Strain Gage Instrumentation and Calibration of A Transport Aircraft Fuselage in Longitudinal Bending

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16. Abstract

A strain gage instrumentation system was designed, fabricated, installed, tested, and calibrated for use on a full-scale transport type fuselage structure. Hydraulic jacks were used to apply loads to generate longitudinal bending moments on the transport aircraft fuselage structure. Strain gage data and load data were measured, recorded, and analyzed by means of a computer-supported data acquisition system. Results are presented as graphs of apparent strain at a given fuselage station, as a function of fuselage longitudinal bending moment.

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EXECUTIVE SUMMARY

A strain gage instrumentation system was designed, fabricated, installed, tested and calibrated for use on a full-scale transport type fuselage structure. Hydraulic jacks were used to apply loads to generate longitudinal bending moments on the transport aircraft fuselage structure. Strain gage data and load data were measured, recorded, and analyzed by means of a computer-supported data acquisition system. Results are presented as graphs of apparent strain at a given fuselage station, as a function of fuselage longitudinal bending moments.

INTRODUCTION

A full-scale transport airplane "Controlled Impact Demonstration" (CID) program was conducted by the Federal Aviation Administration (FAA) and NASA-Dryden on December 1, 1984 at Edwards Air Force Base/NASA-Ames/Dryden Flight Research Facility, Edwards, California. The major goal of the the CID experiments was to demonstrate and validate technology that can improve transport aircraft occupant crash survivability through reduced postcrash fire hazard and improved crash impact protection. One of the objectives related to improved crash impact protection focused on the acquisition of airplane structural data that would provide baseline impact and structural information that enhances the fundamental knowledge and understanding of transport crash structural behavior.

Selected CID aircraft fuselage and wing structure stations were instrumented with full strain gage bridges and associated wiring and equipment. Also, two data conditioning/acquisition systems were installed onboard the CID aircraft.

Prior to the crash impact demonstration of the CID aircraft, the Crashworthiness Branch at the FAA Technical Center conducted a parallel experiment at their Atlantic City test site for the purpose of providing initial strain gage calibration data and information directly related to the projected strain gage calibrations and test data acquisition on the CID airplane. The FAA Technical Center tests complimented the projected NASA/FAA strain gage calibrations and provided preliminary data values and data conditioning information pertinent to these particular CID efforts.

A portion of the instrumentation package onboard the Boeing 720-027 CID aircraft consists of fuselage mounted strain gage installations to measure the strain in the aft part of the fuselage structure. In order to provide some initial insight and to obtain a preliminary calibration of the candidate instrumentation system without dedicating or compromising the actual flight aircraft, a Boeing 707-131B fuselage located at the FAA Technical Center, Atlantic City Airport, New Jersey was instrumented and loaded in such a manner that the relationship between applied load and structural element strain on the Boeing 720, CID test aircraft could be inferred from the relationships observed on the FAA Technical Center test specimen aircraft, the Boeing 707-131B. Specifically, since the two fuselages of the two Boeing aircraft appear to be similar and are dimensionally identical at fuselage Body Station locations aft of BS-1020, comparable bending moments induced in their structures would produce comparable strains in either structure, up to the point of similarity (and structural fabrication identity) (figure 1). Thus, it was possible to determine and show the feasibility of performing a large-range loading calibration of the non-flight article (the Technical Center Boeing 707-131B) and apply the resulting calibration data to the flight article (CID, Boeing 720) with only an intermediate range proof loading of the latter. By this approach, considerable efficiencies of effort and cost were realized, as well as some initial insight into the strain/bending moment behavior for these types of aircraft fuselage structure. Moreover, when the CID strain gage calibrations are available in dimensional form, meaningful comparisons between the Boeing 720 and Boeing 707 fuselage data can be made.

This report considers the design and installation of the instrumentation and calibration testing performed on the FAA Technical Center Boeing 707-131B fuselage on June 5, 1984. This information was forwarded to NASA-Dryden for their projected B-720 calibrations. (ADFRF-FLRF-8401, October 1, 1984). The results of the FAA Technical Center experiments are shown in a series of dimensional calibration graphs.

TECHNICAL DISCUSSION

The two test aircraft utilized for this strain gage instrumentation and calibration of a transport aircraft fuselage in longitudinal bending were the Boeing 707-131B and the Boeing 720-027. Longitudinal bending is defined in this report as the bending induced along the fuselage length (and about the nose and main landing gear fulcrum points) as caused by vertical up and down loads applied at the tail. Figures 1 and 2, and table 1, depict and compare some of the aircraft's general characteristics and dimensions for the two test vehicles. The load reaction and jacking points are shown as well as the aft fuselage strain gaged stations at BS 1030. The FAA Technical Center test specimen was the Boeing 707-131B and the test specimen for the corresponding FAA/NASA experiment at Dryden (Edwards Air Force Base (AFB), California) was the Boeing 720-027, the candidate aircraft for the Controlled Impact Demonstration (CID).

TABLE 1. TEST AIRCRAFT GENERAL DATA

Aircraft Version	Boeing 720-027	Boeing 707-131
FAA Type Certificate Data Sheet	No. 4A28	No. 4A21
Aircraft Serial Number	18066	17668
Maximum Ramp Weight	230,000 (pounds)	248,000 (pounds)
Maximum Landing Weight	175,000 (pounds)	190,000 (pounds)
Fuselage Length	1,566 inches	1,666 inches
Fuselage Length (Aft of BS 1030)	646 inches	646 inches
Moment Arm Between Load Application Station and Instrumented Station	532 inches	411 inches

As depicted in figures 1 and 2, it can be reasoned that, for geometrically and elastically identical structures of the aft section of the fuselage (i.e., aft of BS-1020), a moment distribution induced in the aft structure by a vertical load applied near the tail and reacted by the nose and main gear support points will be similar in both aircraft and proportional to the product of the applied load and the application distance (i.e., the moment arm). Although it is assumed, for the purpose of this experiment, that the two fuselage structures aft of BS-1020 are essentially geometrically and elastically identical structures, no detailed construction parts number and "parts-count" comparison was made of the two test aircraft fuselages. It is recognized that, depending on the buyer/customer, each aircraft could have different structural versions, but it is presumed that structural changes in the very aft sections of these two aircraft are not vast. Further, for identically-placed strain sensors (strain gages) on the identical structures, the observed strains due to identical bending loads will be identical. In actuality, since the fuselage beam is composed of many elements joined together and the placement of gages on the stringers is subject to some variation, the observed strains will not be exactly identical. Proof loading of the flight aircraft should be a necessary but sufficient experiment to correlate the two structure/instrumentation systems.

Figure 3 presents a cross section of Body Station 1030 (BS-1030) on the Boeing 720/CID aircraft and indicates the strain gages instrumentation locations (A, B, C, and D) at this body station. This body station is identical to Body Station 1030 on the FAA Technical Center Boeing 707-131B aircraft which was instrumented as documented in figure 4. Note that the individual gages were combined into four element bridges, as indicated in figure 4, in such manner as to make them sensitive to longitudinal bending loads but insensitive to lateral bending, shear and axial loads and that bridge output in millivolts depends upon excitation voltage and gage factor (appendix). Referring to the expressions developed in the appendix, the bridge outputs can be expressed as follows:

For channels 1 and 2:

$$\text{Apparent microstrain} = \frac{\epsilon_A - \epsilon_B}{1 + \epsilon_A + \epsilon_B}$$

For channels 3 and 4:

$$\text{Apparent microstrain} = \frac{\epsilon_A - \epsilon_C}{1 + \epsilon_A + \epsilon_C}$$

where ϵ_i is the strain in the micro inches per inch (μ in/in) at location i.

