Steam Generator Evaluation
Ginna Steam Generator Tube Failure Incident
January 25, 1982
R. E. Ginna Nuclear Power Plant
Docket No. 50-244

Addendum 2
Laboratory Fatigue Testing

Revision 0
May 18, 1982

FATIGUE TESTING OF STRUCTURALLY DEGRADED MODEL 44 STEAM GENERATOR TUBING
(7/8" O.D. x 0.050" WALL)

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Fatigue Testing Program

The purpose of this testing program is to determine the fatigue characteristics of structurally degraded tubes such as seen in the Ginna-B Steam Generator.

For structurally degraded tubing, the predominant cyclic loading results from fluid interaction (with or without lateral load impacts). Therefore, the tube response of prime interest is of a high cycle fatigue nature. However, in light of the time constraint, the actual testing performed was of a low cycle fatigue nature. An attempt was made to accelerate the fatigue damage by specifying dynamic vibration amplitudes significantly higher than those a structurally degraded tube in the steam generator would experience. In the following the results of high amplitude - low cycle testing will be correlated to analytically predicted tube responses under low amplitude - high cycle conditions typical of flow-induced vibration loadings.

Three types of tests were performed in conjunction with the fatigue testing program:

Strain Survey Tests

Basic Fatigue Tests

Impact Fatigue Tests

The strain survey tests were performed to experimentally determine the relationship between deflection and stress at various locations for a length of steam generator tubing between the tube sheet and first support plate with a locally degraded region. Strain gages were installed at the point of maximum tube deflection and at locations in the degraded region. The specimen was then vibrated at different amplitudes and the strains measured. Stress values were calculated from the measured data.

In the basic fatigue tests nominal 0.875 inch O.D. x 0.50 inch thick tubes were mechanically degraded locally near one end and set in a tube sheet simulation (collar) at that end and a tube support plate simulation at the other. The tube end conditions approached approximately either a "fixed-pinned" or a "fixed-fixed" situation. The structurally degraded section was typically 2.0 inches long with its center 4.0 inches from the tube sheet simulated end. Two damaged configurations were tested: flattened (to simulate a full collapse) and kidney-shaped (to simulate a partial collapse). The flattened shape was achieved by clamping the 2 inch section of the tube in a vise, and squeezing the tube. The kidney-shaped section was one in which half of the tube circumference was made to nestle into the other half.

For the impact fatigue tests a length of tubing between a tube sheet and first support plate simulation with a locally degraded region approximately four inches from the tube sheet simulation was vibrated such that it would impact against a fixture causing an impact type load. To accomplish this a chisel with a rounded tip was positioned near the end of the degraded region so that the specimen would hit the chisel on each vibration cycle. The chisel was instrumented with a calibrated semiconductor strain gage to obtain a reactive load measurement.

Test Equipment and Setup

Figures 1 through 4 show the basic test setup used. A vibration exciter was attached to the tube with a small hose clamp approximately 12 inches from the simulated first support plate end of the tube. Deflections were monitored with a linear variable differen- tial transformer. The deflection was set by adjusting a micrometer to the specified (single amplitude) deflection. The tube was then vibrated until it just touched the micrometer. The LVDT output was then observed and maintained at that amplitude for the duration of the test. An instrumentation block diagram for the basic test setup is shown in Figure 5.

Two different support configurations were used for these tests, a fixed-fixed and a fixed-pinned condition. The faces of the support blocks were 51.8 inches apart for the fixed-fixed configuration with the degraded portion of the tube centered four inches from one face. In the fixed-pinned case the distance between the support fixtures was 57.8 inches.

The fixed support consisted of a four inch long block through which a 0.89 inch diameter hole was drilled to accept the tube (test specimen). The first two inches of the tube were rolled into the block. The pinned support restraint consisted of a .030 inch thick stainless steel sheet through which a hole was drilled to accept the tube, which was epoxied in place.

After these fixtures were attached to the test specimen, the assembly was bolted to a strong back; an 8 x 8 inch wide flange beam. In order to expedite testing, the strong back for the start of the first test consisted of 1 x 6 inch steel bar which was bolted to a bedplate.

