New Folder Name Corrugated Tube Test Report

LIGO-T900026-00-B

102

List of 4/10/92

CORRUGATED TUBE TEST REPORT

L. Jones
3/2/90

Summary:

A test was conducted to check the accuracy of a mathematical model of stresses in a spiral corrugated tube. Deflections were measured under three types of loadings, and compared with values predicted by the model; actual deflections were typically one third to one half those predicted. This demonstrated that the model was not suitably accurate, and a very involved, "constituent" analysis would be necessary to fully understand the cross coupled stresses of a spiral corrugated tube.

Background:

Events leading to the test are included in two documents attached:

1. "Analysis of Corrugated Beam Tube Task," transcript of document received from stress analyst consultant R. Bamford of JPL on 5/8/89. This was sent in response to an initial visit with Bamford, requesting an analysis of the corrugated design.
2. "Corrugated beam tube analysis," memo from L. Jones to W. Althouse, dated May 23, 1989.

Objectives:

The subject test of this report was recommended as item b. and c. of reference 2. above. Its purpose was to check the accuracy of the crude math model developed by Bamford, to see if a constituent analysis was necessary. The analysis and resultant model are attached.

Method:

After discussion with W. Althouse, it was decided to perform the testing on campus, if possible, for best coordination. Norm Keidel, manager of Central Engineering Services (CES), was approached and agreed to perform the test. Work Order No. MW98075 was initiated, and CES personnel procured the corrugated tube section and fabricated the necessary fixtures. The approach is described in the attached memo from L. Jones to W. Althouse, "Test of cross coupling of corrugated pipe stresses," dated June 20, 1989. Methods were reviewed with Bamford and revised as necessary.

Three measurements (diameter, twist, and length) were to be made for each of three load configurations (axial, torquing, and axial/internal pressure). Axial load was to be applied with weights borrowed from JPL, with a minimum loan duration. All equipment was checked out with a "wet run" before the weights were requested, and problems were discovered with the fixture that measured diameter. Inadequate fixture stiffness and tube deflections from holding the fixture in place both caused unacceptable repeatability. These were corrected with design modifications. Measurements were made as follows:

a. diameter: micrometer-type fixture, with 0.0001 inch dial indicator; special fittings to mate with fittings brazed to two orthogonal positions at midpoint of tube. This allows fixture to "hang" in place, with only a light stabilizing force added manually, for consistent, repeatable readings (see Figures 1-5).

b. twist: machinist's scales, with 0.010 inch graduations, were mounted circumferentially near each end of the tube, at positions 180 degrees apart (see Fig. 6). Two theodolites were set up to read these scales from opposite sides of the tube (Figs. 7-10). Averaging the apparent circumferential twist effects caused by load of readings taken from opposite sides of the tube cancels out errors caused by any leaning of the tube due to the load.
c. length: a carpenter's retractable tape rule with 1/16 inch graduations was mounted near one end of the tube and its reference end clamped near the other end (see Figs. 11-12). Reference lines were scribed on the tube surface for reading points (Fig. 13).
d. other measurements: pressure was measured by a Bourdon-type gauge, with 0.01 psi divisions and a fresh calibration (Fig. 14). Air temperature near the tube was measured with a bulb-type thermometer (Fig. 15). Time of day for each reading sequence was recorded.

The tube purchased for testing was a 2 foot ID, 20 foot long lockseam culvert pipe of 16 gauge, galvanized carbon steel. The lockseam spiral joint (a crimped design) was judged acceptably stable for the objectives of this test. End plates, 1 inch thick, were welded to the tube to aid in applying loads. The initial setup was made with the tube in a vertical position, in a hole at the corner of the CES lab (this was necessary for proper crane clearance). Figures 7 and 8 show the relative positions of the inside and outside theodolites, locked to swinging only in the vertical plane through the tube axis; scale readings were made at a vertical reference line.

Axial load, Test condition/no. 1-9: Data were first taken with no load on the tube, then the 5050 lb axial load was applied (Fig. 1) and several sets of data were taken. The load was removed, and data were taken.

Internal pressure and axial load combined, Test condition/no. 10-14: The axial load was reapplied, and 10.94 psi internal pressure was applied (compressed air); data were taken. The pressure was vented, axial load removed, and data were taken.

Torquing load with bending, Test condition/no. 15-20: The tube was removed from the vertical position and placed horizontally on supports. Horizontal arms were welded to each end plate for applying torque. The theodolites were mounted on each side of the tube in the horizontal plane through the tube axis, and locked to swinging in that horizontal plane; readings were taken at a horizontal reference line. Data were taken with no added loads, then approximately 1320 lb weights were added one end of each arm (diagonally opposite). A crane hook was attached to one of the unweighted arm ends, and the assembly was lifted until the only effective ground contact was at the arm end diagonally opposite the crane attachment point (see Fig. 9). More data sets were taken; the assembly was again lowered, the weights removed, and data sets were again taken.

Torquing load with bending (revised), Test condition/no. 21-27: When the torqueing method was reviewed with Bamford, he recommended a repeat of the test, with a different method. The new method was similar to the former, except that the weights were in place (with supports underneath) for the "unloaded" readings. As before, the "loaded" reading was taken when the crane had lifted the weighted arms off the supports. This test was performed as recommended.

Results:

Magnitude of the deflections measured are compared with the values predicted by the math model in Table 1. Data sheets are attached. In general, the predictions were larger than deflections measured by a factor of two or three. This was not the case for diameter measurements; measurement errors may have caused this discrepancy, since the magnitudes were very small. Note: the predictions shown in the memo of June 20 were changed substantially by corrections made to the analysis; Table 1 shows the corrected values. Torquing test data from the revised method are shown. The test item was stiffer than expected. Lower deflections indicate smaller stresses than expected from the model's results, since deflection is proportional to stress.

The results were discussed with Bamford, who was not surprised by the magnitude comparisons. He stated that his analysis was a membrane type, and neglected bending effects. Bending effects would likely cause the type of deviation from predictions experienced. He stated that in his judgement, further analysis (constituent) is appropriate, and repeated that he would not be the person to do that.

I asked him about buckling, which he said is a separate issue. Using NASA SP-8007 and SP-8032 as design guides, he chose 0.067 inch thickness as being appropriate for our application; this would provide nearly equal safety factors for both membrane and buckling failure (except for the bakeout on membrane stress, which could be considered as a one-shot "proof test").

