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COOLING TUBES: MONOTONIC AND CYCLIC SHEAR TESTS FINAL REPORT

by

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ABSTRACT

In the prestressed concrete reactor vessel (PCRV), cooling tubes are welded on the concrete side of the cavity liners. These cooling tubes are placed at pitches determined by the design temperature limits of the liner/concrete interface and are subject to shear loading resulting from prestressing, pressurization, temperature, and creep of the PCRV. This test program consists of both monotonic and cyclic testing of models simulating prototype cooling tube/concrete assemblies. The Phase III tests determined the stiffness characteristics and failure modes of four possible cooling tube configurations having round and square cross sections. A comparison with the previously obtained results of the Phase I and Phase II tests on 1-in. x 1-in. square tubes is also included.

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FIGURES

FIGURES (continued)

FIGURES (continued)

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TABLES (continued)

1. INTRODUCTION

The cavities in a prestressed concrete reactor vessel (PCRV) are lined with a steel membrane which provides an impermeable barrier between reactor primary coolant and the concrete structure. Cooling tubes are continuously welded on the concrete side of the cavity liners at a pitch controlled by the design temperature limits of the backing concrete. These cooling tubes are subject to shear loading from the following potential sources:

1. Noncyclic Loading:

   a. PCRV prestressing; developing strain gradients in the liner due to cavity distortion.

   b. Time effects of concrete creep due to prestress loading; which causes additional liner strain gradients.

   c. Liner discontinuities; geometrical and yield strength differences between adjacent liner panels.

2. Cyclic Loading:

   a. PCRV pressurization and depressurization due to reactor operation.

   b. PCRV temperature variation due to reactor operation.

The tests reported here represent Phase III of the General Atomic (GA) cooling tube shear test program. The specimens used model a segment of the prototype liner consisting of a 3/4-in.-thick liner, a backing concrete block, and a cooling tube welded to the liner and embedded in the concrete. Four different cooling tube configurations, two round-tube and two square-tube cross sections were used in the test program. Specimen loading consisted of monotonic shear loading to failure and displacement-controlled cyclic shear loading.

The Phase I and Phase II tests (Ref. 1) were performed on a cooling tube having 1-in. x 1-in. square cross section. The Phase I tests were conducted on single-plate specimens with coolant tubes welded on both sides of the liner plate and the assembly cast in concrete. The Phase II tests were conducted using double-plate specimens having two plate/cooling tube specimens cast in one block of concrete with a gap of $\sim$1 in. between them.

2. TEST PURPOSE AND PROGRAM

The purpose of the Phase III tests is to provide design information on four different cooling tube configurations that may be used in the prototype vessel. The four different cooling tube configurations consist of two round cross section (1 in. Schedule 40, and 1-1/4 in. Schedule 40) and two square cross section (1-1/4 in. x 1-1/4 in. x 1/8 in., and 1-1/2 in. x 1-1/2 in. x 1/8 in.) tubes. The following items are included in the study.

1. Load/displacement curves are developed from the monotonic tests. These curves are used to establish the stiffness characteristics of the embedded cooling tubes.

2. The monotonic tests are also used to develop the ultimate displacement characteristics and failure mode of the tested geometry. The ultimate displacements obtained are to be used to establish the shear displacement allowables per ASME Section III, Division 2.

3. Displacement-controlled cyclic tests are performed to determine the effect of cyclic loading on stiffness characteristics, ultimate displacement, and failure mode of the cooling tubes.

The cooling tube shear tests performed are listed in Table 1 (Ref. 2); the test sequence and dates are listed in Table 2.

3. TEST SETUP AND LOADING

Twelve specimens were tested in this program. Each specimen modeled an 8-in.-wide liner/cooling tube prototype assembly. A 16-in.-long tube was used, with the central 8-in. section welded to a 3/4-in.-thick steel plate. The 8-in. length was used as the test section, while the 4-in. length on each side of the test section was isolated from the concrete by styrofoam. This configuration was used to eliminate the stiffening effect of the welded end caps of the tube from the test section and to prevent a leak source that was recorded in the Phase II test program. The cooling tube material, the cooling tube welding procedure, and the casing of concrete are described in Appendices A, B, and C, respectively. The cooling tube specimen is shown in Fig. 1. The two bolts shown in the figure were used to minimize relative movements between the cooling tube and concrete during specimen handling. These bolts were removed after the specimen was placed in the loading fixture.

The test fixture and the hydraulic jack used to apply the shear load to the specimen are shown in Fig. 2. Details of the hydraulic system, controls, and instrumentation data center are described in Appendix D. The needle control valves shown in Fig. D-4 were added after the first tests (specimen 3). The test performed on specimen 3 was loaded by a start/stop method because the loading rate could not be reduced to the specified level. The valves were required to limit the hydraulic fluid flow and, therefore, produce the desired loading rate.

To simulate the actual prototype condition, prestressing was applied to each specimen prior to testing. To accomplish this, the specimen was placed in the test fixture and three prestressing rods were inserted in the PVC pipes (Fig. 1). The prestressing load was then applied on each of the rods by tightening the end nuts to produce the specified value of 32,000 lb. This loading produced approximately 600 psi average compression in the concrete. After the initial specified prestressing had been reached, the test fixture end plates were tightened in place to prevent the preload in the specimen from relaxing (see Fig. D-1). The prestressing load on each specimen is listed in Table 3.

The cooling tube of each specimen was pressurized to approximately 20 to 25 psig. This pressure was monitored and a limit switch was used to shut down the test when the pressure dropped to 15 psig. Inability of the tube to hold pressure was defined as failure.

A specimen plate holddown fixture limited the liner/concrete separation. The holddown fixture was instrumented to monitor the separating load and displacement developed with the increased shear displacement. The holddown configuration in this first test (specimen 3) consisted of one 8-in. bar directly above the test section of the tube (Fig. 3). After the testing of specimen 3, a change was made to a two-line contact holddown (Fig. 3). The new arrangement simulated the prototype anchor stud restraint. The contact lines were 2 in. long and located approximately 3 in. from the centerline of the tested tube length on both sides of the centerline. The clearance provided between the holddown fixture and the specimen was also changed from 0.020 in. to zero, and ribs were added to increase the fixture stiffness. The holddown fixtures used for various specimens are listed in Table 4.

4. TEST RESULTS

4.1. MONOTONIC TESTS

The load/displacement results of the monotonic tests are shown graphically in Figs. 3 through 6 and in tabular form in Tables 3 through 12. Figures 3 through 6 also illustrate the vertical displacement of each cooling tube specimen as recorded by the vertical displacement transducer shown in Fig. 2. A summary of the monotonic shear test results listing ultimate displacement, type of failure, and maximum normal load developed is given in Table 13. Photographs of the concrete damage and tube distortion for each specimen are given in Figs. 7 through 18. The typical mode of tube failure was a tear in the tubing material just above the filler weld, as shown in Fig. 15.

The results obtained for specimen 3 (the first in the test sequence) were significantly different from those for the remaining specimens. One factor that probably contributed to this difference in behavior was the start/stop loading used in specimen 3. However, the major contributor is assumed to be the degree of restraint offered by the two holddown fixtures, which were described in the previous section. The ultimate displacement increased from 0.059 in. for specimen 3 (using the single contact over the tube test section) to an average value of 0.37 in. for 10 specimens using the double contact restraint simulating the prototype anchor restraint. The mode of failure changed from concrete shear (specimen 3) to a tube crack causing a pressure drop and an automatic test shutdown.

The cooling tube stiffness characteristics were defined using the initial portion of the load/displacement curves, as shown in Figs. 19 and 20. The slope of the chord connecting the origin and the point on the curve corresponding to 0.002 in. displacement was arbitrarily chosen to represent the initial stiffness of each cooling tube. The calculated initial stiffness values are listed in Table 14 along with a second slope defined to represent the load/displacement curves of the tested tubes from 0.002 in. to 0.010 in. displacement.

The load/displacement test results for specimen 8 showed a marked difference from those of the similar specimen 7 (Fig. 6). This difference is particularly obvious in the expanded scale of Fig. 20 (in the initial displacement range). Some possible explanations for this difference in behavior are: (1) material yield strength differences between the tubes, (2) free movement between the tube and the concrete, and (3) different concrete response. A difference in material yield strength was suggested because of the difficulty experienced in the annealing process, where a large variation in yield strength was obtained with relatively small changes in annealing time and/or temperature, as described in Appendix A. A tensile test was performed on sections cut from the tested cooling tubes to assure that the same annealing effects were obtained in both specimens (7 and 8). The tensile test results (Table 15) indicated that both tubes received the same annealing treatments in that they produced approximately the same mechanical properties. This observation eliminates the difference in yield strength as a possible cause for the relatively low load/displacement curve of specimen 8, leaving the free motion and different concrete response as the possible causes. However, it is not understood why specimen 8 was the only specimen for which this phenomenon occurred.

Under monotonic loading, both the square and round cross section tubes showed similar initial stiffness. The ultimate displacements of the round and square cross section tubes were also similar, with the round tube having a slightly higher average ultimate displacement. None of the tubes showed a decrease in load for displacements up to and including the ultimate displacement.

4.2. CYCLIC TESTS

The test performed on specimens 9 through 12 was a combined cyclic and monotonic test. The cyclic test was conducted for 8000 cycles with stepped increases in displacement amplitude at 2000-cycle increments (Table 1). This was followed by a monotonic test to failure. An electronic control device failed during the initial cycling of specimen 12, causing premature failure of the specimen. Therefore, no information was collected for specimen 12.

The load relaxation curves and the hysteresis curves for the first cycle of each specified displacement amplitude for specimen 9 are shown in Figs. 21 through 25. The load/displacement curves for the monotonic tests, conducted after the cyclic loadings for specimens 9, 10, and 11, are shown in Figs. 26 through 28. The ultimate displacements developed in these specimens were approximately the same as those developed in the monotonic-only tests (Table 13). The initial stiffnesses after cycling, however, were lower than those developed for the same tube configuration in the monotonic-only tests (Table 14). An explanation for the difference in stiffness is that the cyclic loading crushed the concrete locally, thus enabling the cooling tube to deflect more readily. Figures 29 through 32 are photographs showing concrete damage and tube distortion after post-cyclic monotonic loading.

The cyclic stiffness characteristics are listed in Table 16 and shown in Figs. 33 through 35. Specimens 9 and 10, having the same geometry, had a marked difference in first cycle stiffness results. This difference is similar to that between the monotonic-only test results of specimens 7 and 8, although not as large. The first advance and retract loading cycle in the $\pm$0.002-in. cyclic displacement test and the monotonic-only test stiffness are all representative of the initial stiffness characteristics of the cooling tube. That is, the average initial stiffness under cyclic loading of specimens 9 and 10 in both the advance and retract directions is 1.14,* which is in good agreement with the average monotonic stiffness of specimens 1 and 2 at 1.06. Thus, the overall average initial stiffness of the 1-1/4-in. ∅ Schedule 40 tube configuration is 1.11 with a potential variation from 1.94 to 0.58. The cyclic effects on the initial stiffness at each tested amplitude are shown in Figs. 33 through 35.

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*Expressed in millions of pounds per inch of tube per inch of deflection.

5. DISCUSSION

The purpose of this test program was to establish the load/displacement characteristics of four potential prototype liner cooling tube configurations. The tests were structured to develop the monotonic load response of the cooling tube/concrete assembly and to determine the ultimate displacement and failure mode. A cyclic loading test was also performed in a displacement-controlled mode with the amplitude increased in steps. This testing technique was incorporated to determine the effects of cyclic loading on initial stiffness, ultimate deflection, and failure mode.

The cooling tube stiffness depends on the type of concrete, the concrete prestressing level, and the degree that the liner is held against the concrete (i.e., liner stiffness as affected by the anchorage system). The concrete type and strength in these tests were modeled to represent the prototype (Appendix C). The models were also prestressed to the same level expected in the prototype near the liner/concrete interface. Therefore, both the concrete properties and prestressing level were essentially eliminated as parameters in applying the test results to the prototype cooling tubes.

The liner modeled in the test program is representative of flat surface regions of the prototype vessel. The holddown configuration proved to be very important in the ultimate displacement characteristics and failure mode. The holddown fixture used in the majority of the specimens was intended to model the anchoring effect of the studs. The fixture had two contact lines, one on either side of the tested tube at approximately the stud pitch used in the majority of the prototype liner regions. The purpose of using an external device rather than the actual anchor studs was to monitor the normal load developed as a function of the shear displacement.

The prototype liner strain and cyclic variations result from the following loading conditions: (1) prestress and subsequent creep, (2) system startup/shutdown, and (3) system load variations. The prestressing plus creep condition is expected to produce the maximum liner strain and strain gradients resulting in the maximum loads across the cooling tubes. This is a one-time loading, with the majority of the creep movement taking place before vessel startup. The initial monotonic stiffness values are representative of the shear anchorage effect in this loading condition. The cyclic loading resulting from startup/shutdown and system load variations is superposed on the prestressing plus creep condition. The load differentials across the tubes in these cyclic loading cases are relatively small. In a typical cold-liner concept, the liner strain developed from the pressure loading is counteracted by the strains developed from the thermal loading. The net cyclic loading variation is small in comparison to the prestressing plus creep loading condition. The test results shown in Figs. 33 through 35 show that the cooling tube shear stiffness reduces under a cyclic loading condition. It is therefore recommended that a reduced stiffness (from the monotonic results) be used to represent the anchorage effect of the cooling tubes under cyclic loading. Based on the test results, it appears that a 50% stiffness reduction of the monotonic value can be considered conservative.

The test results also indicated that the vertical displacement of the liner plate at the tube location and the corresponding normal load [recorded by the load transducer mounted in the holddown fixture (Tables 5 through 12)] are small in the shear displacement range expected in the prototype.

The Phase I and Phase II test results are consistent with the results obtained from Phase III. The test specimens of Phase I [cooling tubes welded on both sides on a single plate embedded in concrete (see Fig. 36)] and Phase II [double plate specimen with each plate anchored to the backing concrete block with two anchor studs (see Fig. 36)] both used a 1-in. x

1-in. square tube. The Phase I results showed a greater shear stiffness than the Phase II results. The difference in stiffness was similar to that obtained from the different holddown fixture used for specimens 3 and 4 (Fig. 36). This difference in cooling tube anchorage effect is what could be expected between totally constrained geometries of small penetrations and the cavity liners.

The average ultimate displacement of two Phase I specimens was 0.15 in., and the failure mode was a crack in the fillet weld with considerable distortion (Ref. 1). The ultimate displacement of the Phase III specimen 3 was considerably less at 0.059 in., and the failure mode was concrete shear with little or no tube distortion. The difference in the mode of failure and the ultimate displacement may be attributed to the difference in the amount of liftoff permitted.

The average ultimate displacement of the Phase II specimens was 0.090 in. (3 specimens). In all three cases, failure was described as concrete shear allowing liner separation and corresponding tube deformation and causing pressure leakage at the brazed joints at the end of the specimen tube. The photographs of a failed specimen (Ref. 2), however, did not reveal any more concrete damage than the Phase III specimens. The Phase III results suggest that the leaking end caps limited the ultimate displacement of the Phase II specimens. Therefore, the test results are not inconsistent with Phase III.

6. CONCLUSIONS

1. Similar monotonic load/displacement characteristics were observed for all four different cooling tube configurations. The initial stiffness (K_1) ranged from 0.67×10^6 to 1.73×10^6 lb/in. of tube/in., and the ultimate displacement ranged from 0.285 in. to 0.507 in. with an average of 0.37 in.

2. No specimen failure occurred during the cyclic loading tests. These consisted of four displacement-controlled loads of 2000 cycles each with the amplitudes of 0.002 in., 0.004 in., 0.006 in., and 0.008 in.

3. Monotonic tests to failure of the specimen which had been subjected to the cyclic loading described in 2, above, showed that the ultimate displacement and failure modes are approximately the same as those developed in the monotonic-only tests. The initial stiffnesses (K_1) of these specimens, however, are significantly lower than those of the comparable specimens tested under the monotonic-only loading (Table 14).

4. It is recommended that a 50% reduction in the monotonic stiffness be used to represent the anchorage effects of the cooling tubes under cyclic loading.

7. REFERENCES

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8. TABLES

TABLE 1

COOLING TUBE SHEAR TESTS[a]

Loading	Specimen No.	Cooling Tube Configuration	Test Controlled Displacement	Remarks
Monotonic	1, 2	1 1/4 in.Ø	Pull to failure	Apply a unidirectional monotonic shear load on each test specimen until cooling tube failure (tube pressure loss) or gross slippage occurs.
	3, 4	1 in.Ø	Pull to failure	
	5, 6	1 1/2 in.Ø	Pull to failure	
	7, 8	1 1/4 in.Ø	Pull to failure	
Cyclic + Monotonic	9, 10	1 1/4 in.Ø	Cycle according to the following schedule: $\pm$0.002 in. for 2000 cycles; $\pm$0.004 in. for 2000 cycles; $\pm$0.006 in. for 2000 cycles; $\pm$0.008 in. for 2000 cycles. At approximately 8000 cycles, if no failure, reduce load to zero, then apply monotonic load to failure.	Apply monotonic and cyclic shear loads on each test specimen per test procedure until cooling tube failure (tube pressure loss) or gross slippage occurs.
	11, 12	1 1/2 in.Ø		

[a] Data from Ref. 2.

TABLE 2
COOLING TUBE SPECIMEN TEST SEQUENCE

Loading	Specimen No.	Test Sequence	Date Tested
Monotonic	1	3	9/1/78
	2	4	9/6/78
	3	1	8/17/78
	4	2	8/30/78
	5	7	9/20/78
	6	8	9/22/78
	7	5	9/7/78
	8	6	9/18/78
Cyclic + Monotonic	9	9	10/5/78 - 10/19/78
	10	10	10/25/78 - 11/10/78
	11	11	11/15/78 - 12/5/78
	12	12	12/12/78 - 12/13/78

TABLE 3
CONCRETE PRESTRESSING LOAD VALUES BEFORE AND AFTER TEST

Specimen No.	Initial Prestressing Load Cells Values (lb)			Load Cell Values After Test (lb)		
	L5	L7	L9	L5	L7	L9
1	32267	31743	31969	29304	28691	28872
2	31615	31100	31562	30874	30426	30499
3	--[a]	--	--	--	--	--
4	32178	31711	31812	30607	30137	30029
5	32326	31840	31875	30430	30233	29591
6	31941	32000	31906	29867	30169	29654
7	32119	32225	32000	30578	30554	30029
8	31763	31807	31937	30281	31004	30749
9	31941	31968	31875	28414	28209	28403
10	32059	32000	31906	31200	31036	31062
11	31081	32000	31312	29778	30458	30311
12	31940	32161	32094	Test control malfunction		

[a] No record.

TABLE 4
COOLING TUBE TEST FIXTURE HOLDDOWN ARRANGEMENT

Specimen No. (in order tested)	Cooling Tube Configuration	Holddown Configuration	Initial Clearance Between Holddown Fixture and Specimen (in.)
3	1 in. Ø	Line contact over total length of tested tube (∼8 in.)	Loose fit (<0.02)
4	1 in. Ø	Two-line contact simulating anchor studs	↓
1	1-1/4 in. Ø	↓	↓
2	1-1/4 in. Ø	↓	↓
7	1-1/4 in. ⧄	↓	0.010
8	1-1/4 in. ⧄	Stiffners added to holddown fixture	0
5	1-1/2 in. ⧄	↓	0
6	1-1/2 in. ⧄	↓	0
9	1-1/4 in. Ø	↓	0
10	1-1/4 in. Ø	↓	0
11	1-1/2 in. ⧄	↓	0
12	1-1/2 in. ⧄	↓	0

TABLE 5
COOLING TUBE STATIC TEST OF SPECIMEN 1

Horizontal		Vertical	
Displacement (in.)	Load (lb/in. of tube)	Displacement (in.)	Load (lb)
0	0	0	0
--[a]	40	0	0
--	490	0	0
0.0013	2070	0.003	0
0.007	3510	0.013	890
0.0168	4500	0.023	1900
0.025	5360	0.033	2780
0.0644	6086	0.053	6199
0.145	6200	0.098	11950
0.227	5150	Gage removed	15500
0.305	4822	Gage removed	18400
0.39	4830	Gage removed	21000
Failure - tube pressure leak			

[a] Displacement values below range of instrumentation.

TABLE 6
COOLING TUBE STATIC TEST OF SPECIMEN 2

Horizontal		Vertical	
Displacement (in.)	Load (lb/in. of tube)	Displacement (in.)	Load (lb)
0	0	0	0
0.00044	242	0	0
0.00066	1400	0.0001	144
0.0062	2710	0.0044	168
0.013	3680	0.0136	216
0.019	4520	0.0229	760
0.024	5250	0.0305	1920
0.028	5870	0.0372	2690
0.033	6310	0.0427	3364
0.055	6280	0.065	5920
0.087	6030	0.091	9070
0.104	5996	Gage removed	10480
0.202	6253	Gage removed	16891
0.255	5466	Gage removed	19702
0.3	5466	Gage removed	21048
0.41	5450	Gage removed	23280
Failure - tube pressure leak			

TABLE 7
COOLING TUBE STATIC TEST OF SPECIMEN 3

Horizontal		Vertical	
Displacement (in.)	Load (lb/in. of tube)	Displacement (in.)	Load (lb)
0	0	No data because of malfunction in data taking equipment	
0.006	3510		
0.007	3540		
0.0094	4270		
0.011	4630		
0.018	6060		
0.0214	5750		
0.024	6120		
0.03	6840		
0.044	6450		
0.059	6060		
Failure - concrete shear			

TABLE 8
COOLING TUBE STATIC TEST OF SPECIMEN 4

Horizontal		Vertical	
Displacement (in.)	Load (lb/in. of tube)	Displacement (in.)	Load (lb)
--[a]	636	0	0
0.00177	1240	0.0018	0
0.004	1900	0.0107	0
0.007	2500	0.0189	575
0.012	3020	0.0244	900
0.023	4440	0.0295	2955
0.032	5070	0.034	3676
0.041	5390	0.0385	4445
0.053	5300	0.0428	5130
0.183	5170	0.096	11533
0.507	4980	Gage removed	23546
	Failure - tube pressure leak		

[a] Displacement values below range of instrumentation.

TABLE 9
COOLING TUBE STATIC TEST OF SPECIMEN 5

Horizontal		Vertical	
Displacement (in.)	Load (lb/in. of tube)	Displacement (in.)	Load (lb)
0	0	0	0
--[a]	2309	0	24
0.000022	2513	--	--
0.00045	2725	--	48
0.00089	3089	--	72
0.0018	3376	0.0006	204
0.0027	3603	0.0009	312
0.0031	3800	0.0014	457
0.0042	3989	0.0019	600
0.006	4436	0.0126	961
0.0098	5435	0.0157	1826
0.0196	6571	0.022	3772
0.043	5780	0.033	6487
0.101	5720	0.051	10692
0.201	6010	0.074	16531
0.301	5980	0.088	21048
0.345	5750	0.091	22525
	Failure - tube pressure leak		

[a] Displacement values below range of instrumentation.

TABLE 10
COOLING TUBE STATIC TEST OF SPECIMEN 6

Horizontal		Vertical	
Displacement (in.)	Load (lb/in. of tube)	Displacement (in.)	Load (lb)
0	0	0	Equipment malfunctioned
--[a]	1911	--	Equipment malfunctioned
0.00045	2090	--	Equipment malfunctioned
0.00089	2380	--	Equipment malfunctioned
0.0018	2660	--	Equipment malfunctioned
0.0029	3180	--	Equipment malfunctioned
0.0067	4280	0.0058	Equipment malfunctioned
0.0143	5870	0.014	Equipment malfunctioned
0.022	6828	0.021	Equipment malfunctioned
0.0469	5632	0.033	Equipment malfunctioned
0.101	5435	0.056	Equipment malfunctioned
0.135	5480	0.066	14538
0.199	5780	0.081	17950
0.245	6030	0.090	20305
0.302	6070	Gage removed	22804
Failure - tube pressure leak			

[a] Displacement values below range of instrumentation.

