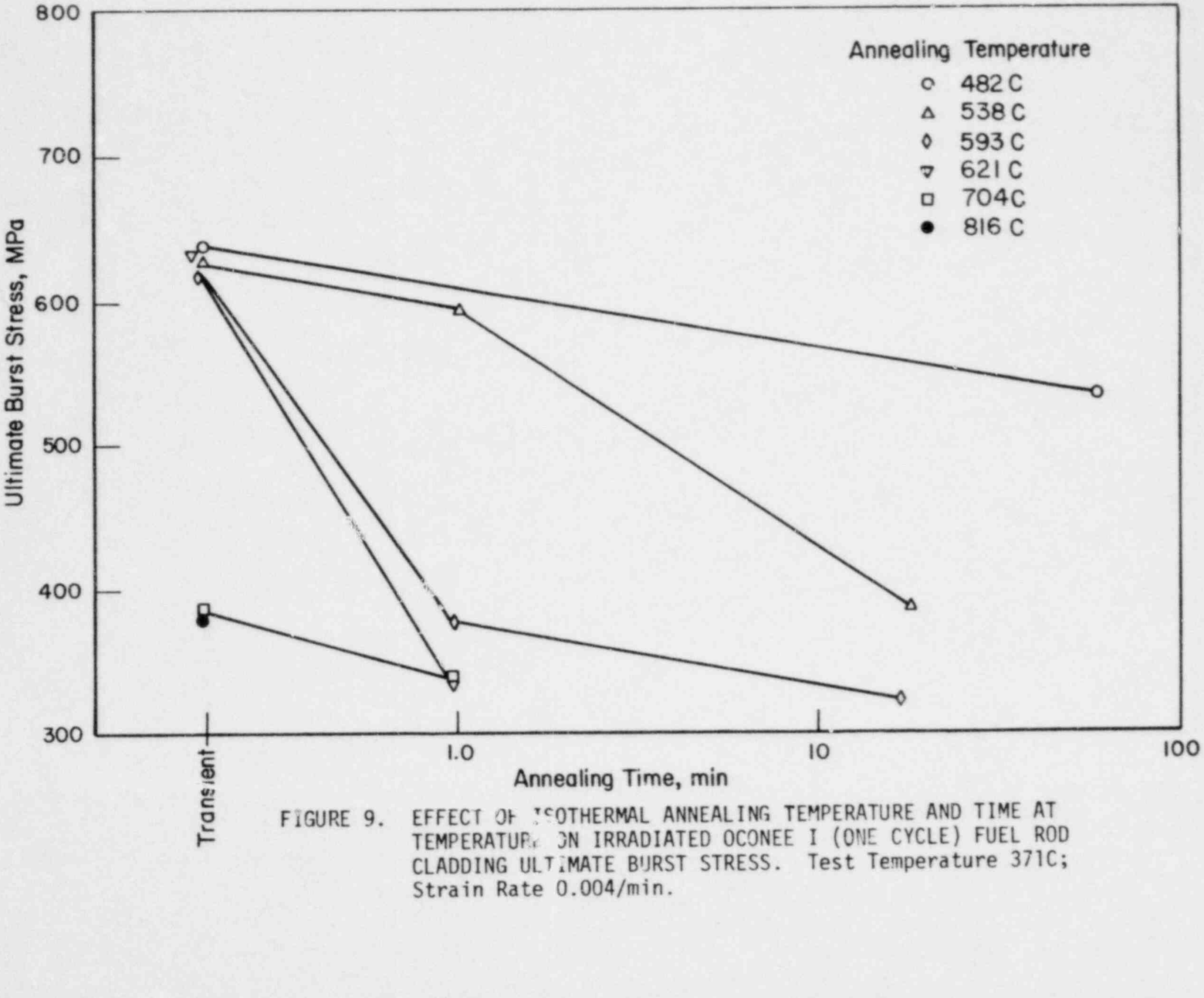

FIGURE 9. EFFECT OF ISOTHERMAL ANNEALING TEMPERATURE AND TIME AT TEMPERATURE ON IRRADIATED OCONEE I (ONE CYCLE) FUEL ROD CLADDING ULTIMATE BURST STRESS. Test Temperature 371C; Strain Rate 0.004/min.