ANALYSIS OF CORRUGATED BEAM TUBE TASK

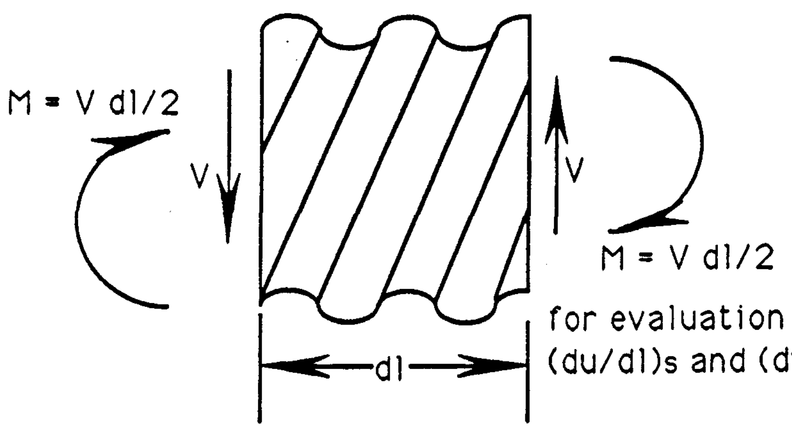
Background:
It is proposed that spiral welded corrugated tube be used between pumping stations on LIGO. Temperature and pressure changes will induce twist and axial loading into the tube and the pumping station. To evaluate these forces and the alignment of the tube the constituative relations (including coupling terms) must be known. There will be N corrugations within the plate width b.

Problem:
Find compliance due to pressure and force along 3 axes and moments about 3 axes or an equivalent relationship as a function of t/R, q/R, N, 2a/R, E.

Radial	$\Delta r/R$		XX--X--	p	Pressure
Axial	dw/dl		XX--X--	P	Axial load
Shear	(du/dl)s		--X----	V_1	M=0 at CL of element
	(dv/dl)s	=	---X---	V_2	
Torsion	dø/dl		XX--X--	T	Torque
Bending	R/r_1		-----X-	M_1	Moment
	R/r_2		------X	M_2	

expected non-zero terms shown as X

Determine displacement due to p and Temp and impose loads which cancel.



for evaluation of (du/dl)s and (dv/dl)s

Other terms:
t = wall thickness
R = mean radius of wall
q = corrugated profile wavelength
2a = corrugated profile double amplitude
E = modulus of elasticity
r = radius
ø = torsion angle

from R. Bamford
5/8/89

LIGO PROJECT ENGINEERING

CALIFORNIA INSTITUTE OF TECHNOLOGY

TO W. Althouse DATE May 23, 1989

FROM L. K. Jones EXTENSION 2970 MAIL CODE 102-33

SUBJECT Corrugated beam tube analysis

The current baseline design for the 48" ID, 16 km length of beam tube used for LIGO is smooth wall, spiral formed, 1/8" thickness, Type 304L stainless steel, with carbon steel stiffening rings welded externally every 2'. A preliminary, approximate analysis suggests that a corrugated design of 0.054" thickness would meet code requirements for external pressure; this offers a potential savings of several millions of dollars in stainless steel reduction and eliminating the requirement for stiffening rings.

Along with the potential savings comes added risk in the area of structural adequacy. Loads on the pipe include external pressure, thermal expansion, handling during fabrication and installation, supports, and earthquake-induced. Due to the spiral nature of the corrugations, these loads may apply torque to the pipe, and analysis of the resultant stress is not straightforward. This was discussed with Bob Bamford of JPL, who feels that corrugated pipe is a natural for this application, but is strongly concerned that structural performance be well understood. He recommends the following program:

a. develop a crude math model of the pipe to aid in scaling test results

b. plan a test on an existing piece of corrugated drain pipe (galvanized steel) to measure torquing as a function of axial load

c. perform test from b. (done by others)

d. analyze test results and determine if e. is necessary

e. perform a constituent analysis on the pipe (done by others)

f. using the results of e., recommend wall thickness and sheet width for known loads and available corrugation profile.

g. plan a developmental study of fabricating and testing stainless steel pipe sections of LIGO diameter, thickness, and corrugation profile for weld leakage and structural adequacy tests (done with others)

Bob's estimate of time required for items a., b., d., and f. above is approximately two man weeks. He expects that the constituent analysis (done by others) may require a man month. The object of the analysis is to provide us with the proper wall thickness and sheet width (determines helix angle of pipe); we would use a corrugation profile with existing tooling.

LIGO PROJECT ENGINEERING

CALIFORNIA INSTITUTE OF TECHNOLOGY

TO W. E. Althouse

FROM L. K. Jones

EXTENSION 2970

DATE June 20, 1989

MAIL CODE 102-33

SUBJECT Test of cross coupling of corrugated pipe stresses

Three tests are proposed, applying different types of loads on a stock piece of galvanized, corrugated pipe (24 inch dia, 20 feet long, 1/2 x 2 2/3 inch corrugations). During the tests, the following measurements are made to determine the deltas caused by the particular load:

a. diameter;
b. length; and
c. circumferential twist (end to end).

The three tests, along with the respective load measurements, are as follows:

1. internal air pressure of 10 psi, with radial effects only (longitudinal effects eliminated by using a sliding piston as one end cover, supported by a tie rod in tension, or compensated for by applying an axial force to each end cover, equal to the pressure force applied), recording the pressure;
2. axial force of 5000 lb, recording the measured force; and
3. torsional load of 120,000 inch lb, over the length of the pipe, recording the measured load.