TABLE 11
COOLING TUBE STATIC TEST OF SPECIMEN 7

Horizontal		Vertical	
Displacement (in.)	Load (lb/in. of tube)	Displacement (in.)	Load (lb)
0	0	0	0
0.00022	76	0	0
0.00044	863	0	0
0.00155	1600	0	0
0.0029	2200	0	0
0.0058	2680	0.0015	0
0.0095	3430	0.005	360
0.0126	4040	0.009	421
0.016	4570	0.013	781
0.0188	5060	0.017	1260
0.0223	5540	0.02	1862
0.025	5996	0.023	2403
0.057	4560	0.04	4805
0.147	4540	0.073	8867
0.221	4890	0.094	11883
0.335	5260	Gage removed	16016
0.425	5420	Gage removed	19020
Failure - tube pressure leak			

TABLE 12
COOLING TUBE STATIC TEST OF SPECIMEN 8

Horizontal		Vertical	
Displacement (in.)	Load (lb/in. of tube)	Displacement (in.)	Load (lb)
0	0	0	0
--[a]	45	0	0
--	106	0	0
0.0025	197	0	0
0.0045	303	0	48
0.0085	477	0	--
0.014	680	0.0009	240
0.021	1560	0.0018	589
0.025	2695	0.0038	1050
0.03	3510	0.0073	1682
0.035	4040	0.0115	2403
0.056	4100	0.022	3941
0.104	4330	0.041	6921
0.2	4790	0.068	11126
0.309	5270	Gage removed	15283
0.395	5450	Gage removed	18671
Failure - tube pressure leak			

[a] Displacement values below range of instrumentation.

TABLE 13
COOLING TUBE SPECIMEN MONOTONIC TEST RESULTS

Specimen No.	Load Rate (in./min.)	Ultimate Displacement (in.)	Type of Failure	Maximum Vertical Load at End of Test (lb/8 in. of tube)
1	0.012	0.39	Tube pressure leak	21000
2	0.009	0.41	Tube pressure leak	23280
3[a]	Loaded in steps	0.059	Concrete shear	15600 (est.)
4	0.0067	0.507	Tube pressure leak	23546
5	0.007	0.345	Tube pressure leak	22525
6	0.018	0.302	Tube pressure leak	22804
7	0.008	0.425	Tube pressure leak	19020
8	0.009	0.395	Tube pressure leak	18671
9[b]	0.014	0.285	Tube pressure leak	21913
10[b]	0.018	0.325	Tube pressure leak	26189
11[b]	0.048	0.312	Tube pressure leak	21552
12[b]	Deflection control malfunction - no test data			

[a] Used one-piece holddown fixture (Table 4).

[b] After 8000 cycles of increasing amplitude testing.

TABLE 14
COOLING TUBE STIFFNESS CHARACTERISTICS FOR MONOTONIC LOADING

Specimen No.	Specimen Configuration	K_1 [a] (x 10^6 lb/in. of tube/in.)	K_2 Second Slope to Define Stiffness Curve to 0.01 in.
1	1-1/4 in.Ø	1.16	0.19
2	1-1/4 in.Ø	0.95	0.18
3	1 in.Ø	--[b]	--
4	1 in.Ø	0.67	0.19
5	1-1/2 in.⍁	1.73	0.25
6	1-1/2 in.⍁	1.44	0.25
7	1-1/4 in.⍁	0.96	0.2
8	1-1/4 in.⍁	0.1	0.04
9[c]	1-1/4 in.Ø	0.35	0.26
10[c]	1-1/4 in.Ø	0.26	0.25
11[c]	1-1/2 in.⍁	0.78	0.45
12[b]	1-1/2 in.⍁	--[c]	--

[a] See Fig. 19 for definition of slopes.

[b] Did not record.

[c] After ~8000 cycles of increasing amplitude testing - monotonic load to failure.

TABLE 15
TENSILE TEST RESULTS FOR MATERIAL OF SPECIMENS 7 AND 8[a]

Mechanical Property	Specimen 7		Specimen 8	
	Sample 1	Sample 2	Sample 1	Sample 2
Yield strength, psi	25890	--	21413	27149
Ultimate strength, psi	41045	41021	39435	41931
Reduction in area, %	85.6	86.9	87.6	79.7
Elongation, %	28	31	29	28

[a]Tensile coupons were machined from the tubes of the specimens tested.

TABLE 16
COOLING TUBE STIFFNESS CHARACTERISTICS FOR CYCLIC LOADING TESTS

Displacement Amplitude	K_1 (x 10^6 lb/in. of tube/in.)								
	Specimen 9			Specimen 10			Specimen 11		
	Cycles	Retract	Advance	Cycles	Retract	Advance	Cycles	Retract	Advance
±0.002	1	1.94	1.37	1	0.58	0.65	1	1.75	1.35
	19	1.53	1.24	97	0.4	0.59	4	1.38	1.3
				764	0.4	0.47			
				1126	0.4	0.42			
±0.004	2003	1.13	1.19	2026	--	--	2063	1.05	1.2
	2909	0.9	0.85	2050	0.28	0.24	2789	1.0	1.3
	3913	0.7	0.8	3011	0.28	0.28	3250	0.9	1.2
				3701	0.33	0.33			
±0.006	4012	0.9	0.98	4123	0.33	0.35	4081	0.8	0.8
	5186	0.5	0.7				4252	0.85	0.8
							5535	0.85	0.75
±0.008	6026	0.23	0.35	6131	0.23	0.1	6101	0.7	0.5
				6305	0.2	0.13	7032	0.75	0.55
				6780	0.21	0.1	7618	0.7	0.6
				8020	0.2	0.1			

9. FIGURES

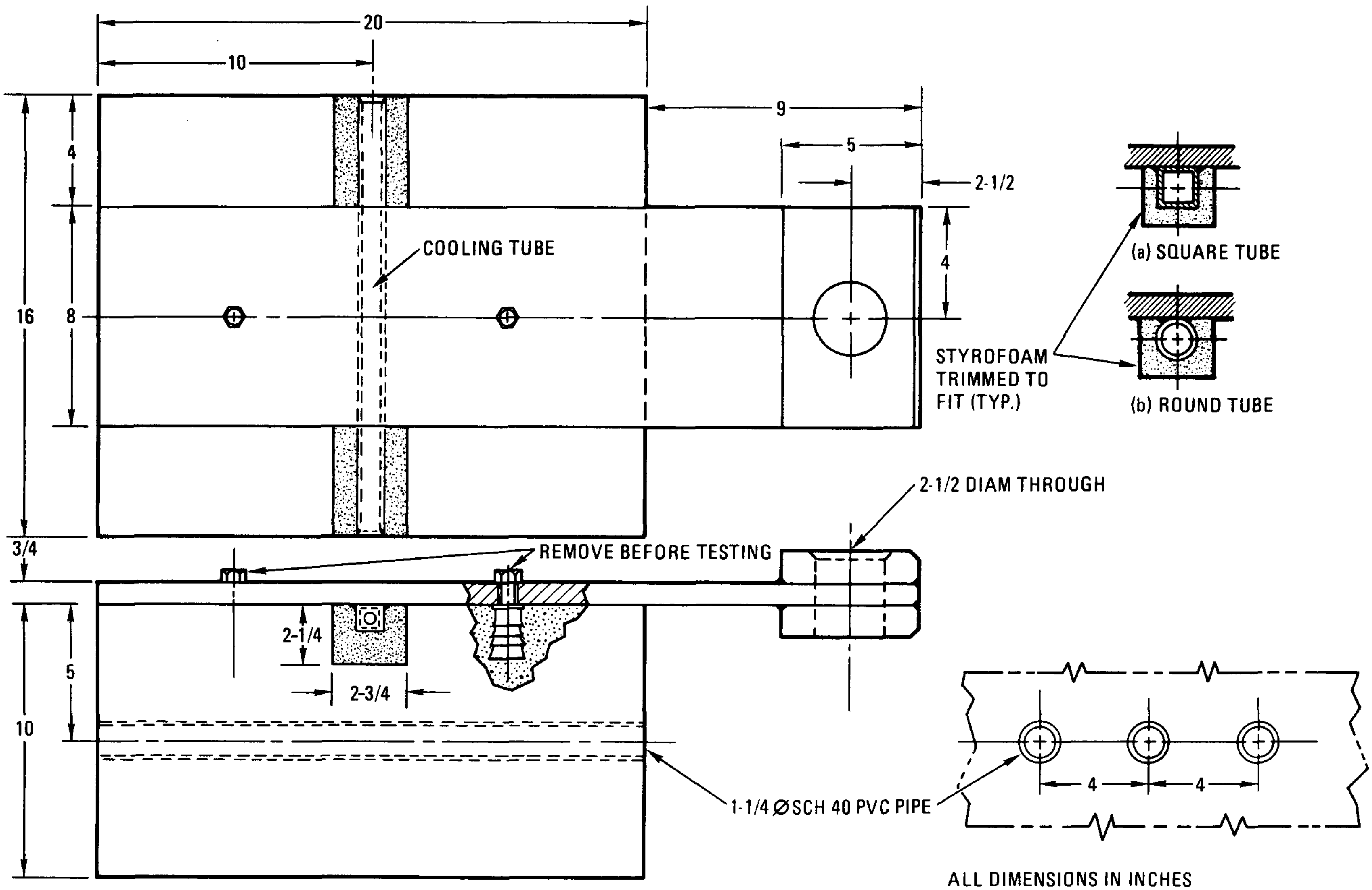


Fig. 1. Cooling tube specimen

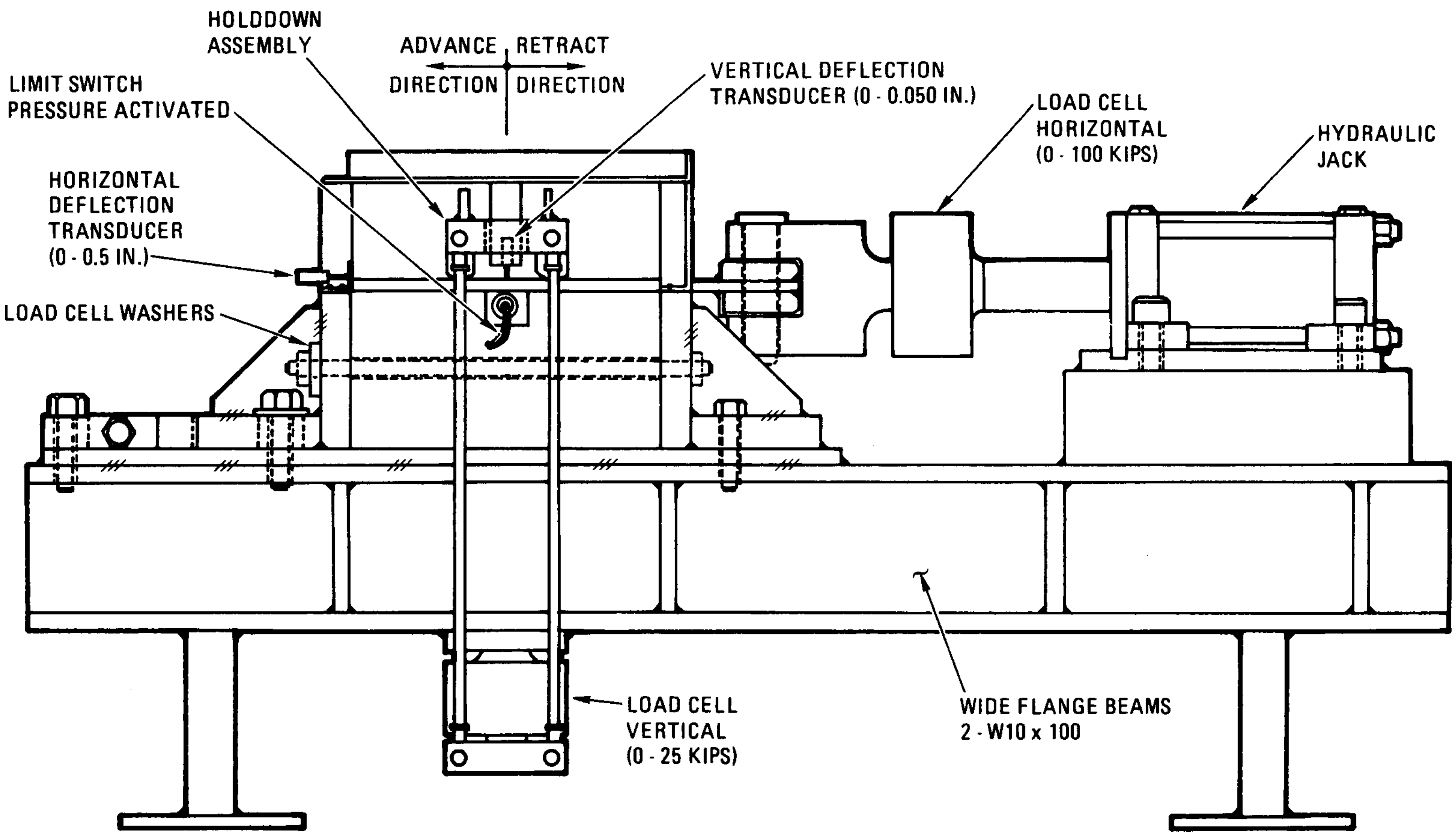


Fig. 2. Loading frame assembly and instrumentation, side view

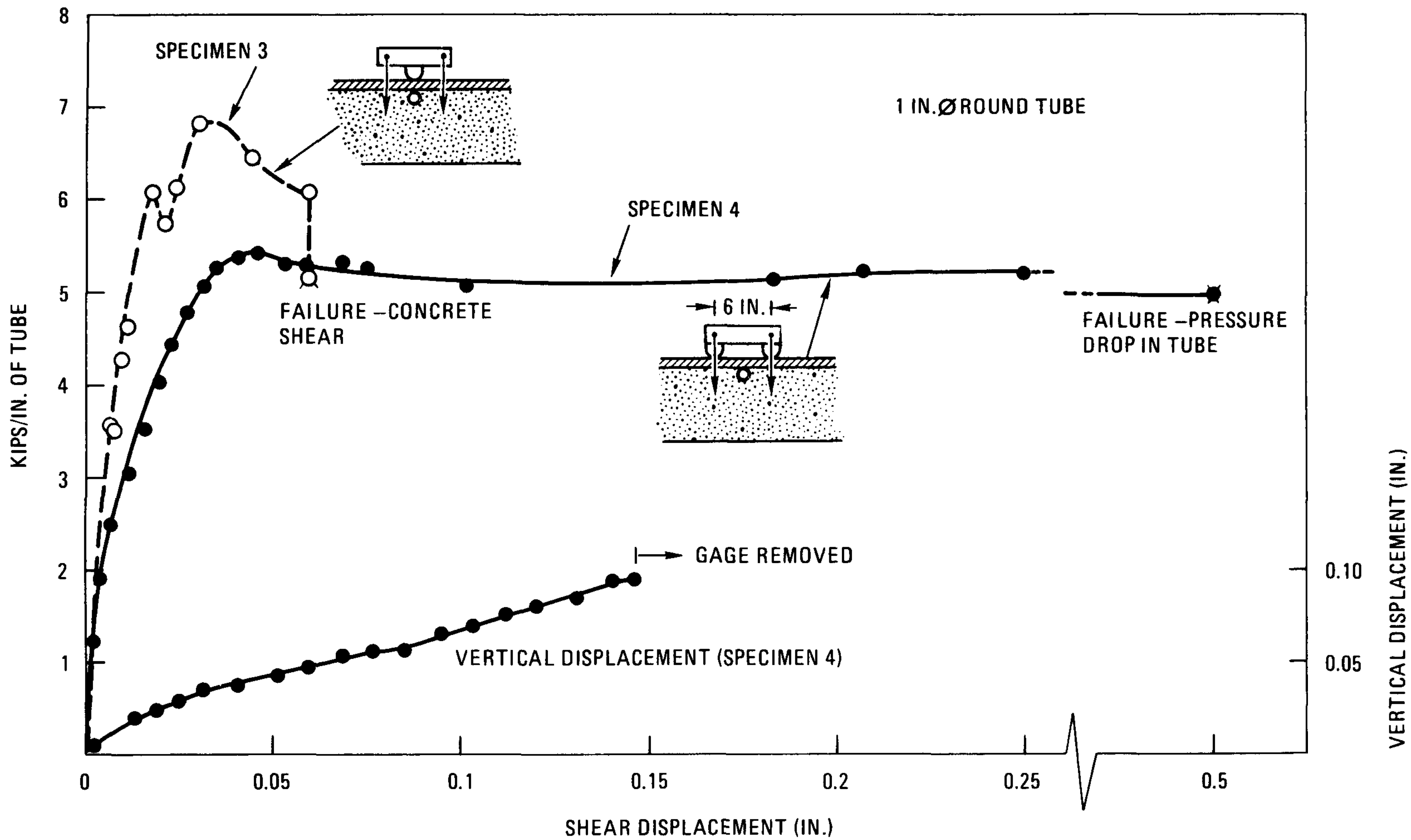


Fig. 3. Load/displacement curves, 1-in. Schedule 40 tubing, specimens 3 and 4

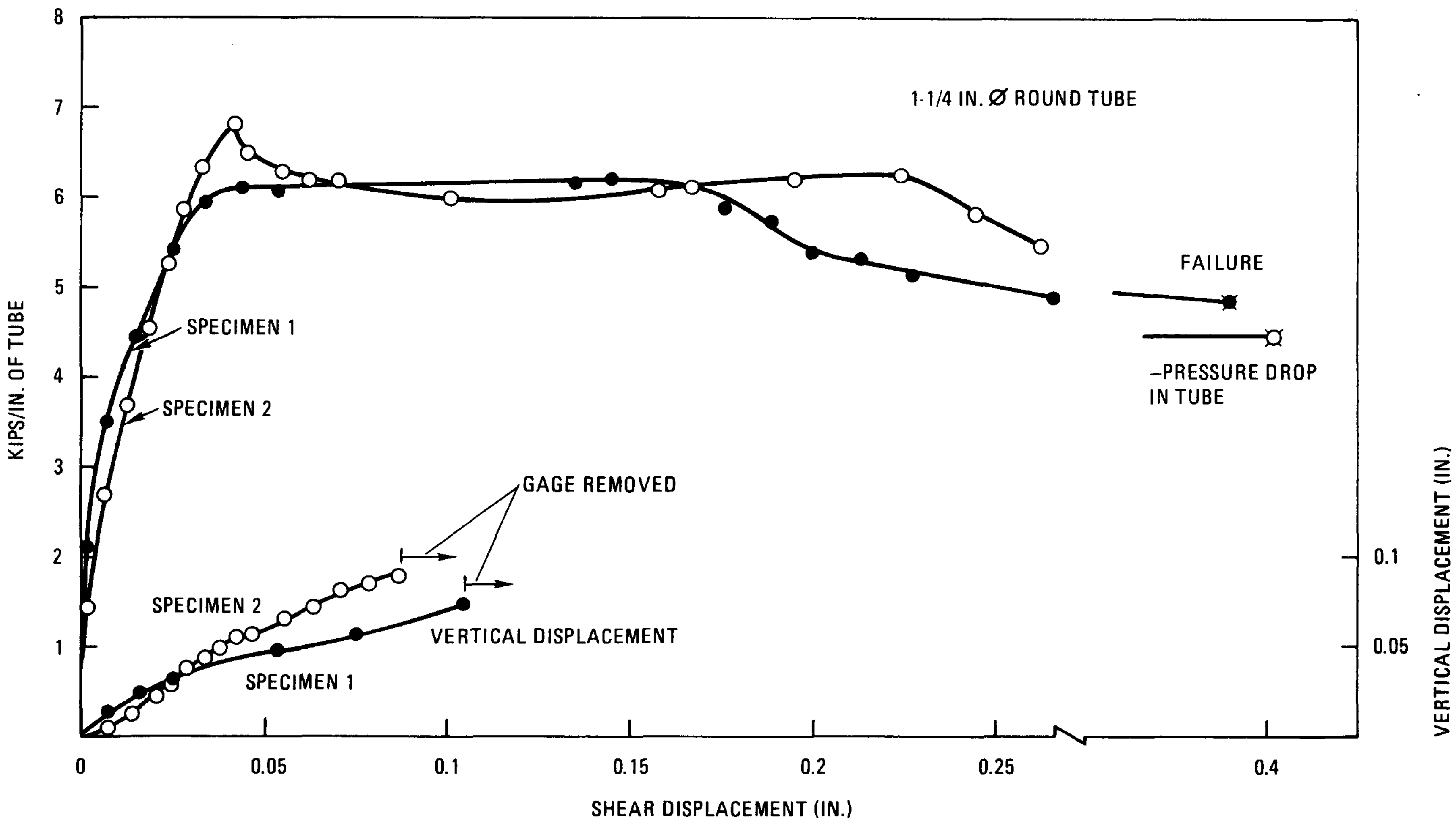


Fig. 4. Load/displacement curves, 1-1/4-in. Schedule 40 tubing, specimens 1 and 2