An interpretation of the bridge output information is to regard the entire fuselage as a beam instrumented to read longitudinal bending with two independent sets of instrumentation. Thus, by means of the calibration data presented herein and the bridge outputs, the bending moment at Body Station 1030 can be evaluated (redundantly). Reduction of the data presented later in this report gives the following relationships:

For channels 1 and 2:

Moment (per unit microstrain) at Body Station 1030

$$M_{BS1030} = 34{,}400 \ \frac{\text{in-lb}}{\mu\epsilon_{1,2}} \qquad \text{[Floor Orientation]}$$

For channels 3 and 4:

Moment (per unit microstrain) at Body Station 1030

$$M_{BS1030} = 25{,}000 \ \frac{\text{in-lb}}{\mu\epsilon_{3,4}} \qquad \text{[Lower Orientation]}$$

Test Arrangement and Approaches

Figures 5 through 13 present photographs of the calibration test arrangement and the various items of test apparatus, identified as follows:

Figure 5 - Boeing 707-131 Fuselage
Figure 6 - Main Gear Bogie Jacks
Figure 7 - Aft Body Station Attachment Rig
Figure 8 - Tail Loading Structure and Aft Fuselage
Figure 9 - Tail Upload at Aft Pressure Bulkhead
Figure 10 - Tail Download at Aft Pressure Bulkhead
Figure 11 - Calibrated Load Cell
Figure 12 - Data Acquisition System and Support Computer
Figure 13 - On-Site Data Monitoring, Conditioning and Printing Setup

Two items of test apparatus are of particular interest; the tail load cell pictured in figure 11 allowed direct measurement of the vertical, up and down loads applied to the fuselage and greatly increased the confidence level in the data (figure 14). Also, the portable computer-supported data acquisition system (housed in the van) allowed reduced (dimensional) data plots to be available virtually online (figures 12 and 13). These facilities permitted the tests to be conducted and data reduced in one afternoon of testing.

The vertical load application apparatus, consisting of loading fixtures, a wide nylon bridle strap around the forward part of the fuselage and anchored to the ground (to inhibit nose lift-off for large tail downloads) and calibrated hydraulic jacks (figures 5 through 11), allowed precise vertical loading and positioning of the fuselage with backup transduction in the form of calibrated hydraulic pressure gages. These gages, calibrated in pounds-of-force at the jacks, were hand recorded and the data are presented in table 2. It should be noted that the bending moment data of figures 15 thru 18 were plotted using only the more accurate load cell readings shown in table 2. The hydraulic gage gear location readings also shown in the table are listed for the record only.

The loading apparatus and tail yoke were qualified for operation at loads up to 13,500 pounds at the tail jacking point and as limited by yeild stress (no factor of safety) in the loading fixture yoke.

TEST RESULTS

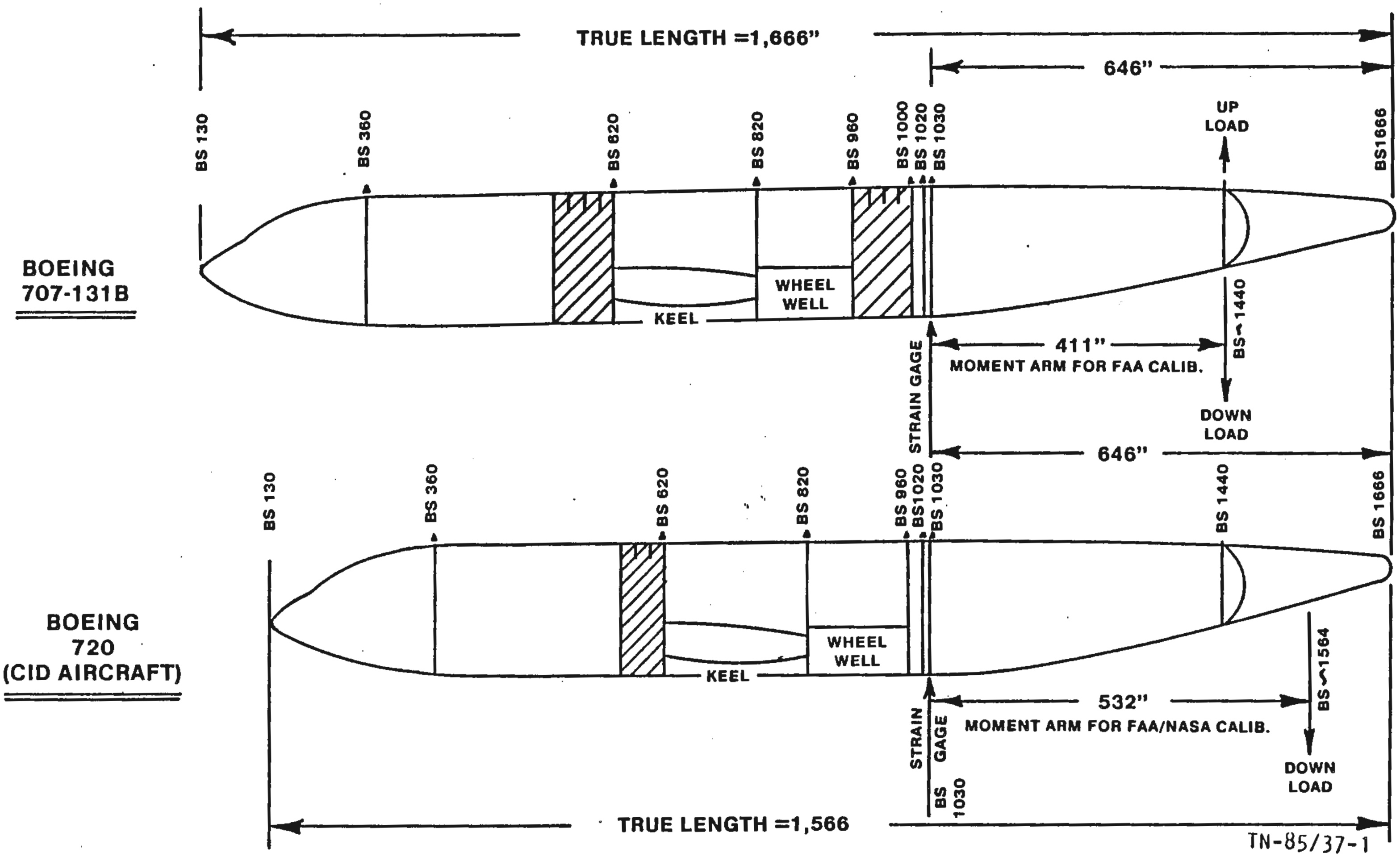
The test results are presented in figures 15 through 18; figures 15 and 17 are graphs of primary channels for upward and downward loadings. Figures 16 and 18 are plots of the secondary (or redundant) channel data. Comparison of primary and secondary plots demonstrates that both channels are in good agreement for all loadings.

The data presented in figures 15 through 18 serve to calibrate the instrumentation for measuring fuselage longitudinal bending moment at BS 1030 (as induced by a vertical load applied at a moment arm of 411 inches from BS 1030). For downloads these data are quite linear and give slopes of 34,400 in-lb/$\mu\epsilon$ for channels 1 and 2, and 25,000 in-lb/$\mu\epsilon$ for channels 3 and 4. The upload data are quite nonlinear, due possibly to the uploading of the riveted structure by removal of the dead weight gravity loading. The slopes as drawn reflect the apparent zero shift.

The tail movement and fuselage deflection data presented in figure 19 serve to indicate further the nonlinear nature of the structure around the zero absolute load.