Expected readings (in inches) are as follows:

Test	ΔD	ΔL	ΔT
1	0.005	4.58	2.79
2	0.021	2.10	1.32
3	0.026	2.65	1.68
Reading accuracy	0.002	0.05	0.03

FIG. 1 DIAMETER MEASUREMENT FIXTURE

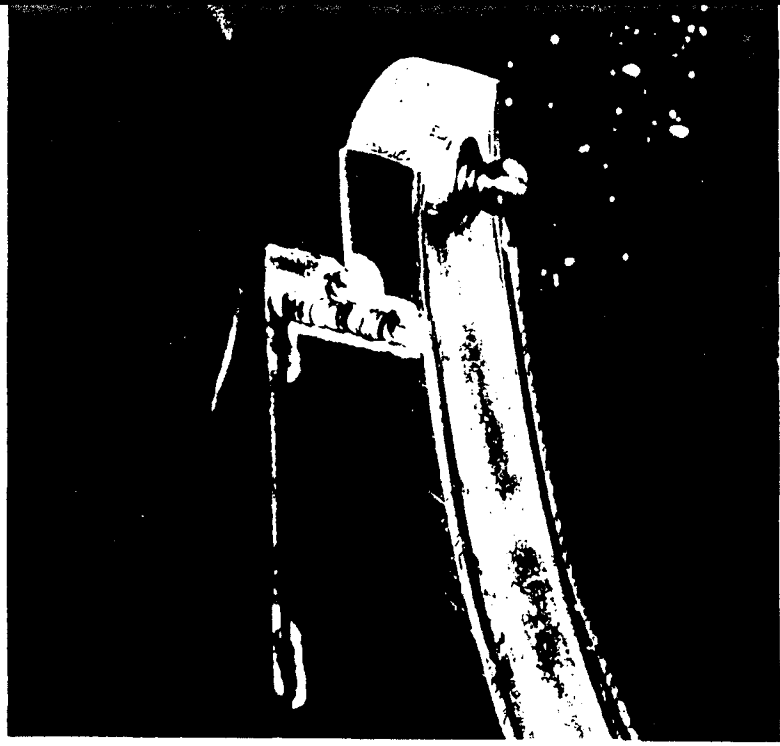


FIGURE 3 DIAMETER FIXTURE - REFERENCE BALL

FIGURE 2 DIAL INDICATOR

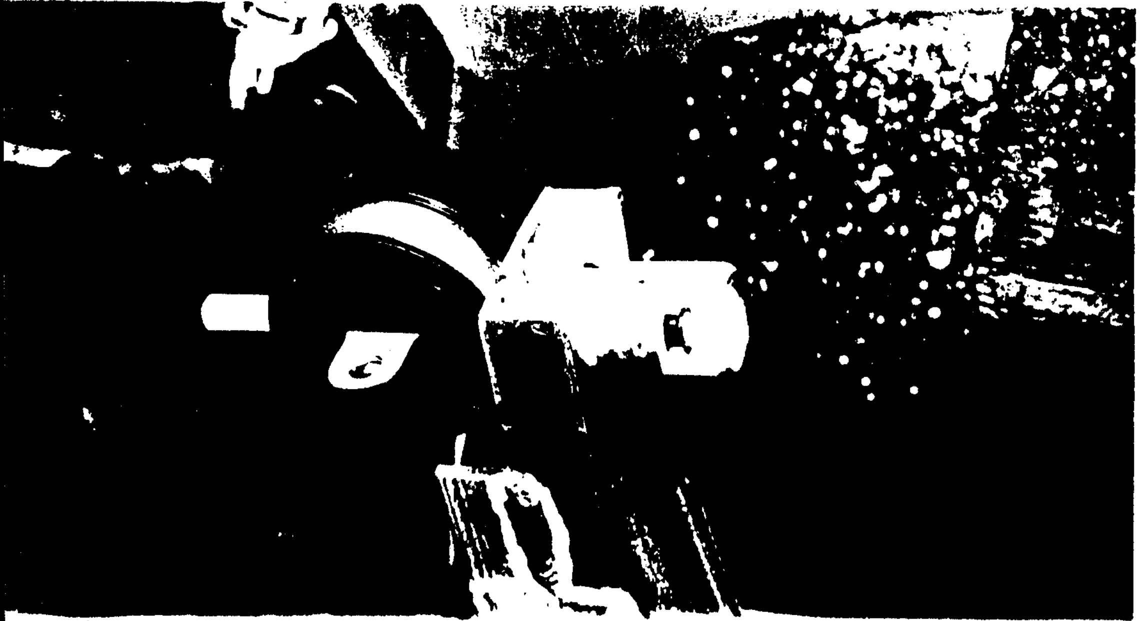


