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TENSILE AND BURST TESTS IN SUPPORT OF THE CADMIUM SAFETY ROD FAILURE EVALUATION (U)

By

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MASTER

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EXECUTIVE SUMMARY

The reactor safety rods may be subjected to high temperatures due to gamma heating after the core coolant level has dropped during the ECS phase of a hypothetical LOCA event. Accordingly, an experimental safety rod testing subtask was established as part of a task to address the response of reactor core components to this accident. This report discusses confirmatory separate effects tests conducted to support the evaluation of failures observed in the safety rod thermal tests.

As part of the failure evaluation, the potential for liquid metal embrittlement (LME) of the safety rod cladding by cadmium (Cd) - aluminum (Al) solutions was examined. Based on the test conditions, literature data, and U-Bend tests, it was concluded that the SS304 safety rod cladding would not be subject to LME by liquid Cd-Al solutions under conditions relevant to the safety rod thermal tests or gamma heating accident. To confirm this conclusion, tensile tests on SS304 specimens were performed in both air and liquid Cd-Al solutions with the range of strain rates, temperatures, and loading conditions spanning the range relevant to the safety rod thermal tests and gamma heating accident. No reduction in ductility or strength was observed for the tensile tests in Cd-Al or Cd liquid metal solutions relative to the tests in air; therefore, the results of the tensile tests demonstrate that neither Cd nor Cd-Al mixtures embrittle SS304 under the conditions relevant to this evaluation. The tensile tests also illustrated the effect of temperature and strain rate of the presence and magnitude of serrations in the SS304 stress-strain curve. The decrease in the ductility of SS304 associated with the slow strain rates was also demonstrated.

The safety rod cladding ductility (e.g. hoop strain at failure) was also examined as part of the failure analysis. In order to confirm the estimated cladding ductility and to illustrate the nature of a pure mechanical cladding failure (e.g. overpressure), pressurized tube tests were performed on safety rod cladding samples. A pressurized tube burst test demonstrated that the safety rod cladding has good 550°C ductility under high strain rate biaxial loading conditions and that the methodology employed in this task to predict failure strains for cold-worked SS304 under biaxial loading conditions is reasonable. A second pressurized tube test demonstrated that the safety rod cladding could withstand at least 80% of the burst pressure for 6 hours and that little or no creep deformation would be accumulated over this period.

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1. INTRODUCTION

The reactor safety rods may be subjected to high temperatures due to gamma heating after the core coolant level has dropped during the ECS phase of a hypothetical LOCA event. Accordingly, an experimental safety rod testing subtask was established as part of a task to address the response of reactor core components to this accident (Thomas 1991). The experimental subtask compliments the structural evaluation (finite element analysis) of the safety rod (Gupta 1991). This report discusses confirmatory separate effects tests conducted to support the evaluation of failures observed in the safety rod thermal tests.

The active, or cadmium (Cd) bearing, portion of the safety rod consists of a 0.756" diameter aluminum alloy (Al-6061) core, a 0.05" thick Cd layer, and a 0.042" thick Type 304 stainless steel cladding. A cross section of the safety rod is shown in Figure 1. As part of the manufacturing process, a thin (≈ 1 mil) nickel (Ni) flash coating was applied to the Al-6061 core to aid in Cd application, and the stainless steel cladding was swaged from 1" to 0.94" outer diameter so as to contact the Cd layer.

The safety rod thermal tests are described in Thomas et al. (1991). These tests consisted of subjecting safety rod segments to elevated temperatures to determine their time-temperature failure threshold. The peak temperature, rate of temperature increase, and hold time at the peak temperature were test variables. Twenty-five tests were conducted using specimens taken from 4 different safety rods at maximum test temperatures between 500 and 900°C. Five failures occurred via rupture of the stainless steel cladding. Three of the failures occurred at maximum temperatures between 521 and 590°C; these failures occurred with specimens taken from a single safety rod in tests using a slow thermal ramp rate (≈ 4°C/min). The other two failures occurred above 830°C; these failures occurred with specimens taken from two separate safety rods using a fast thermal ramp rate (> 100°C/min). No failures occurred below 521°C.

The examination of failed specimens and failure evaluation are discussed in Thomas et al. (1992). As part of the failure evaluation, the potential for liquid metal embrittlement (LME) of the safety rod cladding by cadmium (Cd) - aluminum (Al) solutions was examined. Based on the test conditions, literature data, and U-bend tests, it was concluded that the SS304 safety rod cladding would not be subject to LME by liquid Cd-Al solutions under conditions relevant to the safety rod thermal tests or gamma heating accident. To confirm this conclusion, tensile tests on SS304 specimens were performed in both air and liquid Cd-Al solutions. The tensile tests are discussed in Section 2.

The safety rod cladding ductility (e.g. hoop strain at failure) was also examined as part of the failure analysis. Sufficient literature data was available to estimate the cladding failure strain considering the effects of cladding temperature, strain rate, cold work, and biaxial loading. In order to confirm the estimated cladding ductility and to illustrate the nature of a pure mechanical failure (e.g. overpressure) for the cladding, pressurized tube tests were performed on safety rod cladding samples. These tests are discussed in Section 3.

The conclusions from the tensile and pressurized tube tests are presented in Section 4.

These tests were conducted at the Westinghouse Science and Technology Center (WSTC). They were considered scoping in nature and were not carried out under an NRTSC technical procedure; however, the NRTSC experimental QA procedure guidelines were employed where possible. Per NRTSC QAP III-2, the data from these tests do not require qualification for critical applications since they were confirmatory in nature and were not the sole basis for the conclusions reached in the failure evaluation concerning safety rod cladding ductility and LME susceptibility.

Attachment A is the WSTC report which describes these tests and presents the experimental results. The test data, photographs of the experimental rigs, specimen manufacture information, and calibration data are filed with the task records. The workscope for these tests is given as Attachment B; the workscope is part of Interworks Requisition 96472-0897742 (J.A. Begley, Westinghouse Science and Technology Center, Pittsburgh, PA).

2. TENSILE TESTS

The tensile tests were performed to examine the susceptibility of SS304 to liquid metal embrittlement (LME) by Cd and Cd-Al solutions under conditions (strain rate & temperature) relevant to the safety rod thermal tests and gamma heating accident. The results from the U-bend tests and literature review (Thomas et al. 1992) indicated that this system would not be susceptible to LME under these conditions.

The experimental conditions and results are summarized in Table 1. The "fast" strain rate ($3x10^{-3}$ min^{-1}) bounds the highest strain rate expected for the temperature ramp rates predicted for the gamma heating accident. Susceptibility to LME generally increases with increasing strain rate (Thomas et al. 1992). The calculations performed to date for the gamma heating accident indicate that at least 30 minutes is required to reach peak safety rod temperatures less than 600°C (Cooper and Taylor 1991). The highest measured hoop strain for specimens tested at or below 600°C was 5.5% (Thomas et al. 1992). Therefore a hoop strain of 6% and ramp time of 20 minutes were selected as bounding ($0.06/20 = 3x10^{-3}$ min^{-1}). Note that this strain rate is 2 orders of magnitude below the upper end of the LME susceptibility range, 0.6 min^{-1} (Thomas et al. 1992), and is just below the strain rate range employed in standard tensile tests, $5x10^{-3}$ to $5x10^{-2}$ min^{-1} (ASTM Standards E21-79 and E8-88). Fast strain rate tests were conducted over a range of temperatures from 325 to 600°C. The "slow" strain rate ($8x10^{-5}$ min^{-1}) bounds the lowest strain rate in the safety rod thermal tests. For this purpose, a minimum hoop strain of 1% over a period of 2 hours was adopted ($0.01/120 = 8x10^{-5}$ min^{-1}). Only one set of air and liquid metal tests at 550°C was conducted at this strain rate since it is expected to give lower LME susceptibility. The first two tests listed in Table 1 were conducted to qualify the experimental setup and data acquisition systems, and were conducted with variable strain rates. A single test was conducted in Cd-Al at 550°C with a strain rate of $9x10^{-4}$ min^{-1} as part of the test procedure development.