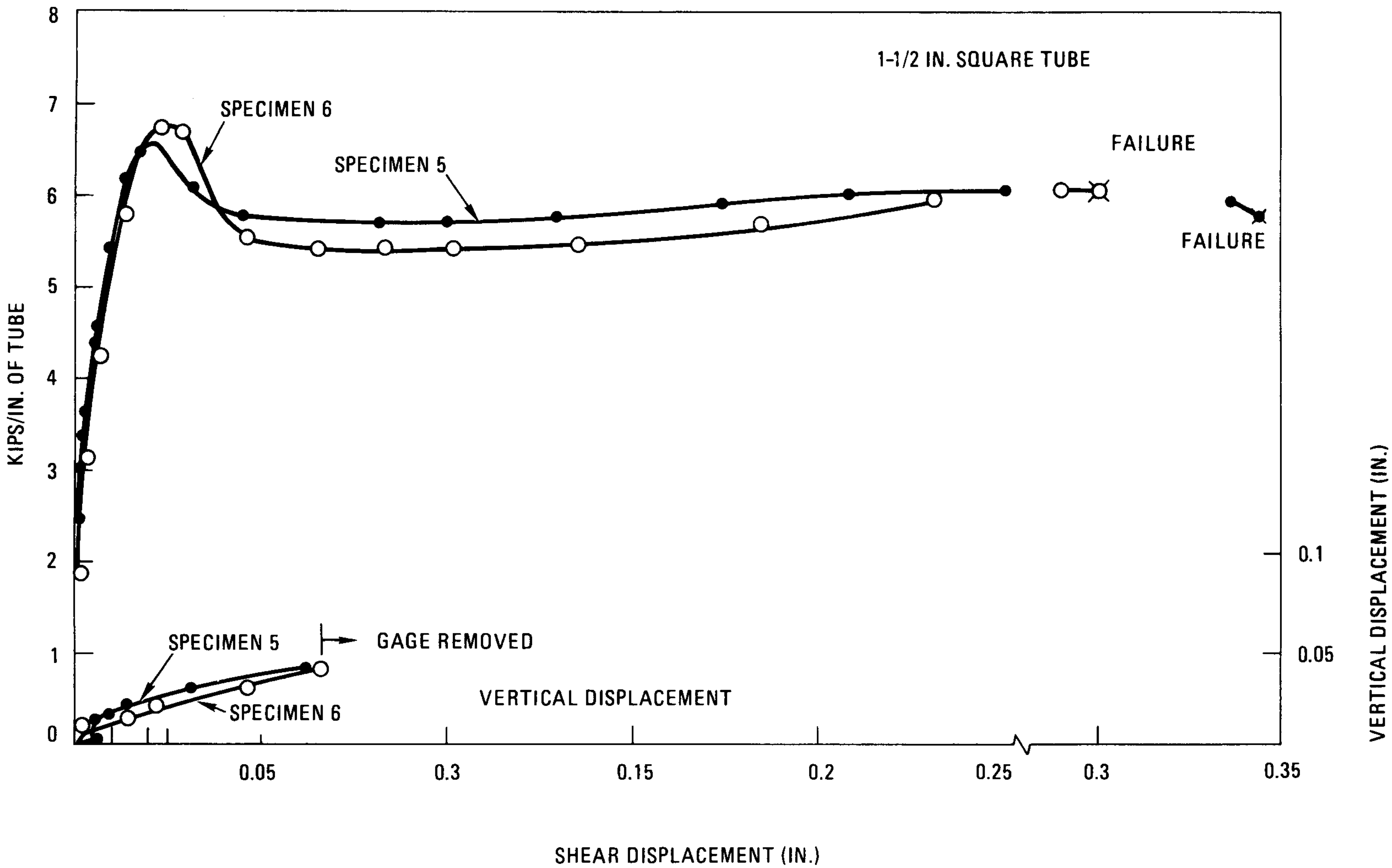


Fig. 5. Load/displacement curves, 1-1/2-in. square tubing, specimens 5 and 6

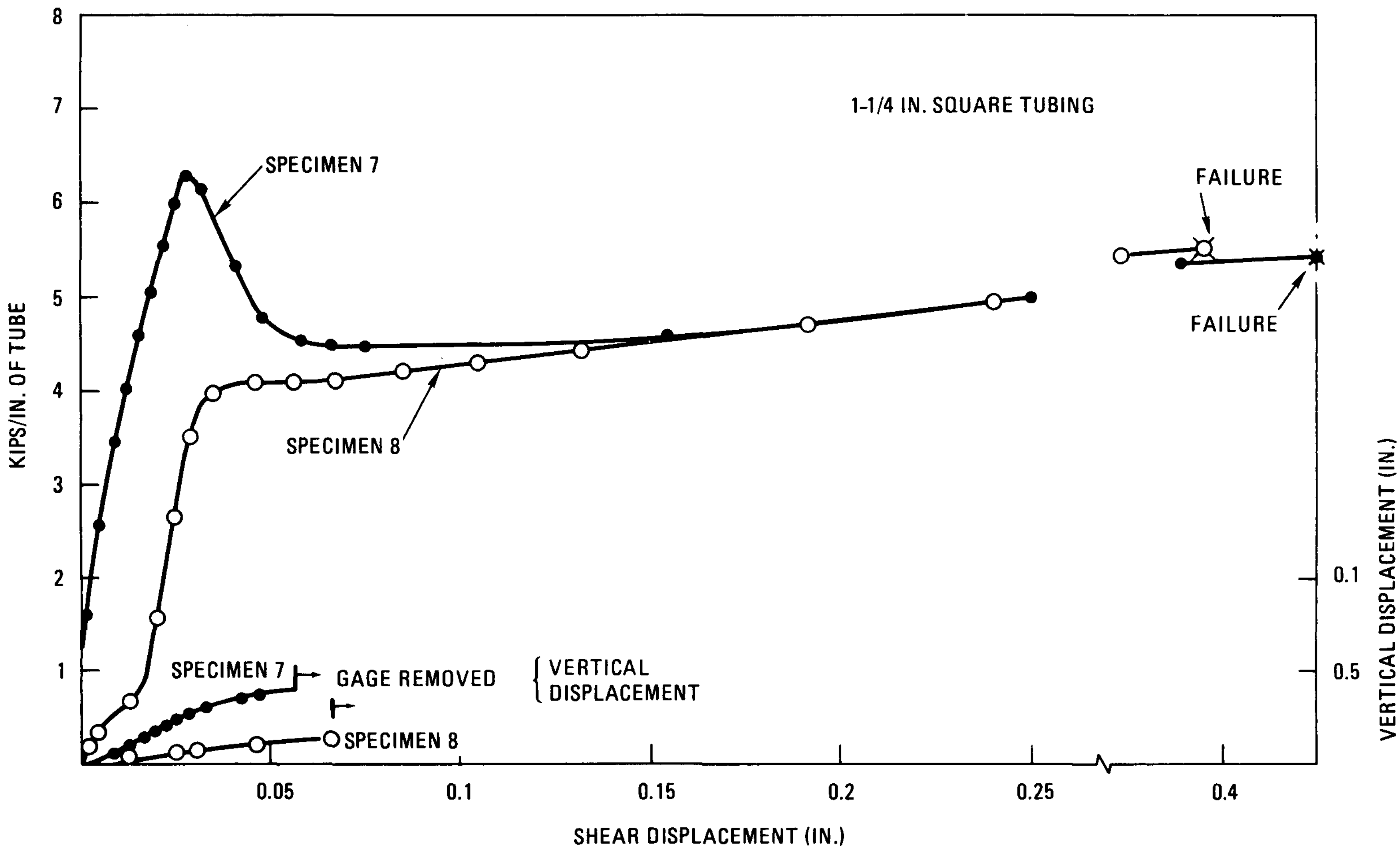
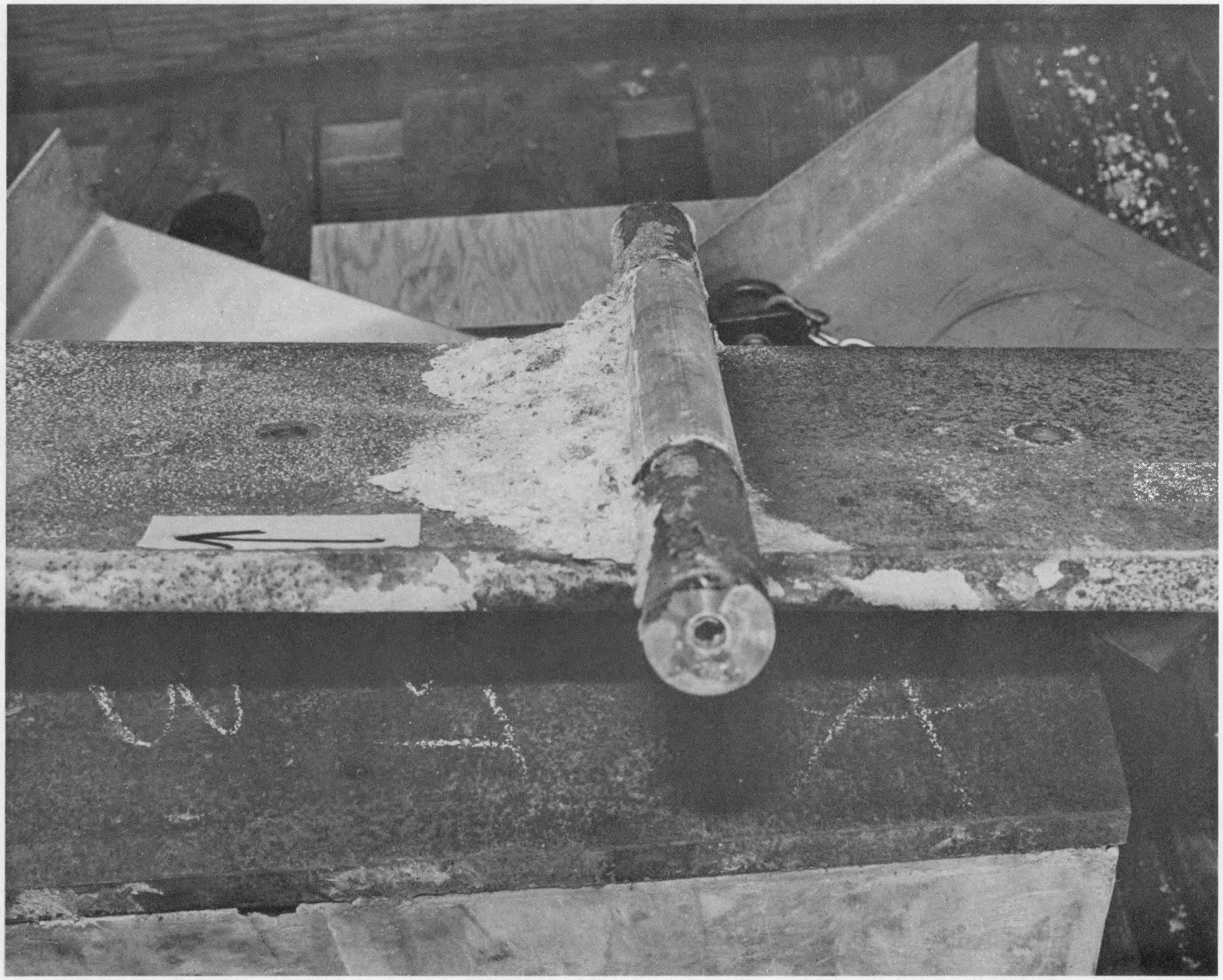


Fig. 6. Load/displacement curves, 1-1/4-in. square tubing, specimens 7 and 8



781733

Fig. 7. Cooling tube/concrete damage after monotonic test, specimen 3 (1-in. Schedule 40)

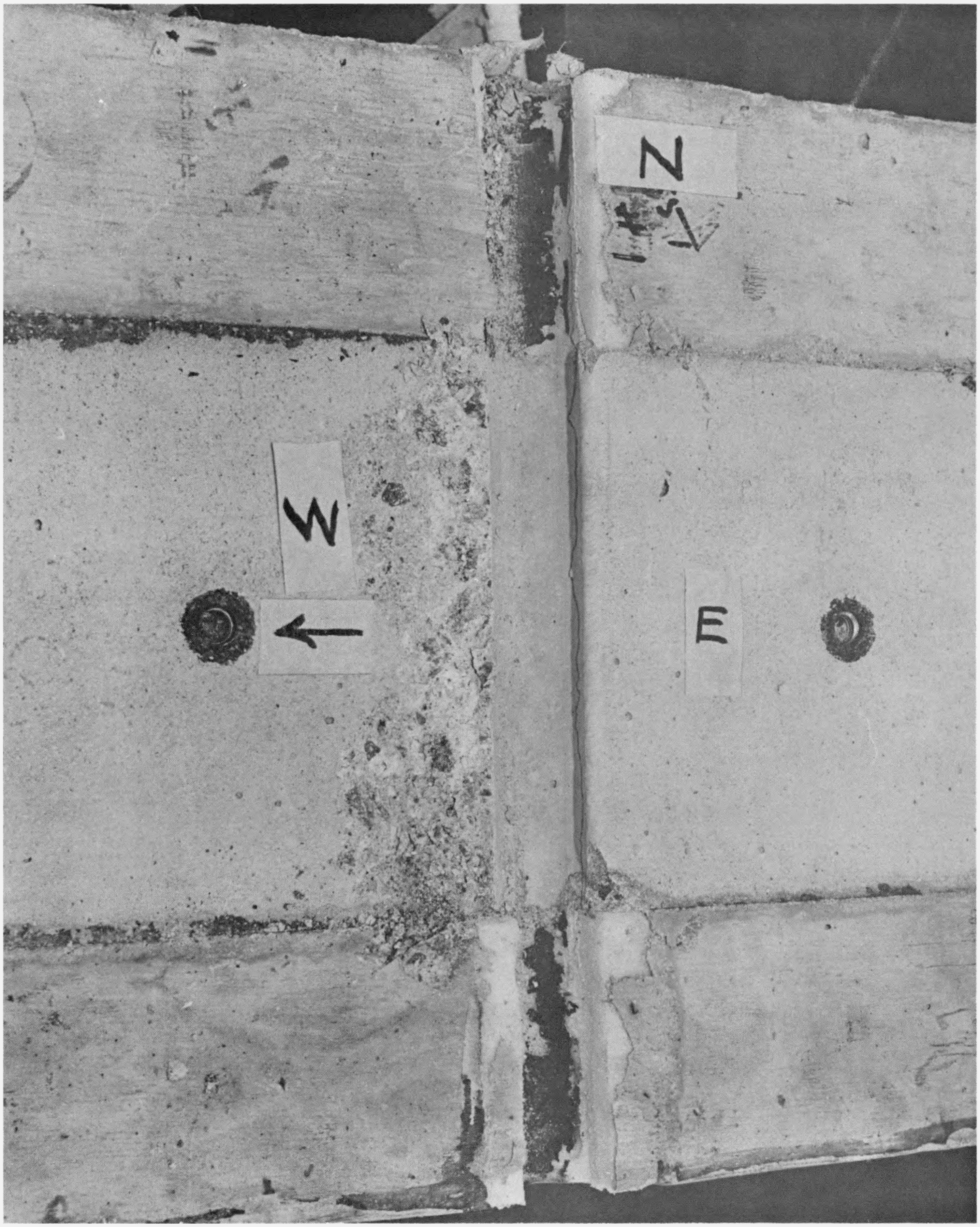


Fig. 8. Concrete damage after monotonic test, specimen 3 (1-in. Schedule 40)

781856

Fig. 9. Round tube distortion after monotonic test, specimen 4 (1-in. Schedule 40)

781852

Fig. 10. Concrete damage after monotonic test, specimen 4 (1-in. Schedule 40)

781857

Fig. 11. Round tube distortion after monotonic test, specimen 2 (1-1/4-in. Schedule 40)

781850

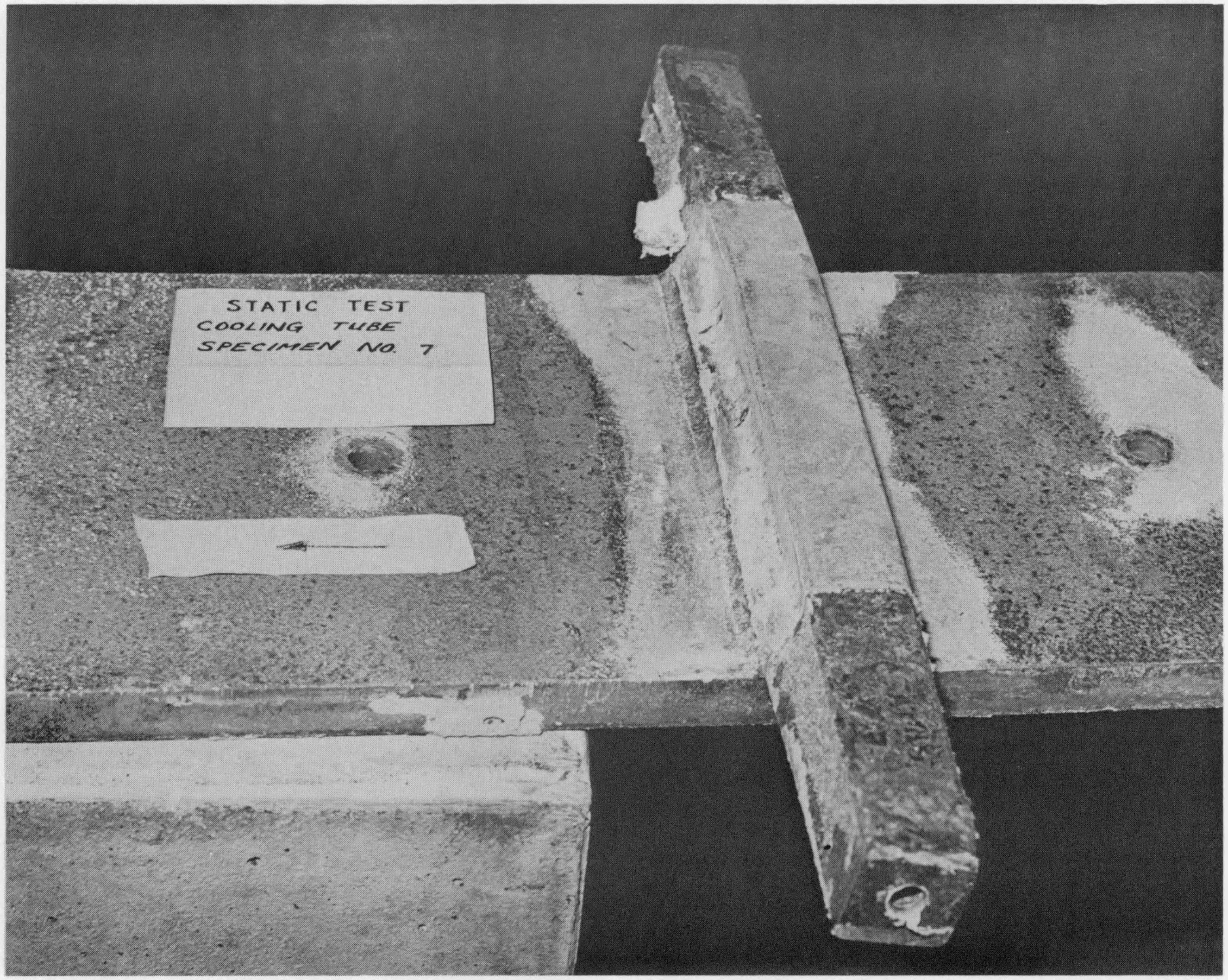
Fig. 12. Concrete damage after monotonic test, specimen 2 (1-1/4-in. Schedule 40)

790113

Fig. 13. Square tube distortion after monotonic test, specimen 5

790114

Fig. 14. Concrete damage after monotonic test, specimen 5 (1-1/2-in. square tube)

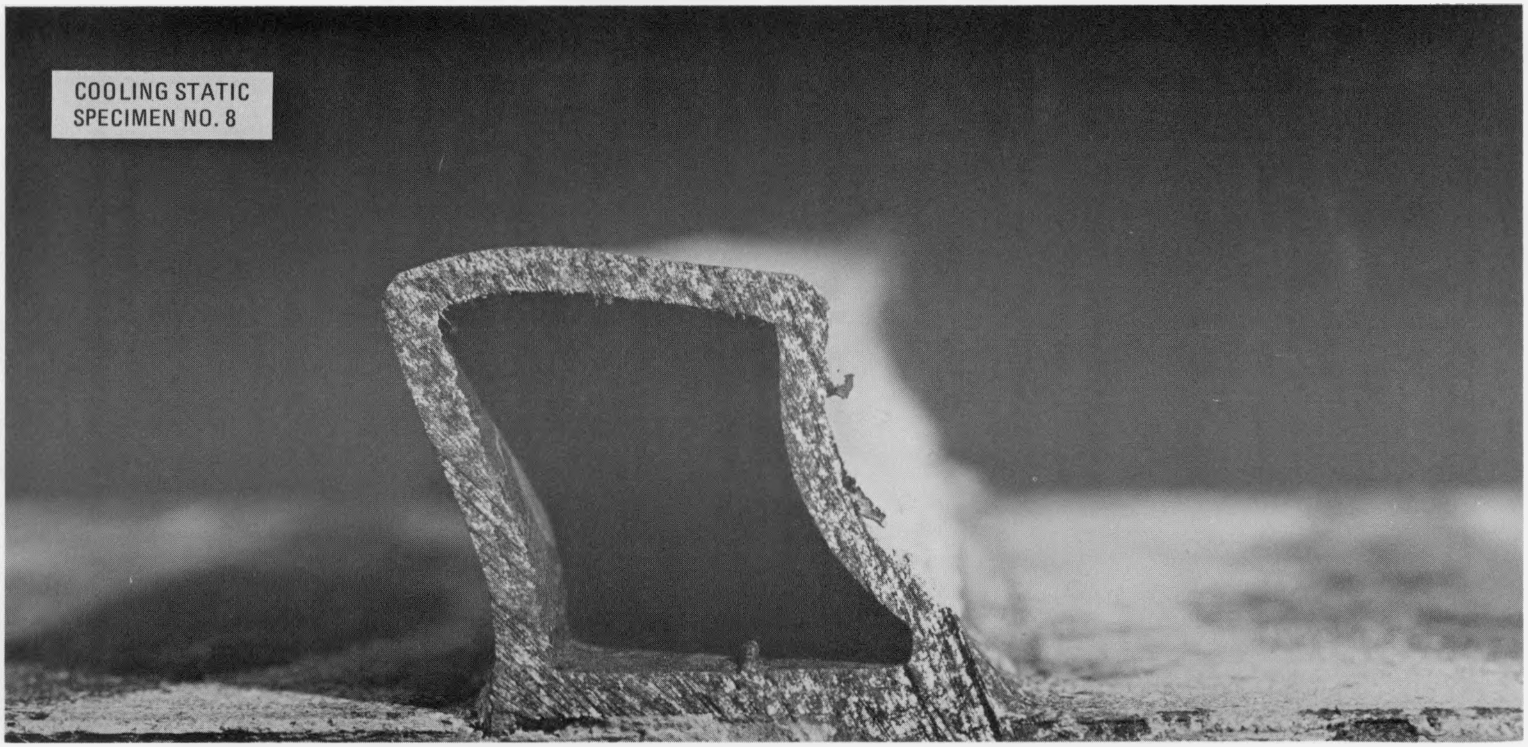


781859

Fig. 15. Square tube distortion after monotonic test, specimen 7 (1-1/4-in. square tube)

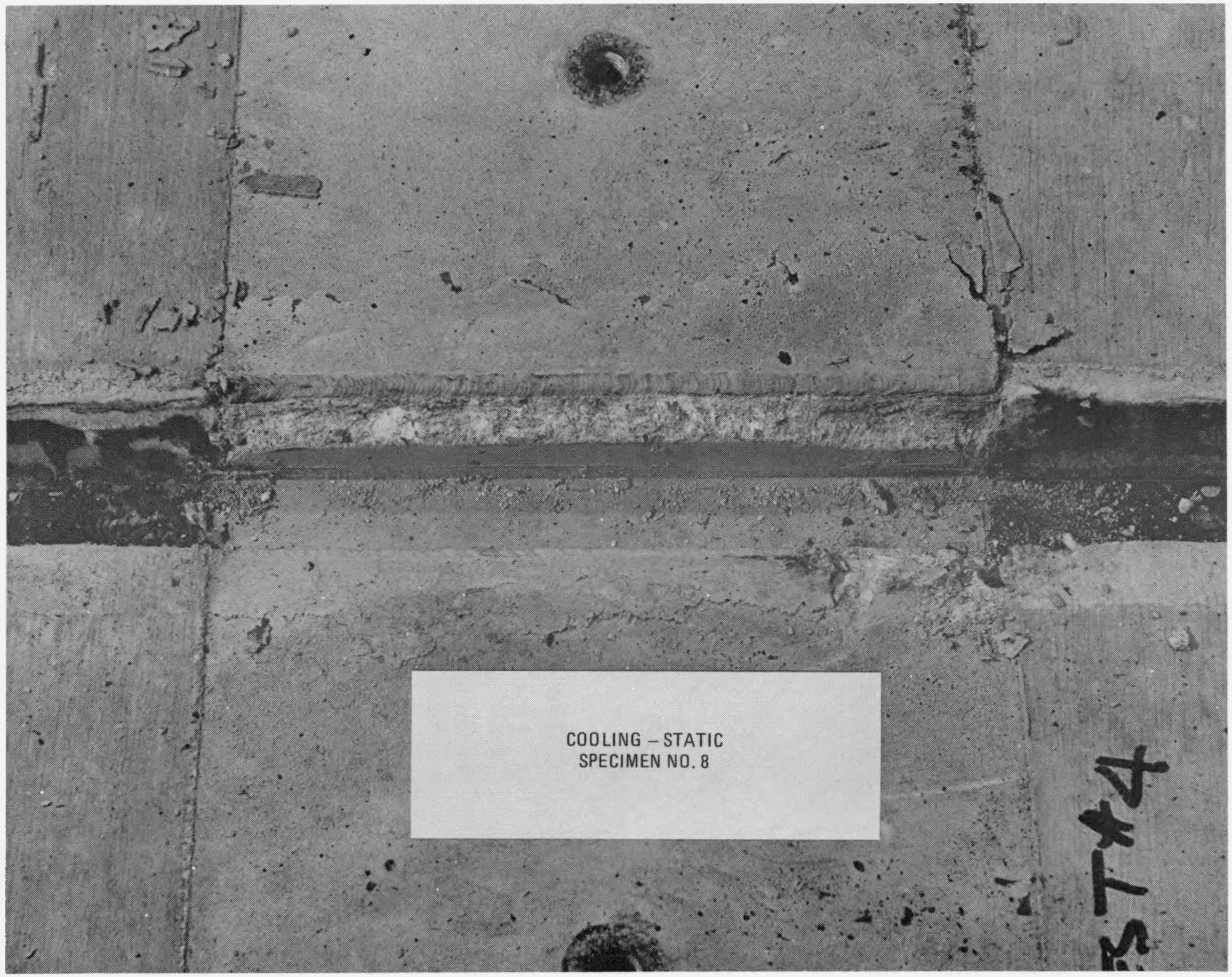
781855

Fig. 16. Concrete damage after monotonic test, specimen 7 (1-1/4-in. square tube)