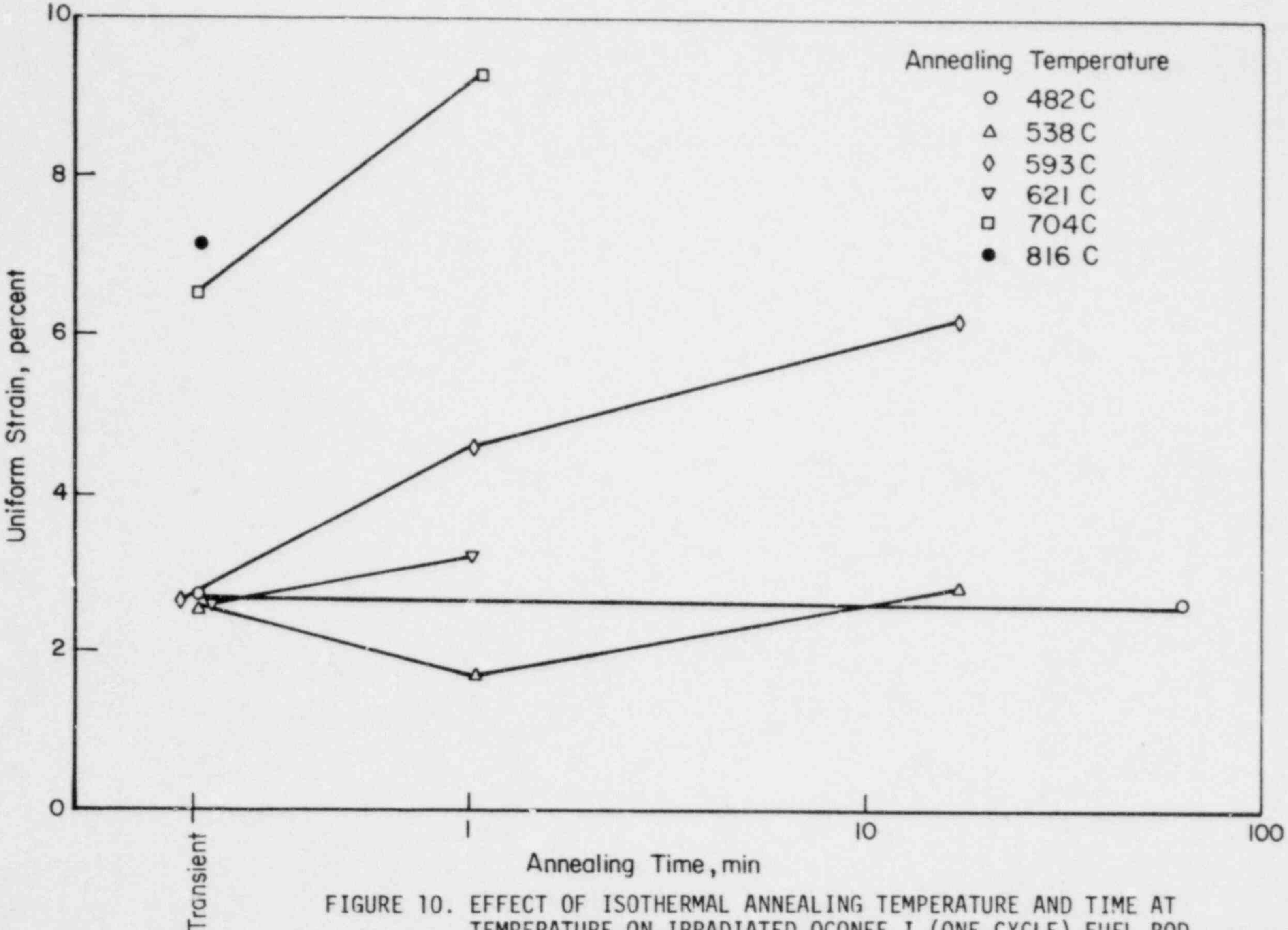

FIGURE 10. EFFECT OF ISOTHERMAL ANNEALING TEMPERATURE AND TIME AT TEMPERATURE ON IRRADIATED OCONEE I (ONE CYCLE) FUEL ROD CLADDING UNIFORM BURST STRAIN. Test Temperature 371C; Strain Rate 0.004/min.