The tubes were oriented so the axis of the minimum cross section of inertia of the degraded region was parallel to the strong back. The vibration exciter was attached to the tube approximately 12 inches from the end of the tube farthest from the degraded region. The direction of vibration was vertical.

In the cases where a constant axial load was applied*, the tube was instrumented with four axial strain gages at 90° increments around the tube, six inches from the simulated first support plate support. The

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* If tubes in the steam generator are assumed to be axially restrained at the first tube support, an axial tensile load of the order of 1000 lb. exists on a plugged tube in a hot leg wedge area due to tube-to-shell and tube-to-tube thermal interactions during steady-state power operation.

required strain for a 1000 lb. axial load was calculated from the specimen geometry for a modulus of elasticity of 31.7×10^6 psi. The axial loads were applied with a screw arrangement prior to tightening the second mounting block. The tube strain was monitored during loading and tightening and was periodically checked during the test.

Special fixturing was developed to impose impact loads on the tube in the degraded region. The impact fixturing was installed on the strong back. The two major problems in the fixturing design were the need to provide a hard impact surface which would not deform significantly during the course of the test and to provide a means of measuring the impact forces. In order to avoid time consuming machining and heat treating, a commercially available cold chisel was used to provide the impacting surface. The sharp end was ground to a blunt surface approximately 30 mils wide. This chisel was then instrumented with four semiconductor strain gages. This type of instrumentation provides very high frequency responses with a minimum of extraneous mass effects.

After the strain gages were installed and prior to actual impact testing, the chisel was mounted in a universal testing machine and loaded against a piece of inconel tubing. Load vs strain curves were obtained with the chisel centered on the tube, as well as with it offset by approximately .050 inches, to obtain an indication of the effects of off center loading. The variation was found to be less than 5 percent.

Three factors contributed to the impact loads obtainable in the test apparatus: the tube velocity at impact, the mass and stiffness characteristics of the tube, and the mass and stiffness characteristics of the backing structure for the impactor or chisel. It was originallly hoped that an impact load magnitude of approximately 450 lb. could be obtained. After considerable effort to stiffen and increase the mass of the backing structure a load of 186 lb. was achieved. It is doubtful that further efforts would have made a significant difference.

Strain Survey Tests

In the strain survey tests strain gages were mounted at the locations shown in Figure 6. The strain survey results for a .3 inch peak to peak deflection are found in Table 1. As can be seen from these results the maximum recorded stress was 31,200 psi tension and the maximum stress difference range was 46,800 psi (fixed-fixed flat degradation with 1000 lb. axial tension). Also the fixed-fixed configuration results in substantially higher stresses than the fixed-pinned configuration for a given vibration amplitude.

Basic Fatigue Tests

Four basic fatigue tests were performed and are discussed below.

A fixed-pinned beam with a 2-inch flat degradation was tested with no axial load. The natural frequency was 39.3 Hz. The fatigue testing was performed for 300,000 cycles at peak-to-peak dynamic amplitude of .05 inch (.05 DA), .07 DA, .09 DA, .12 DA, .16 DA, .20 DA, .25 DA, .30 DA, .40 DA and 3 x 10^6 cycles at .50 DA or a total of 6.3 x 10^6 cycles. There was no failure.

A fixed-fixed beam with a 2-inch flat deformation was tested with a 1000 lb. axial load. The natural frequency was 63.6 Hz. The fatigue test was run for 200,000 cycles at .05 DA and 2.0 x 10^6 cycles for .3 DA. No failure of the specimen was observed.

A fixed-fixed beam with a 2-inch long flat deformation, with 0.005 inch deep by 1/4 inch long notches at 2 locations within the degraded section, was tested with a 1000 lb. axial load. The specimen was vibrated at .30 DA and failed after 900,000 cycles. Failure did not occur at a notch and this may have been due to the fact that the loading blocks used to deform the tube may have weakened the tube at a non-notched location.