790125

Fig. 17. Square tube distortion in cross section of specimen 8



790111

Fig. 18. Concrete damage after monotonic test, specimen 8 (1-1/4-in. square tube)

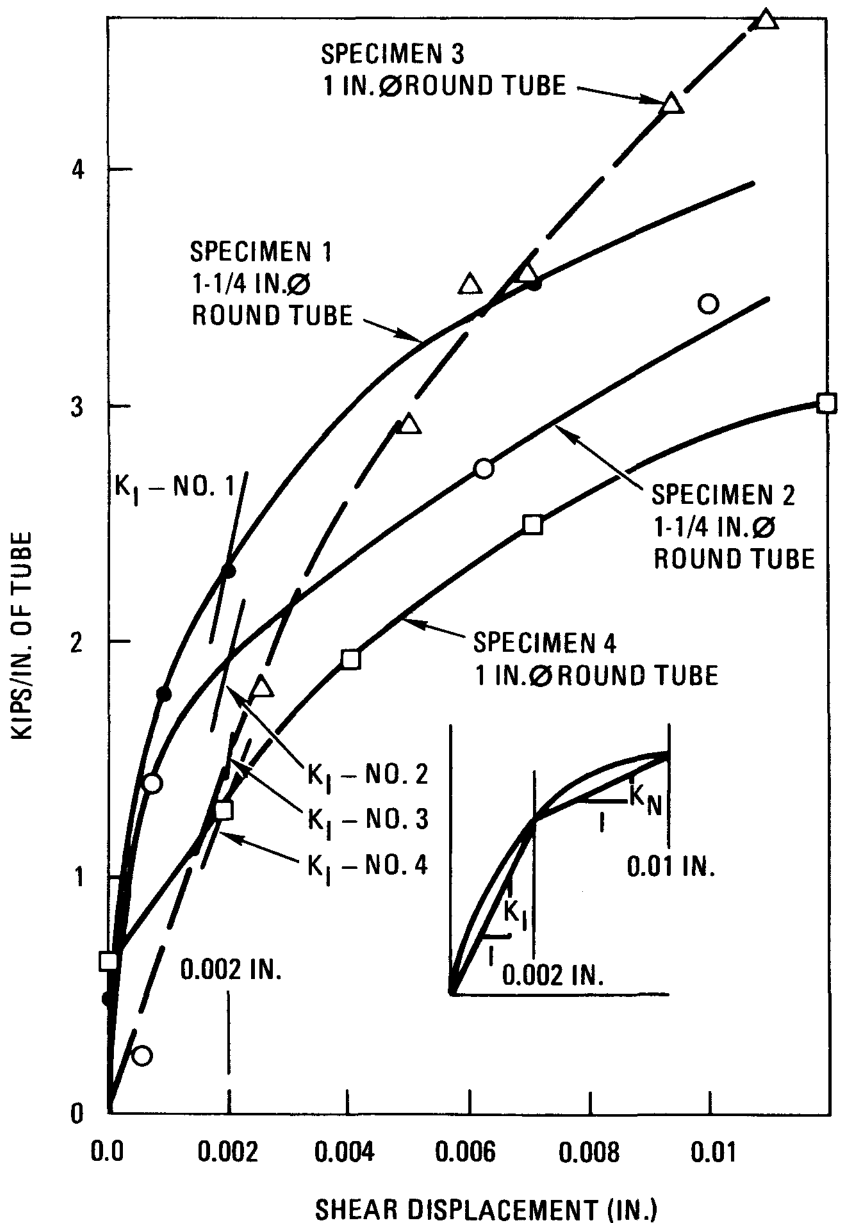


Fig. 19. Initial load/displacement characteristics for round cross section tubing, specimens 1 through 4

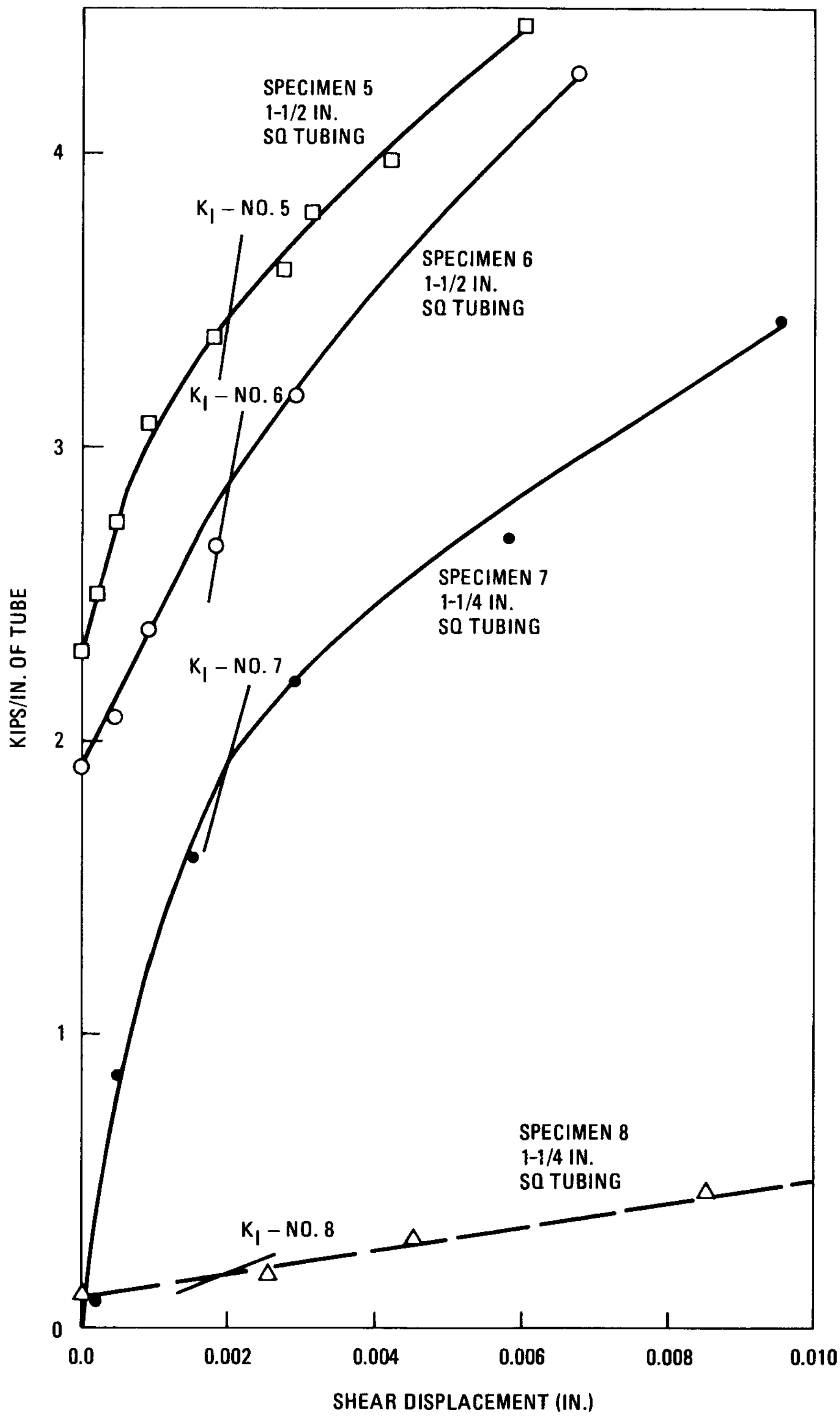


Fig. 20. Initial load/displacement characteristics for square cross section tubing, specimens 5 through 8

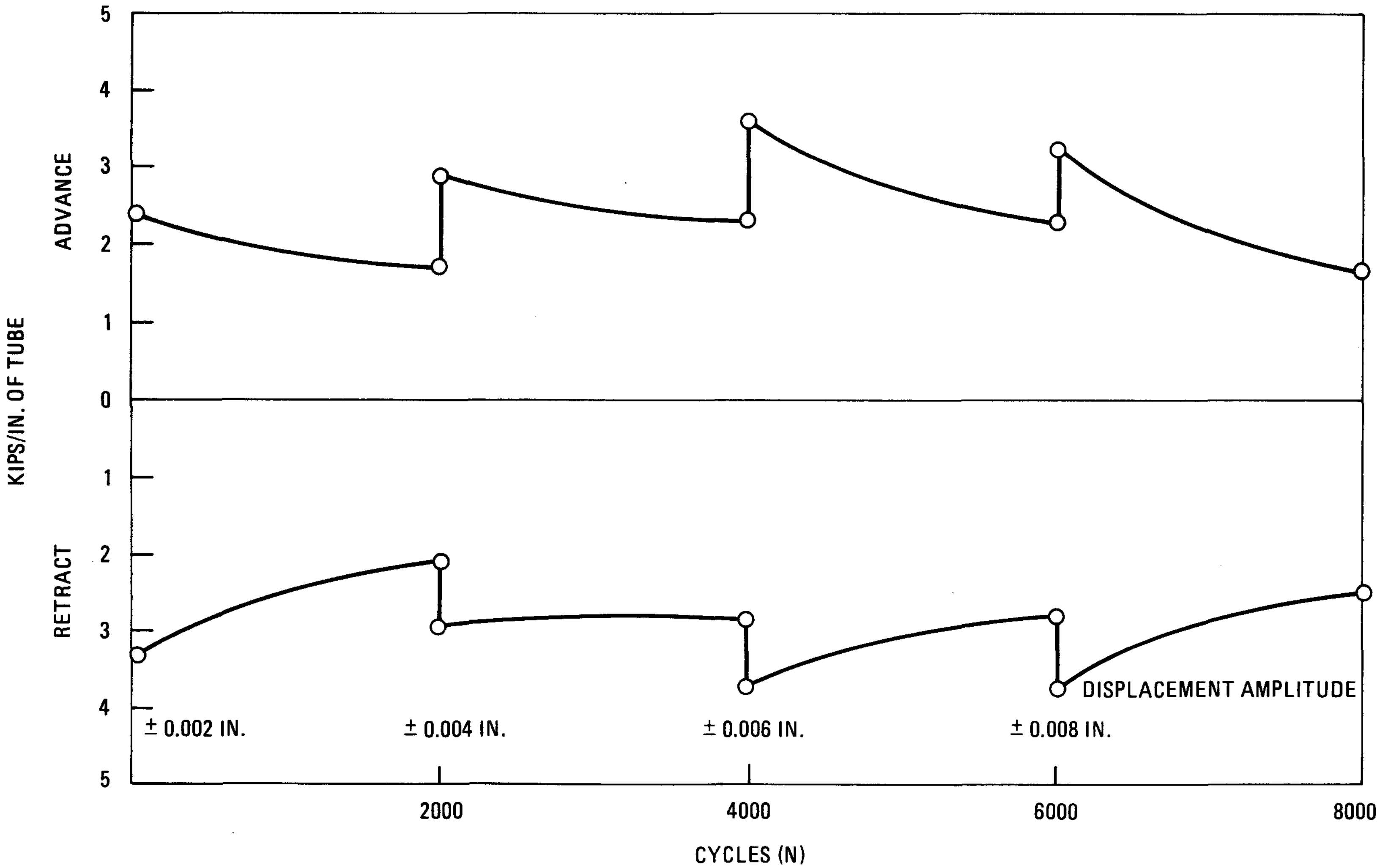


Fig. 21. Typical load relaxation curve for the increasing amplitude fatigue tests, specimen 9

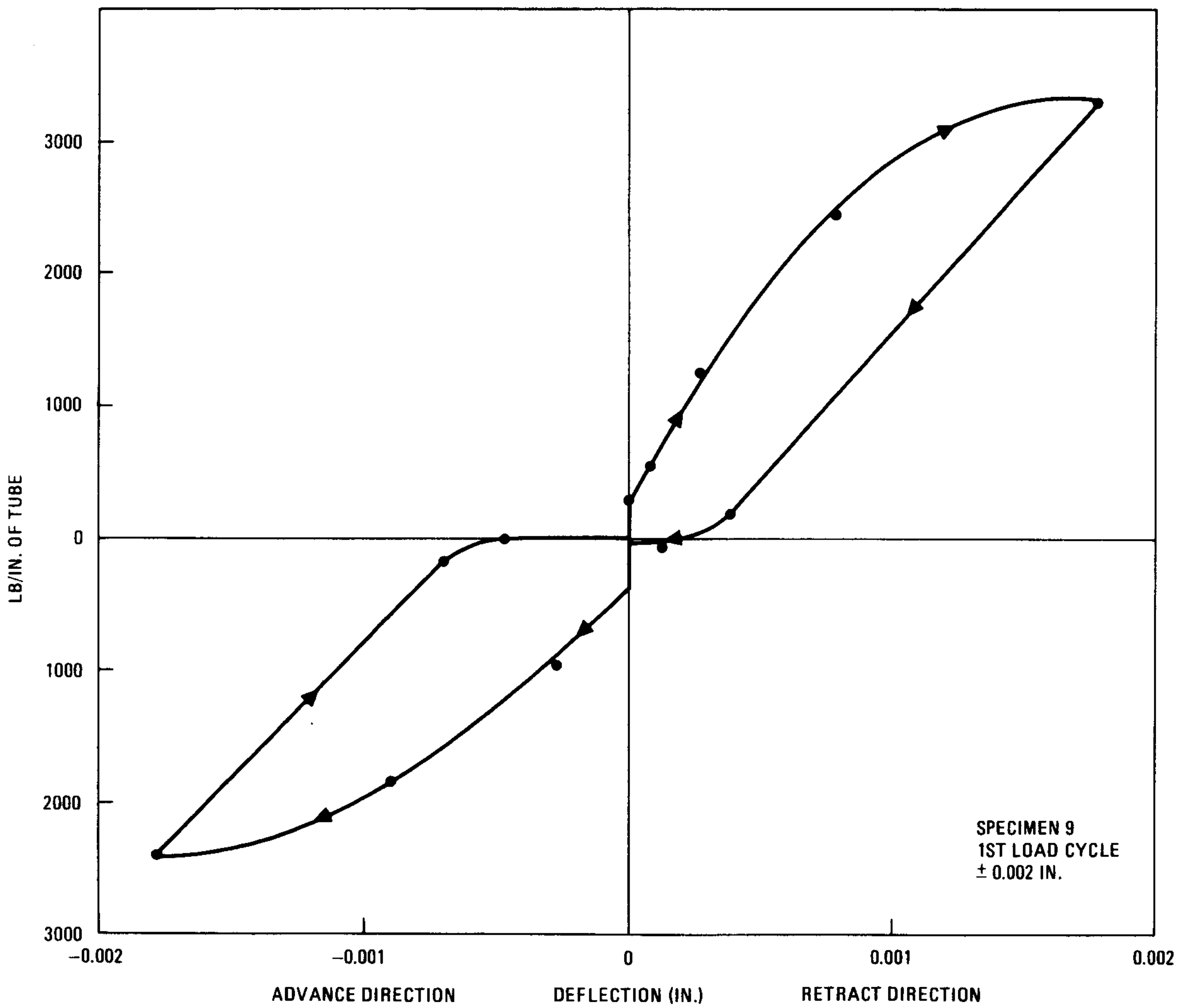


Fig. 22. Load/displacement curve of first cycle of specimen 9 at ±0.002 in.

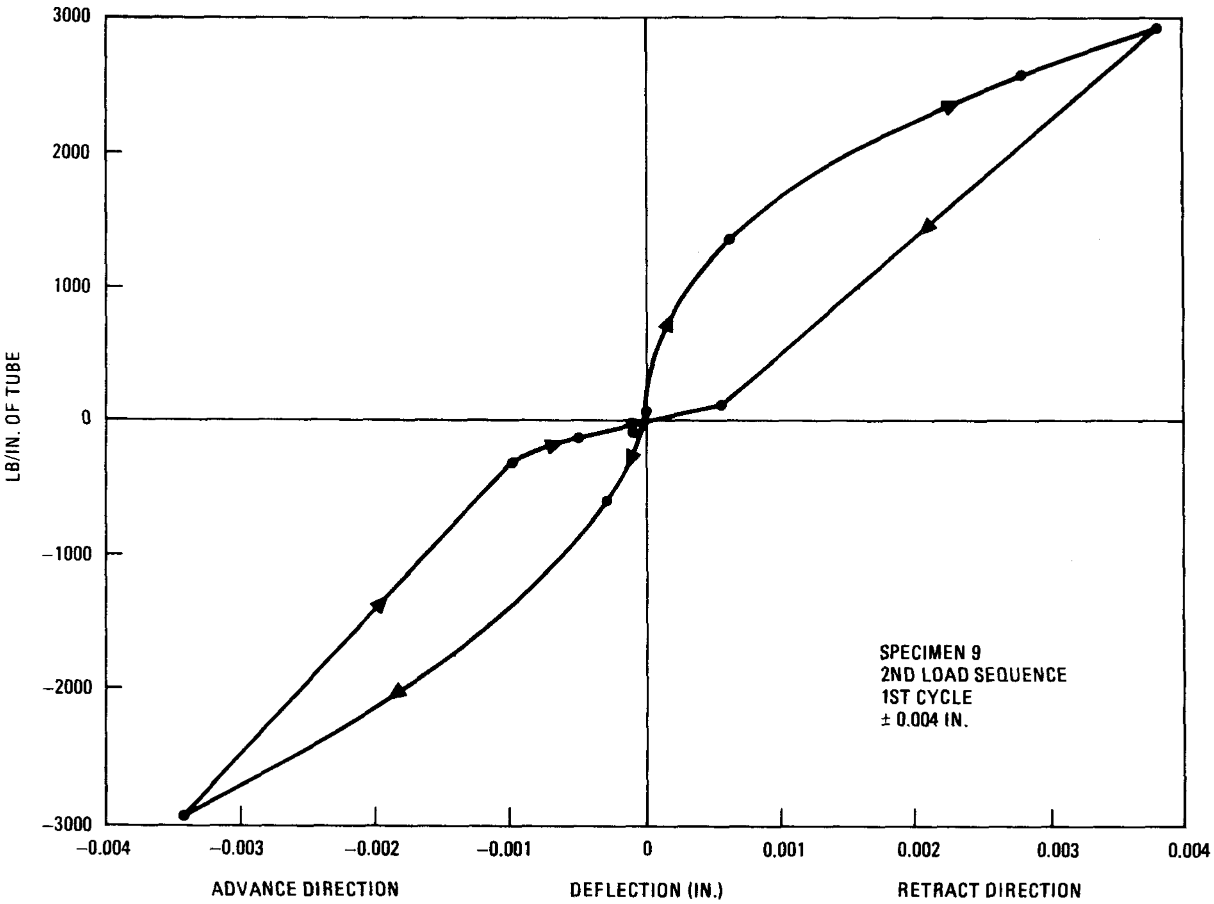


Fig. 23. Load/displacement curve of first cycle of specimen 9 at ±0.004 in.

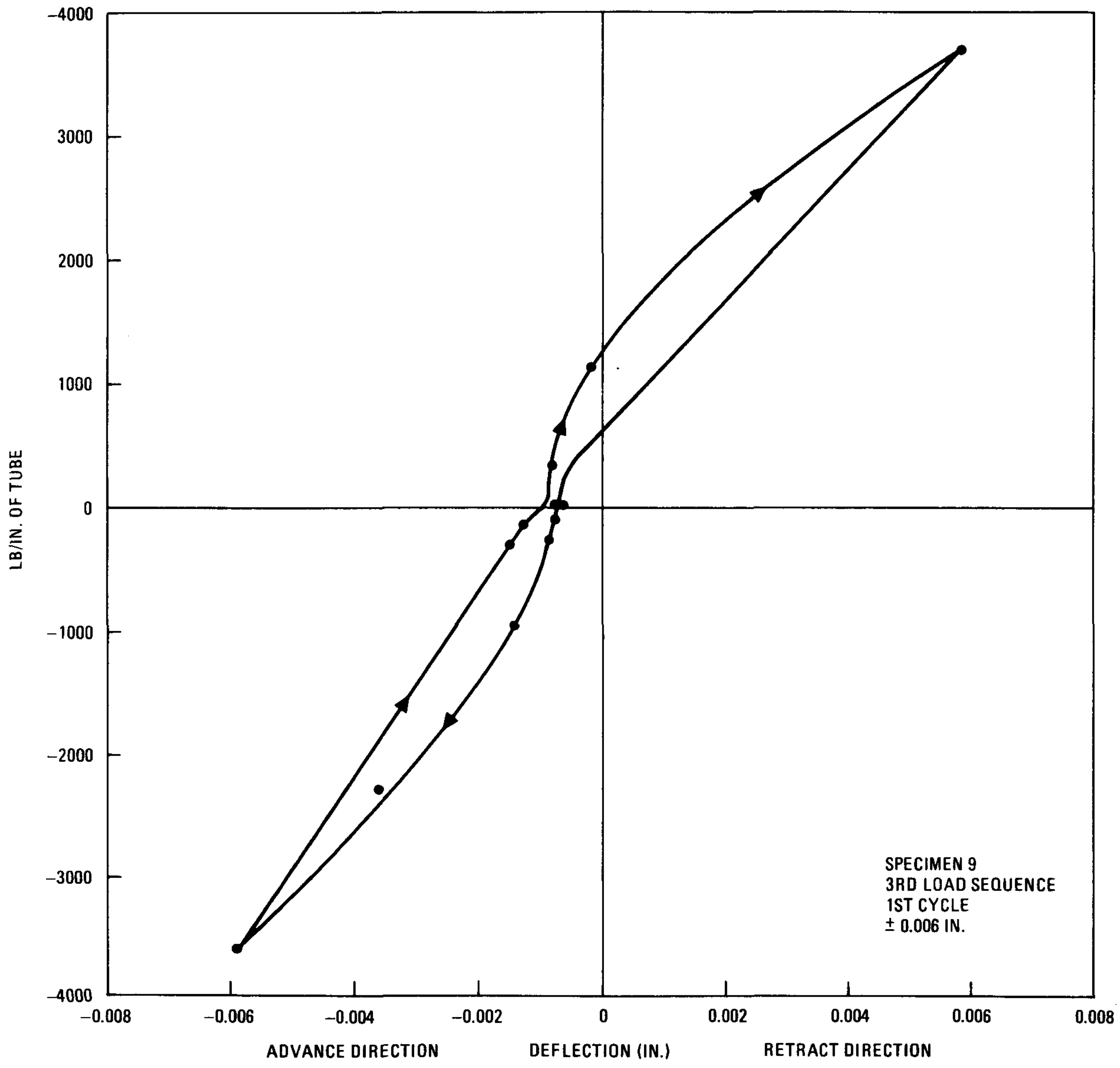


Fig. 24. Load/displacement curve of first cycle of specimen 9 at ±0.006 in.