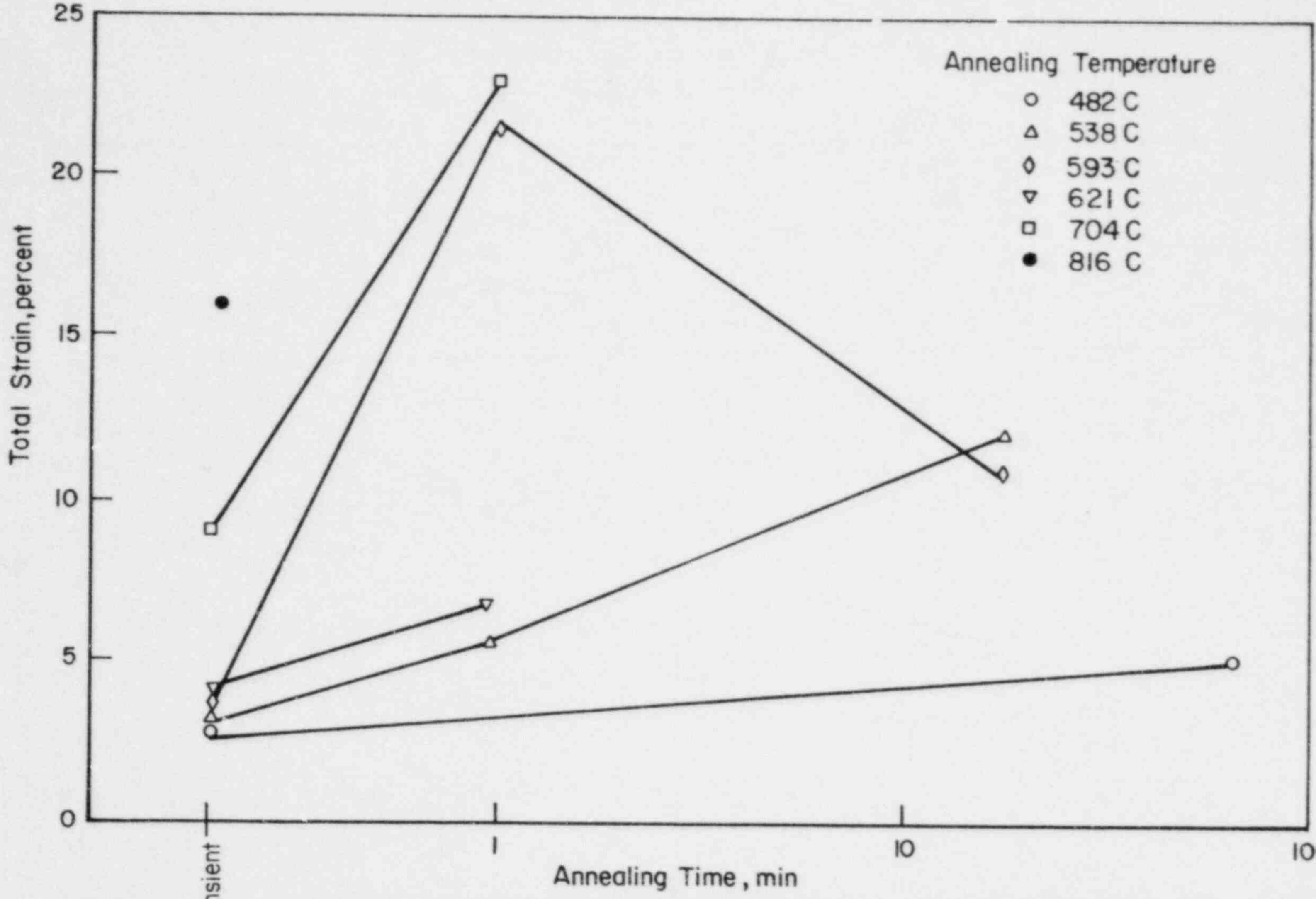

FIGURE 11. EFFECT OF ISOTHERMAL ANNEALING TEMPERATURE AND TIME AT TEMPERATURE ON IRRADIATED OCONEE I (ONE CYCLE) FUEL ROD CLADDING TOTAL BURST STRAIN. Test Temperature 371C; Strain Rate 0.004/min.

TABLE 3. TUBE BURST TEST RESULTS FOR IRRADIATED OCONEE I (TWO CYCLE) ZIRCALOY FUEL ROD CLADDING AS A FUNCTION OF TEMPERATURE AND STRAIN RATE

Specimen Number	Test Temperature C	Strain Rate /Min	STRESS Yield MPa	STRESS Ultimate MPa	STRESS Failure MPa	STRAIN Uniform Percent	STRAIN Total Percent
32062A-12	260	.004	737	794	794	1.7	4.0
32062A-11	316	.004	688	774	774	1.9	2.7
32062A-4	371	.004	654	727	727	2.7	4.0
31778A-9	371	.004	595	714	709	2.7	7.7
32062A-13	427	.004	532	593	583	4.4	14.9
32062A-16	371	.001	598	658	658	2.2	5.5
32062A-17	371	.035	725	725	725	0.8	2.7

TABLE 4. TUBE BURST TEST RESULTS FOR IRRADIATED OCONEE I (TWO CYCLE) ANNEALED ZIRCALOY FUEL ROD CLADDING. Test Temperature 371C; Strain Rate 0.004/min.

Specimen Number	Maximum Temperature C	Heating Rate C/sec	Holding Time Min	STRESS Yield MPa	STRESS Ultimate MPa	STRESS Failure MPa	STRAIN Uniform Percent	STRAIN Total Percent
			Transient Anneals					
31778A-2	482	28	0	570	690	690	2.7	6.3
31778A-4	538	28	0	540	579	579	2.1	3.5
31778-10	593	28	0	617	671	671	1.9	3.0
31778-14	621	28	0	582	625	625	1.3	3.1
31778-15	704	28	0	330	385	348	2.8	10.0
31778-18	816	28	0	279	367	348	5.5	16.1
32062A-18	482	5.6	0	545	660	660	1.3	3.3
32062A-19	538	5.6	0	540	630	630	1.9	4.1
32062A-20	593	5.6	0	561	608	608	1.4	3.2
32211A-18	621	5.6	0	482	505	505	1.6	4.8
32013A-4	704	5.6	0	274	342	340	5.5	25.4
			Isothermal Anneals					
32013A-10	538	28	1	585	620	620	1.4	3.3
32211A-14	593	28	1	463	484	481	1.8	7.7
32013A-22	621	28	1	339	378	358	2.0	14.4
32013A-25	704	28	1	236	331	330	6.3	12.9
32013A-11	538	28	10	505	562	554	1.5	6.3
32013A-21	593	28	10	268	331	331	3.8	17.9
32013A-9	482	28	60	540	579	579	1.8	4.8