The notched specimen tests were included to examine the effect of triaxial loading on LME susceptibility. Only one set of air and liquid metal tests at 550°C was conducted with notched specimens; all other tests were conducted with smooth tensile specimens. The cross head speed for the notched specimen tests was set to the same value as for the smooth specimens tested at a strain rate of $3x10^{-3}$ min^{-1}, although the strain rate in the region of the notch would obviously be larger.

The specimens were machined from mil-annealed SS304 bar stock 0.625" in diameter. The machined gauge length and diameter were 2.00" and 0.35", respectively. Note that the applicable ASTM standards (E21-79 and E8-88) call for a gauge length to diameter ratio (L/D) of 4; these specimens have a 5.7 L/D ratio. This will tend to decrease the effect of necking on total elongation relative to standard tensile specimens (e.g. will give lower values of total elongation). The notched specimens had a notch diameter of 0.252" and a notch root radius of 0.007". A three-zone furnace was used to heat the specimens, and the test temperature was maintained to within ±2°C.

The tests in air were conducted to obtain baseline tensile properties. Liquid Cd with dissolved Al-6061 was employed as the liquid metal solution since this reproduces the conditions in the safety rod thermal tests. A single test at 550°C in pure Cd was conducted for comparison to the 550°C test in Cd-Al. The tests in liquid metal were conducted by affixing a stainless steel cup to the bottom tensile grip. The cup was loaded with 35g of Cd and, for the Cd-Al tests, an Al-6061 inner sleeve. The fast strain rate tests ($3x10^{-3}$ min^{-1} and $9x10^{-4}$ min^{-1}) were conducted with a stainless steel muffle to prevent Cd loss. The slow strain rate tests ($8x10^{-5}$ min^{-1}) required more effective Cd retention since they lasted several days, and a stainless steel bellows affixed over the top end of the specimen was employed for these tests.

Table 1 gives the results for the tensile tests. The yield values correspond to a 0.2% offset on the strain axis. Reduction in Area (RA) values were not available for the specimens tested in liquid metal. The data for the air tests are shown in Figures 2 and 3 along with correlations recommended by Sikka and Booker (1977) for SS304 manufactured in the United States. The $3x10^{-3}$ min^{-1} tensile data should be in good agreement with these correlations since strain rate effects would not be expected to play a role. As can be seen in Figure 2, the yield (YS) and ultimate (UTS) strength data from these experiments are significantly higher than the correlations; the YS values are larger by approximately 70 to 85%, and UTS values are larger by 20 to 25%. This is probably due to cold work (CW) introduced by straightening operations on the bar stock. Based on the evaluation of Moen and Duncan (1976), these strength increases correspond to approximately 4 to 6% CW. The ductility data do not show that same trend; the reduction in area values are in good agreement with the correlation and the total elongation values are approximately 10% below the correlation, which is expected based on the relatively long gauge length employed in these tests. The stainless steel cladding on the safety rods had 6% CW introduced by swaging during manufacture, so that the cold work level in the tensile specimens based on the tensile strength data would be roughly equivalent to that in the safety rod cladding. The total elongation at failure for the test conducted at 550°C with a strain rate of $8x10^{-5}$ min^{-1} should be reduced by approximately 25% relative to the tests employing a $3x10^{-3}$ min^{-1} strain rate (Thomas et al. 1992). Based on the average of the 4 tests conducted with a strain rate of $3x10^{-3}$ min^{-1} (38.9%) and the 2 tests conducted at $8x10^{-5}$ min^{-1} (30.0%), the relative decrease was 23%, which is in excellent agreement with the expected value. The relative decrease for the test conducted with a strain rate of $9x10^{-4}$ min^{-1} was 4%. The decrease in the RA value at 550°C for a strain rate of $8x10^{-5}$ min^{-1} relative to that at $3x10^{-3}$ min^{-1} (e.g. 42.2% vs. 68.7%) is consistent with data reported by Swindeman and Brinkman (1982).

The ratio of the total elongation, YS and UTS data for the liquid metal tests to those conducted in air are shown in Figure 4; in computing these ratios, the data were averaged where two or more data points were available for the same test conditions. No reduction in ductility or strength was observed for the tensile tests in Cd-Al liquid metal solution relative to the tests in air for either strain rate employed or with the notched specimens. The load-displacement curves for these tests are essentially identical. Therefore, the results of the tensile tests demonstrate that neither Cd nor Cd-Al mixtures embrittle SS304 under the conditions relevant to the safety rod thermal tests or gamma heating accident. This is in agreement with the results from the U-bend tests and literature review (Thomas et al. 1992).

The stress-strain (load-displacement) curves for the tests conducted at temperatures above 500°C with a strain rate of $3x10^{-3}$ min^{-1} are serrated. Serrated flow in austenitic stainless steels in this temperature regime has been widely reported in the literature (Barnby 1965, Jenkins and Smith 1969, and Ruggles and Krempl 1991) and is discussed in Thomas et al. (1992) as it relates to deformation of the safety rod cladding. Serrated flow is caused by the Portevin-LeChatelier phenomenon and related to dynamic strain aging (Reed-Hill 1973 and Dieter 1976); it has also been referred to as "jerky" flow. Dislocation locking by impurities and precipitates, and the subsequent generation of additional dislocations and/or unlocking of dislocations, causes the stress required for plastic flow (e.g. the flow stress) to increase and decrease sharply, thus introducing serrations to the stress-strain curve. Increased flow stresses and work-hardening rates accompany serrated flow. For austenitic stainless steels at relatively low temperatures, serrated flow is caused by carbon (C) atoms interacting with dislocations; at higher temperatures, Cr is sufficiently mobile that chromium carbides can precipitate on dislocation lines. At sufficiently high temperatures, the precipitates form quickly enough that serrated flow is not observed throughout the range of the stress-strain curve. At even higher temperatures, serrated flow is not observed at all. The severity of the effect and range over which it will be observed is dependent on the diffusion rates for Cr and C, which are in turn dependent on vacancy concentration. Therefore, cold-worked steel will exhibit serrated flow more severely and at lower temperatures than annealed steel. The serrations observed in these tests are more severe and occur at lower strains than those typically reported for austenitic stainless steels (Barnby 1965 and Jenkins and Smith 1969). Figures 5, 6, and 7 show the load-displacment curves for the tests conducted at temperatures of 500, 550 and 600°C with a strain rate of $3x10^{-3}$ min^{-1}.

Slow strain rates can also enhance serrated flow since the dislocation line velocity will decrease and hence the required Cr and C diffusion rates will decrease; this will decrease the temperature at which serrated flow is observed. Serrated flow was not observed in the test conducted at 550°C with a strain rate of $8x10^{-5}$ min^{-1}. Serrated flow was observed at 550°C and $9x10^{-4}$ min^{-1}, but ceased near the UTS. These observation support the assertion that the range of serrated flow shifts to lower temepratures for slower strain rates.

3. PRESSURIZED TUBE TESTS

Pressurized tube tests were conducted using safety rod cladding samples in order to verify the high-temperature biaxial ductility of the safety rod cladding and demonstrate the nature of an overpressure failure with this material.

Safety rod cladding samples approximately 10" in length were taken from the non-Cd bearing end of one of the safety rods employed in the safety rod thermal tests; this safety rod is referred to as number 3 in Thomas et al. (1991 and 1992). The measured cladding thickness and diameter were 0.037" and 0.94", respectively, which is in good agreement with the values given in Thomas et al. (1992). Two safety rod cladding samples were tested at a temperature of 550°C; the test temperature was held to within ±3°C over the 6" heated length using a three-zone furnace. The internal pressure was applied using nitrogen gas.