FIGURE 4 BRAZED BALL FOR DIAL INDICATOR

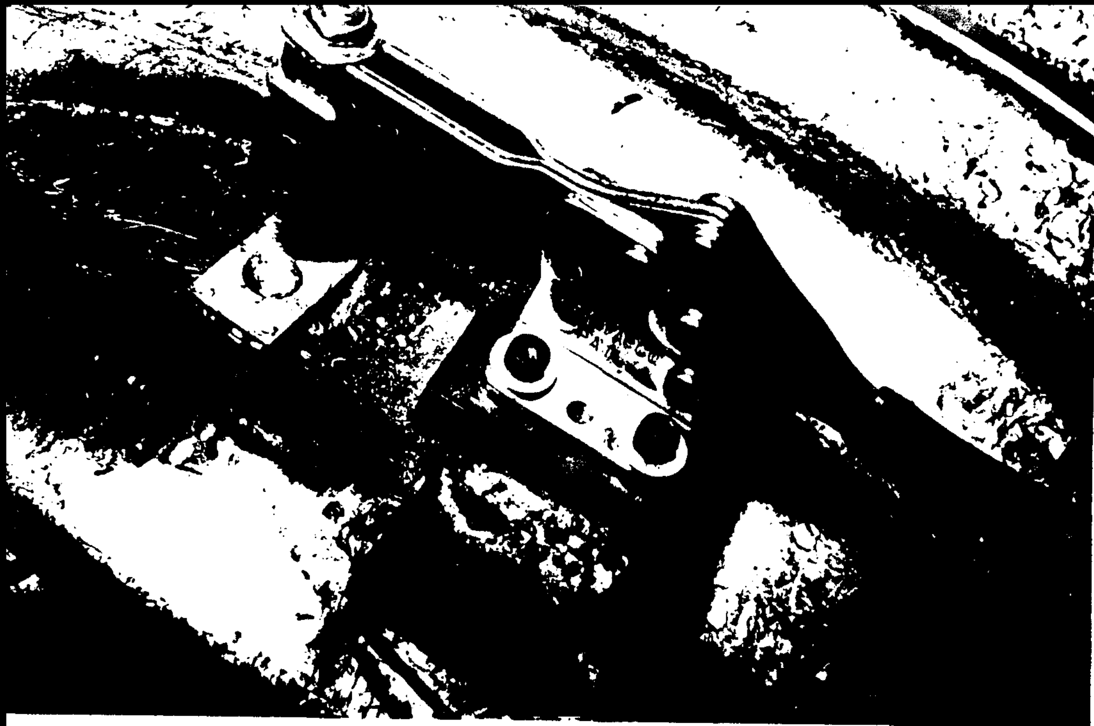


FIGURE 5 BRAZED SOCKET FOR REFERENCE BALL

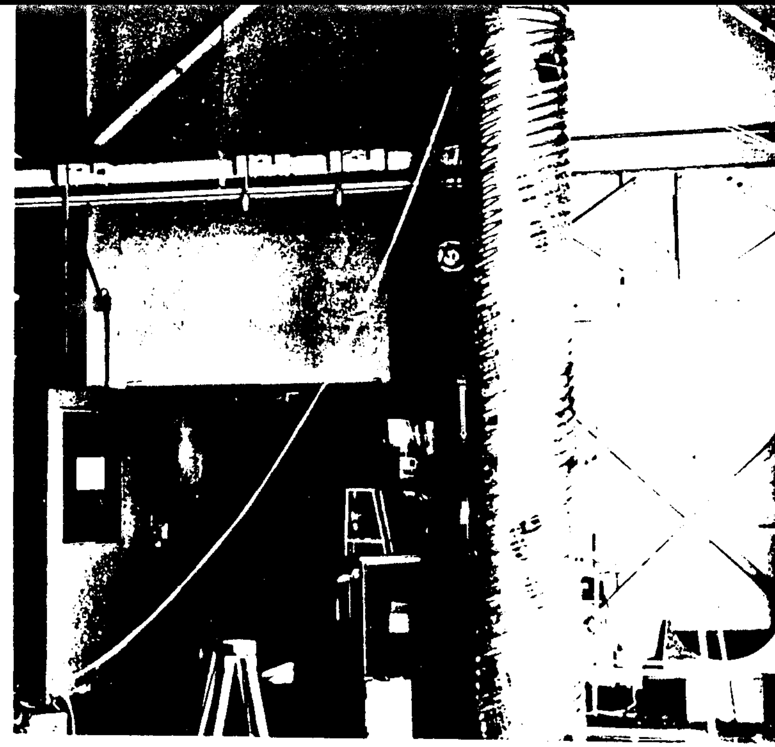
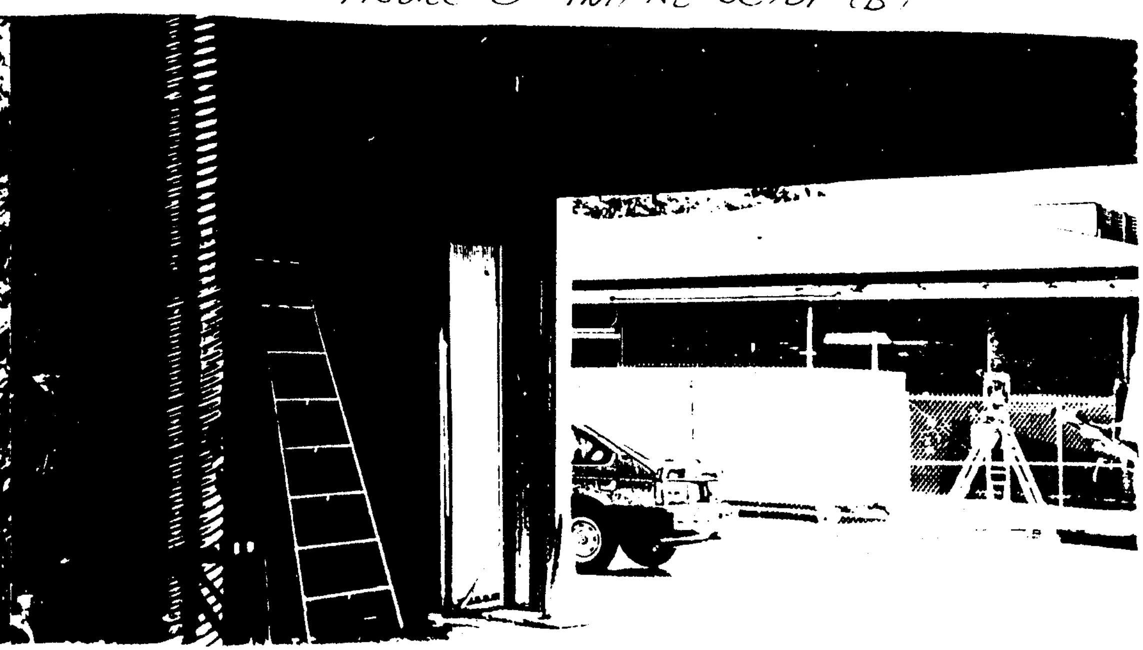


FIGURE 7 INITIAL SETUP (A)

FIGURE 6 MACHINISTS SCALE ON TUBE

FIGURE 8 INITIAL SETUP (B)