A fixed-fixed beam with a 1 inch long kidney-shaped degradation was tested with a 1000 lb. axial load and vibrated at .30 DA. No failure occurred after 6 x 10^6 cycles.

Results of the basic fatigue tests are summarized in Table 2.

Impact Fatigue Tests

The impacting test was performed to simulate the effect of an impact force imposed near a degraded region of a tube. This was done to simulate the effect of a foreign object striking a degraded steam generator tube. In the first test a 2-inch long kidney-shaped degraded region was selected and a 1000 lb. axial load applied. The test specimen was vibrated at .30 DA and impact loads of 75 lb., 132 lb. and 186 lb. applied for 1.8 x 10^6 cycles, 1.1 x 10^6 cycles, and 1.1 x 10^6 cycles, respectively. No failure occurred.

In the second test a 2 inch long flat degraded area was selected and a 1000 lb. axial load applied. The test specimen was vibrated at .30 DA and an impact load of 150 lb. applied for 3 x 10^6 cycles. No failure occurred.

Results of the impact fatigue tests are summarized in Table 2.

Conclusions

The following conclusions are applicable to the above tests:

- Structurally degraded tubing, when subjected to significantly large vibration amplitudes, are not expected to fail due to low cycle fatigue.

- Based on the results of the strain survey, the worst test configuration corresponds to the fixed-fixed tube condition with a 2-inch flat degradation and loaded axially with 1000 lb. tension.

As applicable to the response of steam generator tubing under operating conditions, the following is to be noted.

The proposed ASME high cycle fatigue curve extended to $N = 10^{11}$ cycles for Inconel 600 based on $E = 28.3 \times 10^6$ psi and for temperatures not exceeding 800°F shows an endurance limit of $S_e = 13.7$ ksi. With due corrections for the room temperature modulus of elasticity of 31.7×10^6 psi, $S_e = 14.9$ ksi. In the tests, the maximum stress range based on the strain surveys was 46.85 ksi (alternating stress intensity of 46.85/2 = 23.43 ksi) at a peak-to-peak amplitude of 300 mils. This occurred for the fixed-fixed, 2-inch flat degraded configuration with 1000 lb. axial load. Since the stresses for a given configuration are proportional to the applied vibration amplitudes, the peak-to-peak amplitude for the worst case configuration above, corresponding to the high cycle fatigue endurance limit is

$$DA = \frac{14.9 \times 0.3}{23.43} = 0.19 \text{ inch}$$

This DA is significantly higher than an analytically predicted upper bound amplitude of a structurally degraded tube in the steam generator. Based on the results of the room temperature testing of mechanically degraded tubes, it can be concluded that fatigue failure of structurally degraded steam generator tubing is unlikely under the influence of flow-induced vibration loading alone. Additionally, failures will not be expected as a result of fatigue due to a lateral impact load acting locally at one location. However, the potential for tube cracking and ultimate severence may exist due to progressive notching as a result of repeated impacting at the same location as evidenced by the examination of tube specimens following the impact testing. Furthermore, if the impact location was continually and randomly changed, tube cracking and ultimate failure could result due to the combined effects of notching and fatigue damage.