TABLE 2. LOADING DATA, HYDRAULIC GAGES AND LOAD CELL (LB.)

DATA NO.	MAIN GEAR BOGIE LEFT FRONT	MAIN GEAR BOGIE LEFT REAR	NOSE GEAR	MAIN GEAR BOGIE RIGHT FRONT	MAIN GEAR BOGIE RIGHT REAR	TAIL LOAD	LOAD APPLICATION DIRECTION	LOAD CELL
8	13050							
9	13000	13500	13250	15250	12600	0	UP	
10	11800	12400	15600	14500	12500	2500	UP	2610
11	10600	11000	17900	13400	12450	5000	UP	4860
12	10800	11250	16400	13500	12500	2500	UP	2830
13	11300	12000	13500	13500	12450	0	UP	± 50
14	11500	12000	13400	13500	12450	0	UP	
15	12800	13400	10600	13500	13450	2500	DOWN	2690
16	13550	14100	9000	13500	14100	4750	DOWN	4340
17	13600	14400	10000	13500	14000	2500	DOWN	2700
18	13400	13700	12700	13500	13800	0	DOWN	± 50
19	13400	13900	12900	14000	14000	100	DOWN	100
20	13900	14500	8400	14000	14500	5000	DOWN	4950
21	14000	14850	9950	14000	14200	0	DOWN	100
22	14200	14900	8490	14000	14450	4975	DOWN	4900
23	15050	15500	6200	14500	16000	7500	DOWN	7030
24	15200	15750	5750	14500	16050	7750	DOWN	7440
25	15400	15700	5500	14900	16000	7500	DOWN	7300
26	16000	16550	4000	15400	17000	9750	DOWN	8990
27	16100	16850	5500	15100	16900	5750	DOWN	5680
28	13400	13500	12800	15000	15000	0	UP	± 50
29	10900	11000	17500	13500	12500	5000	UP	4790
30	10800	11000	17500	13500	12500	5000	UP	4810
31	10600	9800	19800	12200	11500	7500	UP	7130
32	8700	8500	21500	11400	10500	9450	UP	8780
33	8500	8300	22000	11000	10200	10000	UP	9380
34	7400	7500	24000	10000	9500	12200	UP	11400
35	8900	9400	19000	10000	9500	5000	UP	5250
36	11500	11950	13500	11500	11000	0	UP	



NOTE: SHADED AREAS REPRESENT TYPICAL ADDED SECTIONS FOR DIFFERENT VERSIONS.