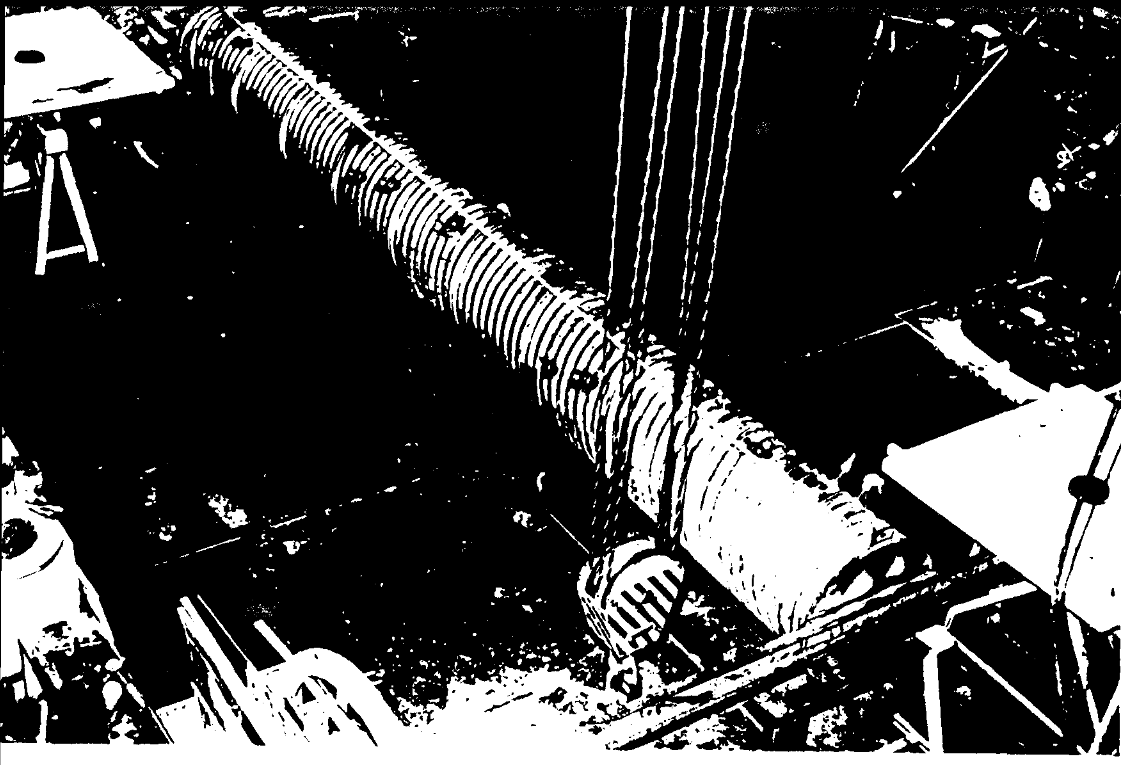


FIGURE 9 FINAL SET UP TORQUING LOAD

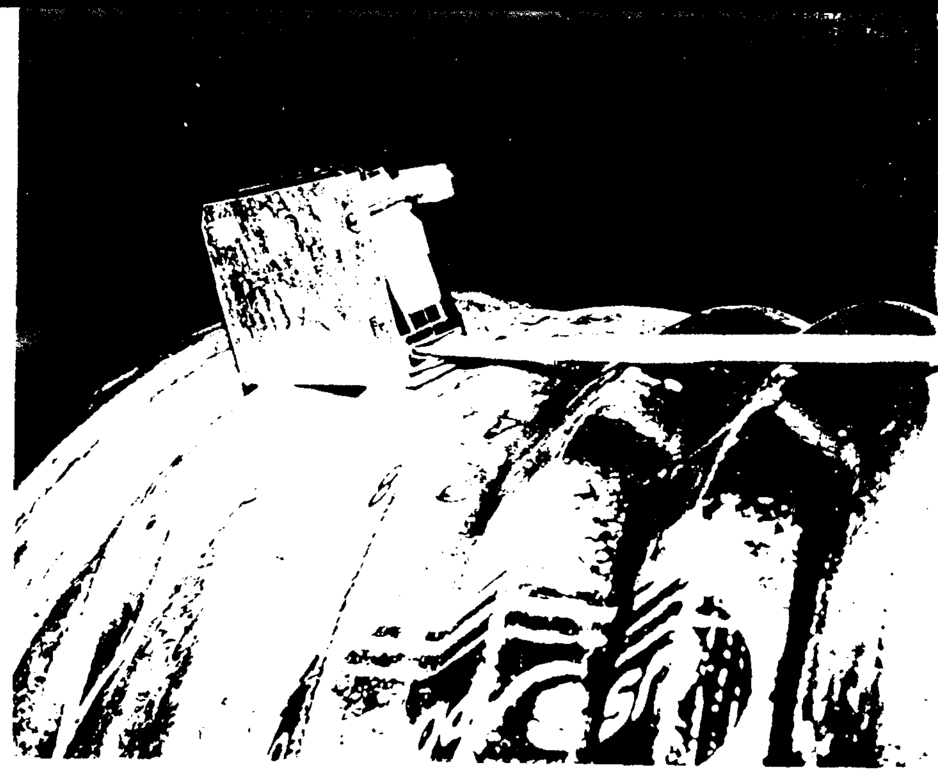
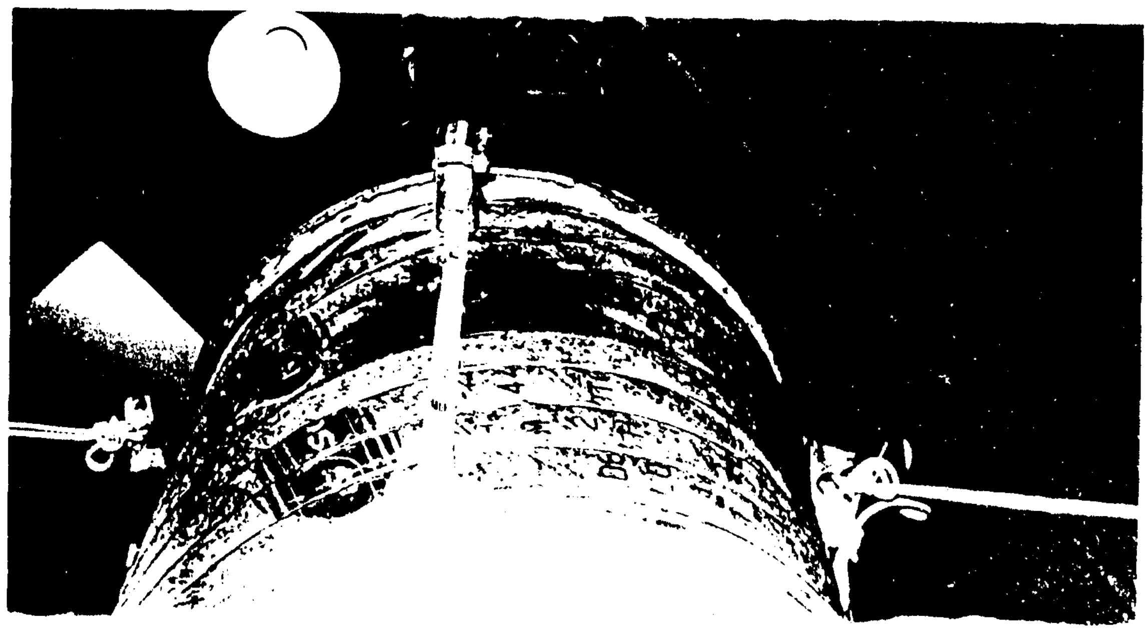