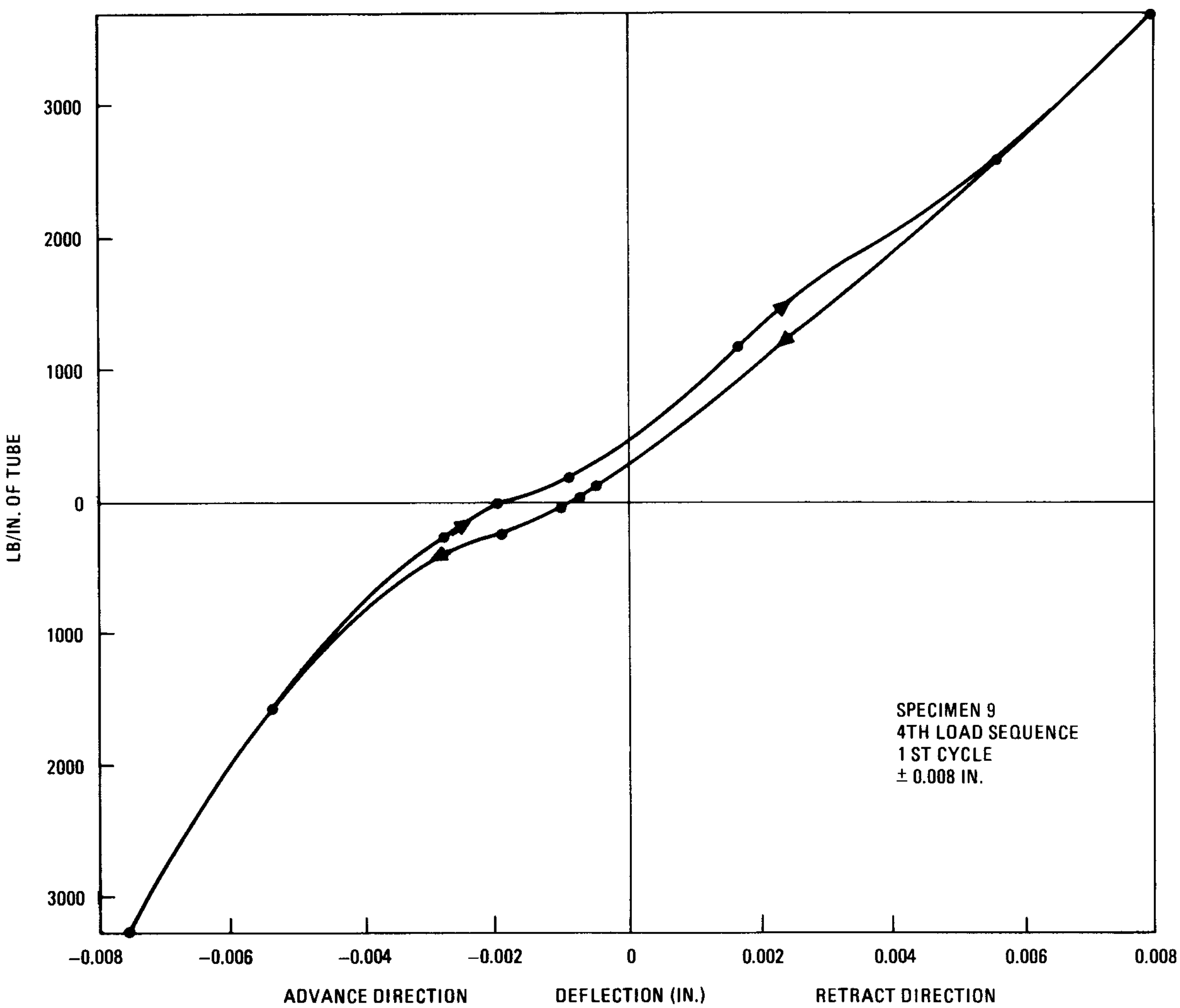


Fig. 25. Load/displacement curve of first cycle of specimen 9 at ±0.008 in.

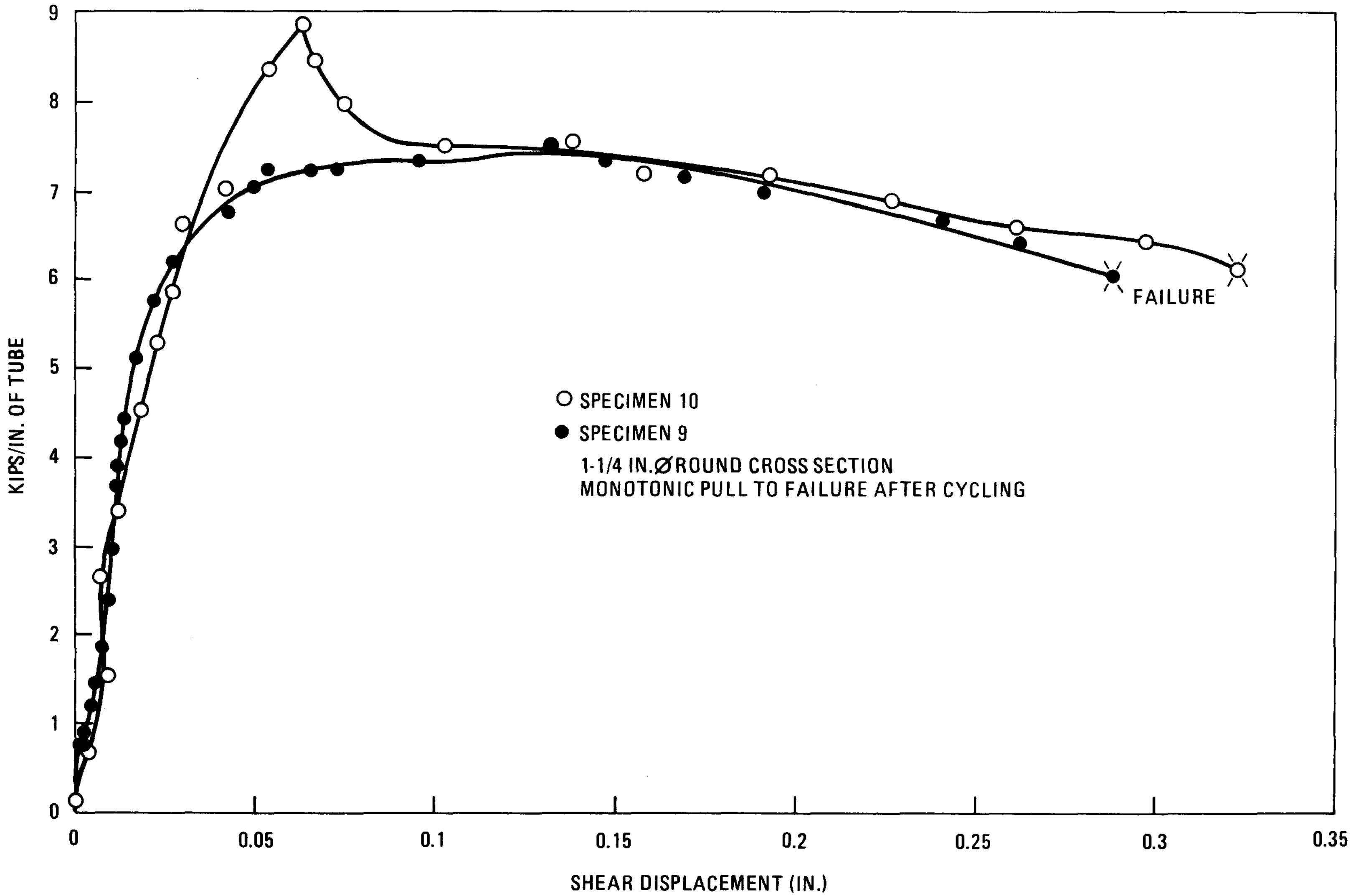


Fig. 26. Load/displacement curves after cycling, specimens 9 and 10 (1-1/4-in. Schedule 40)

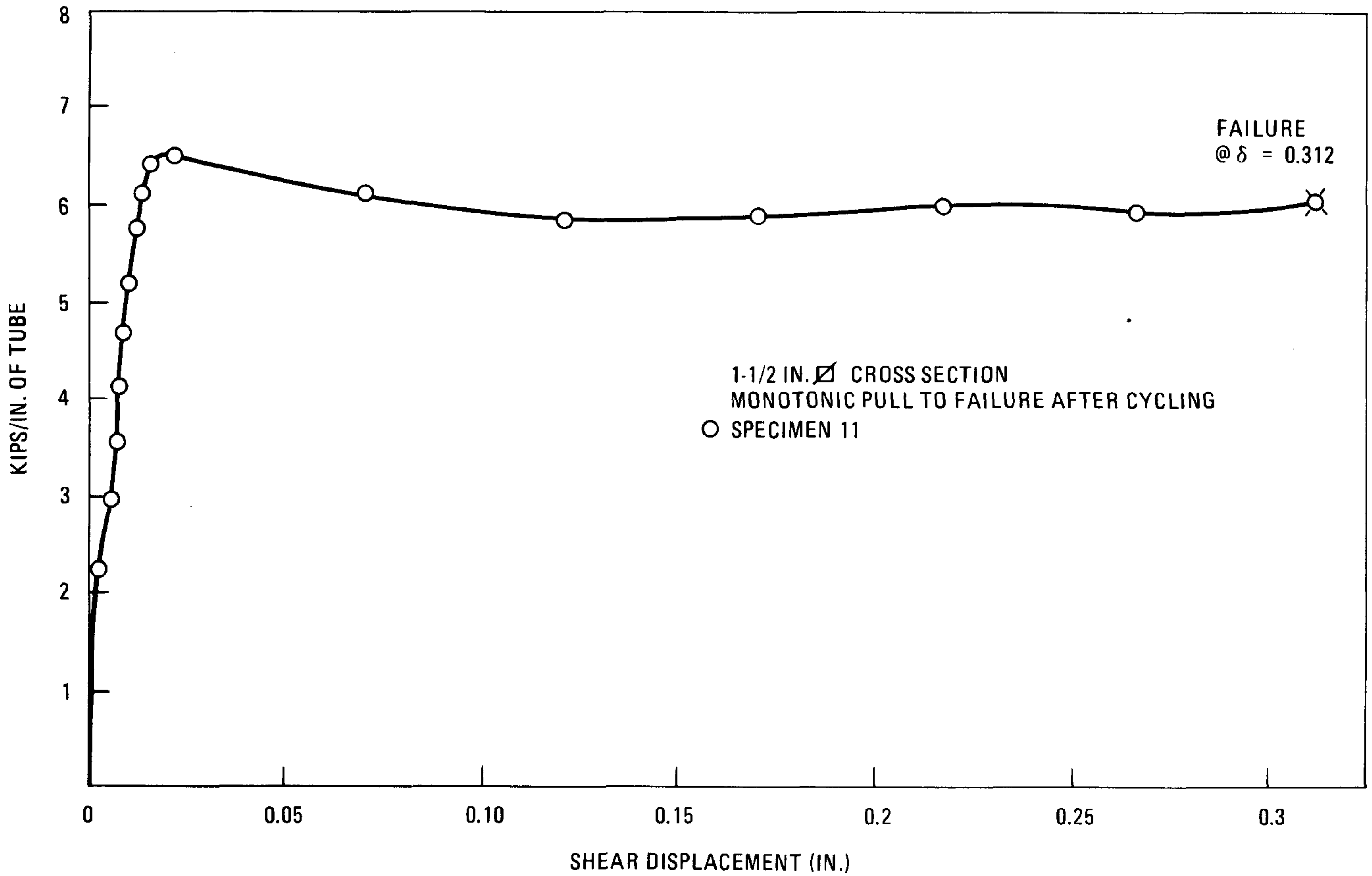


Fig. 27. Load/displacement curve after cycling, specimen 11 (1-1/2-in. square tube)

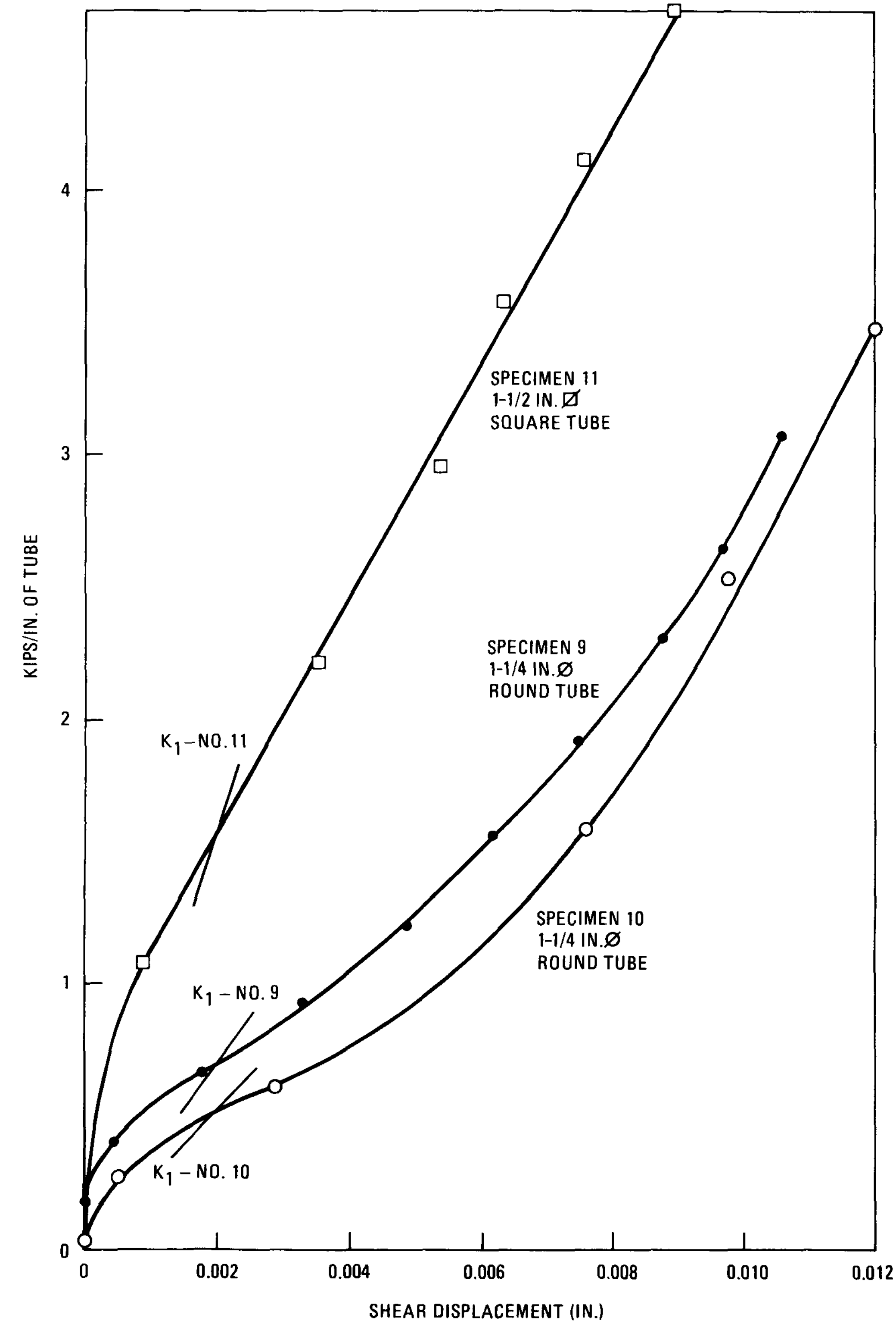
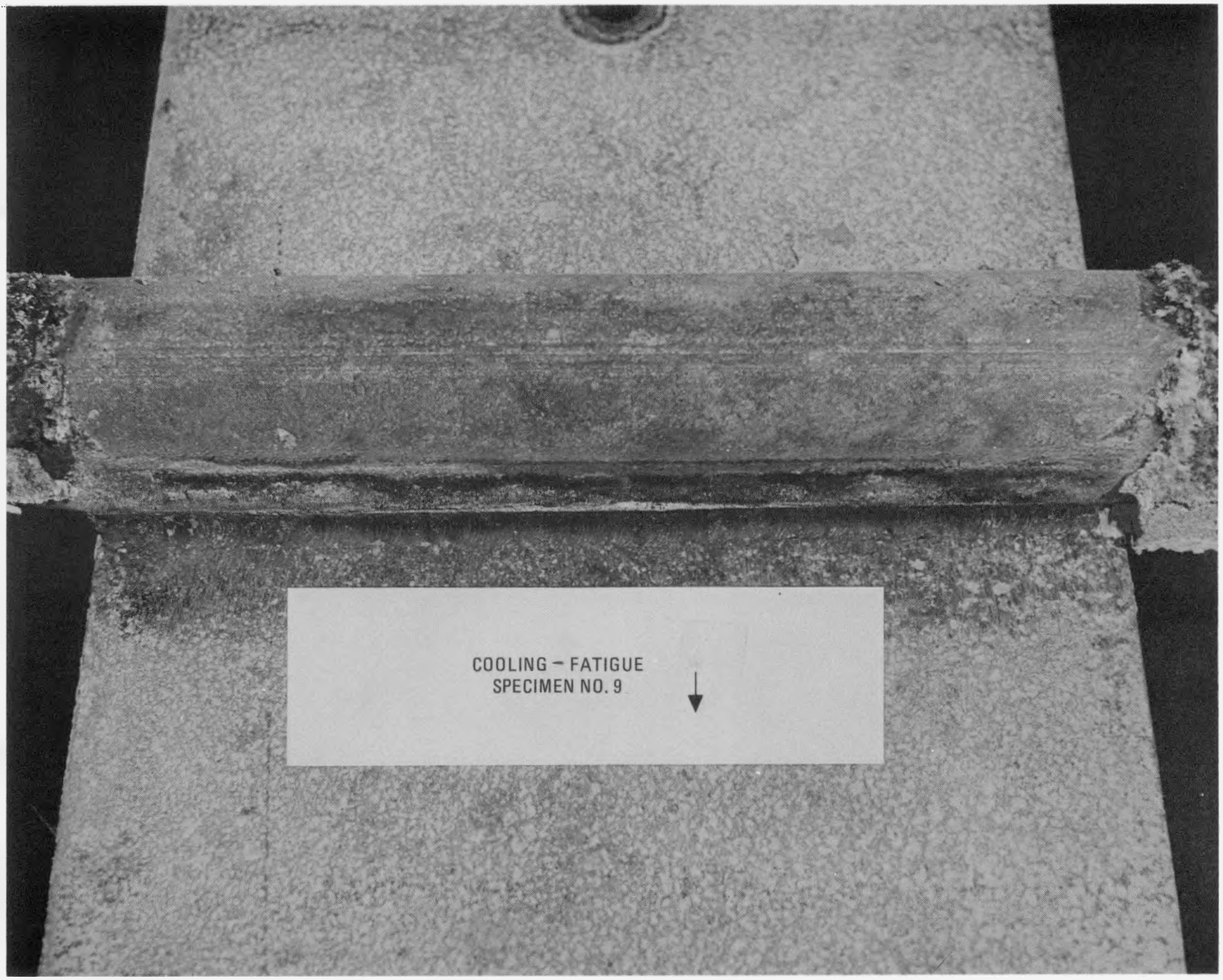


Fig. 28. Load/displacement curves, monotonic load to failure test after ∿8000 cycles

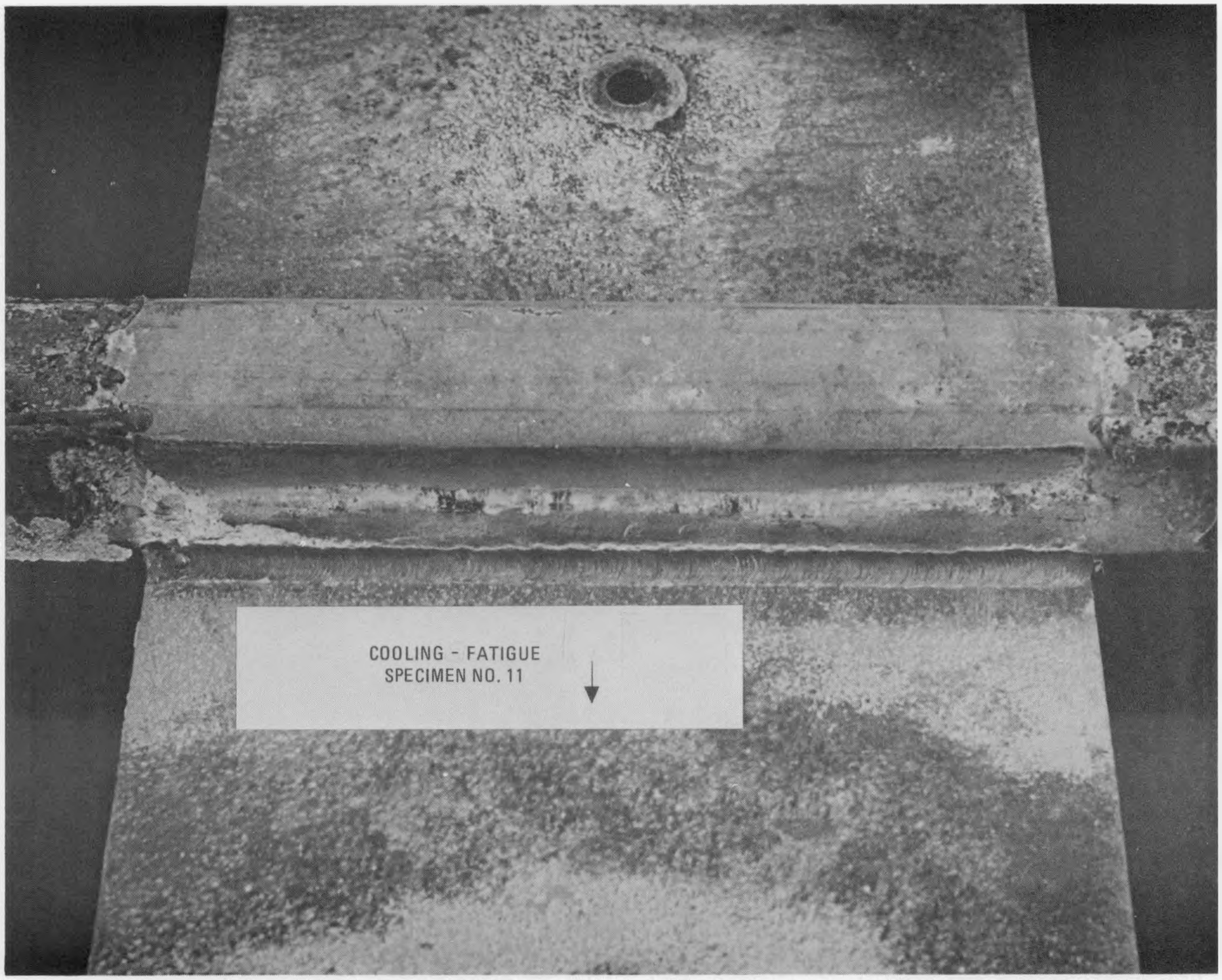


790116

Fig. 29. Round tube distortion after cyclic and monotonic test, specimen 9 (1-1/4-in. Schedule 40)