In the first test, the pressure was rapidly increased to failure (tube rupture); the pressure ramp was approximately linear with time. The cladding ruptured at 4200 psi after a 330 sec. pressure ramp time. The hoop strain (ΔD/D) at failure was 15.4% as measured with a clip gauge, while the post-test circumference measurement gave a hoop strain of 16.3%; the clip gauge value was judged to be more reliable since the circumference measurement includes some deformation induced after the rupture occurred. The predicted hoop strain at failure for the test conditions (550°C, 0.03 min^{-1} avg. strain rate, 6% cladding cold work and biaxial loading) was 15% (Thomas et al. 1992), which is in excellent agreement with the experimental value. This test serves to demonstrate the ductility of the cladding and validate the methodology employed to predict failure strain under these conditions.

The hoop stress for thin walled tubing can be expressed as (Rust 1979):

$$\sigma_{\emptyset} = \frac{P\,r}{t} \qquad (1)$$

where: $\sigma_{\emptyset}$ = Hoop stress,
r = Cladding radius, and
t = Cladding thickness.

The engineering hoop stress for a pressure load of 4200 psi and the pre-test safety rod cladding dimensions given above (r = 0.940"/2, t = 0.037") is 53.4 ksi, which is 75% of the 550°C UTS value from the fast strain rate tensile tests. The measured post-test cladding thickness was 30 mils; assuming no plastic axial strain and using the measured post-test cladding circumference gives a cladding thickness of 31 mils.

The second test consisted of a 6 hour exposure at approximately 3480 psi (83% of the rupture pressure from the first test). This loading is representative of those calculated for the safety rod thermal test conditions using a finite element model of the safety rod (Gupta 1991), and the test time bounds the maximum temperature exposure period during the safety rod thermal tests (Thomas et al. 1992). The cladding survived the test without rupture. The measured plastic hoop strain was 3.4%.

Very little creep strain was accumulated during the 6 hour hold period. The creep strain was estimated to be less than 0.2%; the plot of diameter vs. time taken from the clip gauge signal lacks sufficient resolution to accurately determine this value. Equation 1 gives a hoop stress of 48.3 ksi for a pressure load of 3480 psi and the measured post-test dimensions. Using the best estimate creep law for unirradiated SS304 given in Attachment E of Mertz and Thomas (1991), this hoop stress is predicted to result in a creep rate of 9.3×10^{-3} %/hr. The total creep strain accumulated during the test is therefore predicted to be 0.06%, which is approximately a factor of 3 less than the estimated upperbound value based on the experimental data.

4. CONCLUSIONS

No reduction in ductility or strength was observed for the tensile tests in Cd-Al or Cd liquid metal solutions relative to the tests in air. These tests spanned the range of strain rates, temperatures, and loading conditions relevant to the safety rod thermal tests and gamma heating accident. Therefore, the results of the tensile tests demonstrate that neither Cd nor Cd-Al mixtures embrittle SS304 under the conditions relevant to this evaluation. This is in agreement with the results from the U-bend tests and literature review discussed in Thomas et al. (1992). The tensile tests also illustrated the effect of temperature and strain rate of the presence and magnitude of serrations in the stress-strain curve for SS304. The decrease in ductility associated with the slow strain rate tensile tests (8×10^{-5} min^{-1}) is consistent with the predictions made in Thomas et al. (1992).

The pressurized tube burst test demonstrated that the safety rod cladding has good 550°C ductility under high strain rate biaxial loading conditions and that the methodology employed in Thomas et al. (1992) to predict failure strains for cold-worked SS304 under biaxial loading conditions is reasonable. The second pressurized tube test demonstrated that the safety rod cladding could withstand at least 80% of the burst pressure for 6 hours and that little or no creep deformation would be accumulated over this period. This loading and duration bound those of the safety rod thermal tests and provide further verification that the failures observed below 600°C were not solely mechanical in nature.

These tests were conducted at the Westinghouse Science and Technology Center. They were considered scoping in nature and were not carried out under an NRTSC technical procedure; however, the NRTSC experimental QA procedure guidelines were employed where possible. Per NRTSC QAP III-2, the data from these tests do not require qualification for critical applications since they were confirmatory in nature and were not the sole basis for the conclusions reached in the failure evaluation concerning and safety rod cladding ductility and LME susceptibility.

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Table 1 Tensile Test Data.

Spec. No.	Spec. Type	Environ-ment	Strain Rate (min^{-1})	Temp. (°C)	Yield Strength (ksi)	Ultimate Strength (ksi)	Uniform Elong. (%) [a]	Total Elong. (%) [a]	R.A. (%)
5	Smooth	Air	2.2E-2 [b]	325	36.2	76.8	34.5	41.5	70.5
6	Smooth	Air	4.5e-3 [c]	325	40.2	78.6	34.5	41.5	69.6
17	Smooth	Air	3e-03	325	41.6	79.1	33.2	39.0	69.8
19	Smooth	Air	3e-03	325	41.4	79.4	33.2	39.6	70.7
7	Smooth	Air	3e-03	400	34.7	76.5	35.3	42.2	70.1
8	Smooth	Air	3e-03	400	38.3	78.5	35.0	38.5	69.7
9	Smooth	Air	3e-03	500	33.5	74.6	35.0	41.1	67.5
10	Smooth	Air	3e-03	500	33.2	73.8	34.8	38.5	68.0
12	Smooth	Air	3e-03	550	31.3	71.3	31.0	36.3	68.8
14	Smooth	Air	3e-03	550	30.8	71.4	34.3	41.5	68.6
15	Smooth	Air	3e-03	600	32.4	63.1	25.3	38.3	66.2
16	Smooth	Air	3e-03	600	30.6	62.1	26.0	39.2	66.9
38	Smooth	Air	8e-05	550	32.2	60.8	23.6	29.8	42.2
2	Notched	Air	[d]	550	------	91.4	------	------	------
3	Notched	Air	[d]	550	------	90.3	------	------	------
20	Smooth	Cd-Al	3e-03	325	37.9	78.7	36.8	41.8	------
21	Smooth	Cd-Al	3e-03	400	37.9	77.5	35.1	38.8	------
22	Smooth	Cd-Al	3e-03	500	34.3	75.3	33.6	39.9	------
13	Smooth	Cd	3e-03	550	33.3	70.6	30.8	38.1	------
18	Smooth	Cd-Al	3e-03	550	32.2	69.7	33.8	40.7	------
23	Smooth	Cd-Al	3e-03	600	32.2	60.3	26.2	44.3	------
25	Smooth	Cd-Al	9e-04	550	33.3	68.7	31.2	37.7	------
26	Smooth	Cd-Al	8e-05	550	33.8	61.4	24.3	30.2	------
1	Notched	Cd-Al	[d]	550	------	90.6	------	------	------

Notes:
[a] Gauge length = 2", gauge diameter to length ratio = 5.7.
[b] Dummy test, strain rate = 1.3E-4 min^{-1} to 0.025% strain, then 2.2E-2 min^{-1}.
[c] Dummy test, strain rate = 8.0E-3 min^{-1} to 0.8% strain, then 4.5E-3 min^{-1}.
[d] Crosshead speed as for the smooth bar tests with a strain rate of 3E-3 min^{-1}.

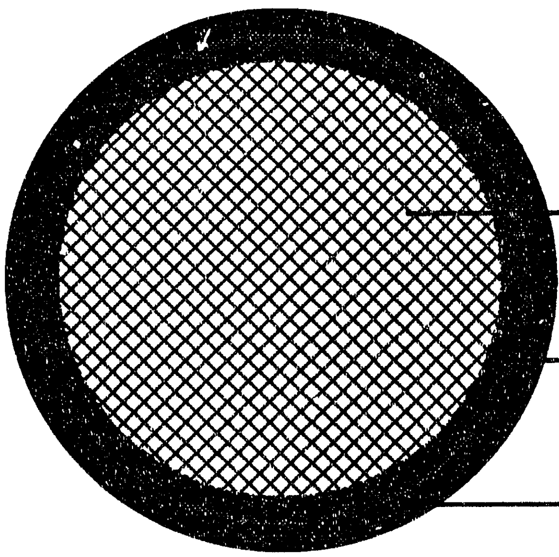

Figure 1 Safety Rod Cross Section.