FIGURE 1. COMPARISON OF TEST AIRCRAFT GENERAL CHARACTERISTICS

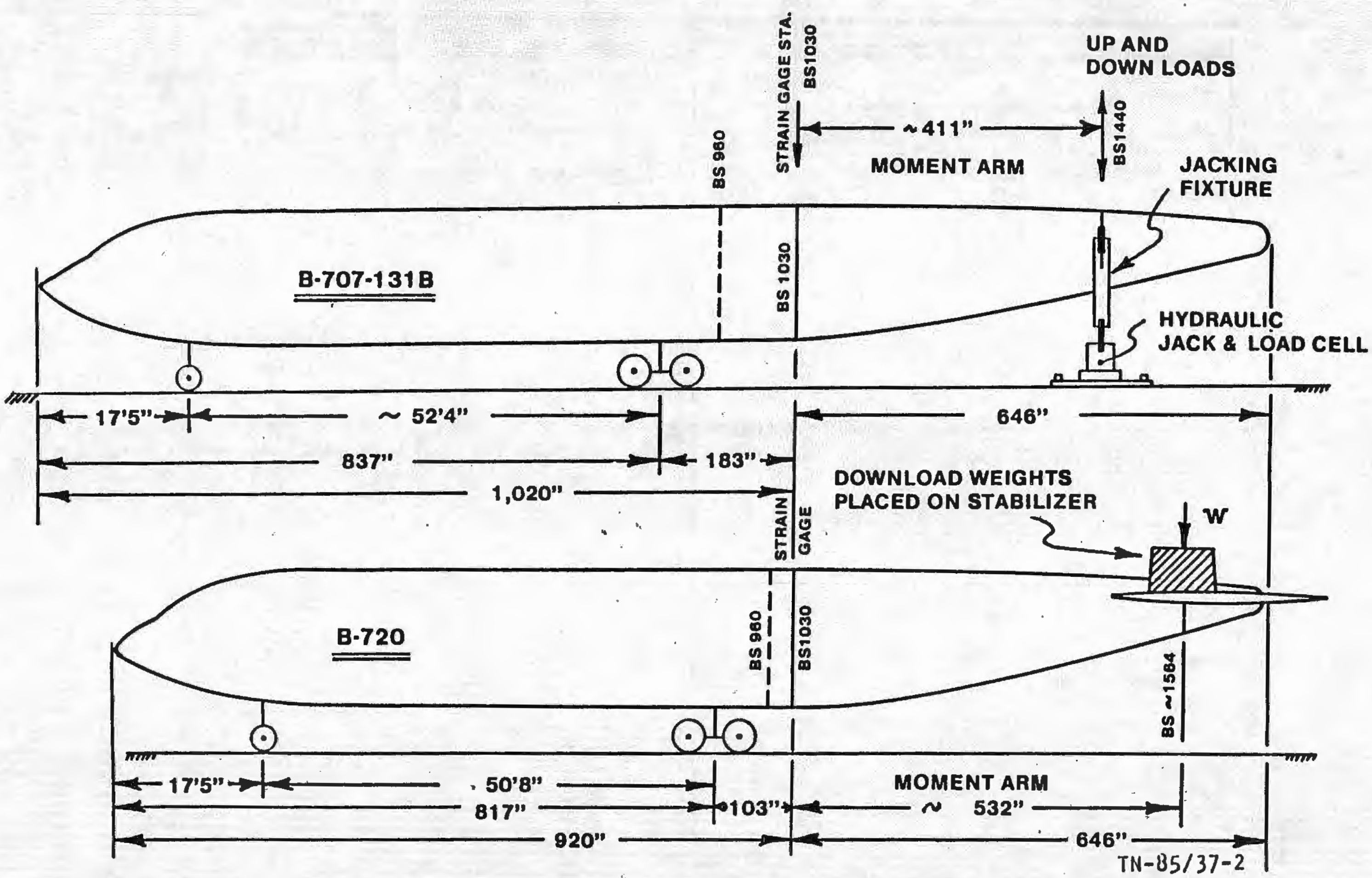


FIGURE 2. LOAD APPLICATION SCHEMATIC

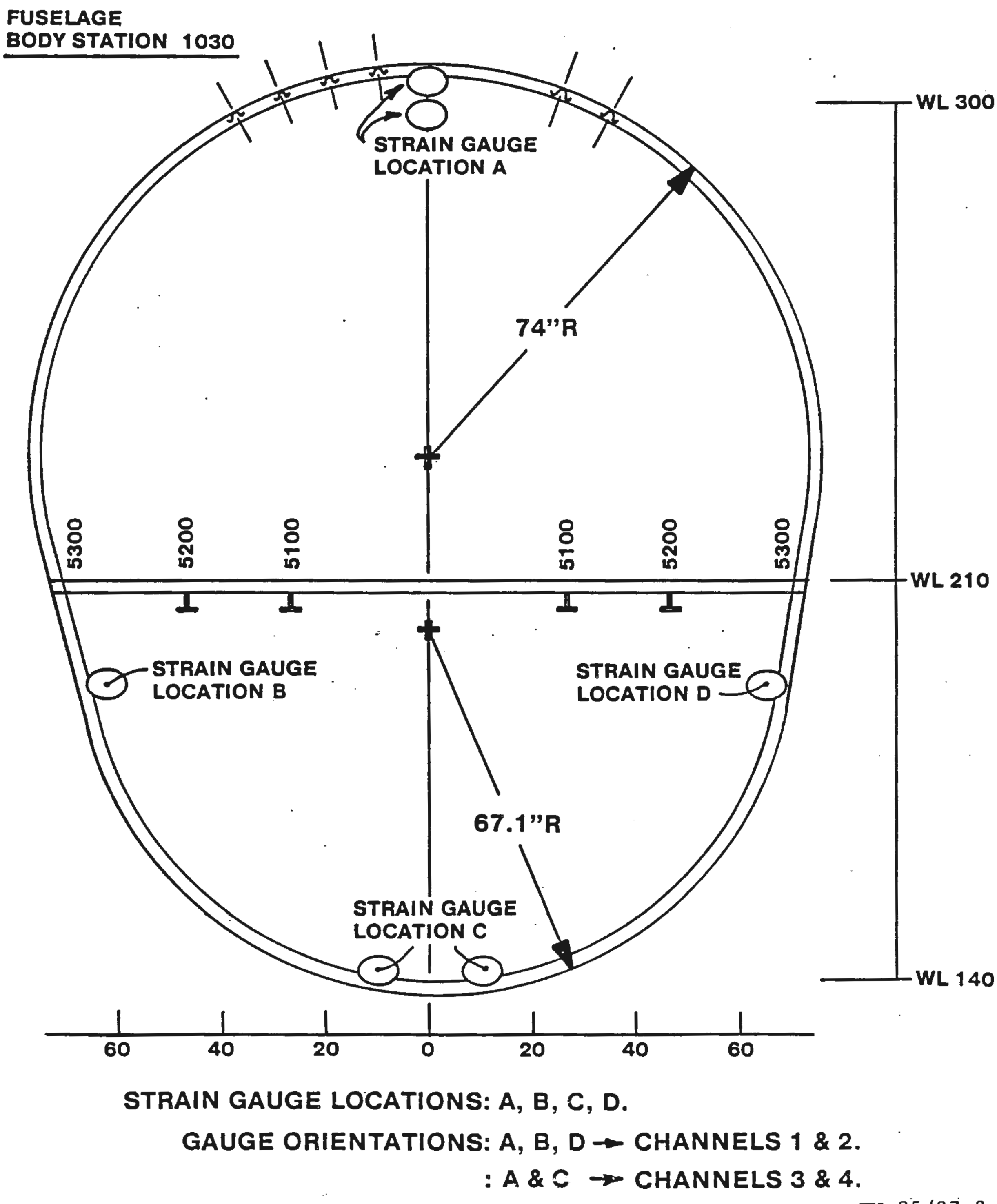


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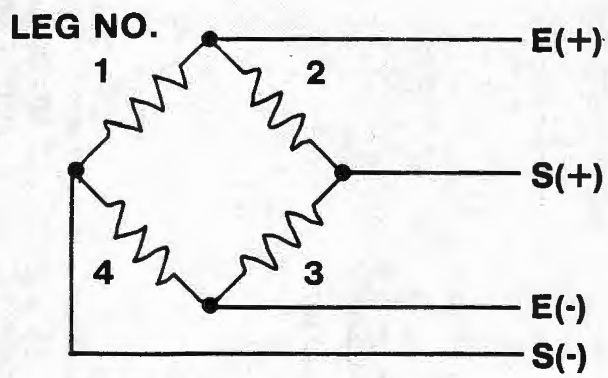
FIGURE 3. FUSELAGE CROSS-SECTION (REAR VIEW)



CHANNEL NUMBER 1: Primary Bridge at Upper and Floor

Legs 1 and 3 at top, upper fuselage
Leg 2 near floor on portside
Leg 4 near floor on starboard side

CHANNEL NUMBER 2: Secondary (Redundant) Bridge at Upper and Floor

Legs 1 and 3 at top, upper fuselage
Leg 2 near floor on portside
Leg 4 near floor on starboard side

CHANNEL NUMBER 3: Primary Bridge at Upper and Lower

Legs 1 and 3 at top, upper fuselage
Leg 2 at bottom (port) lower fuselage
Leg 4 at bottom (stbd) lower fuselage

CHANNEL NUMBER 4: Secondary (Redundant) Bridge at Upper and Lower

Legs 1 and 3 at top, upper fuselage
Leg 2 at bottom (port) lower fuselage
Leg 4 at bottom (stbd) lower fuselage

CHANNNEL NUMBER 5: Load Cell Readout

Calibrated in pounds. Load times 411-inch moment arm equals applied moment (in-lbs).