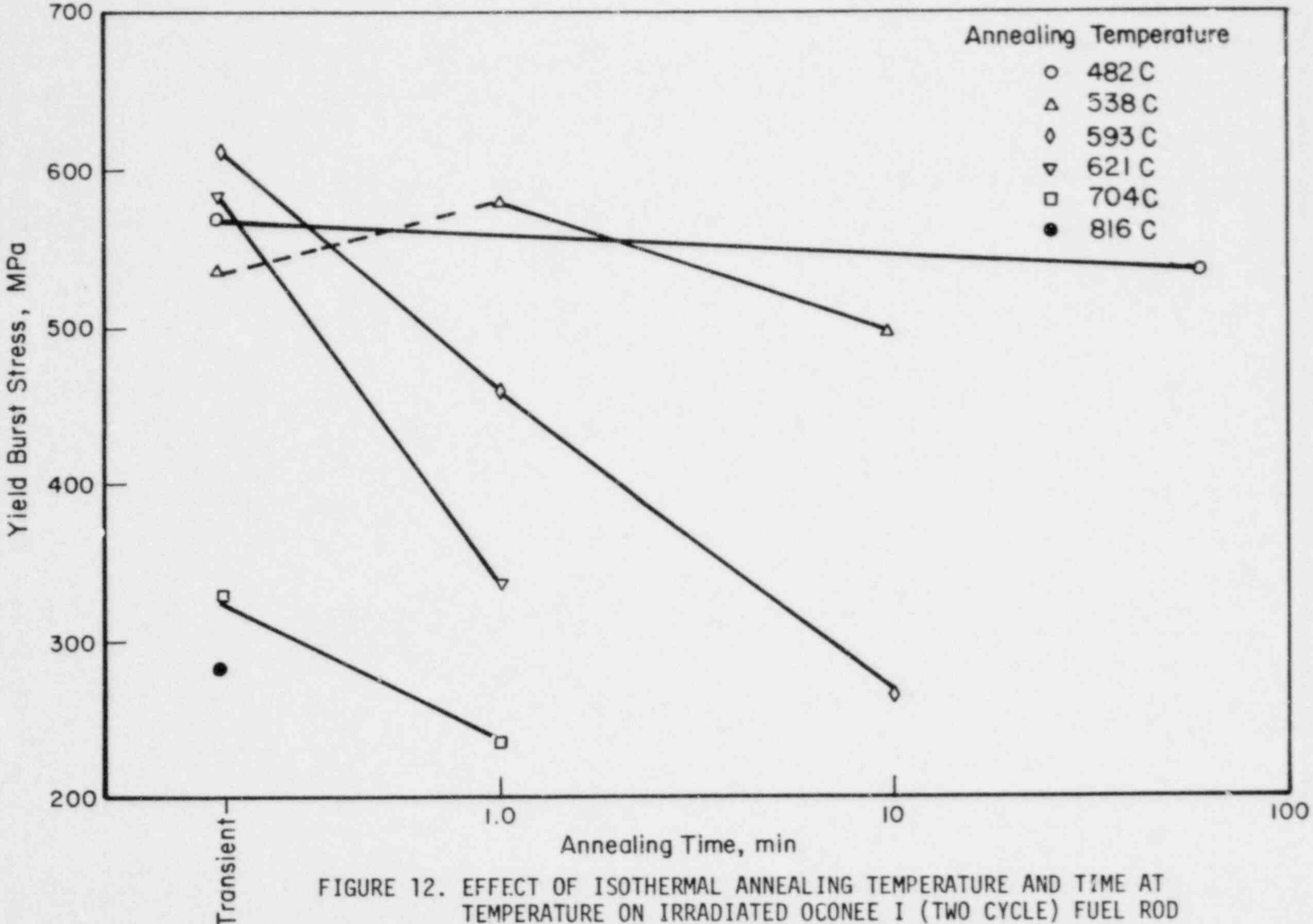

FIGURE 12. EFFECT OF ISOTHERMAL ANNEALING TEMPERATURE AND TIME AT TEMPERATURE ON IRRADIATED OCONEE I (TWO CYCLE) FUEL ROD CLADDING YIELD BURST STRESS. Test Temperature 371C; Strain Rate 0.004/min.