FIGURE 11 LENGTH TAPE

FIGURE 10 REMOVE THE THEODOLITE

FIGURE 12 LENGTH TAPE



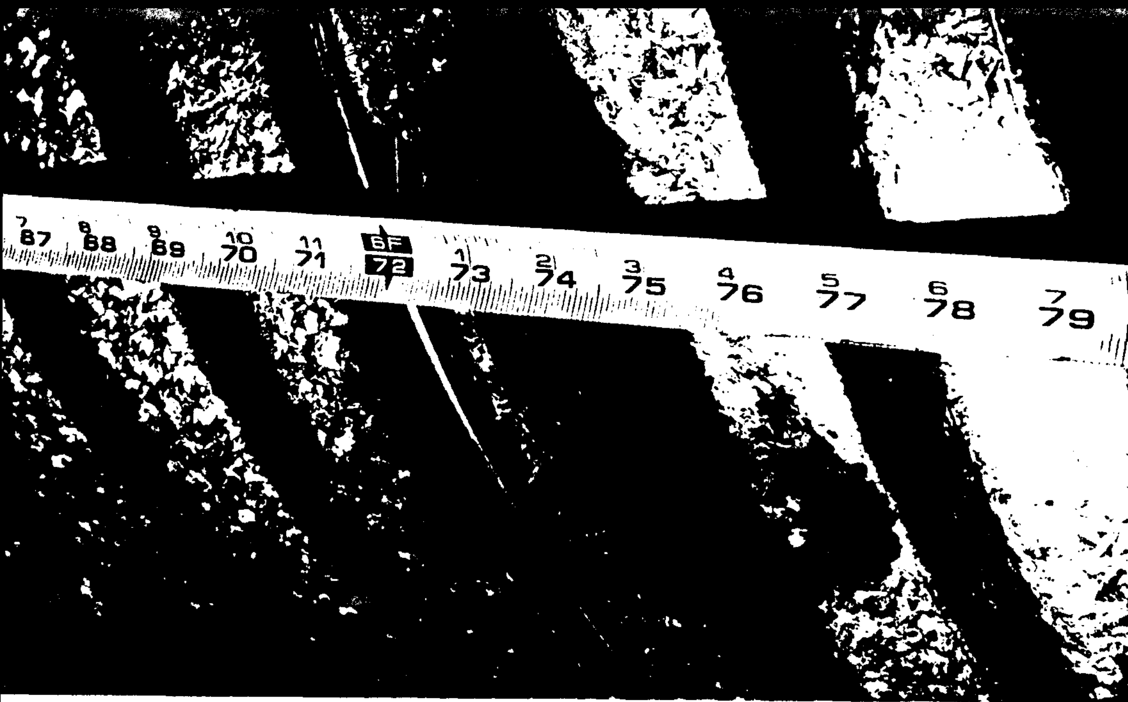


FIGURE 13 LENGTH TAPE & SCRIBE LINE

FIGURE 15 THERMOMETER

FIGURE 14 PRESSURE GAUGE

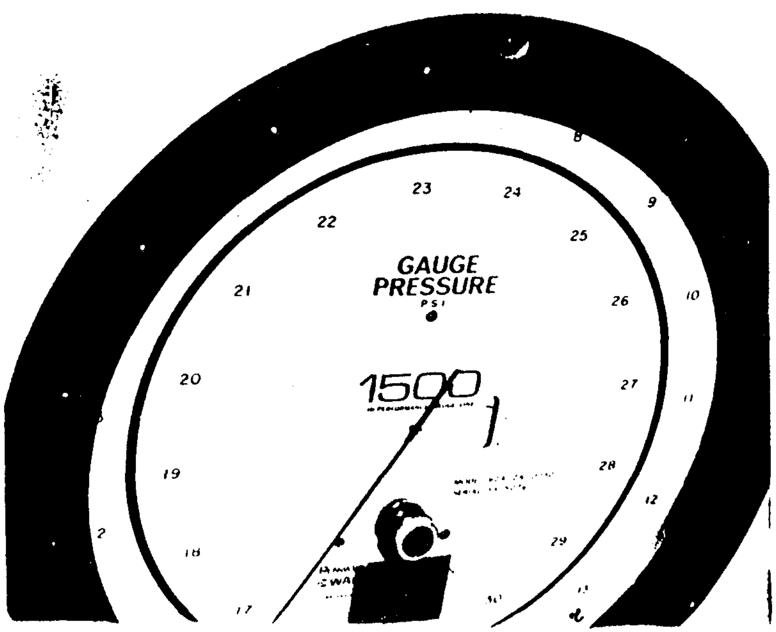


FIGURE 16 APPLYING AXIAL LOAD

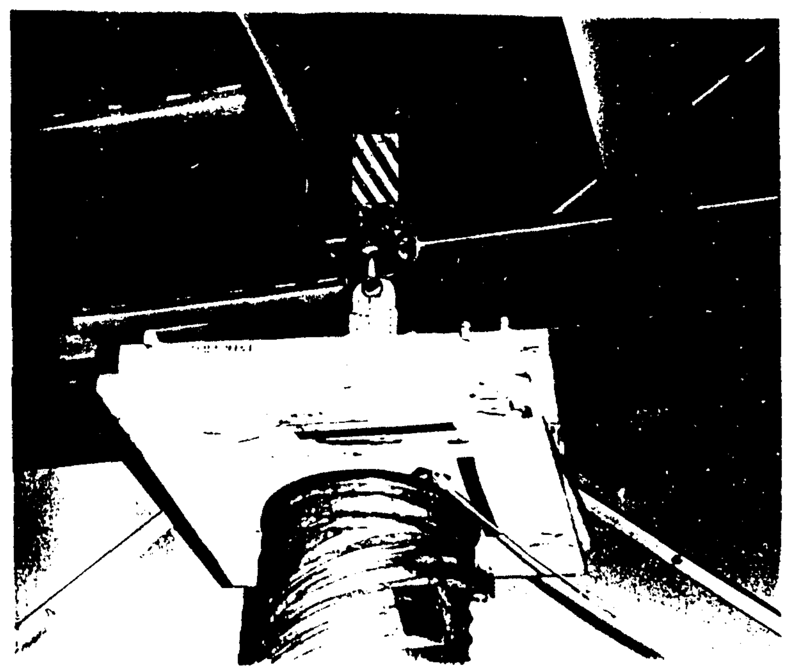


TABLE 1
CORRUGATED TUBE DEFLECTIONS

L. Jones
2/28/90

Load Condition:		P = 5000 lb	T = 120 Kip	p = 10psi, P = 5000 lb	
Deflections, corrected analysis:	ΔL	1.060	-1.320	0.210	all @
	ΔT	-0.784	1.037	-0.147	R = 12", L = 240"
	ΔR	0.0063	-0.0081	0.0021	