FIGURE 4a. STRAIN GAGE INSTRUMENTATION LAYOUT

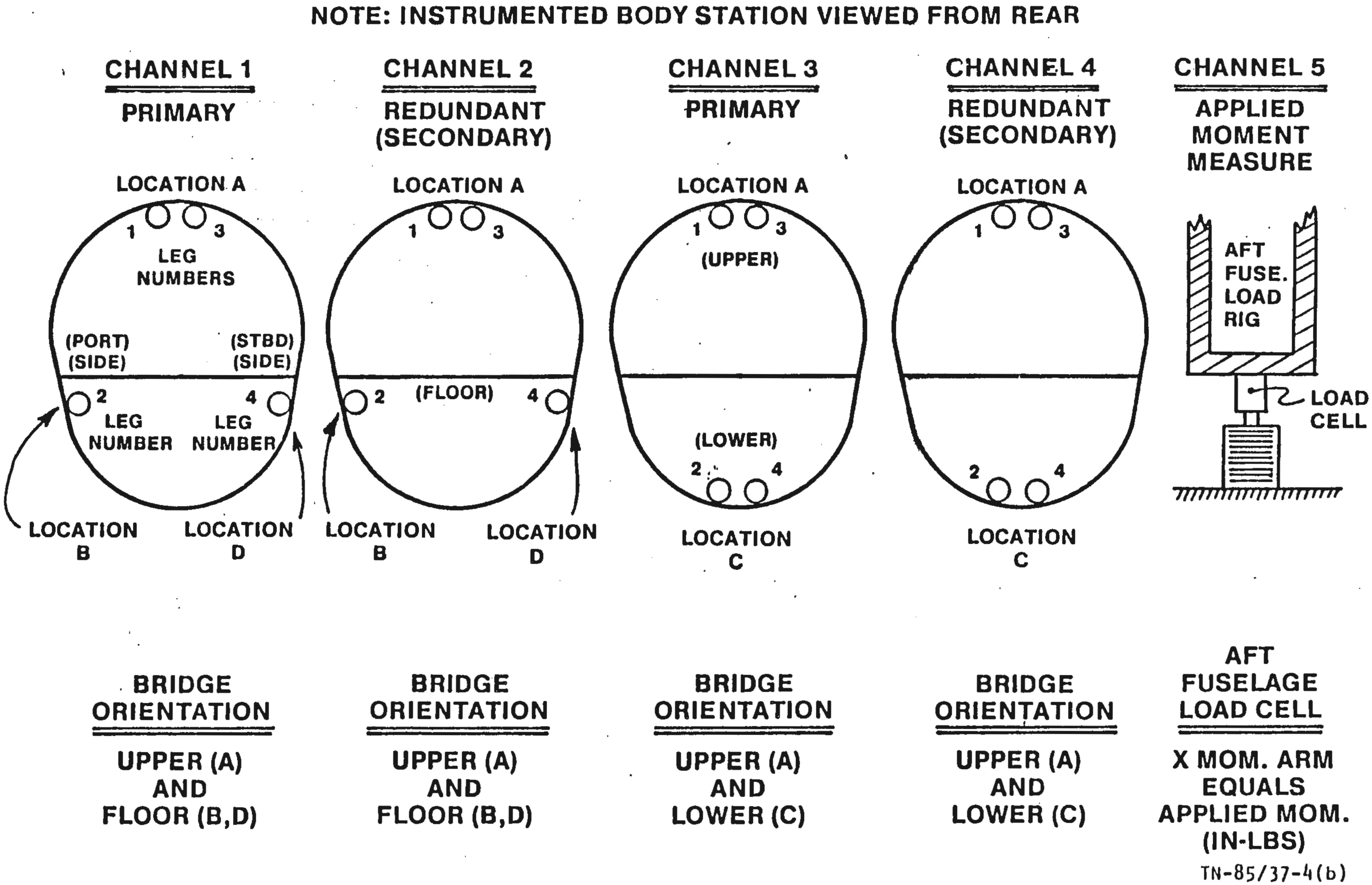


FIGURE 4b. STRAIN GAGE LAYOUT AND LOAD CELL VERSUS CHANNEL NUMBER

FIGURE 5. BOEING 707-131 FUSELAGE

FIGURE 6. MAIN GEAR BOGIE JACKS

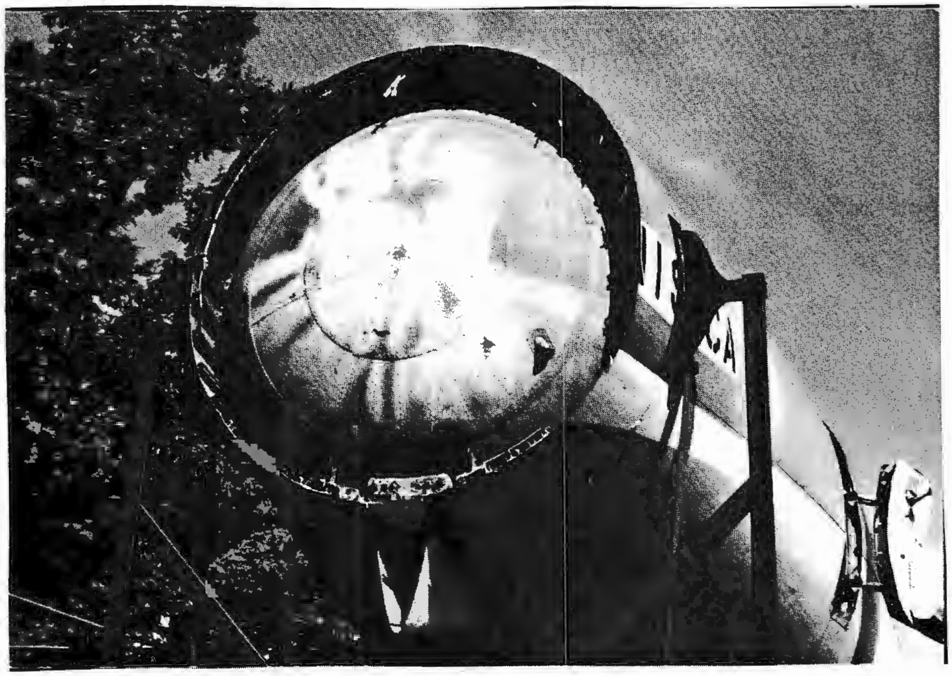


FIGURE 7. AFT BODY STATION ATTACHMENT RIG

FIGURE 8. TAIL LOADING STRUCTURE AND AFT FUSELAGE