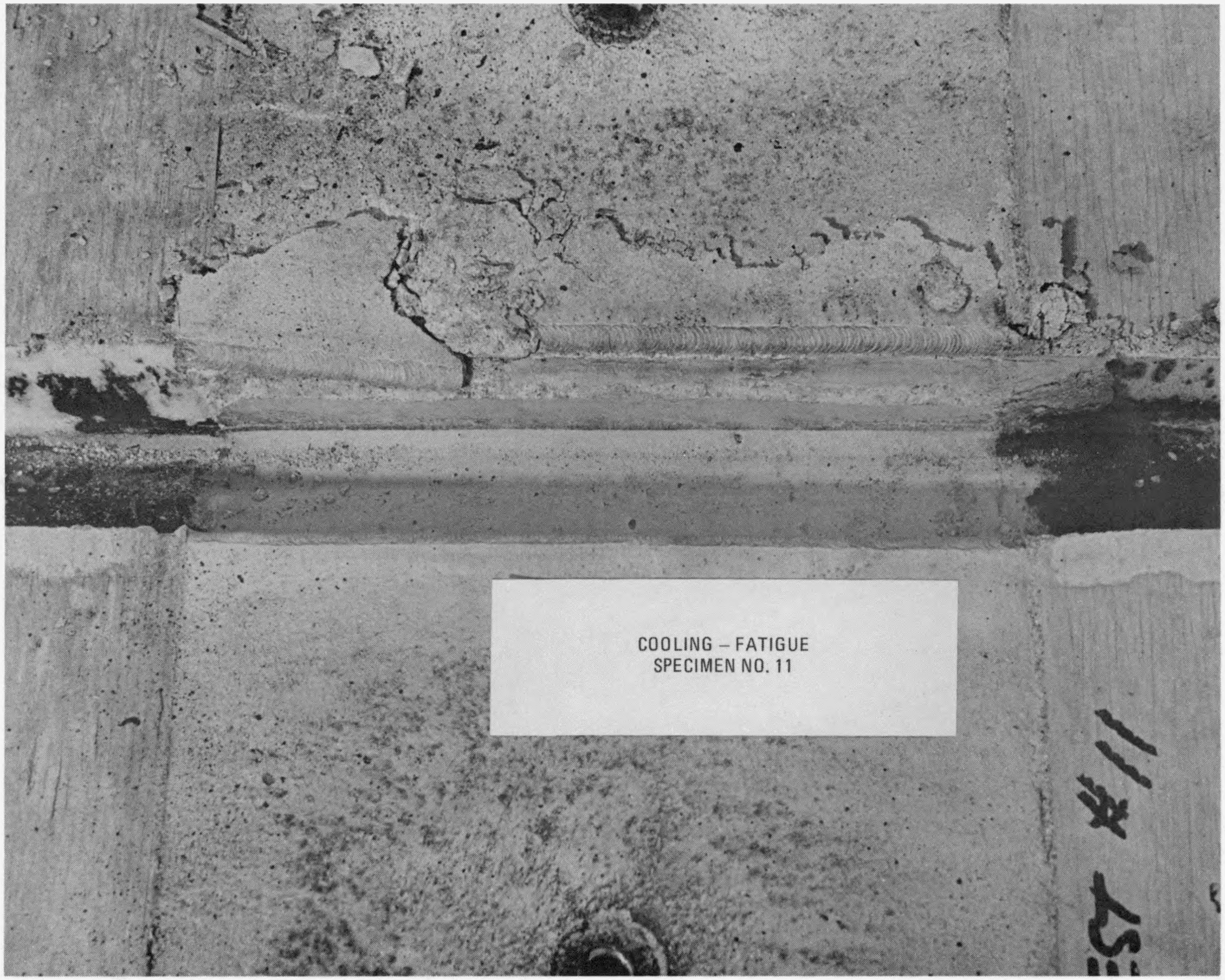
790108

Fig. 30. Concrete damage after cyclic and monotonic test, specimen 9



790117

Fig. 31. Square tube distortion after cyclic and monotonic test, specimen 11



790106

Fig. 32. Concrete damage after cyclic and monotonic test, specimen 11

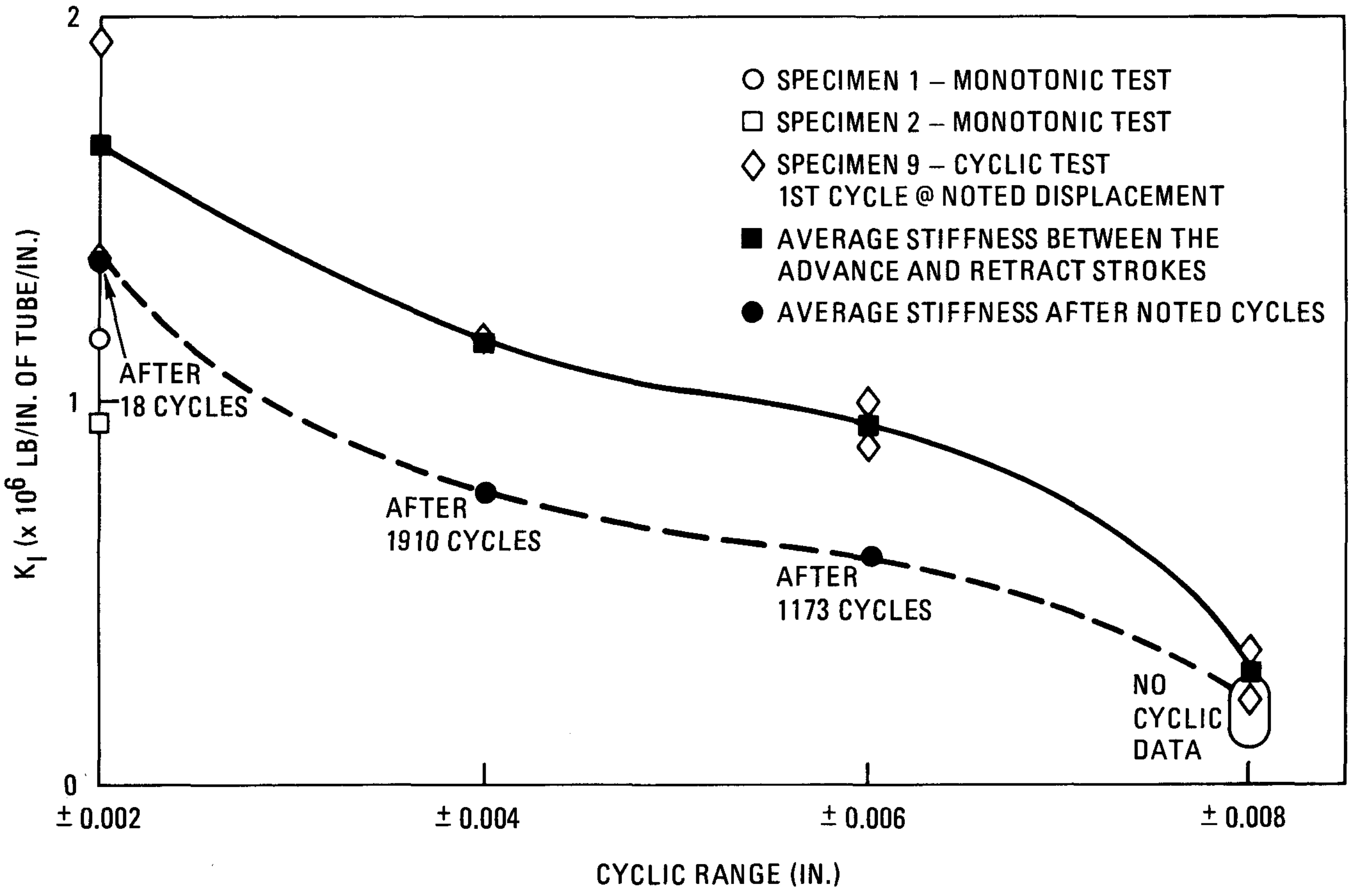


Fig. 33. Cyclic stiffness characteristics for specimen 9 (1-1/4-in. Schedule 40)

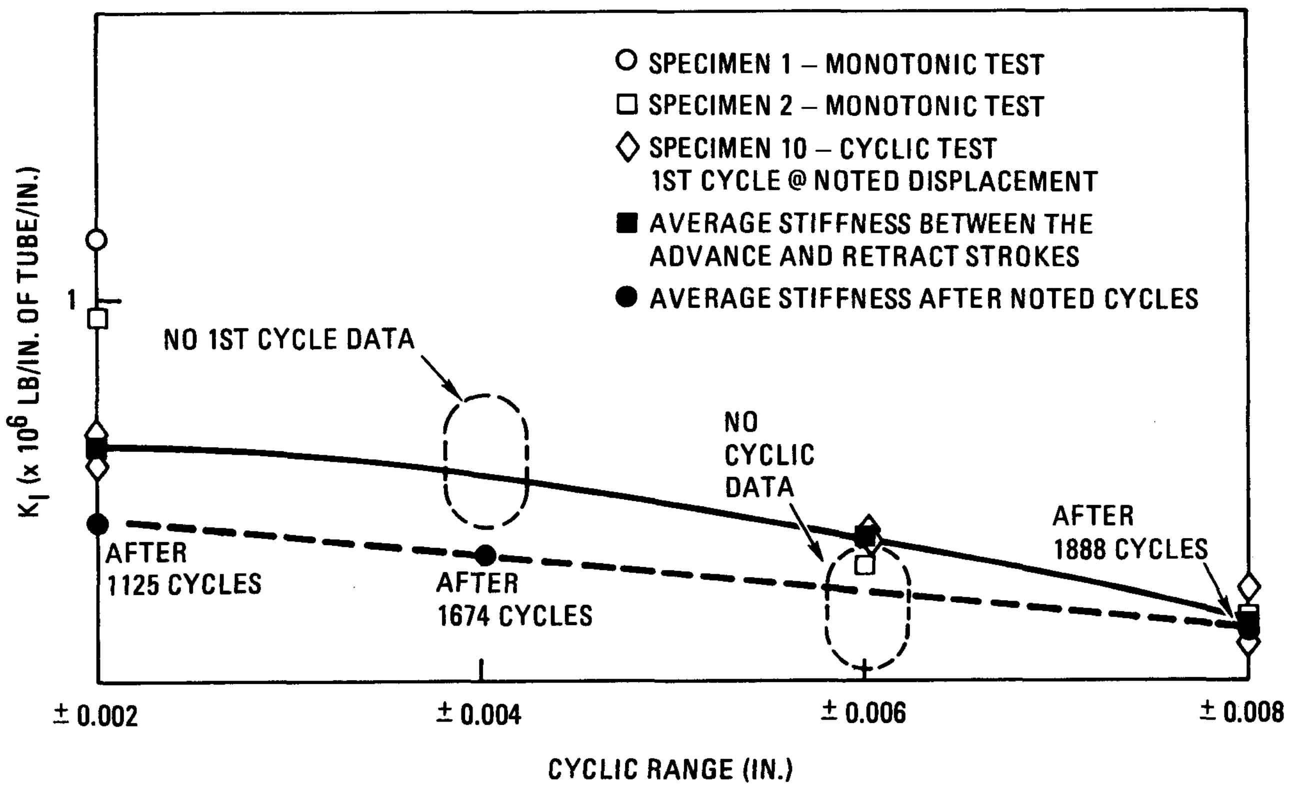


Fig. 34. Cyclic stiffness characteristics for specimen 10 (1-1/4-in. Schedule 40)

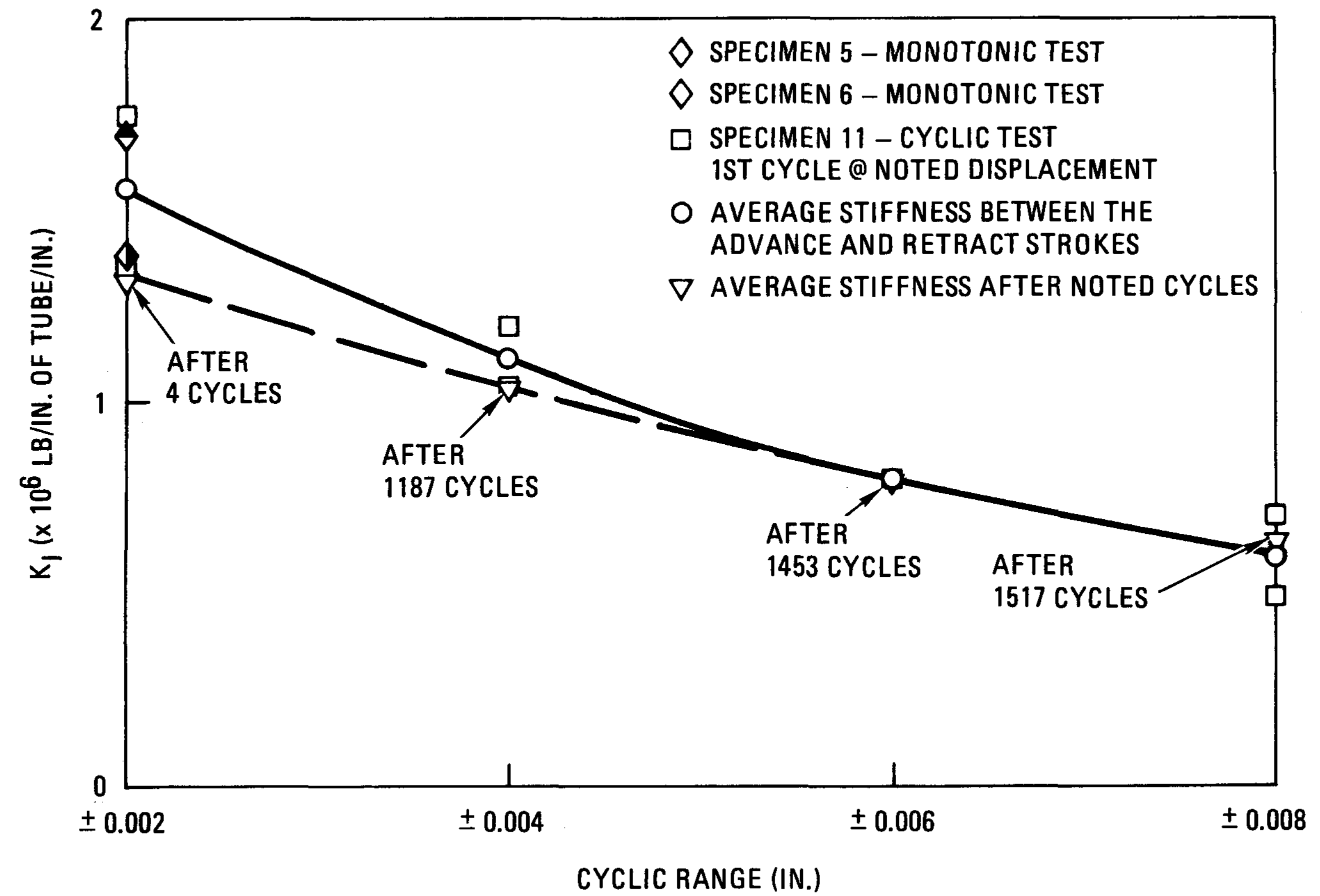


Fig. 35. Cyclic stiffness characteristics for specimen 11 (1-1/2-in. square tubes)

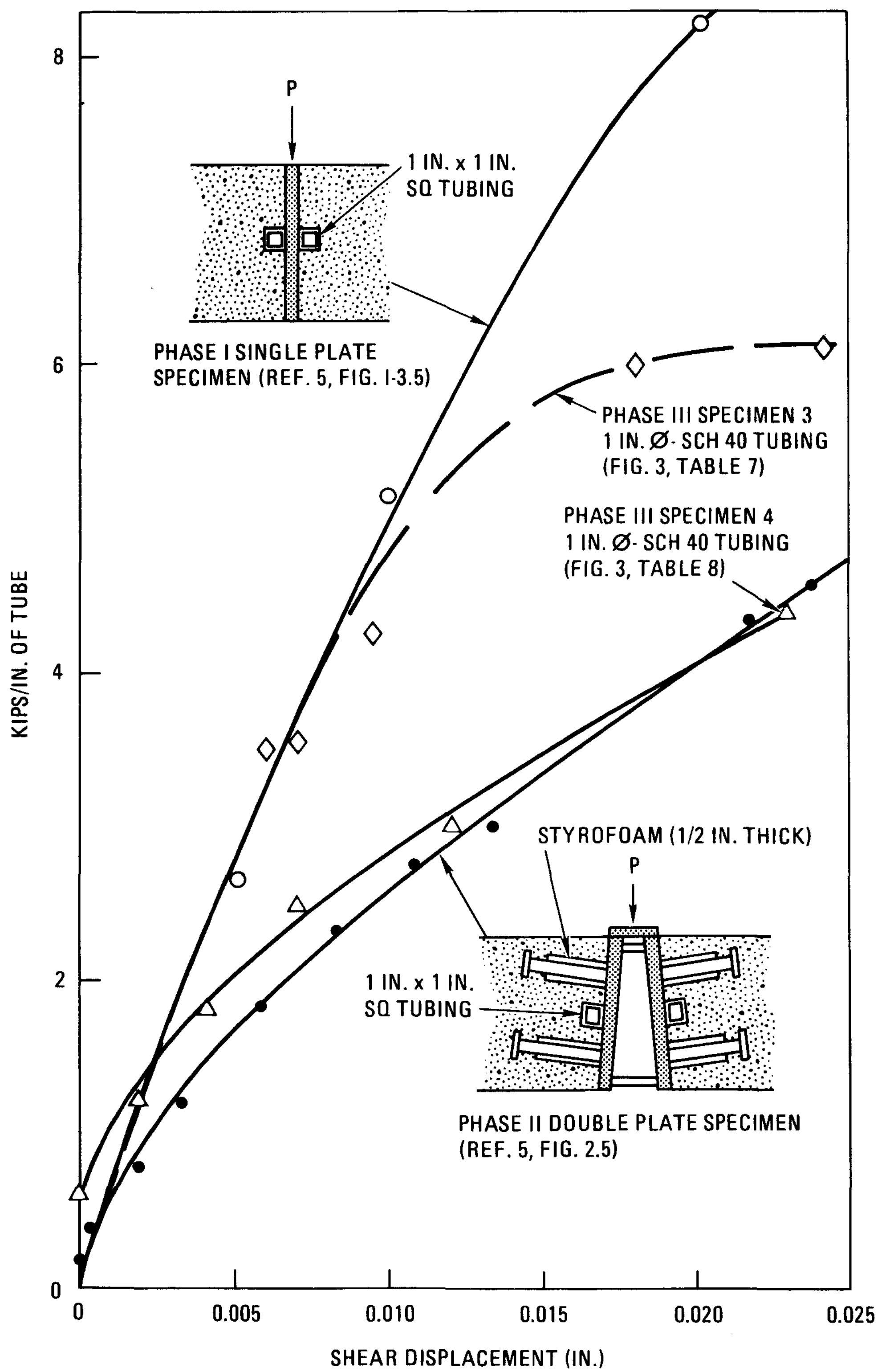


Fig. 36. Comparison of Phase I, II, and III load/displacement curves

APPENDIX A

COOLING TUBE MATERIAL

The cooling tube material specified in General Atomic documents (Table A-1) was not stocked by suppliers. The specified tube material for the round and square cross section could only be obtained through large mill orders. It was therefore decided to purchase off-the-shelf material and heat treat the material to the specified yield strength.

The materials purchased and the specified mechanical properties for both the round and the square cross section tubings are listed in Table A-2. The round cross section tubing material was purchased in the Grade B form such that a simple annealing was required to reduce the yield strength to that specified in Grade A. The specified square cross section tube material, however, was not available in any grade. It was therefore decided to purchase the tubes in the only material available, which was ASTM A-500, Grade A (Table A-2). The yield strength was reduced to that specified in the GA documents through annealing.

The heat treatment performed on each tube configuration and the yield strength that was produced are listed in Table A-3. The first or second annealing attempt produced an acceptable yield strength condition on three of the four configurations. For the fourth configuration (1-1/4 in. x 1-1/4 in. x 1/8 in.), however, prediction of the annealing effect proved to be difficult. The 1-1/4 in. x 1-1/4 in. square tubing was bought to the same specification as the 1-1/2 in. x 1-1/2 in. square tubing but from a different manufacturer (Table A-2). The carbon content (Table A-4) of the 1-1/4 x 1-1/4 tubing was much lower than that of the 1-1/2 x 1-1/2. The difference was considered to be the primary cause of the apparent inconsistency in the annealing effects.

TABLE A-1
GENERAL ATOMIC SPECIFIED LINER COOLING TUBE MATERIALS

Tube Configuration	Material	Minimum Values[a] (ksi)	
		Yield Strength	Ultimate Strength
Round cross section[b]	SA106 Grade A SA53 Type E or S Grade A	30 ↓	48 ↓
Square cross section[c]	SA106 Grade A SA53 Type E or S Grade A or B SA135 Grade A ASTM-A587	30 ↓	48 ↓

[a]ASME Boiler and Pressure Vessel Code, Section II, Part A, Ferrous Materials.

[b]General Atomic Specification No. 900115, "Carbon Steel Pipe with Round Cross Section."

[c]General Atomic Specification No. 900020, "Liner Cooling Tube with Square Section."

TABLE A-2
MATERIAL USED IN COOLING TUBE SHEAR TEST PROGRAM

Tube Configuration	Manufacturer	Specification	Mechanical Properties		
			Yield Strength (ksi)	Ultimate Strength (ksi)	Elongation (%)
Round cross section					
1 in. Sch 40	Gulf States Tube Div.	ASTM/ASME SA-106 Grade B	55.7	76.25	44
1-1/4 in. Sch 40	Gulf States Tube Div.	ASTM/ASME SA-106 Grade B	55	77.5	47
Square cross section					
1-1/4 in. x 1-1/4 in. x 1/8 in.	Maruichi Steel Tube Ltd., Osaka, Japan Sumitomo, Japan	ASTM A-500 Grade A	45.5	51.2	32
1-1/2 in. x 1-1/2 in. x 8/8 in.		ASTM A-500 Grade A	41.25	49.78	33

TABLE A-3
HEAT TREATMENT REQUIRED ON COOLING TUBE MATERIAL

Tube Configuration	Tube Dimensions		Heat Treatment and Effect[(a)]		
	Specified (in.)	As Measured (in.)			
Round cross section					
1 in. Sch 40	O.D. = 1.315 I.D. = 1.0496	O.D. = 1.275 I.D. = 1.008	(1) 1650°F for 30 min, air cool; YS = 47.4 ksi, US = 73.2 ksi	(2) 1650°F for 30 min, furnace cool; YS = 38.5 ksi, US = 67.6 ksi	--
1-1/4 in. Sch 40	O.D. = 1.66 I.D. = 1.38	O.D. = 1.64 I.D. = 1.365	(1) 1650°F for 30 min, furnace cool; YS = 37.4 ksi, US = 66.6 ksi	--	--
Square cross section					
1-1/2 in. x 1-1/2 in. x 1/8 in.	1.5 x 1.5 x 0.125	1.49 x 1.49 x 0.11	(1) 1650°F for 30 min, furnace cool; YS = 34.7 ksi, US = 48.7 ksi	--	--
1-1/4 in. x 1-1/4 in. x 1/8 in.	1.25 x 1.25 x 0.125	1.24 x 1.24 x 0.11	(1) 1650°F for 30 min, air cool; YS = 28.2 ksi, US = 44.2 ksi	(2) 1200°F for 2 hr, air cool; YS = 52.8 ksi, US = 56.6 ksi	(3) 1350°F for 2 hr, air cool; YS = 19.2 ksi, US = 42.6 ksi
			(4) 1300°F for 2 hr, air cool; YS = 27.6 ksi, US = 46 ksi	(5) 1250°F for 2 hr, air cool; YS = 42.6 ksi, US = 52.2 ksi	(6) 1300°F for 1 hr, air cool; YS = 31.2 ksi, US = 47.4 ksi

(a) YS = yield strength; US = ultimate strength.

TABLE A-4
CHEMICAL ANALYSIS OF COOLING TUBE MATERIAL

Tube Configuration	Specification	Chemical Analysis in Percent					Heat No.
		C	Mn	P	S	S1	
Round cross section							
1 in. Sch 40	ASTM/ASME SA-106[a] Grade B	0.19	0.74	0.015	0.010	0.15	HD8960
1-1/4 in. Sch 40	ASTM/ASME SA-106[a] Grade B	0.20	0.75	0.014	0.014	0.17	KD7588
Square cross section							
1-1/4 in. x 1-1/4 in. x 1/8 in.	ASTM A-500 Grade A[b]	0.06	0.35	0.019	0.022	Trace	7-13841
1-1/2 in. x 1-1/2 in. x 1/8 in.	ASTM A-500 Grade A[b]	0.18	0.51	0.024	0.020	0.10	209083

[a] Seamless pressure pipe.

[b] Electric resistance welded square and rectangular tube.

APPENDIX B

COOLING TUBE WELDING

The cooling tubes were welded to the liner plate (SA 537 Class 2, 3/4 in. thick) in accordance with GA specification No. 900006, "PCRV Liner and Penetration Liner Cooling System Specification." Weld samples were prepared for each tube configuration (Figs. B-1, B-2). These samples were sectioned in thirds and photographed, as shown in Figs. B-3 and B-4. A liquid penetration surface examination was performed on one specimen of each configuration. The test was conducted per Section V, Article 6, of the ASME Boiler and Pressure Vessel Code, Section III, Division 1, with the exception of the criteria (CB-5544.2). No surface flaws and/or cracks were reported. The sampling technique used simulates the required prototype cooling tube weld surface examination.