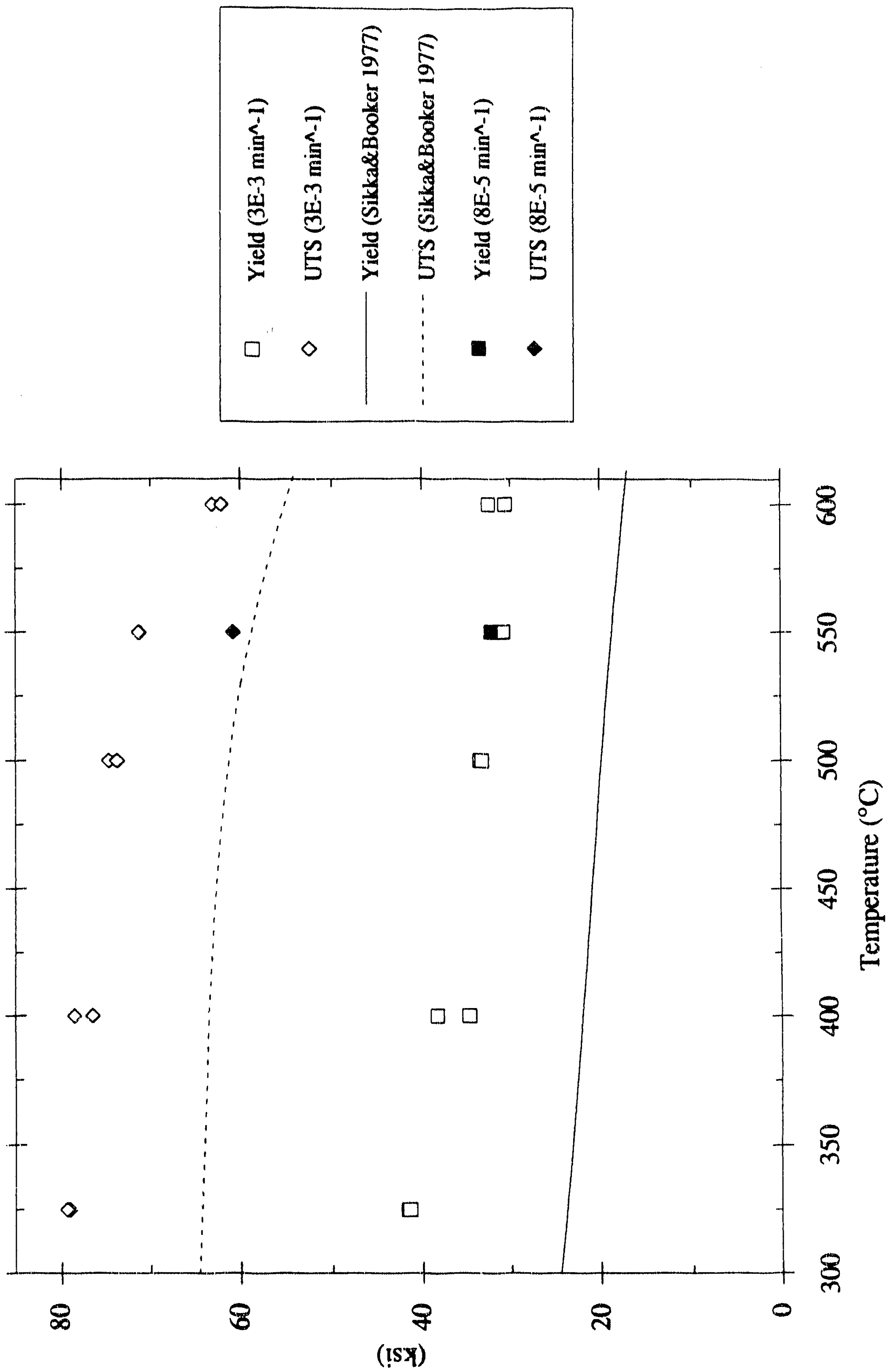

Figure 2 Strength Data (2" gauge length, 0.35" dia.).

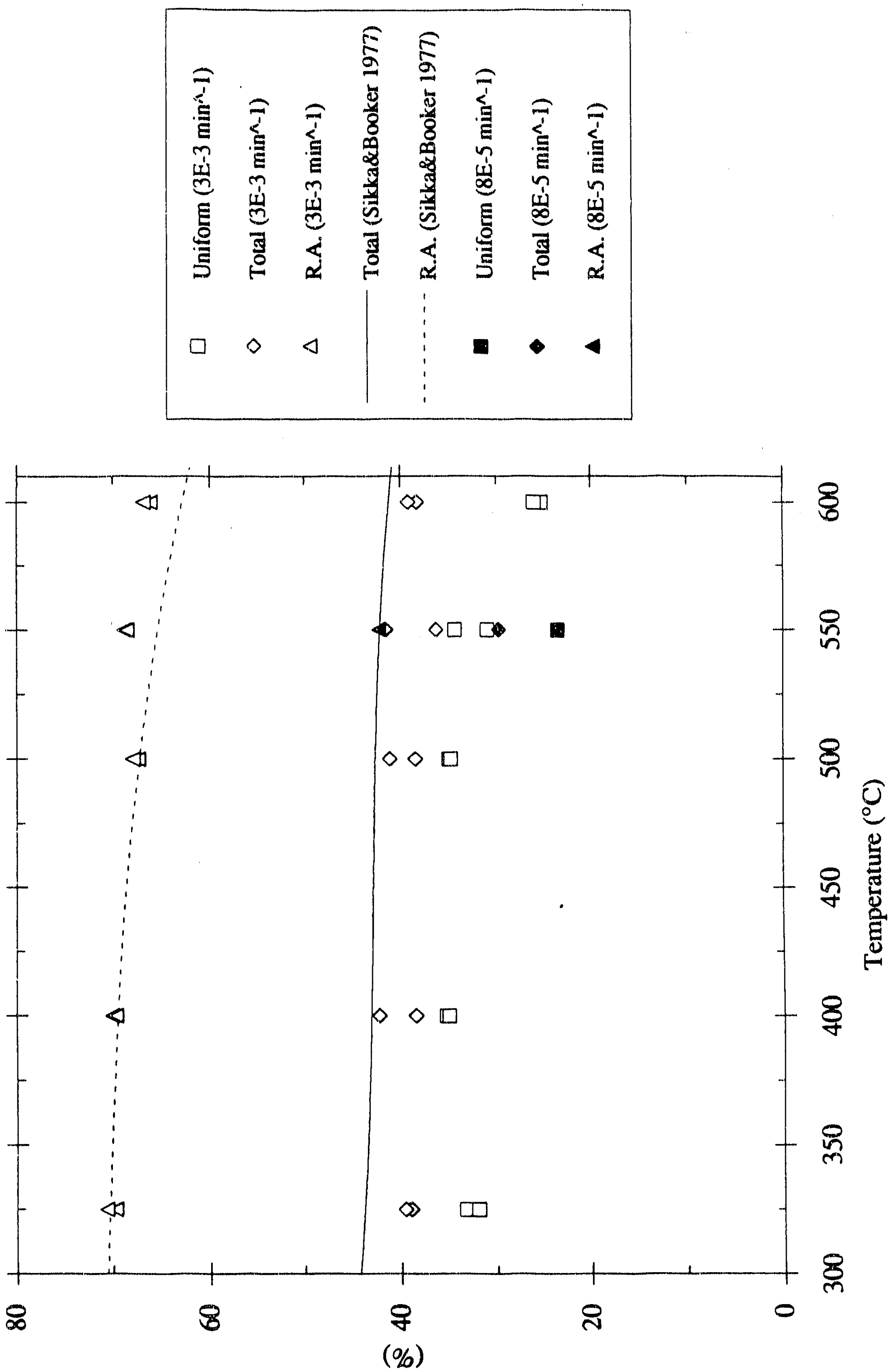

Figure 3 Ductility Data (2" gauge length, 0.35" dia.).