TABLE 1

STRAIN SURVEY RESULTS FOR .3 INCH PEAK TO PEAK DEFLECTION

Test Configuration	Axial Load	Resonant Frequency		Gage 1*	Gage 2	Gage 3	Gage 4	Gage 5	Gage 6
Fixed-Fixed Flat Degradation, 2" long	0 lb.	57.9 Hz	Max Stress Psi	+8400	+17400	+8250	+3900	+17400	+22200
			Min Stress Psi	-8400	-17400	-8250	-3900	-17400	-22200
Fixed-Fixed Flat Degradation, 2" long	1000 lb.	63.6 Hz	Max Stress Psi	+18300	+26700	+15600	+11700	+25200	+31200
			Min Stress Psi	-2700	-11100	0	+3900	-9600	-15600
Fixed-Pinned Flat Degradation, 2" long	0 lb.	39.3 Hz	Max Stress Psi	+3300	+8100	+3400	+2550	+7200	--
			Min Stress Psi	-3300	-8100	-3400	-2550	-7200	--
Fixed-Fixed Kidney-Shaped Degradation, 1" long	0 lb.	59.0 Hz	Max Stress Psi	+9000	+17550	+12750	+15390	+8250	+12750
			Min Stress Psi	-9000	-17550	-12750	-15390	-8250	-12750
Fixed-Fixed Kidney-Shaped Degradation, 1" long	1000 lb.	67.7 Hz	Max Stress Psi	+17550	+24300	+19800	+22800	+16440	+20550
			Min Stress Psi	-1950	-8700	-4200	-7200	-840	-4950

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* Refer to Figure 6 for gage locations.

TABLE 2

FATIGUE TEST SUMMARY

Test No.	Degradation Shape	Configuration	Axial Tension lbs.	Amplitude, Inch (Peak to Peak)	Frequency Hz	Cycles Tested	Results
1	Flat 2" long	Fixed-Pinned	0.	.05 .20 .07 .25 .09 .30 .12 .16 .40 .50	39.3	$.3 \times 10^6$ (each level) 3.6×10^6	No failure
2	Flat 2" long	Fixed-Fixed	1000.	.05 .30	63.6	$.2 \times 10^6$	No failure
3	Flat 2" long	Fixed-Fixed, Notched at transition	1000.	.30	63.6	$.9 \times 10^6$	Failed - not at notch
4	Kidney-Shaped 1" long	Fixed-Fixed	1000.	.30	67.7	6×10^6	No failure
5	Kidney-Shaped 2" long	Fixed-Fixed	1000.	.30	66.6	1.8×10^6 with 75 lb. impact force 1.1×10^6 with 132 lb. impact force 1.1×10^6 with 186 lb. impact force	No failure *
6	Flat 2" long	Fixed-Fixed	1000.	.30	63.6	3.0×10^6 with 150 lb. impact force	No failure *

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* Although no failure occurred, tubes were notched about 25 to 30 mils deep at the location of the impactor.