Load Condition:		P = 5050 lb	T = 166.4 Kip	p = 10.94 psi, P = 5050 lb	
Deflections, predicted for actual test conditions:	ΔL	0.932	-1.609	0.213	L = 211"
	ΔT	-0.506	0.919	-0.103	R = 12.45", L =147.88"
	ΔR	0.0064	-0.0114	0.0023	R = 12.125"
Deflections, test results:	ΔL	0.34 (shorter)	-0.69 (longer)	0.13 (longer)	
	ΔT	-0.190 (wind)	0.347 (unwind)	-0.033 (unwind)	
	ΔR	0.0008 (longer)	-0.0015 (shorter)	0.0017 (longer)	
Ratio: <u>Test results</u> Predicts	ΔL	0.37	0.43	0.61	
	ΔT	0.38	0.38	0.32	
	ΔR	0.13	0.13	0.74	

CORRUGATED TUBE DEFLECTION TEST

24" dia. x 20' long, 16 ga., 2 2/3" x 1/2" corrugation; lockseam, 24" seam-to-seam; galvanized; reformed ends with 26" dia. x 1" plates welded to ends.

Date: 9/5/89
Personnel: N. KEIDEL
L. JONES

APPLIED LOAD, CONFIRMED CRANE HOOK IS LOOSE

Test condition/no.	NO LOAD 1	NO LOAD 2	(LOOSE SCREW)	NO LOAD 3	AXIAL LOAD 4	AXIAL LOAD 5	AXIAL [illegible] 6
time of day	8:13 AM	8:20 AM		8:30	8:58	9:04	9:0[illegible]
pressure, psig	0	0		0	0	0	0
axial load, lb	NONE	NONE		NONE	5050	5050	505[illegible]
torque load, in lb	NONE	NONE		NONE	NONE	NONE	NONE
"A" dia. ref., in	0.0152	0.0162	0.0138	0.0142	0.0147	0.0142	0.01[illegible]
"B" dia. ref., in	0.0049	0.0053	0.0028	0.0026	0.0060	0.0054	0.005[illegible]
axial length L1, in	71.75		71.75	71.75	71.65	71.65	
axial length L2, in	144.56		144.56	144.56	144.35	144.35	
axial length L3, in	212.15		212.15	212.15	211.81	211.81	
"A" upper circum, in	3.68		3.67-3.68	3.67-3.68	(1ST IN SCREW) 4.68	(1ST IN SCREW) 4.69	
"A" lower circum, in	3.00		3.00	3.00	3.20	3.20	
ΔA	0.680		0.675	0.675	1.48	1.49	
"B" upper circum, in	2.325		2.33	2.33	1.89	1.875	
"B" lower circum, in	3.00		3.00	300	2.98	2.98	
ΔB	-0.675		-0.670	-0.670	-1.09	-1.105	
Air temp., C	24		24.5	24.5	25.5	25.5	
time of day	8:19:30 PM		8:30	8:35	9:03:30	9:08:30	
	6½		10 (SPCL)	5	5½	4½	

QUEST[illegible] THAT CRAN[illegible] HOOK MIC[illegible] NOT SUFFIC[illegible] LOOS[illegible] LOWER[illegible] ~1/4" MIC[illegible] CONF[illegible] CRA[illegible] HO[illegible] L[illegible]

CORRUGATED TUBE DEFLECTION TEST

24" dia. x 20' long, 16 ga., 2 2/3" x 1/2" corrugation; lockseam, 24" seam-to-seam; galvanized; reformed ends with 26" dia. x 1" plates welded to ends.

Date: 9/5/89
Personnel: N. KEIDEL
L. JONES

ADD 5050 LB. PRESSURIZING TO 10.94

VENTED; REMOVE WL

Test condition/no.	AXIAL LOAD 7	NO LOAD 8	NO LOAD 9	AXIAL LOAD, INT. PRESSURE 10	AXIAL LOAD, INTERNAL 11 PRESS.	AXIAL LOAD, INTERNAL 12 PRESS
time of day	9:18:00	9:23	9:30	9:54	9:59:30	10:14
pressure, psig	0	0	0	10.94	10.93	10.94
axial load, lb	5050	NONE	NONE	5050	5050	5050
torque load, in lb	NONE	NONE	NONE	NONE	NONE	NONE
"A" dia. ref., in	0.0140	0.0129	0.0126	0.0202	0.0197	0.0198
"B" dia. ref., in	0.0053	0.0025	0.0022	0.0025	0.0021	0.0022
axial length L1, in	71.65	71.75	71.75	71.80	71.80	71.80
axial length L2, in	144.36	144.56	144.56	144.66	144.66	144.66
axial length L3, in	211.81	212.15	212.15	212.28	212.28	212.29
"A" upper circum, in	4.71	3.65-3.67	3.66	4.41	4.42	4.42
"A" lower circum, in	3.20	2.995	2.99	3.10	3.10	3.10
ΔA	1.510 [3]	0.665	0.670 [5]	1.31	1.32	1.32 [7]
"B" upper circum, in	1.87	2.36	2.36	1.50	1.50	1.49
"B" lower circum, in	2.98	3.01	3.01	2.86	2.86	2.86
ΔB	-1.110 [4]	-0.650	-0.650 [6]	-1.360	-1.360	-1.370 [8]
Air temp., C	26	26	26	27	27	27
time of day	9:22	9:30	9:35	9:59	10:04	10:18
	4	7	5	5	4	4

OVERN 10.91 10.93

INSIDE

OUTSIDE

CORRUGATED TUBE DEFLECTION TEST

24" dia. x 20' long, 16 ga., 2 2/3" x 1/2" corrugation; lockseam, 24" seam-to-seam; galvanized; reformed ends with 26" dia. x 1" plates welded to ends.