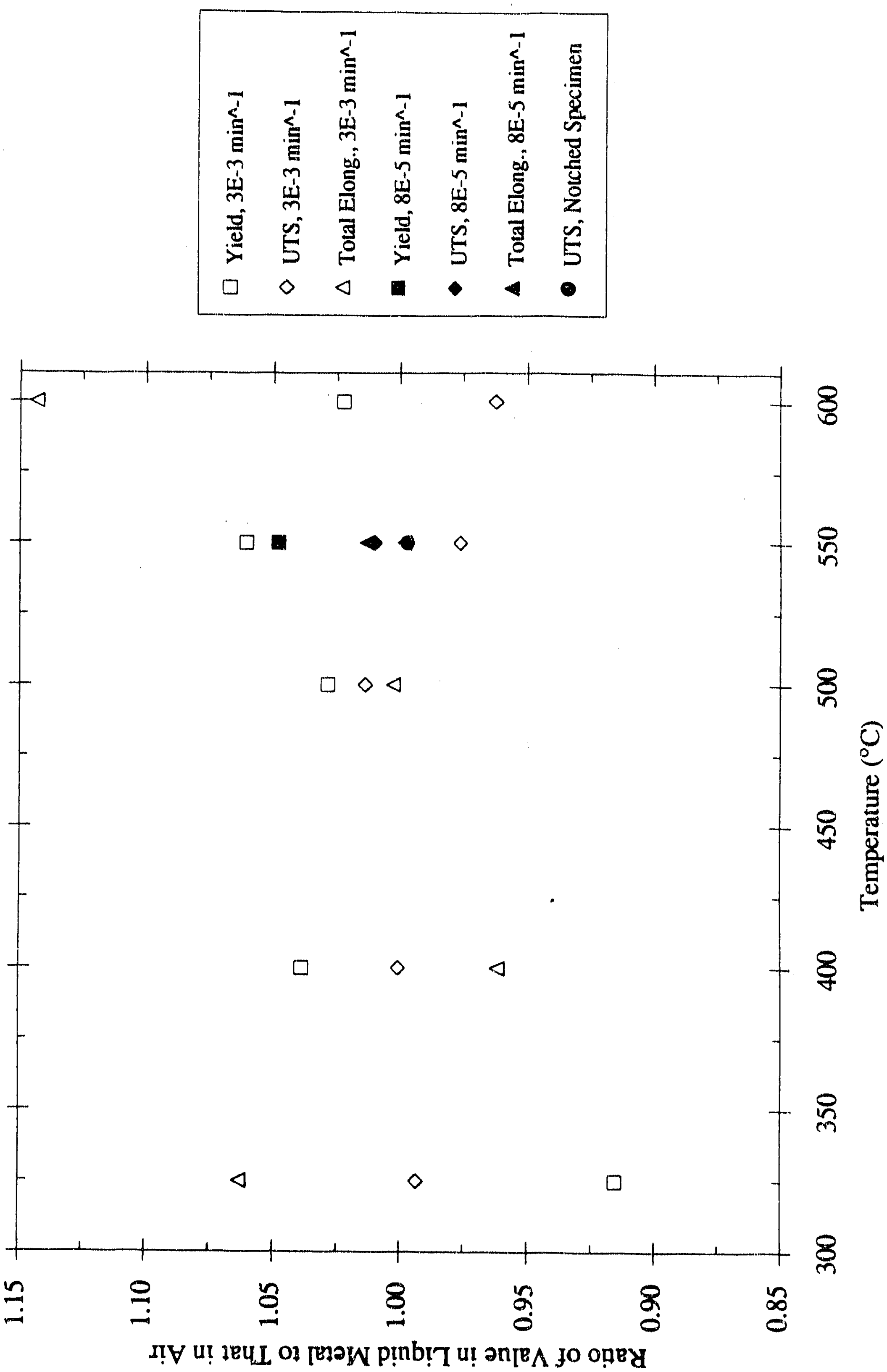

Figure 4 Comparison of Tensile Properties in Liquid Metal and in Air.

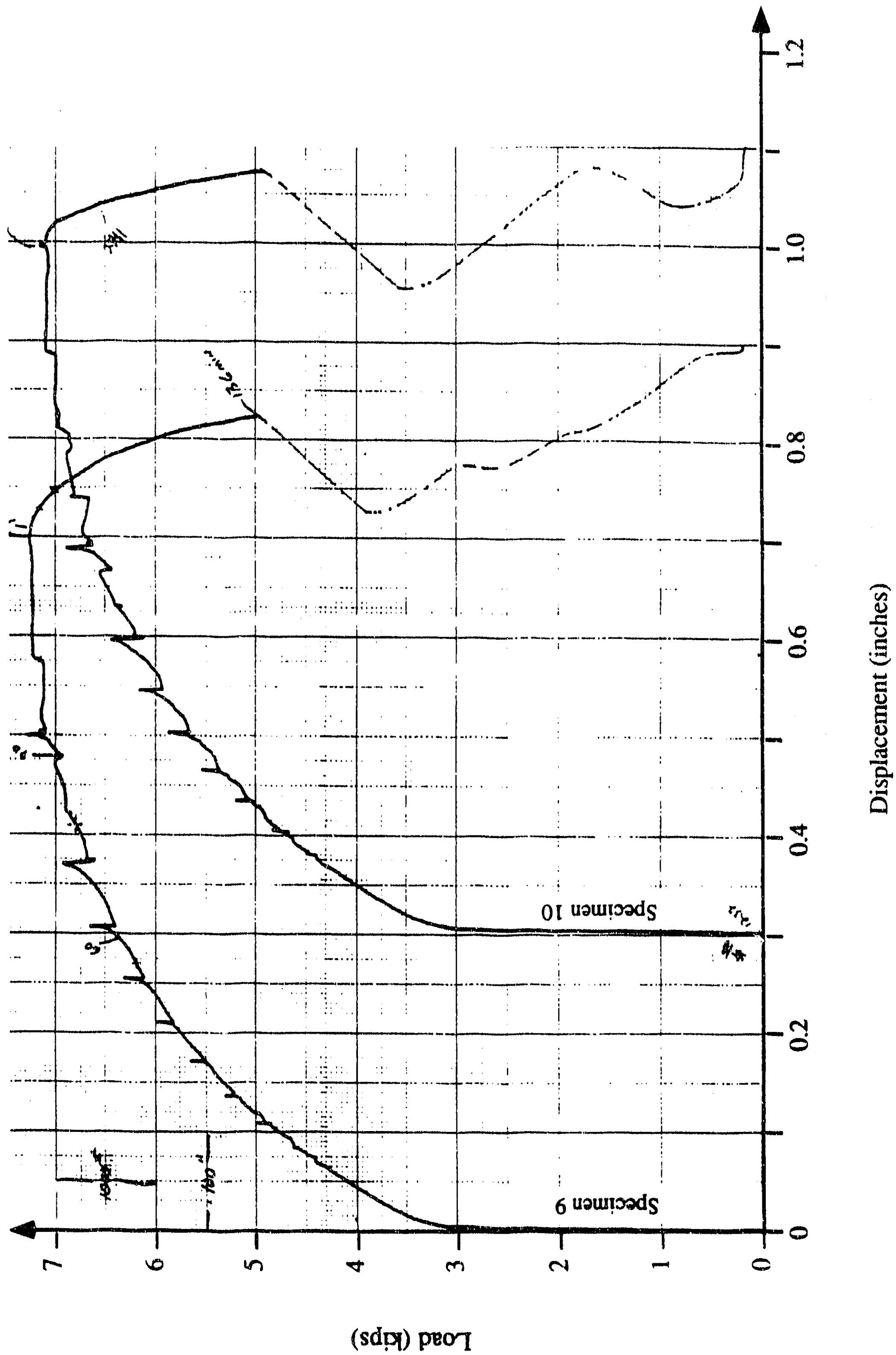

Figure 5 Load-Displacement Curve for Tensile Test in Air at 500°C and 3E-3 min^{-1}.