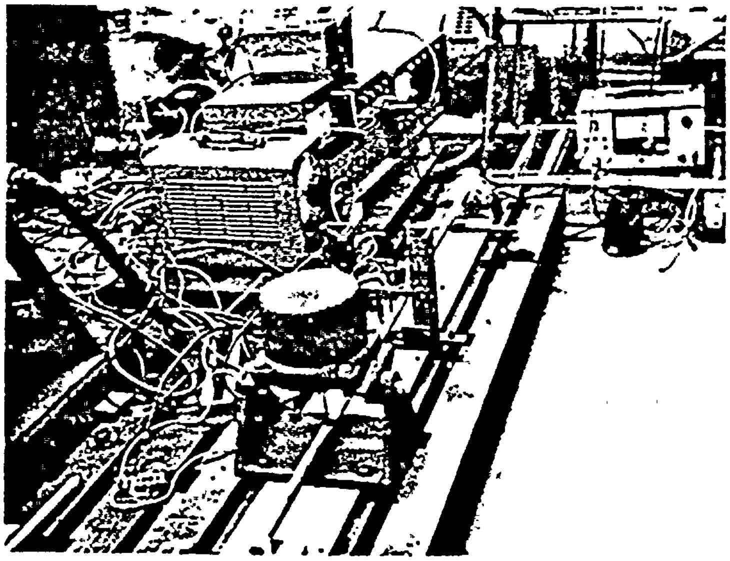


FIGURE 1: VIEW OF FATIGUE TEST SETUP

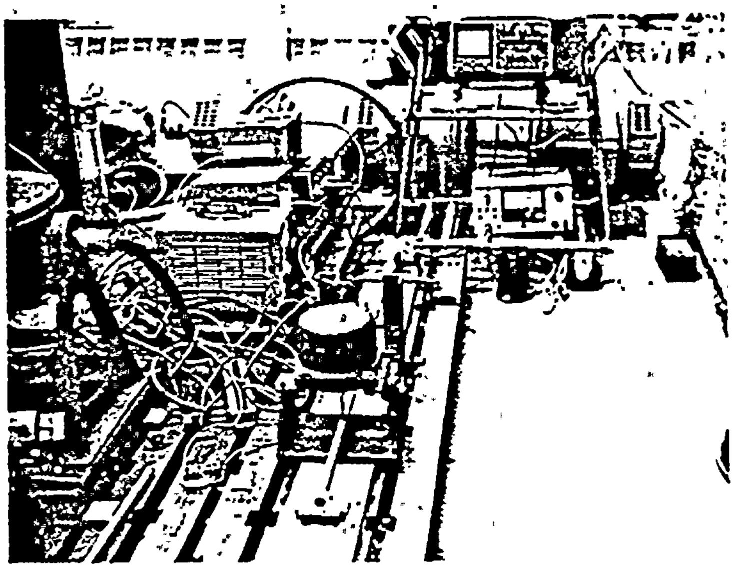


FIGURE 2: ANOTHER CLOSE UP OF FATIGUE SETUP