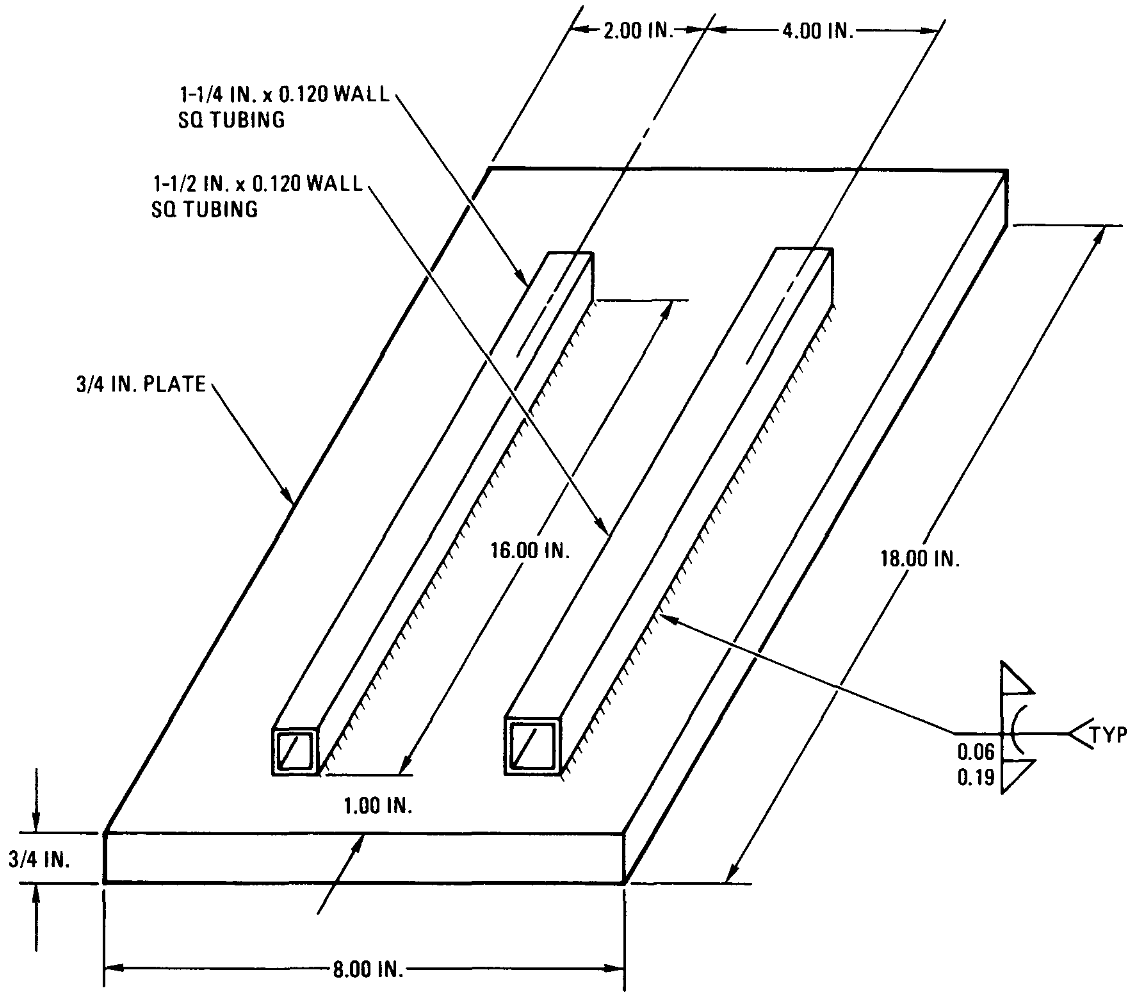


Fig. B-1. Cooling tube test, square weld sample

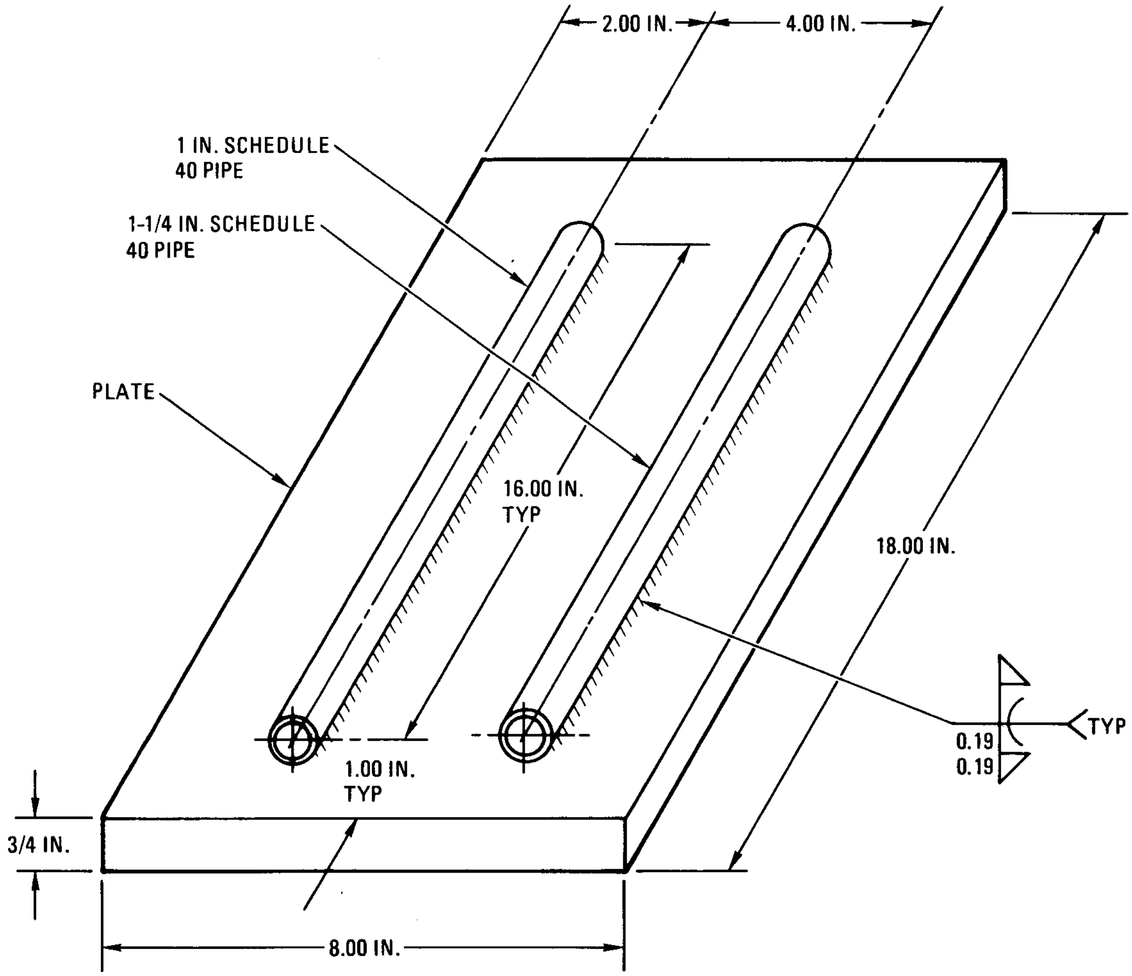
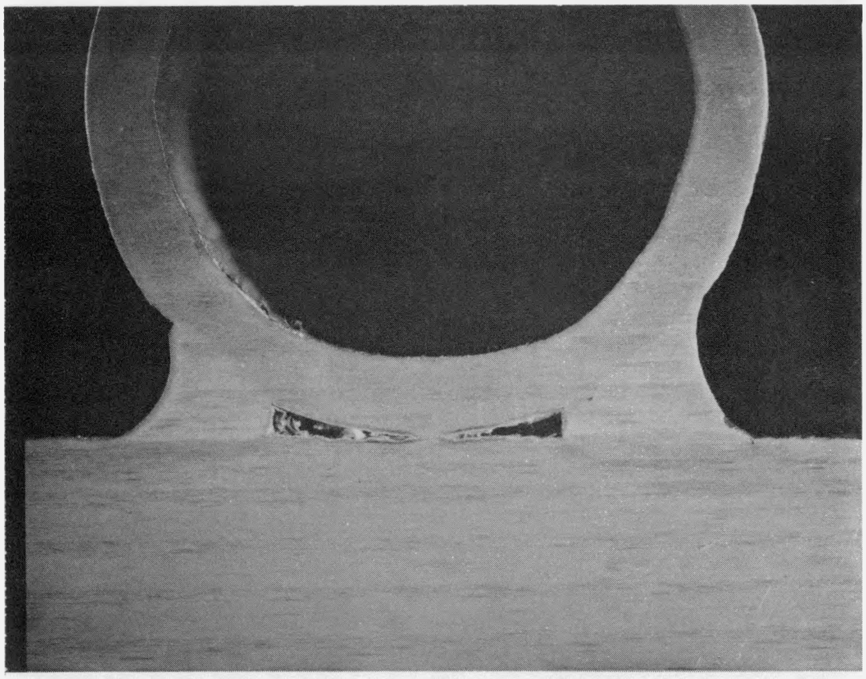
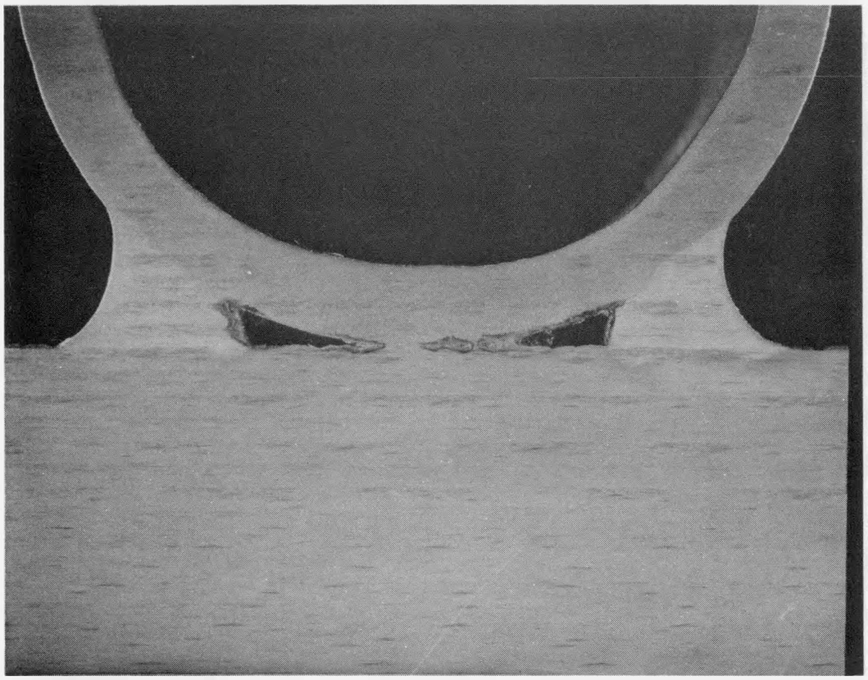


Fig. B-2. Cooling tube test, round weld sample

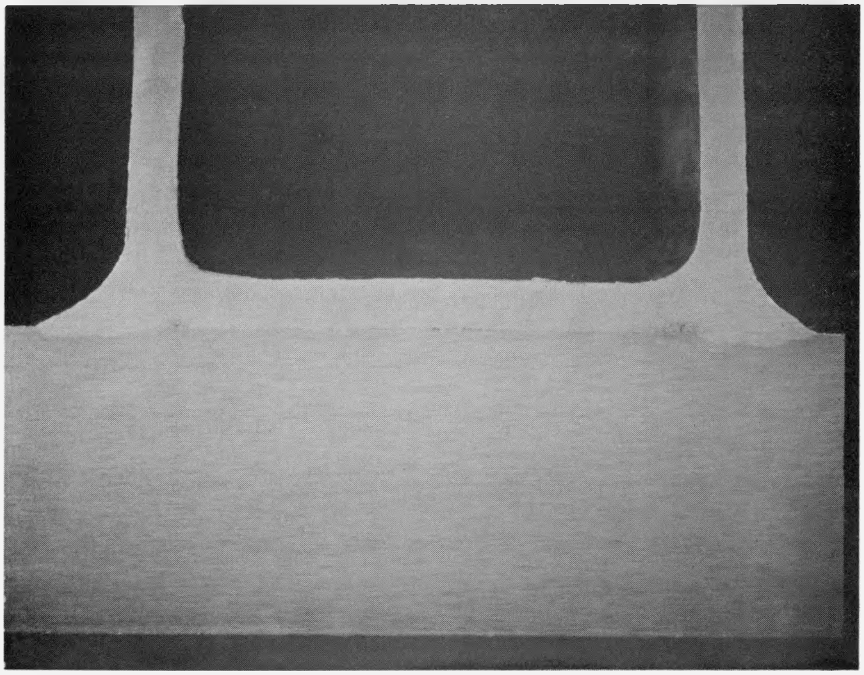


(a) Cross section of 1-in. ∅ typical weld

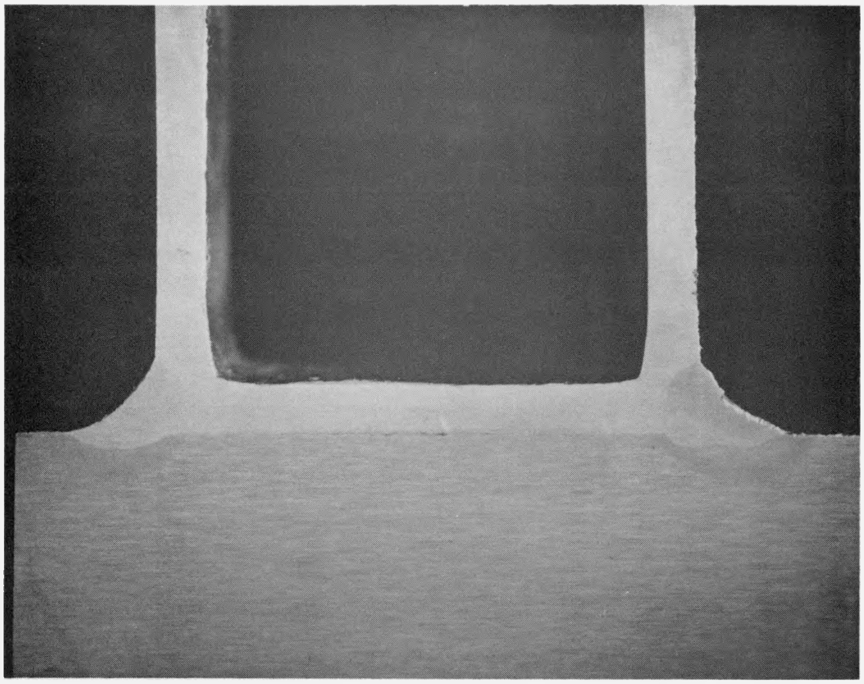


(b) Cross section of 1-1/4-in. ∅ typical weld

Fig. B-3. Weld details of square cross section tubes



(a) Cross section of 1-1/4-in. ∅ typical weld



(b) Cross section of 1-1/2-in. ∅ typical weld

Fig. B-4. Weld detail of round cross section tubes

APPENDIX C

CASTING OF SPECIMENS

All twelve shear specimens were cast at Southern California Testing Laboratory (San Diego) according to GA Specification 903406, "PCRV Liner - Specimens for Shear Tests" (Ref. 3).

The concrete mix was designed on a one cubic yard basis with proportions as follows:

Cement	700 lb
Water	260 lb
Fine aggregate	1207 lb
3/8 in. aggregate	387 lb
3/4 in. aggregate	580.5 lb
1-1/2 in. aggregate	967.5 lb
Admixture	6 fluid oz/100 lb of cement

The casting operation was carried out over a 6-day period, with two batches being cast each day (Table C-1). The batch sizes varied depending on the size and number of shear specimens and test cylinders to be cast. Steel forms were used in the casting operation to assure dimensional control of the concrete block. The specimens were stored outdoors beneath soaked burlap sacks and plastic covering until the last compressive cylinder test was conducted. The cylinder test results for each specimen and the age at testing are listed in Table C-2.

TABLE C-1
COOLING TUBE SPECIMEN CASTING

Casting No.	Batch No.	Cubic Yards	Specimen Cast	No. of Cylinders	Date Cast
1	3	0.084	1	2	5/8/78
	4	0.084	2	1	5/8/78
2	3	0.086	3	2	5/10/78
	4	0.080	4	1	5/10/78
3	3	0.086	5	2	5/12/78
	4	0.086	6	2	5/12/78
4	3	0.080	7	2	5/16/78
	4	0.079	8	1	5/16/78
5	1	0.10	9	3	5/18/78
	2	0.10	10	3	5/18/78
6	1	0.10	11	3	5/22/78
	2	0.10	12	3	5/22/78

TABLE C-2
CONCRETE COMPRESSIVE STRENGTH TEST RESULTS

Specimen No.	Age (days)	Compressive Strength (psi)[a]
1	7/28	6120/7640
2	14	7520
3	7/28[b]	6508/7430
4	14	7160
5	7/28	6410/7040
6	14/28	7340/7415
7	7/28	6970/7560
8	14	7020
9	7/14/28	5980/6080/6990
10	7/14/28	6130/6410/6980
11	7/14/28	6085/6300/6690
12	7/14/28	6225/6700/7270

[a] Specified minimum compressive strength of concrete was 6500 psi at 28 days per GA Document 903406.

[b] Modulus of elasticity at 28 days = 3.6×10^6 psi.

APPENDIX D
TEST SETUP

The PCRV liner cooling tube structural test was conducted in the Experimental Engineering Department test facility of General Atomic Company.

A portable drilling machine and boring bar arrangement was used on each specimen to rebore the hole for the pin connection between the specimen and loading fixture. This operation made pin insertion easy and provided a positive contact surface between the pin and loading block.

The cooling tube shear test program drawing package is listed in Table D-1. The shear test fixture for the cooling tube specimen is shown in Figs. D-1 and D-2. Air-operated hydraulic pumps (see Fig. D-3) supplied pressurized oil to actuate the hydraulic cylinder. Figure D-4 shows the test control and instrumentation setup. Details of the test equipment configuration are given in Figs. D-5 through D-8.

TABLE D-1
DRAWING PACKAGE

Drawing No.	Issue	Title
EE-2517 (2 sheets)	A	Test Rig Assembly
EE-2536	A	Frame Assembly
EE-2518	A	Pin - Cooling Tube
EE-2519	A	Clevis
EE-2520	A	Clevis Pin
EE-2521	A	Load Cell Base
EE-2528	A	Spacer
EE-2529	A	Washer - Cooling Tube
EE-2532	A	Rod Assembly - Cooling Tube
EE-2533	A	Clamp Bar - Cooling Tube
EE-2534	A	Stud - Cooling Tube
EE-2535	A	Bolt - Cooling Tube
EE-2540	A	Rod - Cooling Tube
EE-2541	A	Test Specimen Assembly - Cooling Tube
EE-2559	A	Jam Nut
023663	C	Test Specimen - Cooling Tube
EE-2548	A	Mold Assembly - 16 Inch Cooling Tube
EE-2593	A	Test Coupon - Round Tube
EE-2595	A	Test Coupon - Square Tube
EE-2596	A	Tube Plugs - Tensile Test

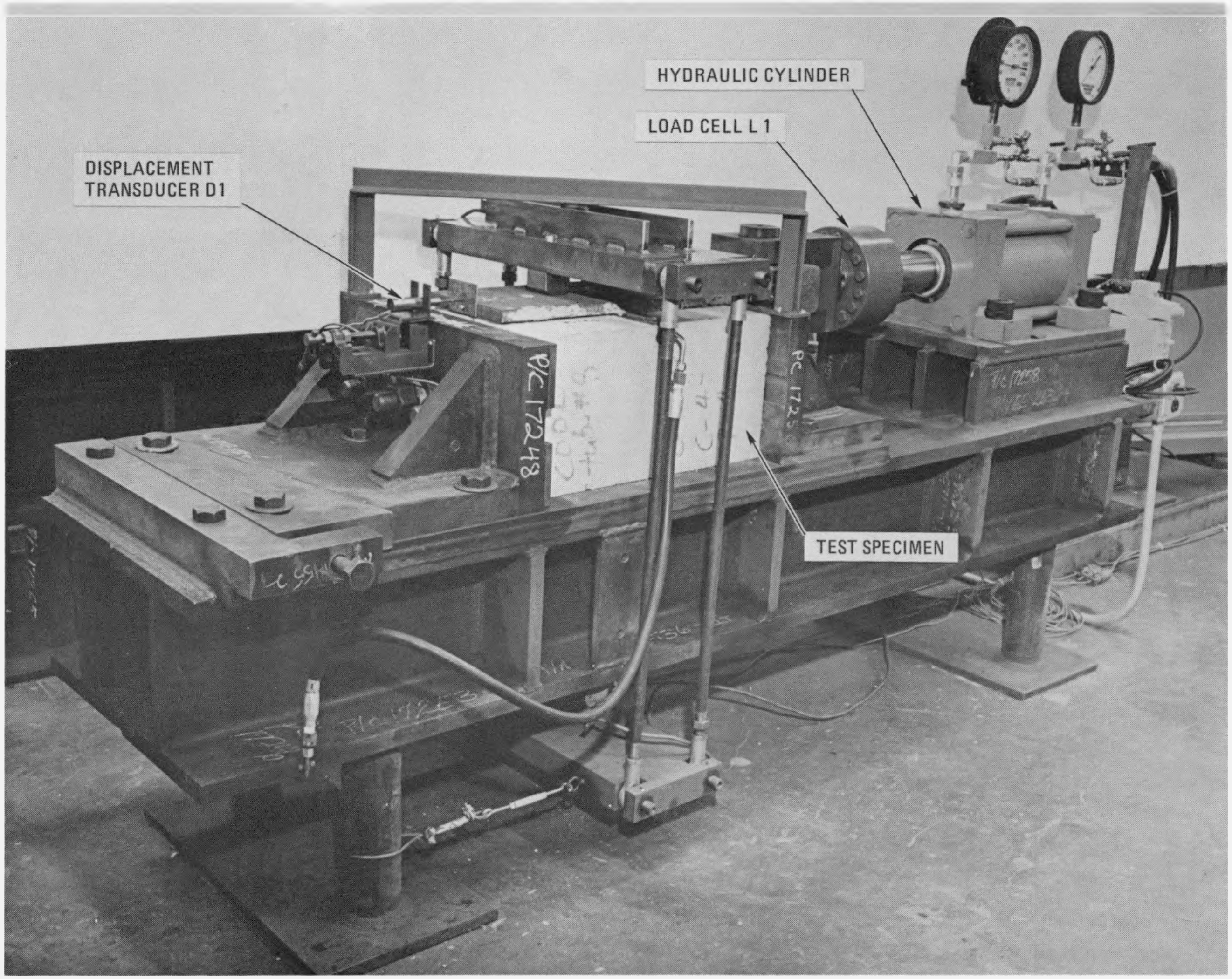


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Fig. D-1. Cooling tube test rig (EE-2517-1)