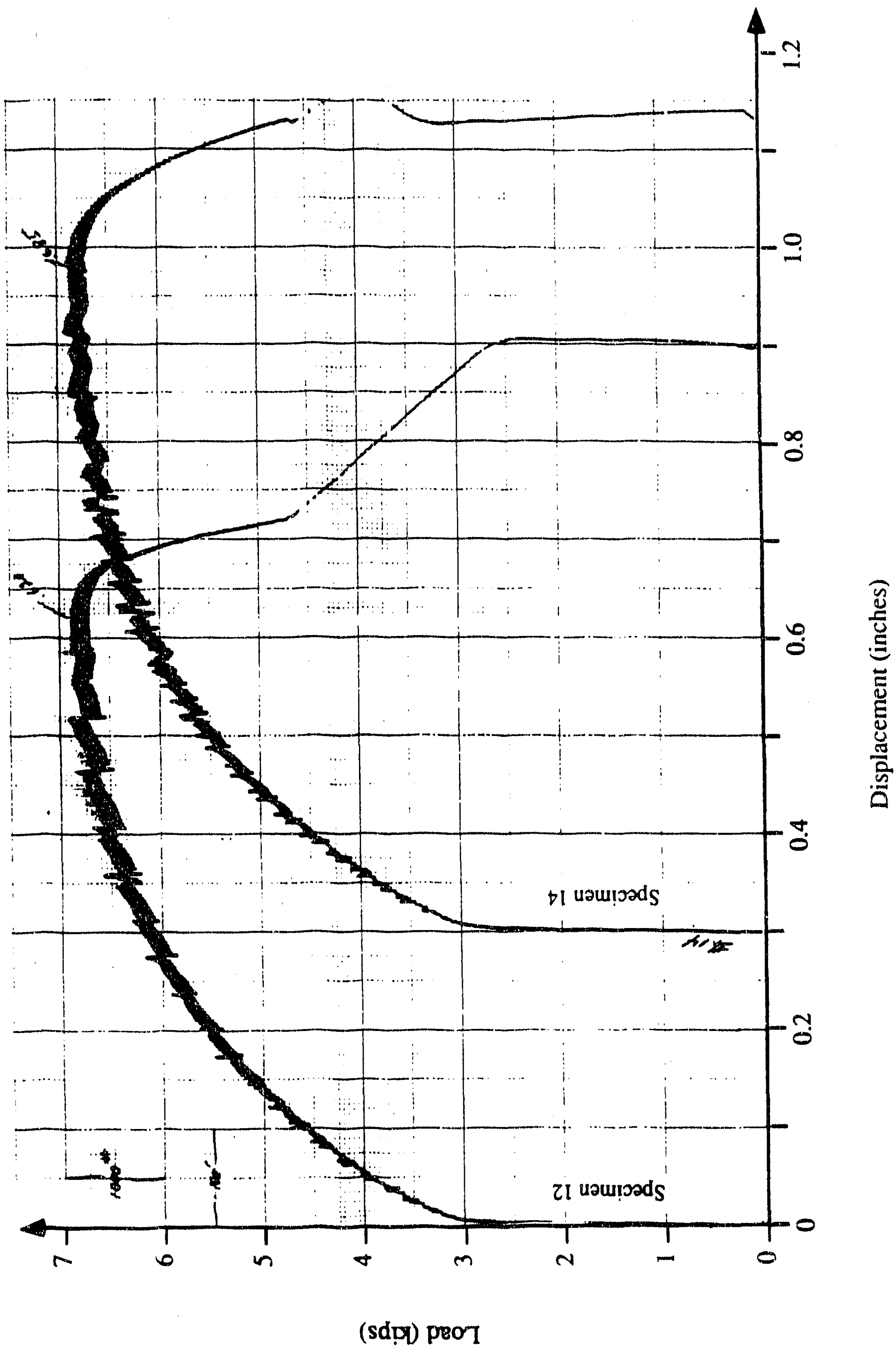

Figure 6 Load-Displacement Curve for Tensile Test in Air at 550°C and 3E-3 min^{-1}.

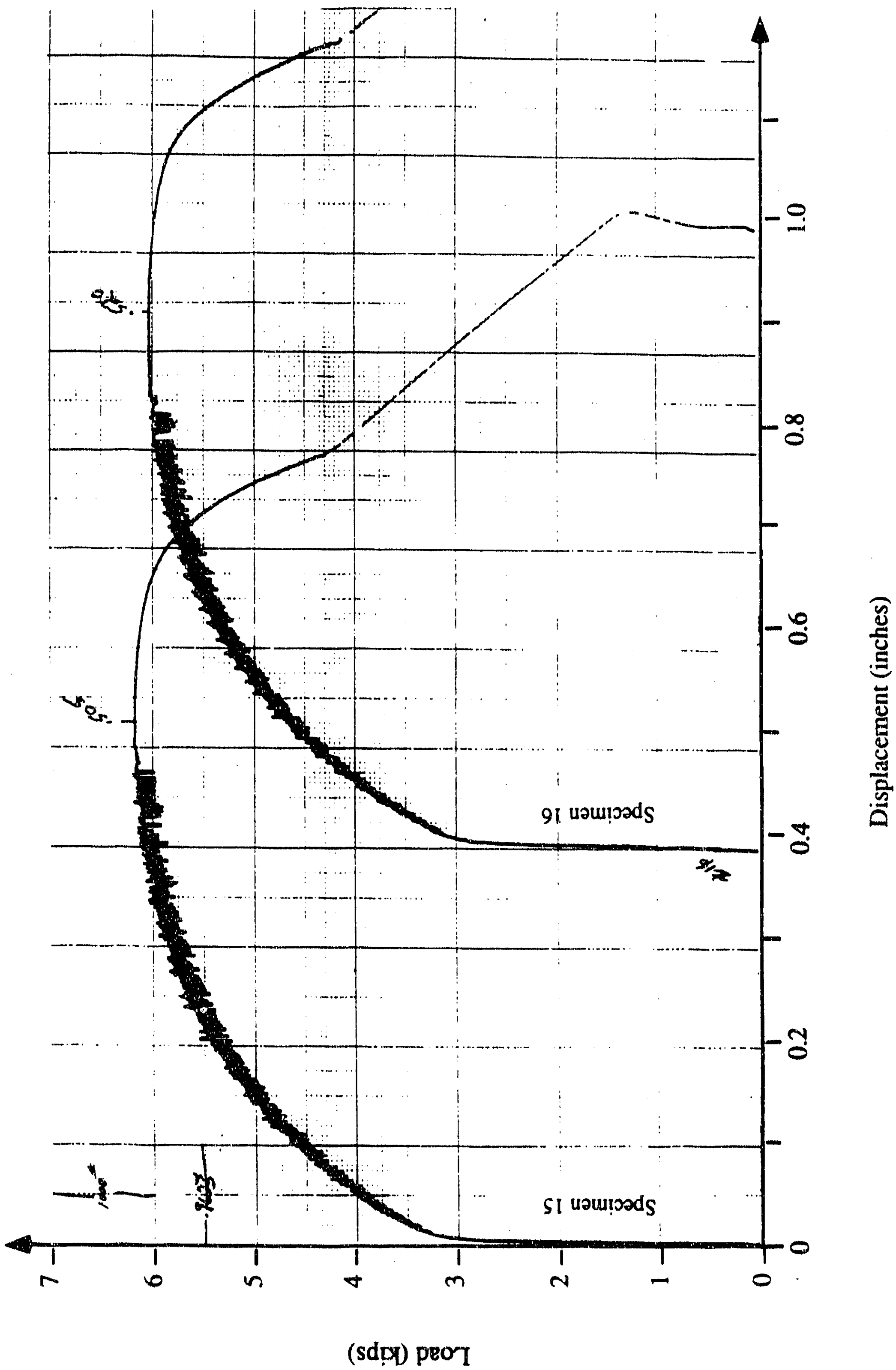

Figure 7 Load-Displacement Curve for Tensile Test in Air at 600°C and 3E-3 min^{-1}.