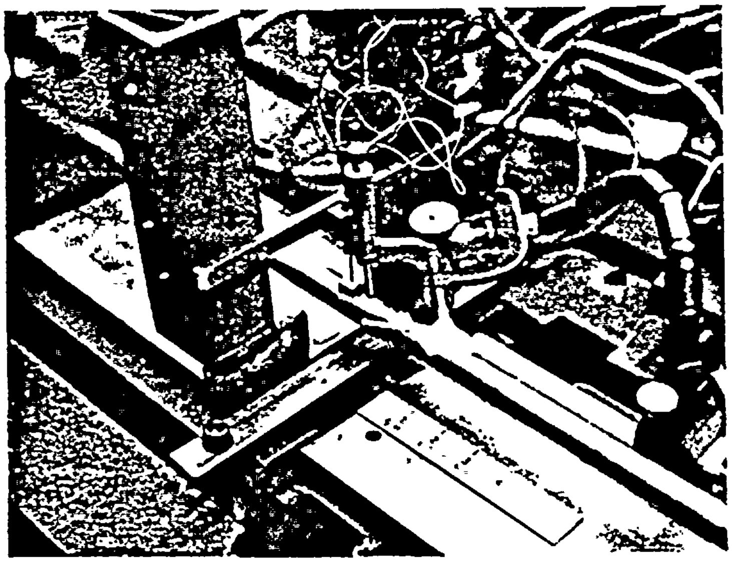


FIGURE 3: CLOSE VIEW OF FATIGUE TEST SETUP

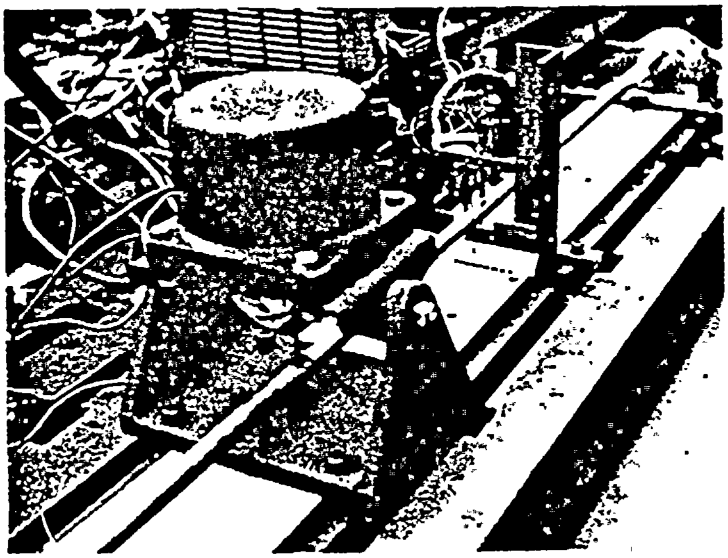


FIGURE 4: ANOTHER CLOSE UP OF FATIGUE SETUP

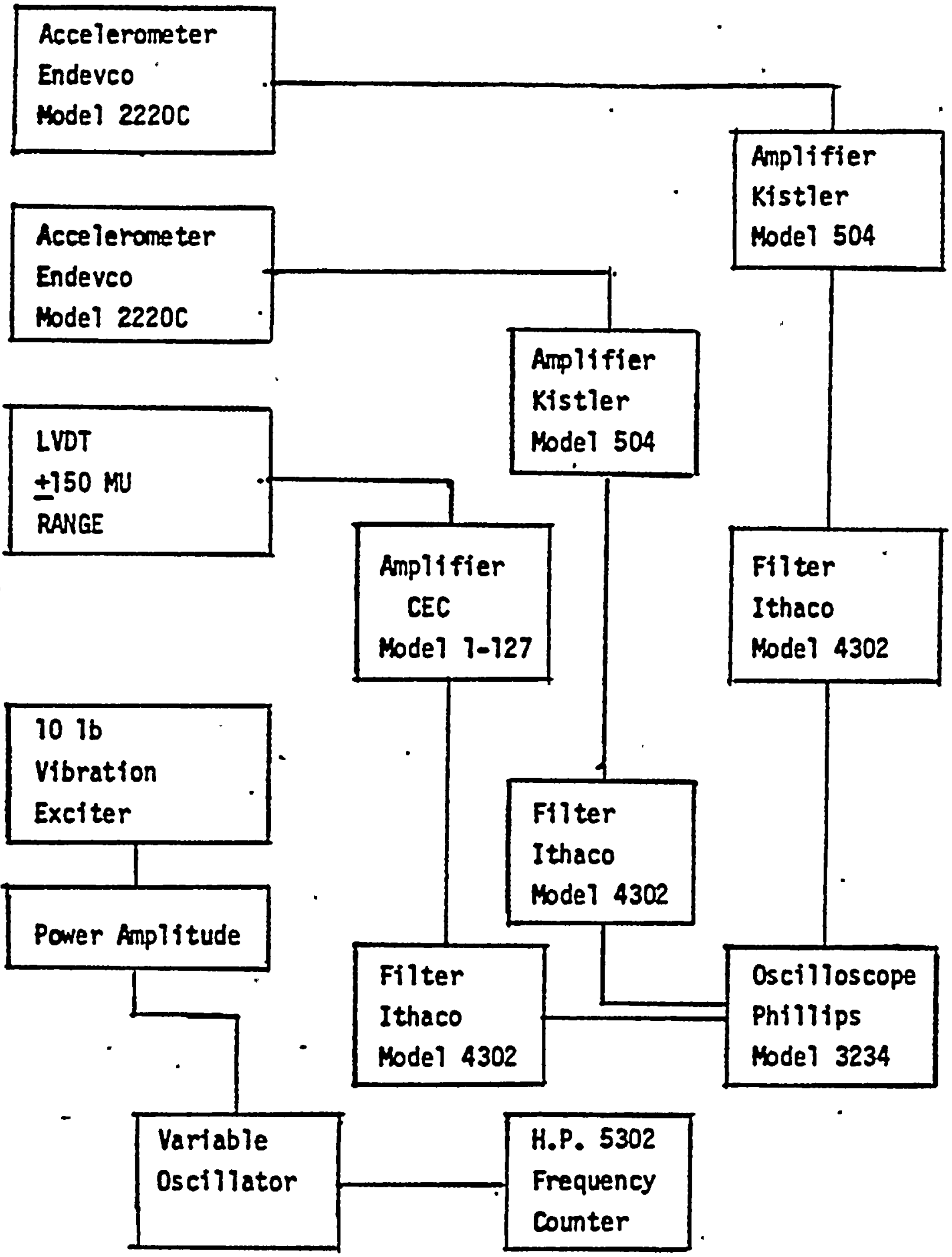