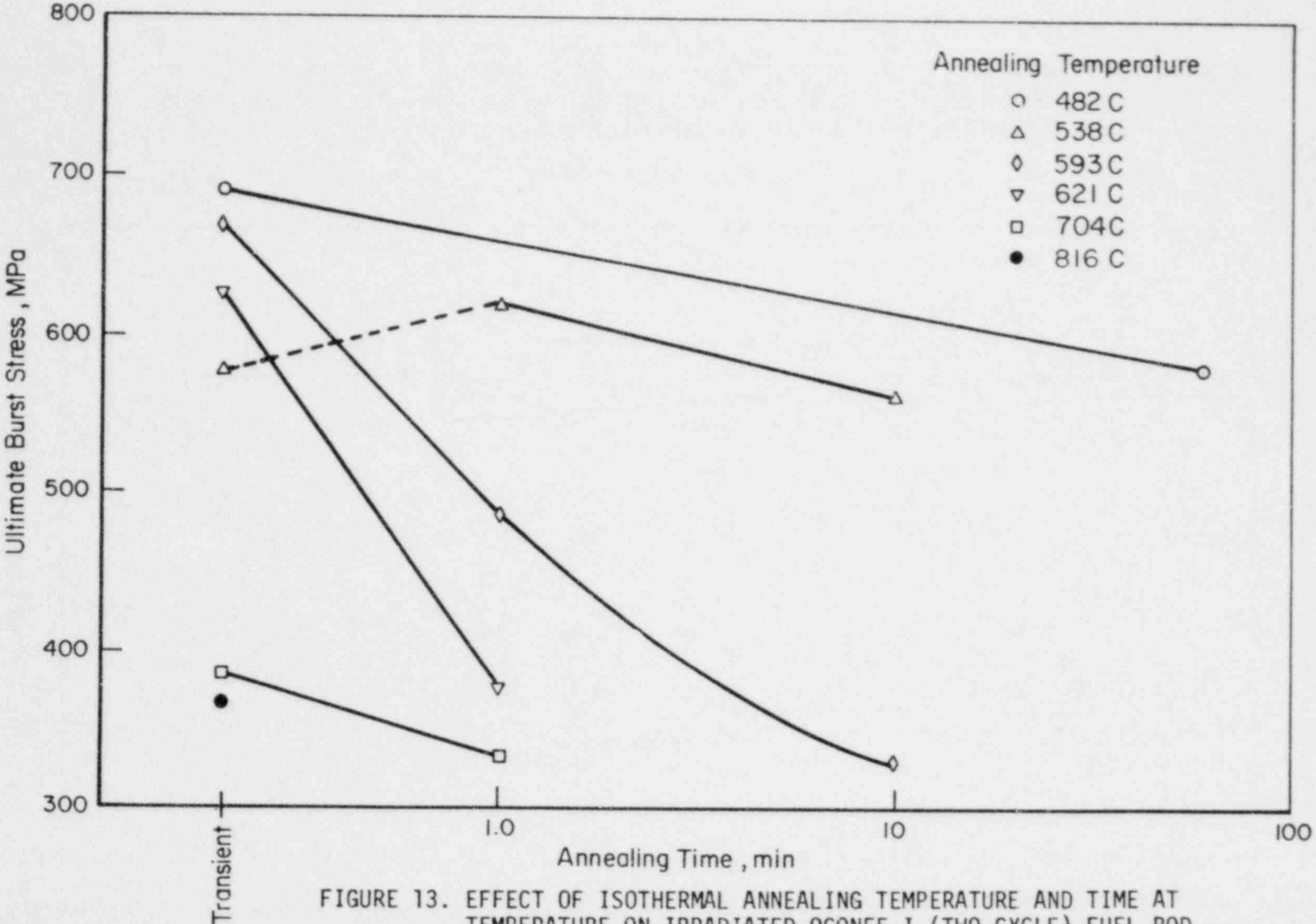

FIGURE 13. EFFECT OF ISOTHERMAL ANNEALING TEMPERATURE AND TIME AT TEMPERATURE ON IRRADIATED OCONEE I (TWO CYCLE) FUEL ROD CLADDING ULTIMATE BURST STRESS. Test Temperature 371C; Strain Rate 0.004/min.

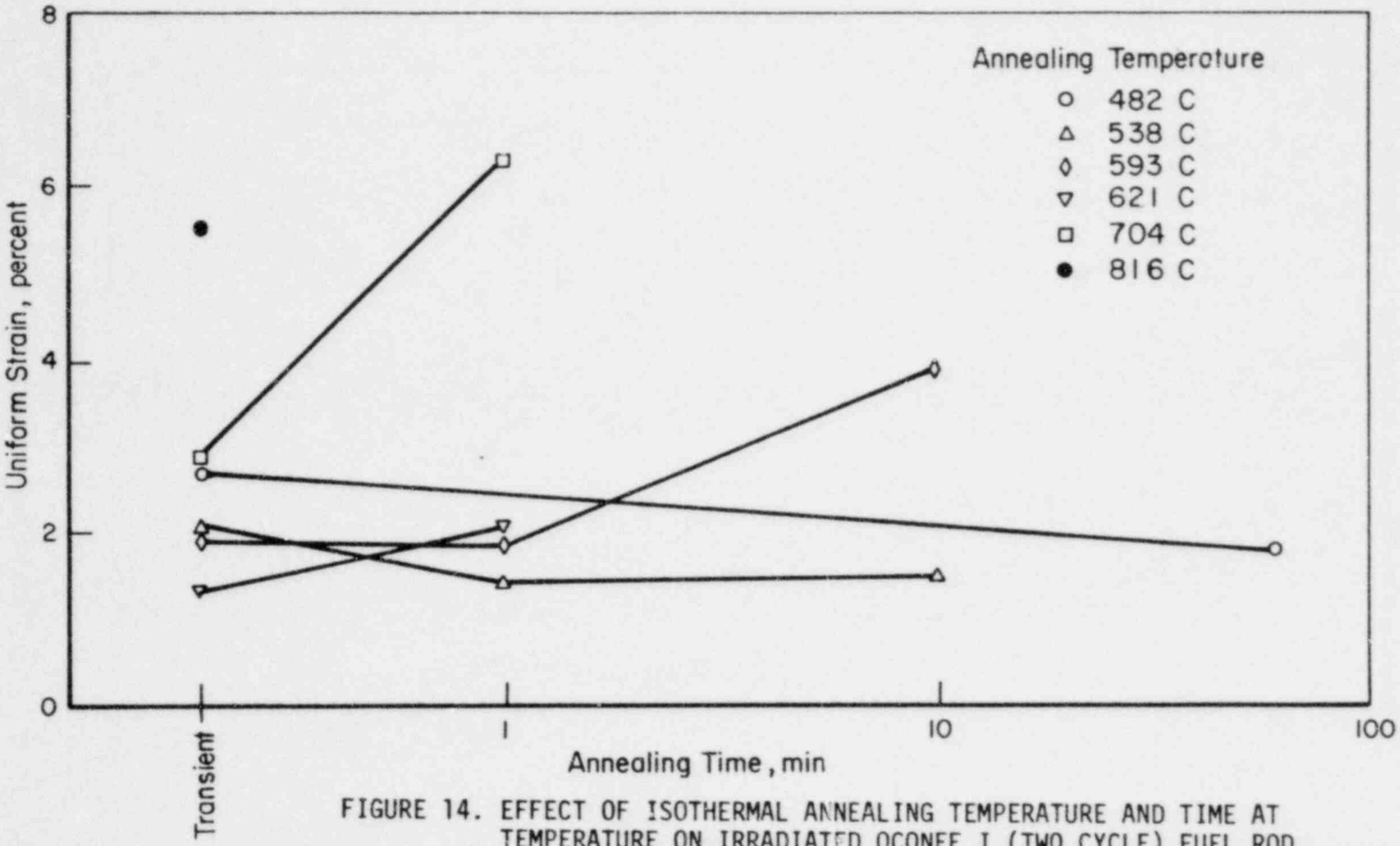

FIGURE 14. EFFECT OF ISOTHERMAL ANNEALING TEMPERATURE AND TIME AT TEMPERATURE ON IRRADIATED OCONEE I (TWO CYCLE) FUEL ROD CLADDING UNIFORM BURST STRAIN. Test Temperature 371C; Strain Rate 0.004/min.