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CTS-92-001
TENSILE AND BURST TESTS OF TYPE 304 STAINLESS STEEL

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One of the postulated accident scenarios for a heavy water reactor results in the exposure of type 304 stainless steel tubing to both internal pressure and liquid cadmium. To aid in the analysis of this accident scenario, information was needed on the effect of liquid cadmium on the mechanical properties of Type 304 stainless steel with emphasis on the evaluation of the possibility of liquid metal embrittlement. At the request of the Savannah River Laboratory of the Westinghouse Savannah River Company, elevated temperature tensile tests of Type 304 stainless steel were conducted in both air and liquid cadmium. Several tubing burst tests were also conducted. This letter report provides formal transmittal of these laboratory test results. Following paragraphs provide descriptions of the test procedures and test results. Conclusions relative to the significance of this test data are also presented.

Two basic types of tests were conducted, standard tensile tests and tubing burst tests. Smooth bar tensile tests were conducted using threaded end specimens with a gage diameter of 0.350 inches and a 2.00 inch gage length. Several notched bar tensile tests were also performed. In these cases the unnotched diameter was 0.350 inches, the notched diameter was 0.252 inches and the notch root radius was 0.007 inches. The test specimens were machined from 0.625 inch diameter annealed bar. The material certification lists the chemistry as:

C	0.058
Cr	18.32
Ni	8.94
Mn	1.78
Si	0.52
Mo	0.51
Cu	0.40
S	0.14
P	0.028
N	0.09
Fe	balance

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All but two of the tensile tests were conducted at a crosshead speed leading to a strain rate of 3e-3/min. on the 2.0 inch gage length. The other two tests were conducted at a strain rate of 8e-5/min. Load versus crosshead displacement curves were recorded for all tests. A gage length extensometer was used for the tests in air. Elongation values were obtained from the extensometer records and correlated with the cross head displacement records. Crosshead displacement records were used to calculate the elongation of specimens tested in cadmium using the correlation factors determined from the tests in air.

A furnace with three independently controlled zones led to a temperature control of ±2°C at the test temperatures of 325°C, 400°C, 500°C, 550°C and 600°C. For tests in cadmium liquid, a stainless steel cup on the bottom tensile grip held 35 grams of cadmium. In order to match the application of interest, a sleeve of aluminum alloy 6061 lined the inside of the stainless steel cup. The cadmium was molten at the test temperatures and was in contact with the gage length of the tensile specimen at the center of the cup and in contact with the aluminum alloy on the inner diameter of the cup. A stainless steel muffle with O-ring seals for the pullrods contained the cadmium which vaporized in the liquid cadmium tests. This sealed muffle extended several inches beyond the furnace and had water cooled ends. A close fitting vent duct was placed to exhaust any possible release of fumes, although monitoring did not detect any release of cadmium vapor. Tests typically lasted 2 hours. Even with a cap on the top of the stainless steel cup a large vapor loss was noted. The cadmium vapor condensed on the cooler parts of the muffle and pullrod assembly. A small solidified pool of cadmium was observed at the bottom of the stainless steel cup at the completion of the tests. The two tests at the slowest strain rate lasted several days. For these tests a stainless steel bellows was attached to either end of the tensile specimen. This effectively prevented any large loss of cadmium by vapor transport during the test.

Burst tests were conducted on Type 304 stainless steel tubing supplied by SRL. This tubing was archive safety rod cladding with a measured diameter of 0.940 inches and a wall thickness of 0.037 inches. One tube was pressurized to burst and the second tube was held at an internal pressure of 3480 psi for 6 hours. Both tests were conducted at 550°C. A a two zone furnace was used to control the test temperature. The temperature distribution and end fitting design was checked out using a dummy specimen. The tube specimens were 9.5 inches in length. The central 6 inches of the specimens were maintained at temperature to within ±3°C. Nitrogen gas controlled by a gas bottle regulator was used to supply the internal pressure. Pressure versus time and pressure versus diameter measurements were recorded autographically. Diameter measurements were accomplished by mounting a clip gage across the specimen diameter. Quartz rods contacted the specimen and extended outside of the furnace to contact the legs of the external clip gage. Tensile and burst test results are presented below.

Tensile test results are listed in Table 1. Values for ultimate strength and elongation are reasonably typical for Type 304 stainless steel. Yield strength levels are higher than expected for material certified as annealed at 1950°F. Some cold work, probably from a straightening process, is the likely cause of the small increase in yield strength. A small degree of cold work is actually in better agreement with the condition of the safety rod cladding which was cold worked a small amount on to the cadmium and aluminum core. There is no difference in the strength and ductility properties between tests in air and tests in cadmium. Tests at a very slow strain rate did reduce the elongation but this occurred in both air and cadmium environments. Figure 1 provides a graphic illustration of the equivalent ductility in air and cadmium tests. Here the ratio of elongation of tests in the cadmium environment to tests in air is plotted versus temperature. This ratio is essentially unity, regardless of the test temperature. No evidence of liquid metal embrittlement is evident.

One tube of Type 304 stainless steel was pressurized to burst at 550°C. The total test duration was about 6 minutes. The rate of expansion of the tube diameter was roughly linear in time. Burst occurred at a pressure of 4200 psi. This was in accordance with expectations. The hoop strain at burst was 15.4% as measured from the pressure-diameter chart. This parameter was 16.3% from post test measurement of the tube circumference. The deformed nature of the tube at burst made measurements difficult. The chart value of hoop strain at burst is considered more reliable. The second tube specimen was pressurized to 3480 psi at 550°C. Upon pressurization a hoop strain of 3.4% developed. The pressure was maintained at 3480 psi for 6 hours. The increase in hoop strain during this time period due to time dependent deformation was less than 0.2%. This is very small compared to the level required for burst.

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Conclusions relative to the tensile and burst tests are relatively straightforward. There was no indication of liquid metal embrittlement of Type 304 stainless steel by cadmium. Tensile properties in air and liquid cadmium over the temperature range of 325°C to 600°C are essentially identical. The burst pressure of the Type 304 safety rod cladding at 550°C was 4200 psi and hold time effects up to 6 hours will not substantially change the burst pressure.