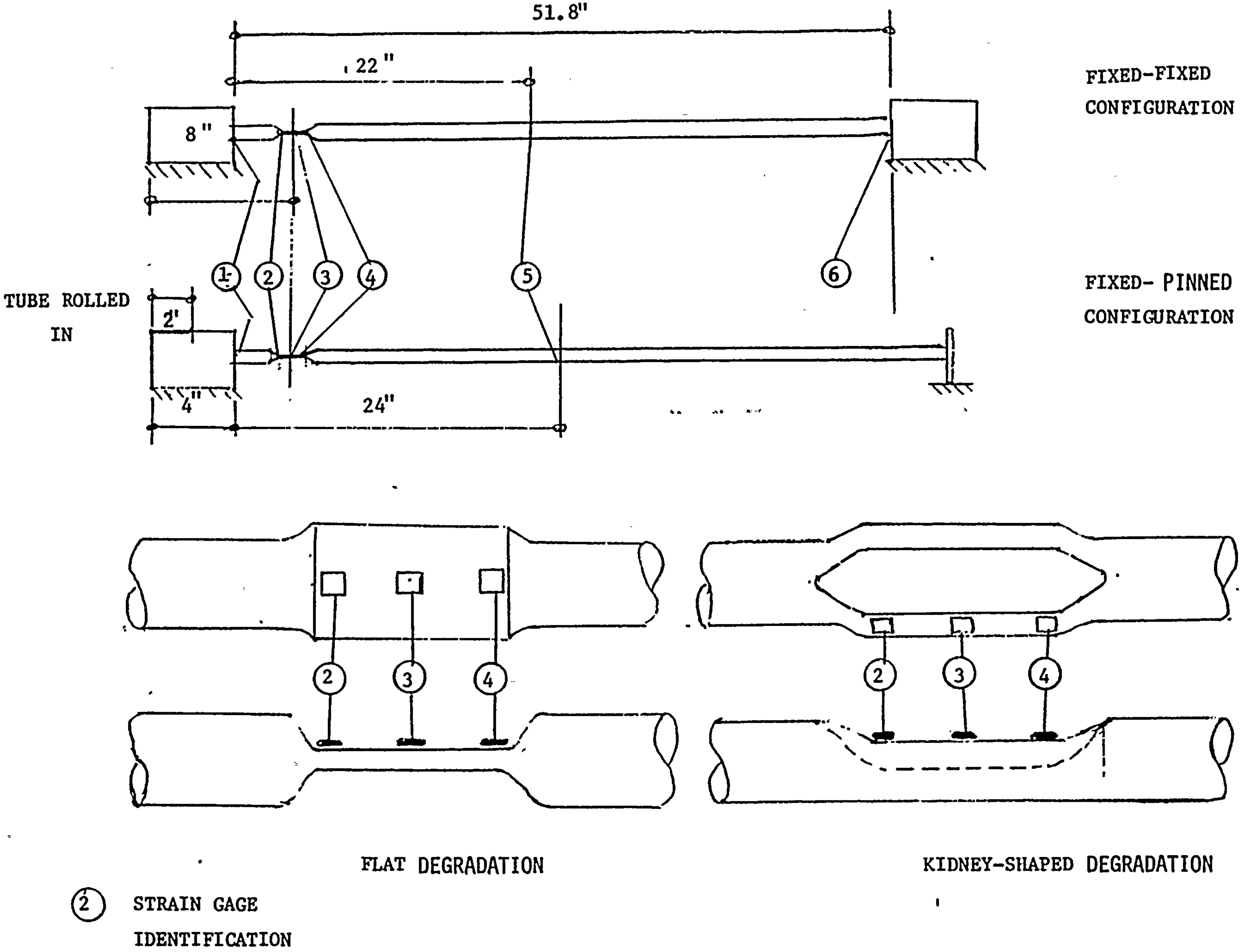


FIGURE 5 INSTRUMENTATION BLOCK DIAGRAM



FLAT DEGRADATION

KIDNEY-SHAPED DEGRADATION

FIGURE 6 – STRAIN SURVEY-TEST CONFIGURATION