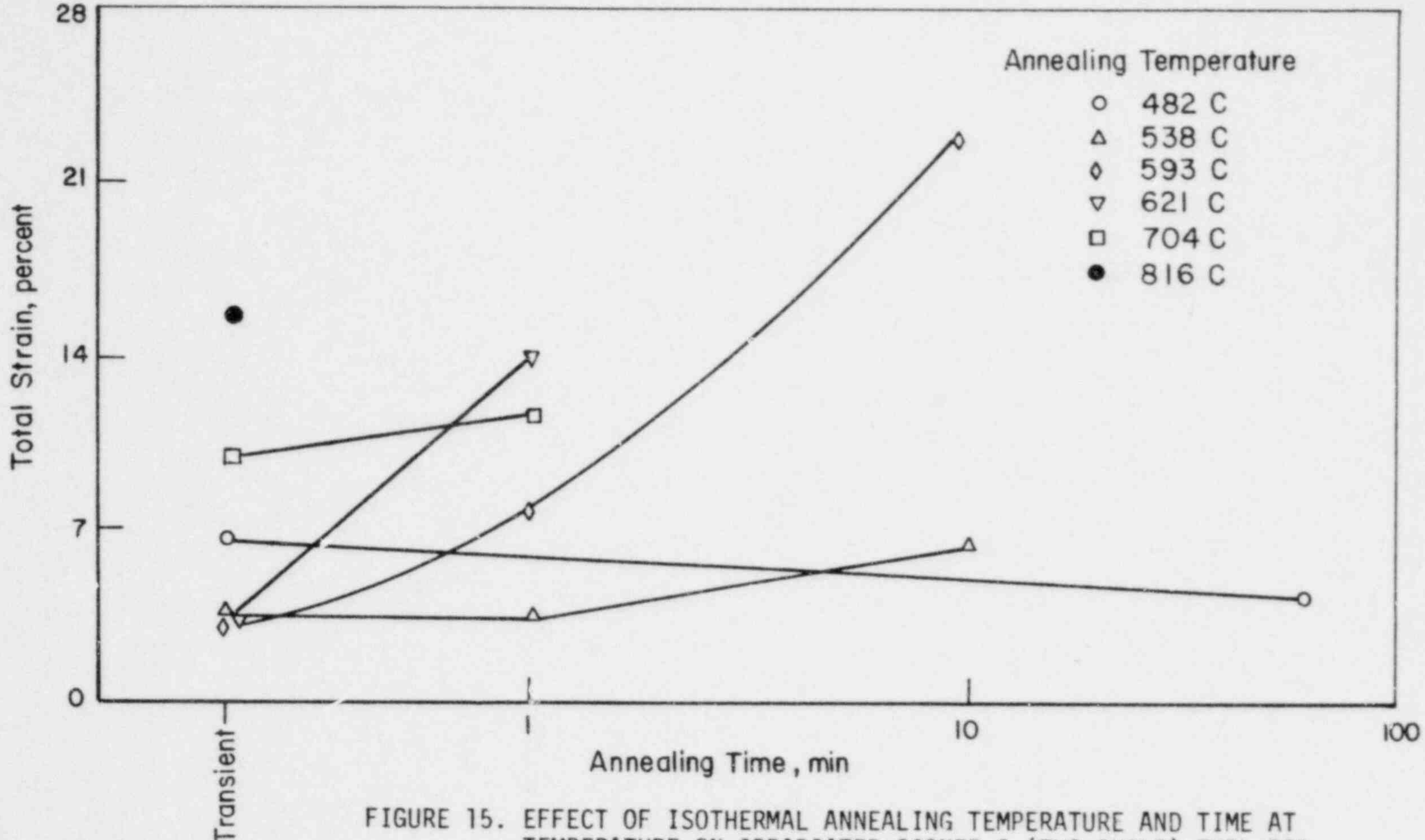

FIGURE 15. EFFECT OF ISOTHERMAL ANNEALING TEMPERATURE AND TIME AT TEMPERATURE ON IRRADIATED OCONEE I (TWO CYCLE) FUEL ROD CLADDING TOTAL BURST STRAIN. Test Temperature 371C; Strain Rate 0.004/min.

Comparison of Burst Data

The effect of irradiation on the engineering burst (hoop) stress for Zircaloy-4 fuel rod cladding irradiated in the Oconee I reactor is illustrated in Figure 1 and the test results are tabulated in Tables 1 and 3. At a test temperature of 260 C, the yield stress increased 11% and the ultimate burst stress increased 7% for specimens irradiated for two cycles when compared to specimens irradiated for one cycle. The yield and ultimate burst stress increased about 25% after one cycle of irradiation at test temperatures of 316, 371, and 427 C. At the test temperature of 316 C and after two cycles of irradiation, the yield stress increased an additional 11% (a total of 36%) and the ultimate stress increased an additional 14% (a total of 34%) when compared with the one cycle test results. At the test temperature of 371 C and after two cycles of irradiation, the yield stress increased an additional 16% (a total of 42%) and the ultimate stress increased an additional 18% (a total of 43%) when compared with the one cycle test results. Finally, at the test temperature of 427 C and after two cycles of irradiation, the yield stress increased an additional 27% (a total of 54%) and the ultimate stress increased an additional 13% (a total of 38%) when compared with the one cycle test results. These results indicate that when the yield and ultimate burst stress for Oconee I reactor Zircaloy-4 fuel rod cladding are compared with unirradiated archive Zircaloy-4 cladding material, both increased about 25% after one cycle of irradiation and approximately an additional 15% after a second cycle of irradiation. A slowing in the increase in stress may indicate that after the cladding is irradiated to some level, saturation occurs. However, final evaluation will come after the three cycle tube-burst tests results are obtained.