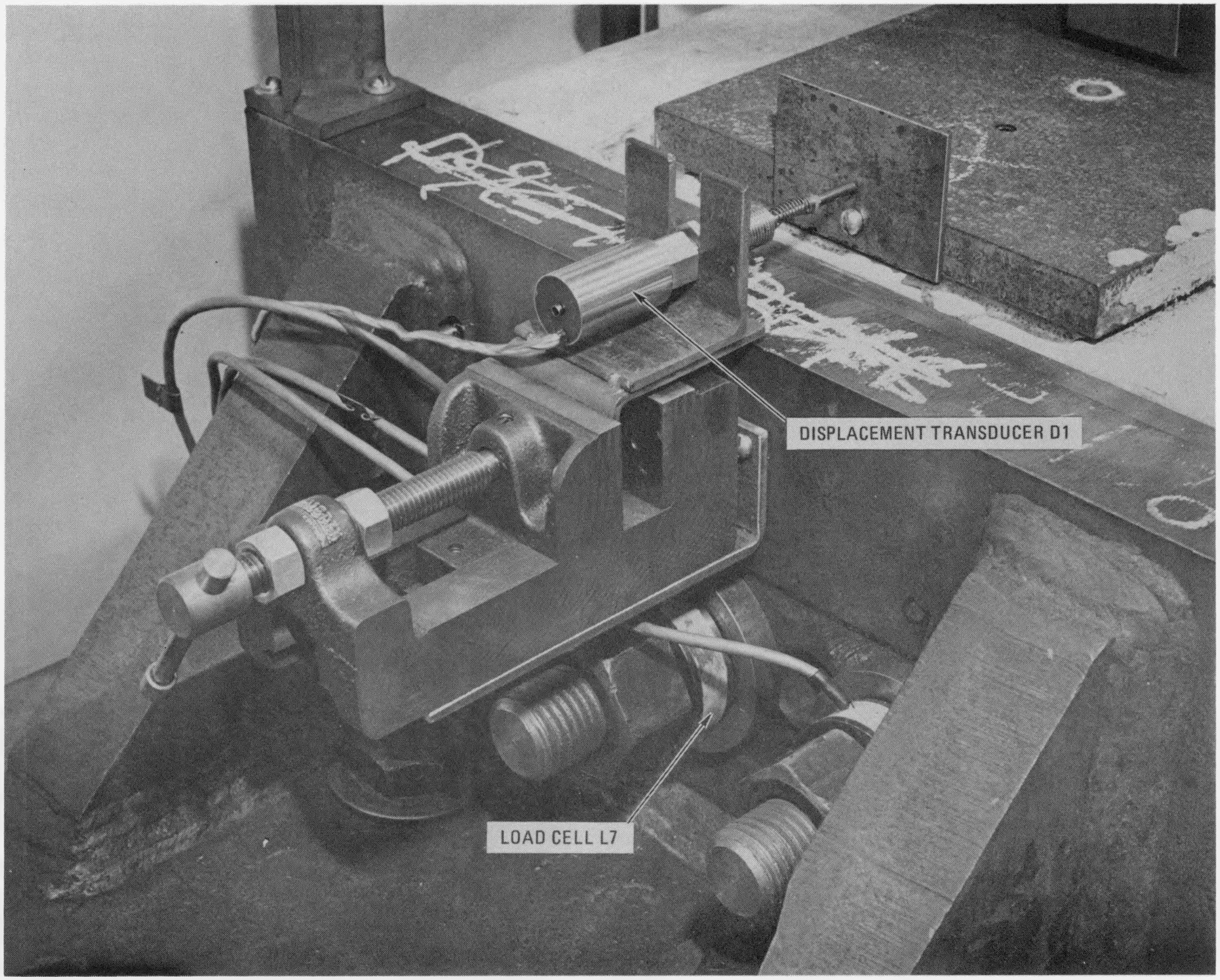

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Fig. D-2. Cooling tube test rig instrumentation (EE-2517-1)

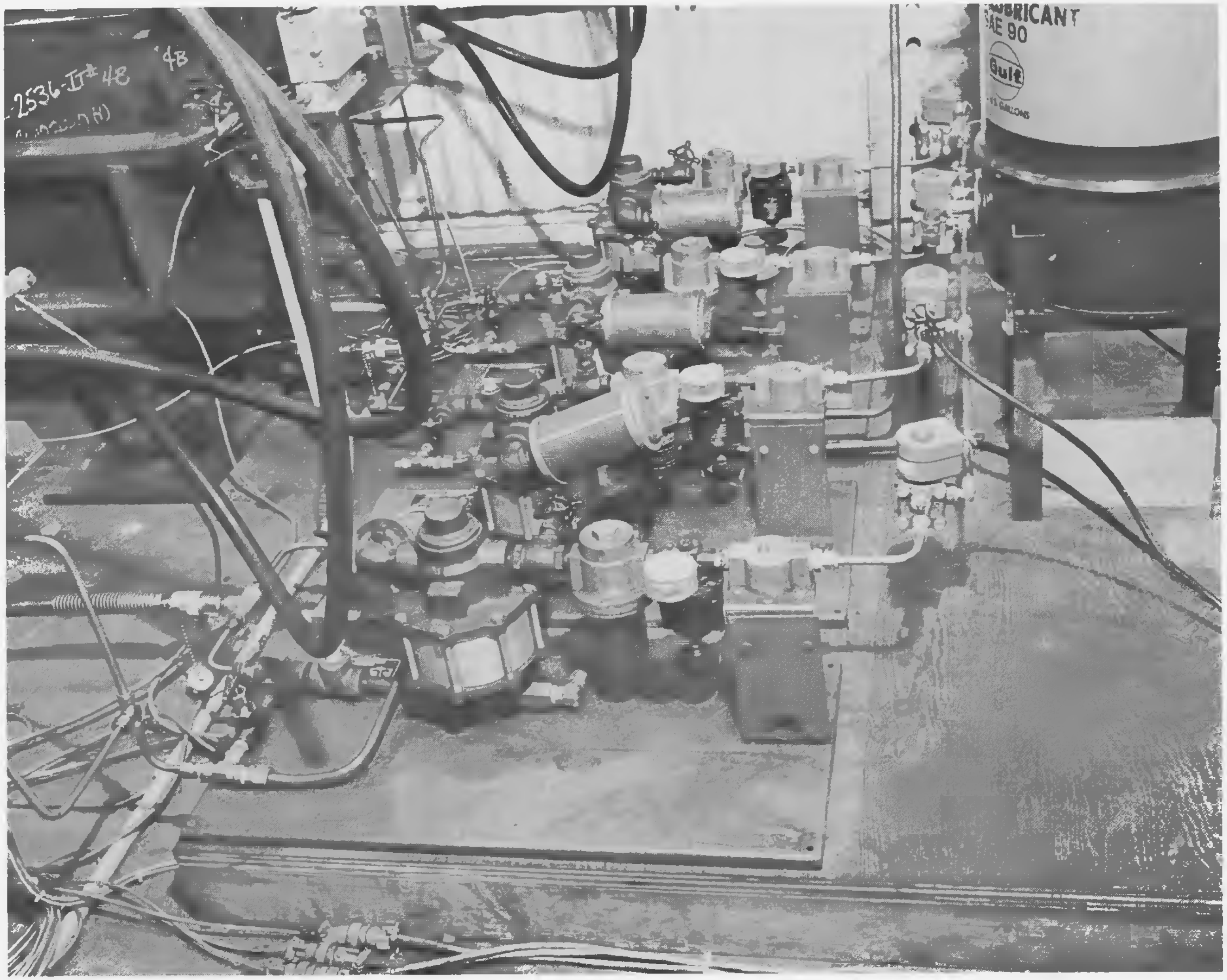

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Fig. D-3. Air-operated hydraulic pumps

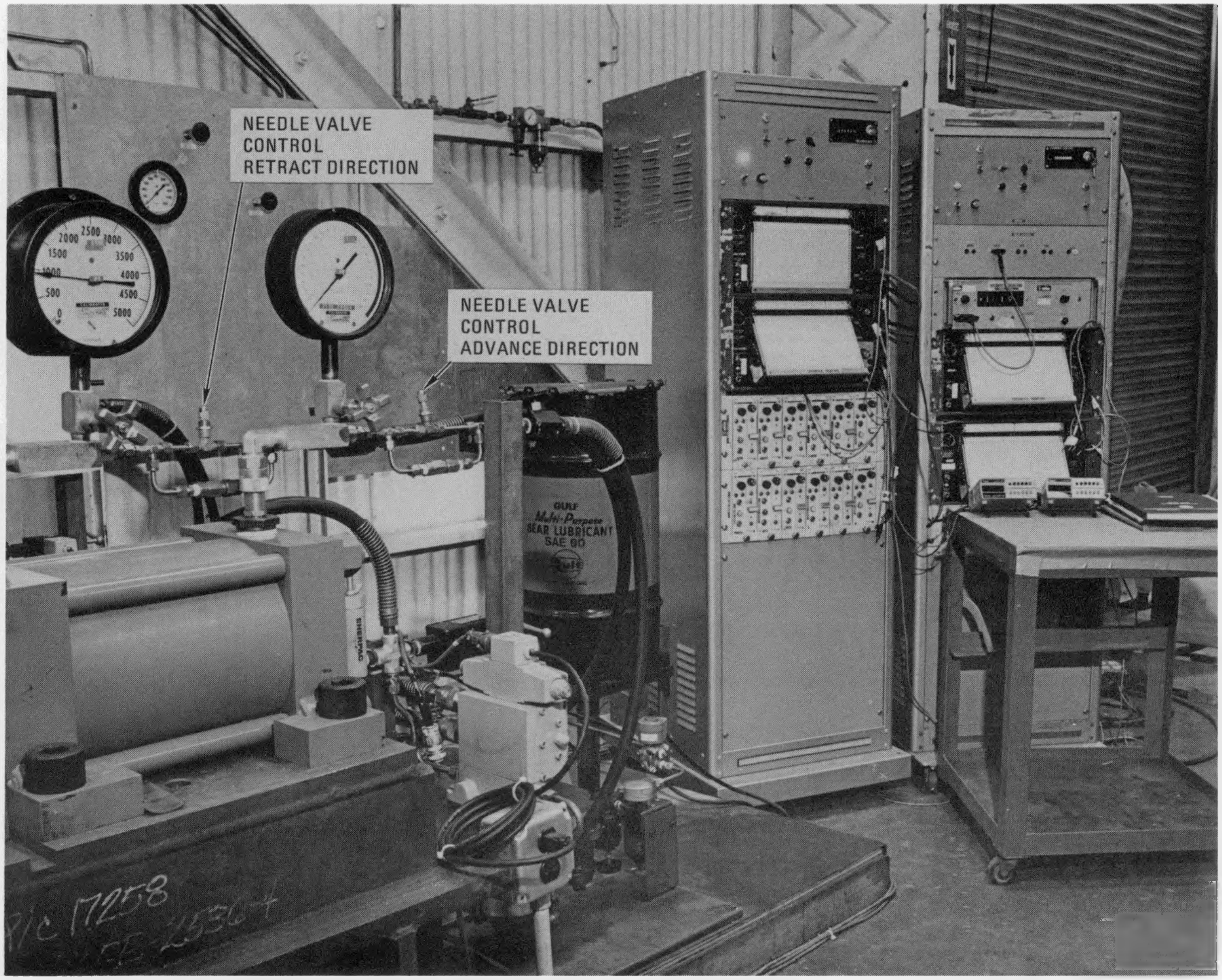

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Fig. D-4. Cooling tube test controls and instrumentation

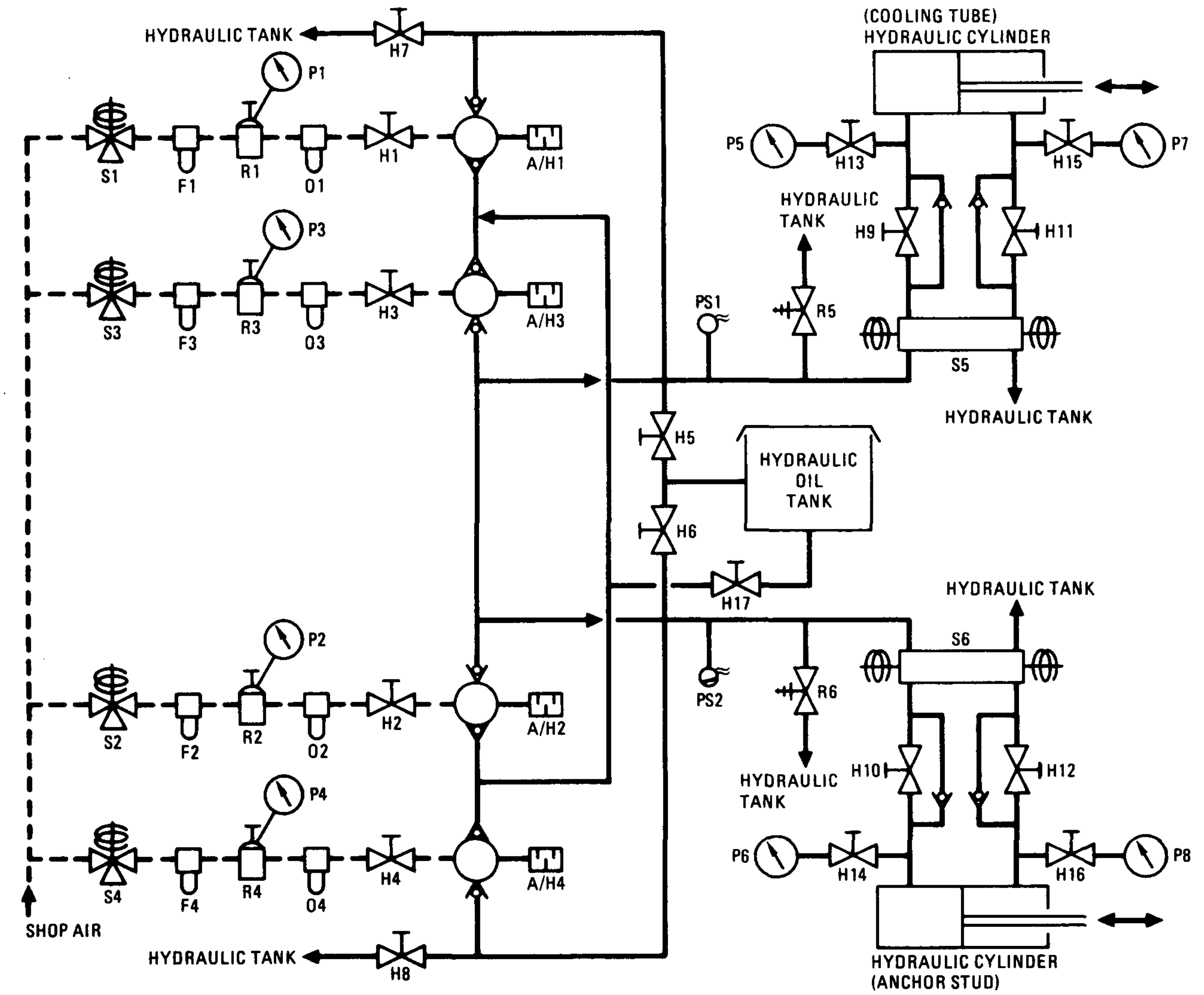


Fig. D-5. Hydraulic load system schematic

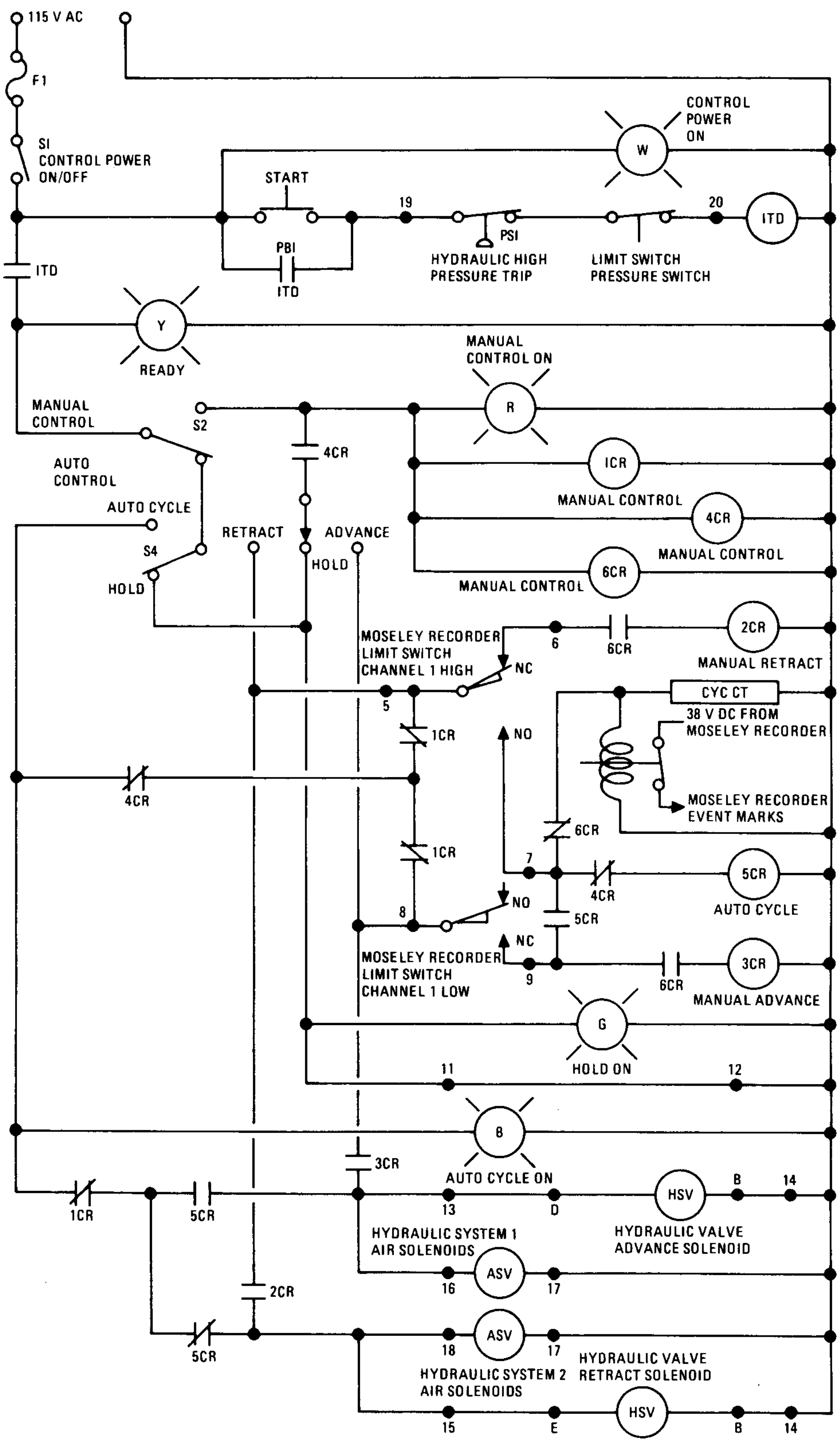
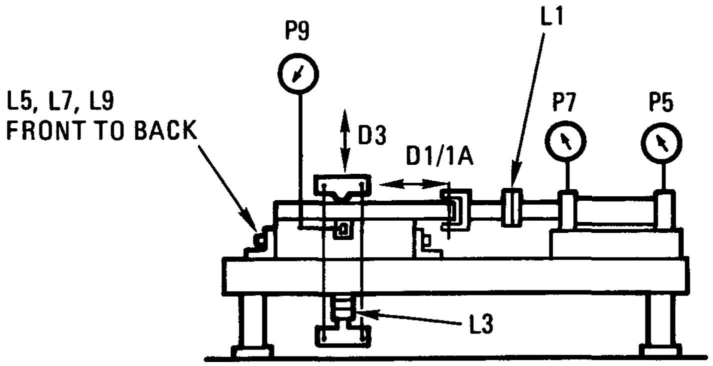


Fig. D-6. Test control circuit schematic

INSTRUMENTATION LIST FOR PCRV COOLING TUBE SHEAR TESTS (PHASE III)						
TEST RIG	MEASUREMENT TYPE	SYMBOL	TRANSDUCER MFG.	NOMINAL RANGE	RECORDER/ INSTRUMENT	REMARKS
EE-2517-1	DISPLACEMENT	D1	AMETEK	0.6 IN.	MOSELEY	MONOTONIC TEST
COOLING	DISPLACEMENT	D1A	DAYTRONICS	0.1 IN.	MOSELEY	FATIGUE TEST
TUBE	DISPLACEMENT	D3	DAYTRONICS	0.1 IN.	MOSELEY	
	LOAD	L1	INTERFACE	50K LB	MOSELEY	
	LOAD	L3	INTERFACE	50K LB	MOSELEY	
	LOAD	L5	SABER	50K LB	METER (DVM)	
	LOAD	L7	SABER	50K LB	METER (DVM)	
	LOAD	L9	SABER	50K LB	METER (DVM)	
	PRESSURE	P5		5000 PSI	GAGE	
	PRESSURE	P7		5000 PSI	GAGE	
	PRESSURE	P9		60 PSI	GAGE	



EE-2517-1 COOLING TUBE TEST RIG

Fig. D-7. Instrumentation for cooling tube test

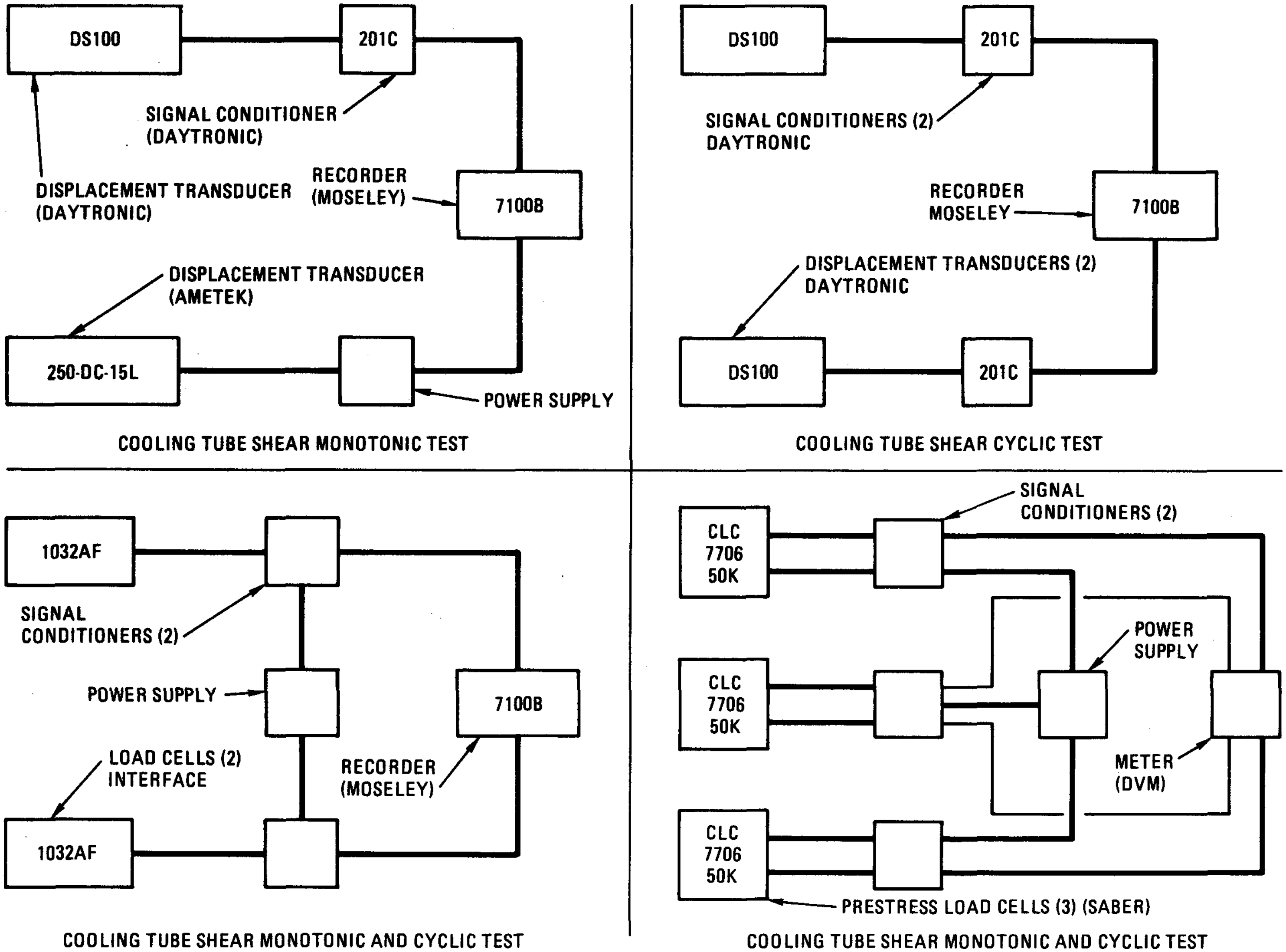


Fig. D-8. Test instrumentation block diagram