Date: 9/5/89
Personnel: N. KEIDEL
L. JONES

Test condition/no.	NO LOAD 13	NO LOAD 14				
time of day	10:45	10:49:30				
pressure, psig	0.03	0.01				
axial load, lb	NONE	NONE				
torque load, in lb	NONE	NONE				
"A" dia. ref., in	0.0132	0.0130				
"B" dia. ref., in	0.0020	0.0020				
axial length L1, in	71.75	71.75				
axial length L2, in	144.56	144.56				
axial length L3, in	212.15	212.15				
INSIDE "A" upper circum, in	3.65	3.65				
"A" lower circum, in	2.99	2.99				
ΔA	0.660	0.660 [1]				
OUTSIDE "B" upper circum, in	2.37	2.37				
"B" lower circum, in	3.01	3.01				
ΔB	-0.640	-0.640 [2]				
Air temp., C	27.5	27.5				
time of day	10:49	10:54:30				
	4	5				

CORRUGATED TUBE DEFLECTION TEST

24" dia. x 20' long, 16 ga., 2 2/3" x 1/2" corrugation; lockseam, 24" seam-to-seam; galvanized; reformed ends with 26" dia. x 1" plates welded to ends.

Date: 9/7/89
Personnel: N. KEIDEL
L. JONES

2 1/16" LIFT @ END R
1316 LBS ON LIFT END
1330 LBS ON SUPP. END

Test condition/no.	NO LOAD 15	NO LOAD 16	TORQUE LOAD 17	TORQUE LOAD 18	NO LOAD 19	NO LOAD 20
time of day	10:57	11:08	12:13	12:19	12:36	12:41
pressure, psig	0	0	0	0	0	0
axial load, lb	0	0	0	0	0	0
torque load, in lb	0	0	(CALC)	(CALC)	0	0
"A" dia. ref., in	0.0145	0.0146	.0081	.0078	.0137	.0138
"B" dia. ref., in	0.0002	0.0000	.0013	.0012	.0018	.0013
axial length L1, in	71.83	71.83	72.04	72.04	71.82	71.82
axial length L2, in	144.59	144.60	145.01	145.01	144.58	144.58
axial length L3, in	212.16	212.16	212.75	212.76	212.13	212.13
"A" ~~upper~~ RIGHT circum, in	2.91	2.91	2.840	2.830	2.94	2.94
"A" ~~lower~~ LEFT circum, in	2.99	2.99	1.590	1.600	3.05	3.05
	-0.08	-0.08 [1]	1.25	1.23 [3]	-0.11 ~~-0.09~~	-0.11 ~~-0.09~~ [5]
"B" ~~upper~~ LEFT circum, in	3.04	3.04	3.265	3.260	3.01	3.01
"B" ~~lower~~ RIGHT circum, in	2.98	2.98	5.19	5.18	2.94	2.94
	0.06	0.06 [2]	-1.925	-1.92 [4]	0.07	0.07 [6]
Air temp., C	25	25	26	26	26.5	26.5
time of day	11:08	11:15	12:19	12:28:30	12:40:30	12:45:30

GAUGE GREW BY 0.0002

GAUGE GREW BY 0.0002

EAST

WEST

CORRUGATED TUBE DEFLECTION TEST

24" dia. x 20' long, 16 ga., 2 2/3" x 1/2" corrugation; lockseam, 24" seam-to-seam; galvanized; reformed ends with 26" dia. x 1" plates welded to ends.

Date: 9/11/89
Personnel: N. KEIDEL
L. JONES

NOTE: "UNLOADED" REFERS TO WEIGHTS MOUNTED ON TORQUE ARMS, WITH SUPPORTS UNDER TORQUE ARMS ONLY, WITH NO HOIST LOADS. "LOADED" REFERS TO HOIST PICKUP AT LIFT HOOK, WITH NO SUPPORTS UNDER TORQUE ARMS EXCEPT AT POINT DIAGONAL FROM LIFT HOOK.

1330 LB @ SUPP. END
1316 LB @ LIFT END

Test condition/no.	UNLOADED 21	UNLOADED 22	UNLOADED 23	LOADED 24	LOADED 25	UNLOADED 26	27
time of day	N 11:20	11:29		11:53	12:02	12:10	12:21
pressure, psig	0	0		0	0	0	0
axial load, lb	0	0		0	0	0	0
torque load, in lb	REF.	REF		96(1316+4 LB) 165.7 K	165.7 K	REF.	REF.
				DYNAMOMETER 1620 LB	1620	-25	
"A" dia. ref., in	.0149	.0148		0.0083	0.0083	.0144	0.013
"B" dia. ref., in	.0024	.0020		.0018	0.0013	0.0016	0.001
axial length L1, in (TOP)	18.50-229.10	18.50-229.10		18.53-229.85	18.55-229.85	18.50-229.10	18.50-2
axial length L2, in (BOTTOM)	17.52-228.54	17.52-228.54		17.52-229.23	17.52-229.23	17.53-228.60	17.52-2
axial length L3, in							
"A" ~~upper~~ RIGHT circum, in	2.750	2.755	2.925	2.900	2.900	2.940	2.94
"A" ~~lower~~ LEFT circum, in	3.230	3.240	3.220	1.170	1.185	3.230	3.23
$\frac{0.190 - .185}{2}$ ΔA	-.480	-0.485	-0.295	+1.730	1.715	-0.290	-0.29
"B" ~~upper~~ LEFT circum, in	3.080	3.080	2.990	3.075	3.075	2.960	2.96
"B" ~~lower~~ RIGHT circum, in	2.575	2.575	2.670	5.480	5.475	2.670	2.66
ΔB	0.505	.505	0.320	-2.405	-2.400	0.290	0.30
Air temp., C	22.5	22.5	22.5	23.0	23.5	23.5	23.5
time of day	11:28	11:38	11:46	12.02	12:09	12:20	12:26

Column 23 (written vertically): SPEC TEST TO CONFIRM AT MEAS. ST. — ROCKED TO STACER CORNER & REMEAS. THEODOLITE

Between columns 24 and 25 (written vertically): .005 [illegible]

Margin labels: EAST ("A" circum rows); WEST ("B" circum rows)