The uniform and total burst (hoop) strains decreased after one cycle of irradiation and an additional smaller decrease after two cycles of irradiation for test temperatures of 260, 316 and 371 C. At a test temperature of 427 C, the uniform strain increased from about 3% to about 4.5% which is expected as the burst stresses increase and the modulus changes slightly. At a test temperature of 427 C, the total strain shows little or no change. The unirradiated, one cycle, and two cycle specimens all exhibit total strains in the range of 15 to 18%. This is unexpected, however, a complete evaluation will be reserved until the threee cycle burst results are available. Note also that at 316 C, a relatively large decrease (70%) in total burst (hoop) strain is induced after one cycle of irradiation and remains low after two cycles of irradiation.

As-received tube-burst specimens were tested at three strain rates, 0.001, 0.004 and 0.035/min; all tests were conducted at 371 C. Both yield and ultimate burst stress increase with increased strain rate and both uniform and total strain decrease with increased strain rate. The tube-burst stresses and strains, upon extrapolation of the data plotted in Figures 4 and 5, appear to converge at a strain rate of about 0.1/min.

Several Zircaloy-4 fuel rod specimens irradiated for two cycles in the Oconee I reactor were transient annealed at a heating rate of 28 C/sec and 5.6 C/sec to temperatures from 482 to 816 C. The specimens were subsequently burst tested at a test temperature of 371 C and at a strain rate of 0.004/min. The results are tabulated in Table 3 and plotted in Figures 6 and 7. Table 2 contains the results of the Zircaloy-4 fuel rod specimens irradiated for one cycle and burst tested as described above. The two cycles tube-burst test results are also plotted in Figures 6 and 7 for comparison.

The burst properties, yield stress, ultimate stress, uniform strain, and total (or failure) strain, show little or no change due to the transient anneal at either 28 C/sec or 5.6 C/sec for annealing temperatures below 600 C. At about 700 C, it appears the burst yield and ultimate stress have reached a plateau for specimens transient annealed at 28 C/sec. It is also tactfully assumed that the specimens annealed at 5.6/sec also will exhibit this same plateau. (See Figures 6 and 7.) The uniform strain are almost constant for both one and two cycle specimens at about 3 to 5%. However, the total strain continues to increase for annealing temperatures from 600 C to 700 C for specimens annealed at 6.5 C/sec and from about 600 C to 800 C for specimens annealed at 28 C/sec.

These results (of tube burst specimens irradiated for both one and two cycles in the Oconee I reactor, transient annealed at either 28 C/sec or 5.6 C/sec and burst tested) indicate that above 700 C the stress are approximately equivalent to unirradiated specimen stresses. Also, tube-burst specimens annealed at 28 C/sec to 800 C and tube-burst specimens annealed at 5.6 C/sec to 700 C exhibit strains equivalent to unirradiated specimen strains.

Figures 8 through 11 are plots of tests results for Zircaloy-4 fuel rod tube-burst specimens irradiated for one cycle in the Oconee I reactor, isothermally annealed for times from 28 C/sec transients to 60 minutes, and burst tested. The tube-burst tests were conducted at a test temperature of 371 C and a strain rate of 0.004/min. The results are tabulated in Table 2. Figures 12 through 15 are plots of the tests results in the Oconee I reactor, annealed, and tested as described above. The results are tabulated in Table 3. These plots show that until the transient annealing temperature exceeds 621 C, the stresses and strain are approximately constant. Between 621 and 704 C, the stresses (both yield and ultimate) decrease rapidly and the strains (both uniform and total) increase rapidly. Above 704 C, the stresses and strains are again approximately constant.

The results of the isothermally annealed specimens indicate an increase in strength (stress) and a decrease in ductility (strain) which persists at a specific time and temperature until the plateau values are approached or reached. Note that even at 482 C, trends are appearing (reduced stress after 60 minutes) which indicate that if a straight line extrapolation of the data is valid and if the cladding were exposed to 482 C temperatures for times between 5 and 10 hours, at least the strengths (stresses) would be approaching their unirradiated tube-burst stress values. Clearly the recovery of irradiation damage by isothermal annealing is both time and temperature dependent. It is further complicated by residual stress recovery above approximately 500 C, recrystallization above about 600 C, and grain growth above 700 C for annealing times as short as a few minutes.[1]

MODELING STUDIES

The modeling studies being carried out under this program are intended to develop a link between the mechanical-property data obtained at Battelle for irradiated Zircaloy and the computer codes being developed elsewhere to describe in-reactor behavior of clad fuel elements under off-normal, transient, and accident conditions. During this reporting period, work has progressed along two fronts: (1) development of a mathematical model to describe mechanical-property recovery under anisothermal conditions, and (2) analysis of Battelle data that describes the behavior of irradiated Zircaloy tubes under tensile loading.