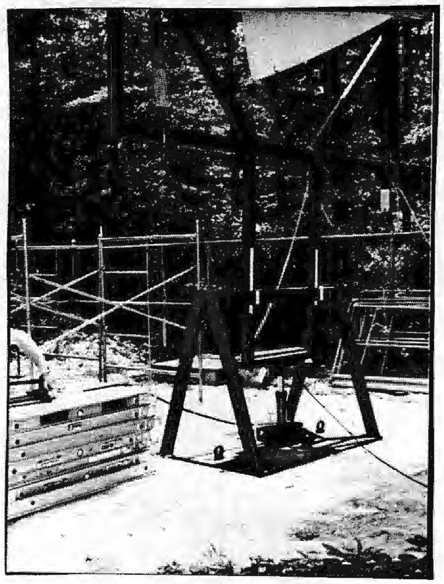


FIGURE 9. TAIL UPLOAD AT AFT PRESSURE BULKHEAD

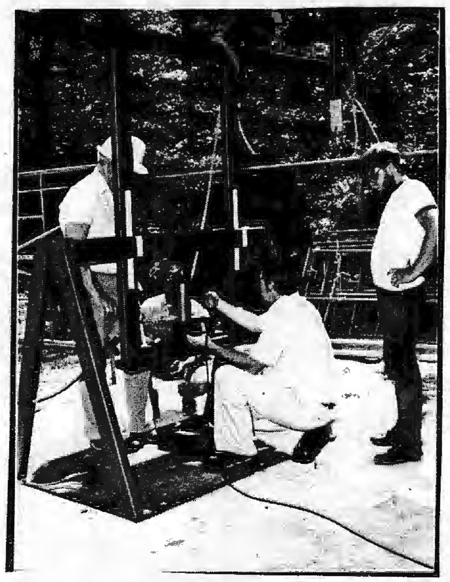


FIGURE 10. TAIL DOWNLOAD AT AFT PRESSURE BULKHEAD

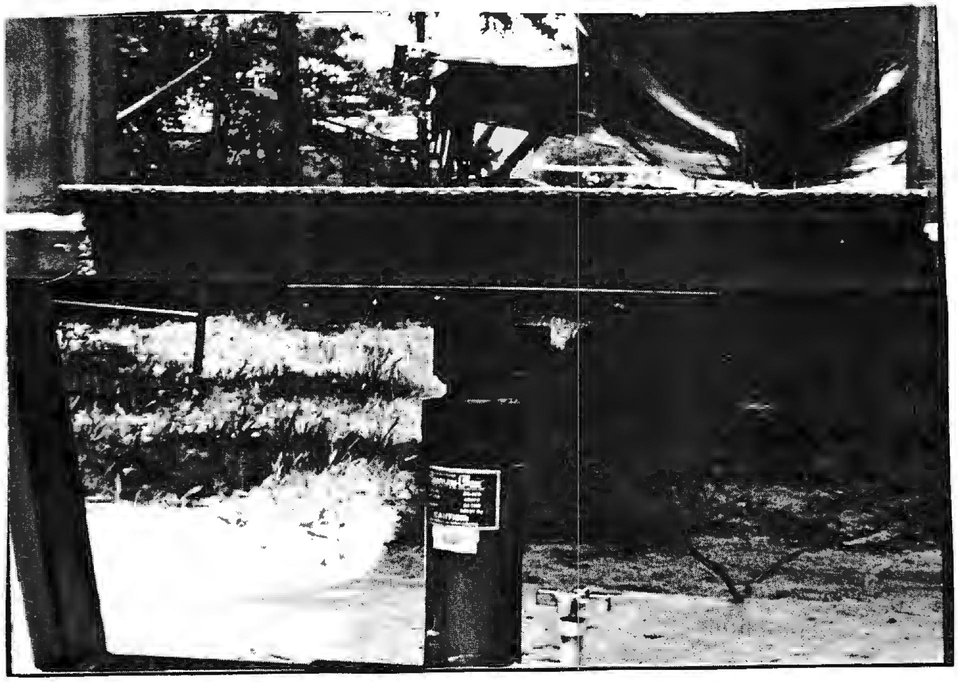


FIGURE 11. CALIBRATED LOAD CELL

FIGURE 12. DATA ACQUISITION SYSTEM AND SUPPORT COMPUTER