J. A. Begley
Corrosion Technology

JAB/maf

Attachments

cc: N. G. Awadalla, SRL
R. J. Jacko, STC

Table 1

Tensile Test Results

Specimen	Test Temp.,°C	Environment	Strain Rate,min^{-1}	Specimen Type	Ultimate Strength	Yield Strength	Total Elong.	Uniform Elong.	Reduction of Area,%
5	325	Air	2.2e-02	Smooth	76.81	36.20	41.5	34.5	70.5
6	325	Air	5.4e-02[a]	Smooth	78.61	40.21	41.5	34.5	69.6
7	400	Air	3e-03	Smooth	76.48	34.72	42.2	35.3	70.1
8	400	Air	3e-03	Smooth	78.51	38.41	38.5	35.0	69.7
9	500	Air	3e-03	Smooth	74.62	33.46	41.1	35.0	67.5
10	500	Air	3e-03	Smooth	73.80	33.24	38.5	34.8	68.0
12	550	Air	3e-03	Smooth	71.31	31.26	36.3	31.0	68.8
14	550	Air	3e-03	Smooth	71.41	30.77	41.4	34.3	68.6
15	600	Air	3e-03	Smooth	63.14	32.43	38.3	25.3	66.2
16	600	Air	3e-03	Smooth	62.11	30.59	39.2	26.0	66.9
17	325	Air	3e-03	Smooth	79.06	41.55	39.0	33.2	69.8
19	325	Air	3e-03	Smooth	79.37	41.37	39.6	33.2	70.7
38	550	Air	8e-05	Smooth	60.81	32.22	29.8	-	-
2	550	Air	b	Notched	91.37	-	-	-	-
3	550	Air	b	Notched	90.31	-	-	-	-
13	550	Cadmium	3e-03	Smooth	70.57	33.26	38.1		
18	550	Cadmium-Al	3e-03	Smooth	69.74	32.22	40.7		
20	325	Cadmium-Al	3e-03	Smooth	78.68	37.94	41.8		
21	400	Cadmium-Al	3e-03	Smooth	77.54	37.94	38.8		
22	500	Cadmium-Al	3e-03	Smooth	75.25	34.30	39.9		
23	600	Cadmium-Al	3e-03	Smooth	60.28	32.22	44.3		
25	550	Cadmium-Al	3e-03	Smooth	68.70	33.26	37.7		
26	550	Cadmium-Al	8e-05	Smooth	61.43	33.78	30.2		
1	550	Cadmium-Al	b	Notched	90.58	-	-		

[a] strain rate of 5.43-02 min.$^{-1}$ to 1% strain, 4.5e-03 min.$^{-1}$ thereafter.

[b] tested at same crosshead speed as smooth bar tests with a strain rate of 3e-03 min.$^{-1}$.

ATTACHMENT B

Portion of Workscope for Interworks Requisition 96472-0897742 Dealing with Burst and Tensile Tests (Rev.1, 3/92)

2.0 WORK SCOPE FOR BURST AND TENSILE TESTS

Westinghouse Savannah River Company (WSRC), through the Savannah River Laboratory (SRL), is currently evaluating the time-temperature response of safety rod materials in support of the Reactor Restart Division. WS&TC (J. A. Begley) is requested to provide the following experiments and evaluations in support of this evaluation:

2.1 Type 304 Stainless Steel Tensile Tests

These tests are intended to determine the susceptibility of SS304 to LME embrittlement by cadmium (Cd) or cadmium-aluminum (Cd-Al) liquid metal solutions. Details of this evaluation are given below:

(i) Test Conditions

- The tests to be conducted are summarized in the table below.

Test	Temp. (°C)	Environ-ment	Strain Rate (min^{-1})	Specimen .Type	No. Tests
1	325	Air	≈ 3E-3	Smooth	2
2	400	"	"	"	"
3	500	"	"	"	"
4	550	"	"	"	"
5	600	"	"	"	"
6	325	Cd-Al	"	"	1
7	400	"	"	"	"
8	500	"	"	"	"
9a	550	Cd	"	"	"
9b	550	Cd-Al	"	"	"
10	600	"	"	"	"
11	550	Air	"	Notched	2
12	"	Cd-Al	"	"	1
13	"	Air	≈ 8E-5	Smooth	"
14	"	Cd-Al	"	"	"

- An air environment may be employed in the oven employed to heat the test specimens to the desired temperature.
- Two specimens are to be used for each test in air at a strain rate of 3E-3 min^{-1} (total of 21 specimens).

<u>(ii) Test Specimens and Equipment</u>

- STC will provide the test specimens all other hardware necessary to conduct the tests.
- Standard 0.350 inch diameter tensile specimens composed of Type 304 stainless steel should be employed. The specimens are to be manufactured from mill annealed bar stock.
- For the test to be conducted in Cd or Cd-Al, this may be accomplished by encapsulating pieces of Cd or (Cd and Al) with the specimen. Other techniques which ensure the desired liquid metal solution is kept in contact with the specimen surface throughout the test will also be acceptable
- The specimens may be heated using a muffle furnace.

<u>(iii) Data Monitoring and Acquisition</u>

- The load and crosshead displacement should be recorded throughout the test in order to construct a standard stress-strain curve.
- All measuring equipment employed must be calibrated; the calibration records are to be provided to SRL as part of the deliverables package.

<u>(iv) Documentation</u>

- A letter report should be provided which describes the experiments and results. Standard tensile properties (e.g. elastic properties, yield strength, ultimate strength, elongation at failure, uniform elongation) should be reported for all tests.
- In addition to (or as part of) the letter report, the following documentation should be transmitted to SRL: all raw data (stress-strain curves), copies of calibration records for measurement devices, photographs of the test set up, and any other information deemed relevant by STC.

2.2 Pressurized Cladding Burst Tests

These tests are intended to illustrate the response of the safety rod cladding to a pure mechanical overpressure in the absence of environmental interaction. Two pressurized cladding burst tests are to conducted using sections of cladding supplied by SRL. Details of this evaluation are given below:

(i) Test Conditions

- Test temperature should be 550°C.
- An inert gas should be employed as the pressurizing medium. Argon gas is acceptable for this purpose.
- The first test is to be conducted by increasing the cladding internal pressure monotonically until failure (cladding rupture) occurs. The rate of pressure increase should be such that failure occurs within 30 minutes of test initiation.
- The first test is to be conducted by pressurizing the cladding to approximately 80% of the burst pressure from the first test and holding at pressure for 6 hours.

(ii) Test Specimens and Equipment

- SRL will provide the safety rod cladding sections to be tested. The cladding is made of Type 304 stainless steel and is approximately 37 mils thick and has a 0.94" outer diameter.
- STC will provide all other hardware necessary to conduct the tests.

(iii) Data Monitoring and Acquisition

- The cladding diameter and test pressure are to be recorded throughout the test.
- All measuring equipment employed must be calibrated; the calibration records are to be provided to SRL as part of the deliverables package.

(iv) Documentation

- A letter report should be provided which describes the experiments and results.
- In addition to (or as part of) the letter report, the following documentation should be transmitted to SRL: all raw data (pressure and cladding diameter as a function of time), copies of calibration records for measurement devices, photographs of the test set up, and any other information deemed relevant by STC.

2.3 DELIVERABLES

2.3.1 Technical Reports:

The experiments identified in this work scope shall be documented in a brief letter report; the minimum content of these reports was given above. The report will be issued within 2 weeks after completion of the the tests.

The work contained in this work scope will complement in-house work in support of critical applications. Hence all work shall be in accordance with (W) Q/A procedures, if such procedures exist and are employed at WSTC. In absence of such formal procedures, the following minimum requirements will be met:

- all measurement equipment shall be calibrated.
- all documentation relative to the tests shall be retained; these are to be delivered to SRL at the conclusion of the work.

The test specimens employed for both the tensile and pressurized cladding tests are to be returned to SRL at the completion of the work so that more detailed examinations may be conducted.

2.4 CONTACTS

Jim Begley will be the STC program coordinator. The contacts for this task and the recipients for the draft and final letter reports at Westinghouse Savannah River Company, Savannah River Laboratory are:

Kelly Thomas	(803) 725-2922
Natraj Iyer	(803) 725-2695
Bill Awadalla	(803) 725-3850

2.5 SCHEDULE

The burst and tensile test experiments will be completed within six months following initiation of the experiments. A report documenting the experiments and results will be delivered to SRL within two weeks following completion of the experiments.

END

DATE FILMED

7 / 28 / 92