MODELING DEVELOPMENT

In the previous progress report (NUREG/CR-0982, BMI-2034), a mathematical model was discussed that can be used to describe the variation with time of a given material property (e.g., ultimate stress, uniform strain, etc.) that characterizes an irradiated material undergoing anisothermal heat treatment. The model consists essentially of an extension of the familiar Johnson-Mehl-Avrami equation to account for time-dependent temperature. In earlier modeling studies (NUREG/CR-0582, BMI-2007, pp 6 ff.), the Johnson-Mehl-Avrami equation had been found to provide a satisfactory description of Battelle data* obtained for the uniform strain of irradiated Zircaloy under the special conditions of constant annealing temperature. Extension of the model thus developed to describe data obtained under anisothermal conditions was found to be generally successful (NUREG/CR-0982, BMI-2034, pp 27 ff.).

A significant problem associated with the anisothermal model, as pointed out previously (NUREG/CR-0982, BMI-2034, pp 27 ff.), is its relative complexity, such that the exact mathematical solution cannot be employed readily in pertinent computer codes for describing fuel cladding behavior. As a result of this condition, a number of approximate solutions are being developed that are relatively simple in form, but yet provide adequate estimates of the "exact" solution under certain conditions. The approaches that are being taken are as follows:

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*These data are presented elsewhere (BMI-NUREG-1956, p. 21).

(1) A power-series that is applicable for relatively small changes of temperature

(2) Various asymptotic expansions that are applicable over certain ranges of values for pertinent parameters.

Specific details regarding these approaches will be presented in a future report. It is simply noted here that these approximate solutions can indeed provide good, and analytically simple, approximations of the exact model within various ranges of parameter values. Indeed, relatively good approximations can be obtained using just one or two of the leading terms of these expansions within certain ranges of the pertinent parameters.

Data Analysis

It was shown previously (NUREG/CR-0982, BMI-2034, pp 30 ff.) that the tensile test data (BMI-NUREG-1956, p. 21) for isothermally annealed, irradiated Zircaloy do not appear to satisfy the following constitutive equation over the entire stress range from yield point to ultimate point:

$$\sigma = \kappa\varepsilon^{n} ,$$

where σ is the true stress, ε the true plastic strain, κ the strength coefficient, and n the strain-hardening exponent, with κ being a function of temperature only and n being a constant. It therefore was apparent that a more detailed assessment of the tensile test data would be required in order to establish a constitutive relation that would more accurately reflect the stress-strain behavior of the data. This assessment is currently under way and will now be described.

The tensile data originally were obtained in graphical form using an x-t recorder. One such graph was obtained for each of the 16 specimens, and on each graph the applied load was presented as a function of specimen length. The first task was to transform the graphical data into digital form that would be amenable to analysis. This was done using the digitizer available in the Battelle Computer Center. In this manner, several hundred data points were obtained for each of the curves. The measurement accuracy obtained using the digitizer was about $\pm$ 0.01 inch.

The next task, which is currently in progress, is to correct any irregularities in the digitized data that resulted from problems associated with the actual experiment (such as slippage of the extensometer that was used to measure specimen length as a function of applied load). Then, the data must be transformed to respective values of true applied stress and true strain, and fater that conversion has been made, the resultant data will be in a form that is appropriate for analysis.

A number of possible constitutive equations will be fitted to the data using a nonlinear-regression-analysis computer code developed at Battelle that is based on the Marquardt algorithm[1]. As was indicated above, this general approach has been used, in earlier work on this program (NUREG/CR-0582, BMI-2007, pp 6 ff.), in an analysis of uniform strain data for irradiated Zircaloy under conditions of time-independent annealing temperature. In this manner, any potentially applicable constitutive equation can be tested against the data by quantitatively determining how well that equation can be "fitted" to the data.

In addition, by fitting a give constitutive equation to each of the 16 sets of data, corresponding sets of data will be obtained for the various parameters of the equation as functions of annealing time and temperature. These can be subjected to further analyses (e.g., as was done with the uniform -elongation data, as described above) to quantitatively relate these parameters to the annealing conditions, again, by fitting the Johnson-Mehl-Avrami equation to the data. The models thus obtained can be extended to anisothermal conditions in the manner described in the last report (NUREG/CR-0982, BMI-2034, pp 27 ff.), and the analytical procedures summarized in the Modeling Development Section above can be utilized to bring the models into a form that is readily usable in pertinent computer codes describing fuel-element behavior.

REFERENCE

(1) A. A. Bauer, L. M. Lowry, and J. S. Perrin, "Evaluating Strength and Ductility of Irradiated Zircaloy", Task 5 Quarterly Progress Report, July through September, 1975, BMI-1938, September, 1975.

(2) D. W. Maquardt, "An Algorithm for Least-Squares Estimation of Nonlinear Parameters", J. Soc, Indust. Appl. Math., 11, 431 (1963).

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16. ABSTRACT (200 words or less)

The Lot 4 material (Oconee I, Three Cycle) was received, visually examined and gamma scanned. The four rods were Babcock and Wilcox (B&W) fuel rods irradiated in the Oconee I reactor, sectioned at B&W, and shipped to Battelle Columbus Laboratories (BCL) in the shipping cask BCL-4. Specimens for tensile, expanding mandrel, tube-burst, and transient heating burst tests were prepared from the Lot 4 rods.

Burst tests were conducted using unirradiated Oconee I archive fuel rod cladding material. Additional burst tests were conducted using Lot 2 (Oconee I, One Cycle) irradiated Zircaloy fuel rod cladding. Also, burst tests were conducted using Lot 3 (Oconee I, Two Cycle) Zircaloy fuel rod cladding. A comparison of Oconee I archive, one cycle, and two cycle tube-burst test results is included.

Modeling studies are continued using a number of constitutuve equations fitted to the BCL tensile data using a nonlinear-regression-analysis computer code developed at Battelle and based on the Marquardt algorithm.

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