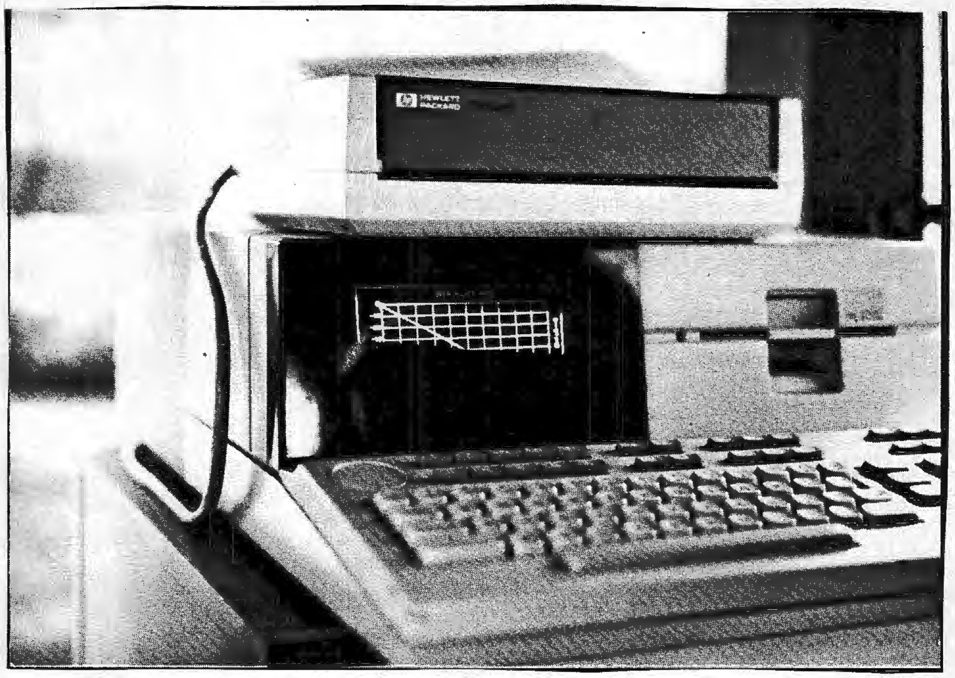


FIGURE 13. ON-SITE DATA MONITORING, CONDITIONING AND PRINTING SET-UP

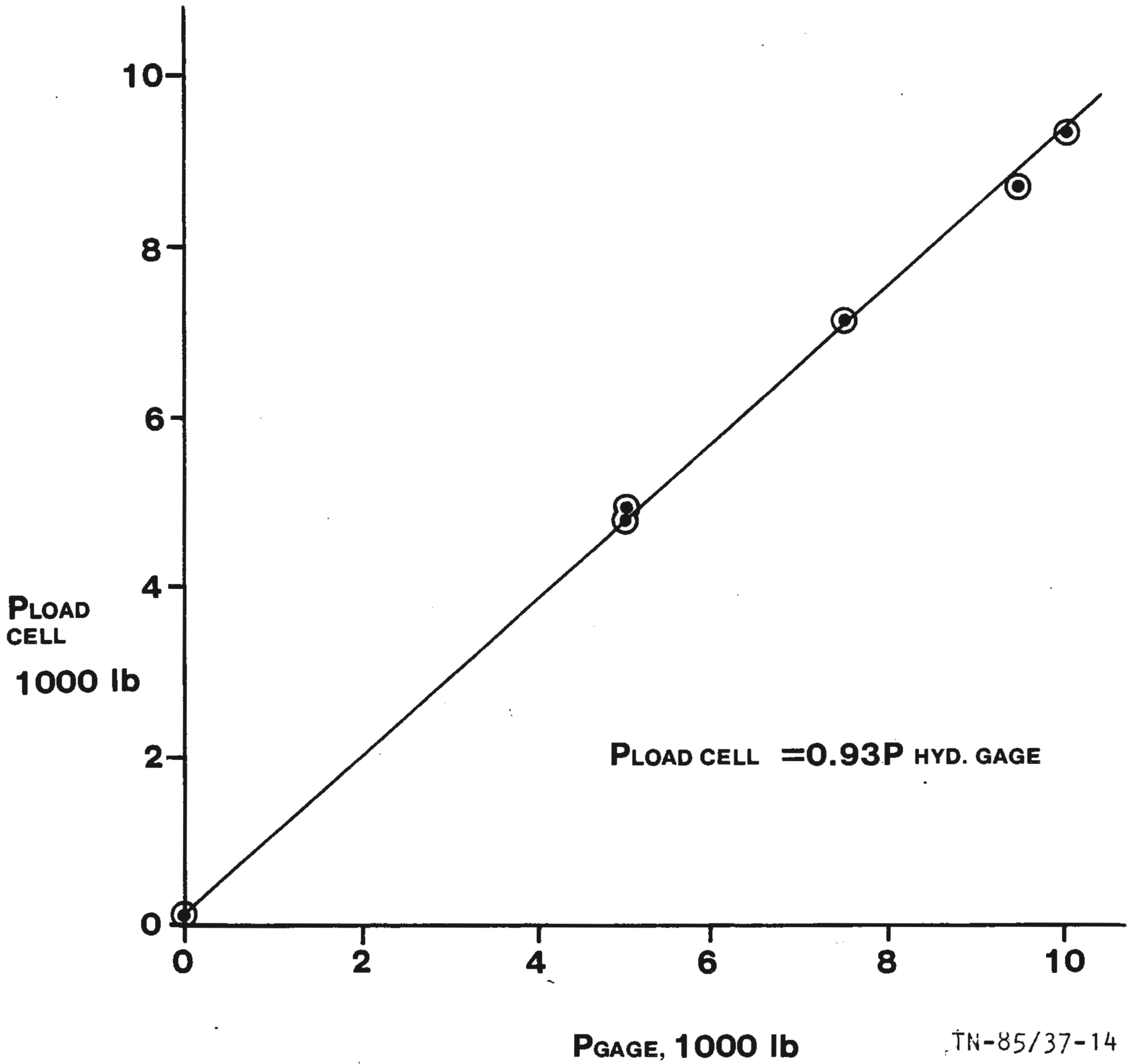


FIGURE 14. COMPARISON OF LOAD CELL AND HYDRAULIC GAGE MEASUREMENTS

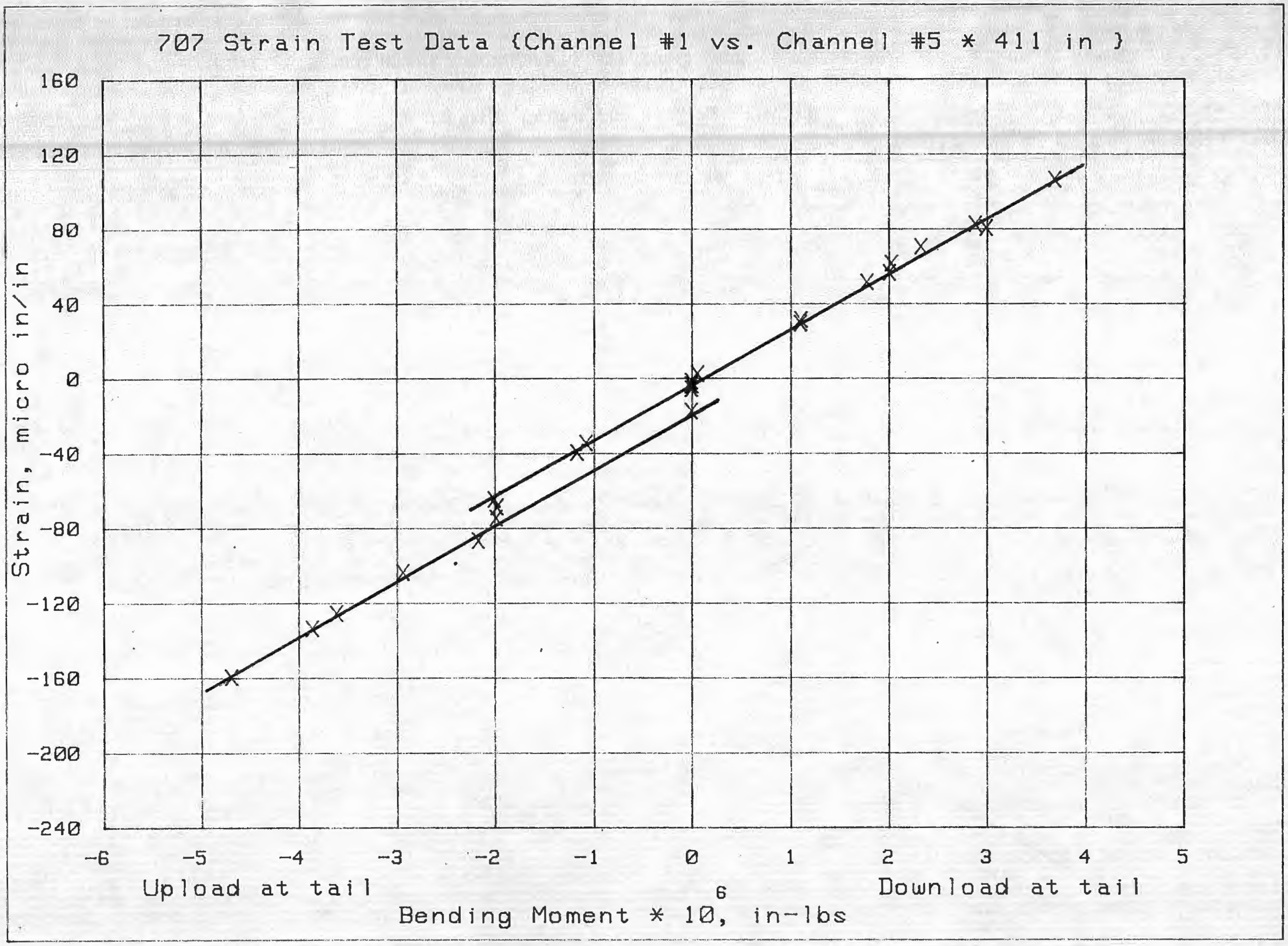


FIGURE 15. PRIMARY STRAIN CHANNEL 1 VERSUS APPLIED BENDING MOMENT

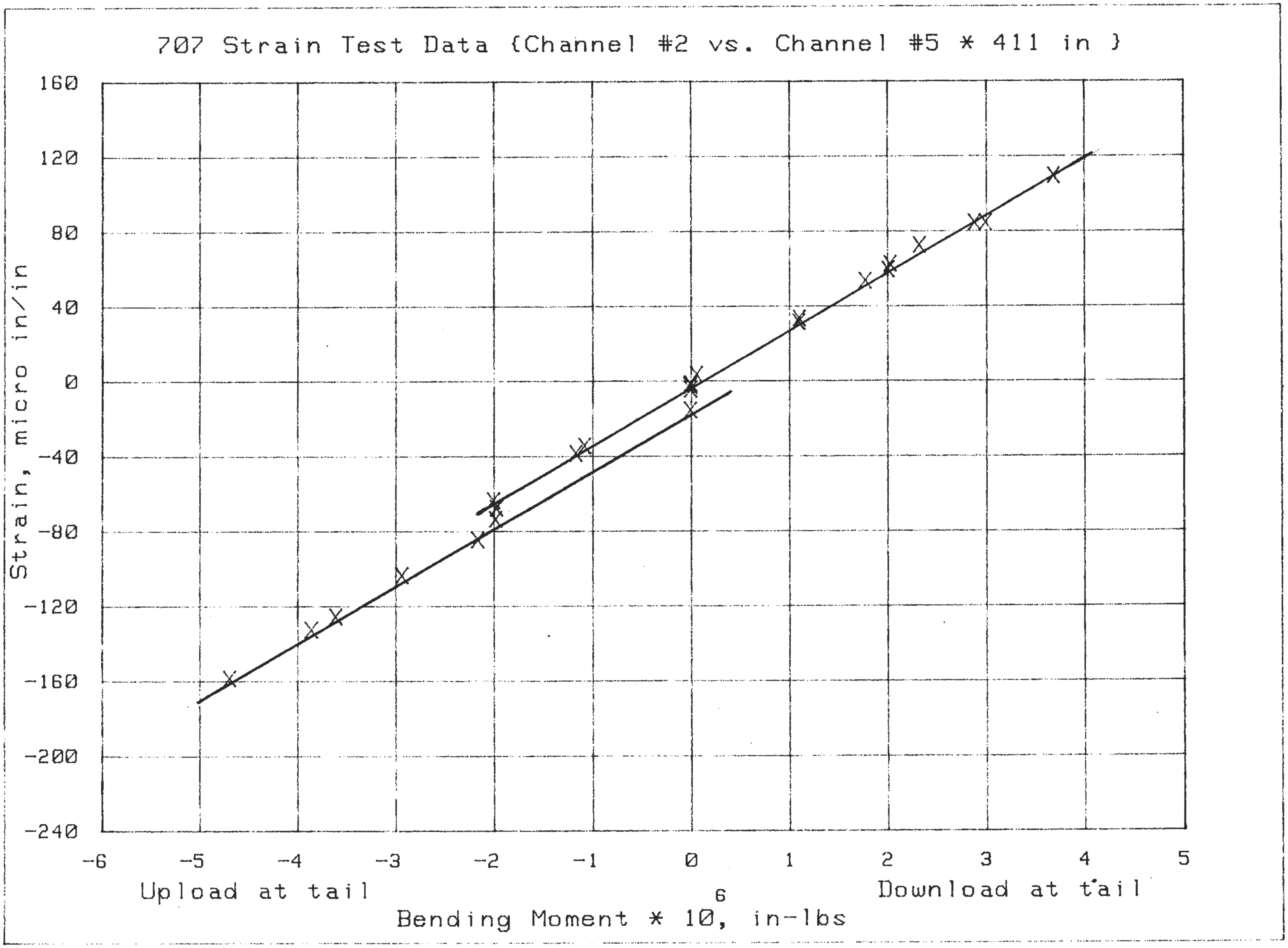


FIGURE 16. SECONDARY (REDUNDANT) STRAIN CHANNEL 2 VERSUS APPLIED BENDING MOMENT

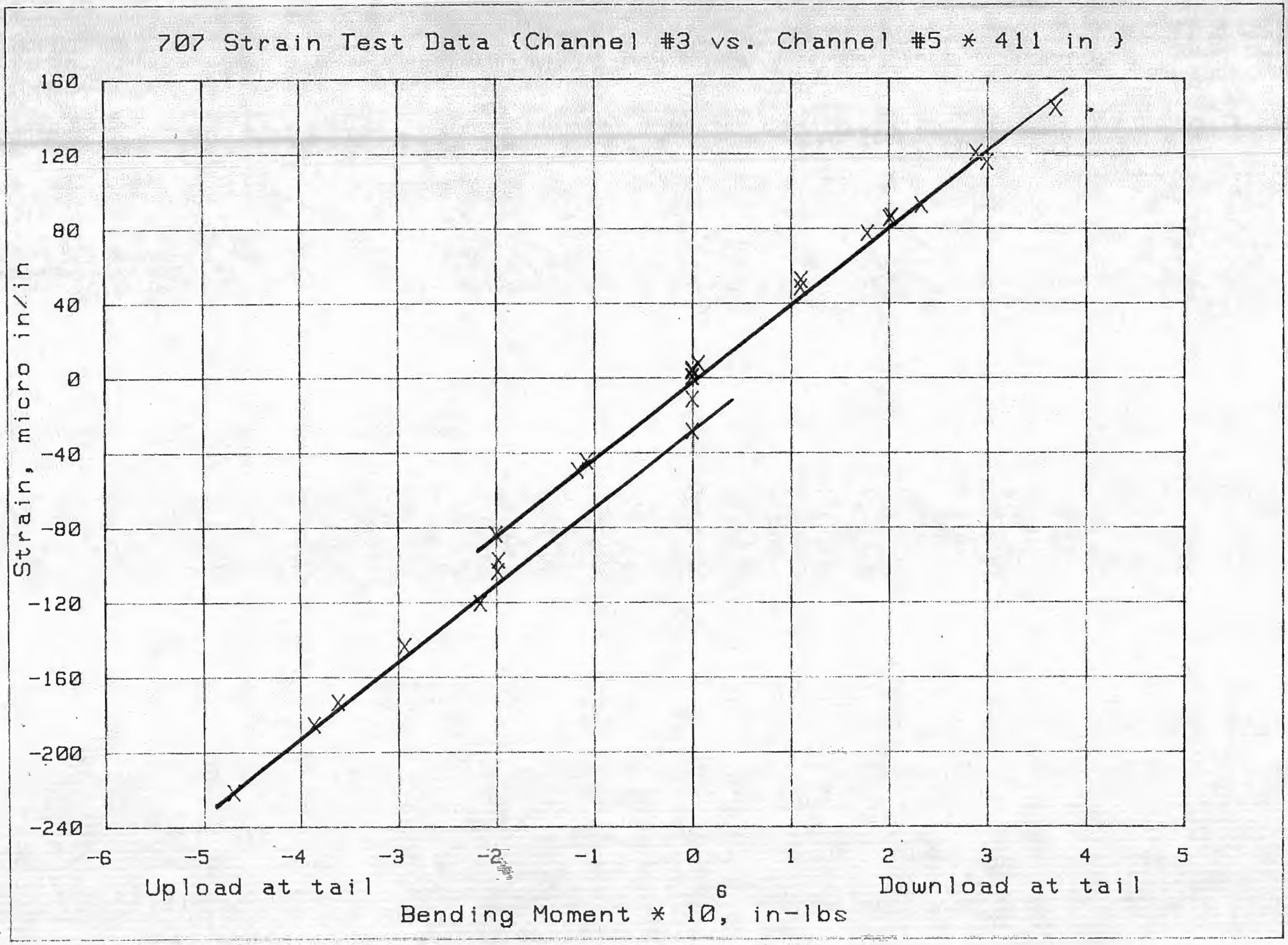


FIGURE 17. PRIMARY STRAIN CHANNEL 3 VERSUS APPLIED BENDING MOMENT

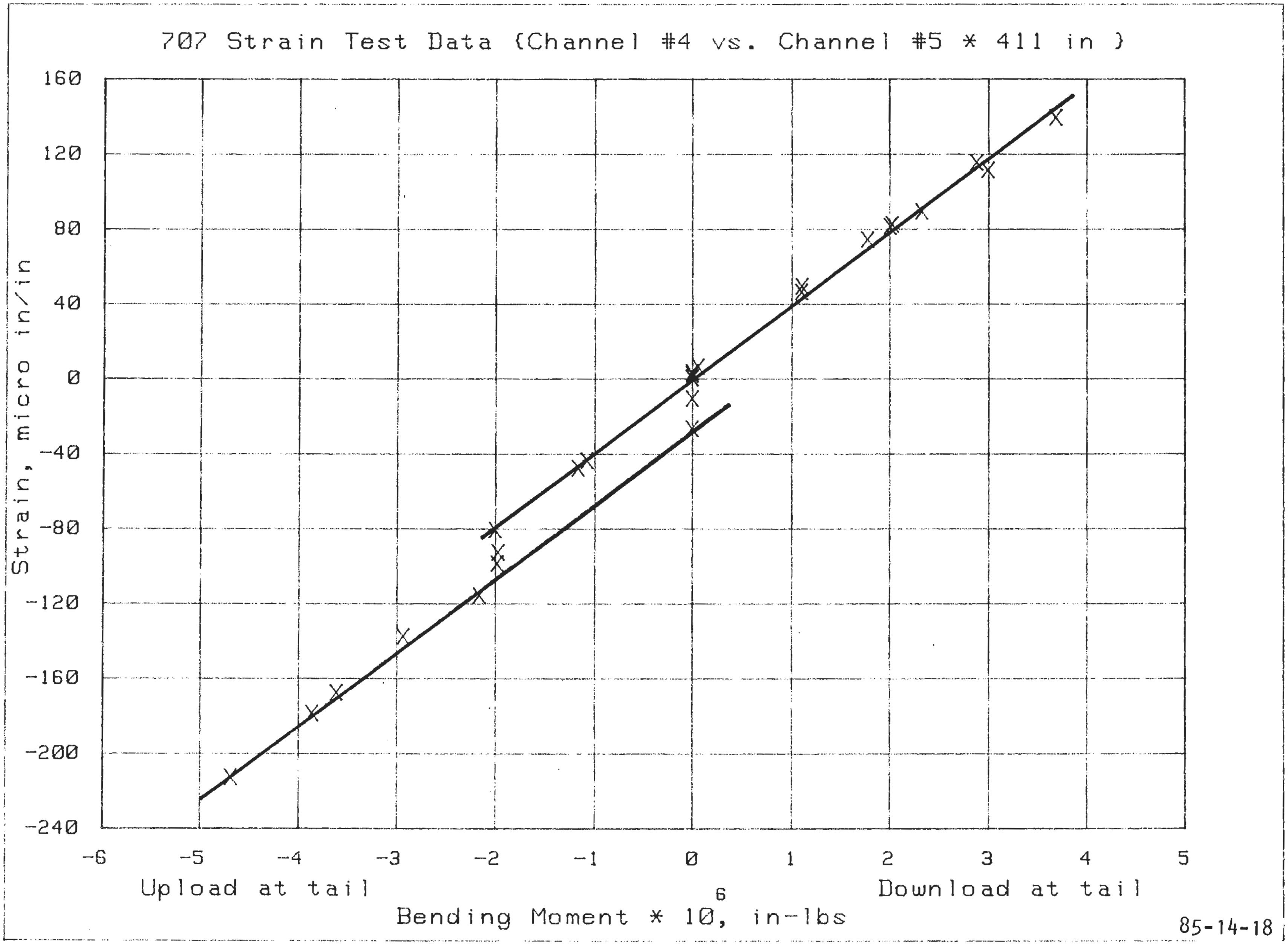


FIGURE 18. SECONDARY (REDUNDANT) STRAIN CHANNEL 4 VERSUS APPLIED BENDING MOMENT

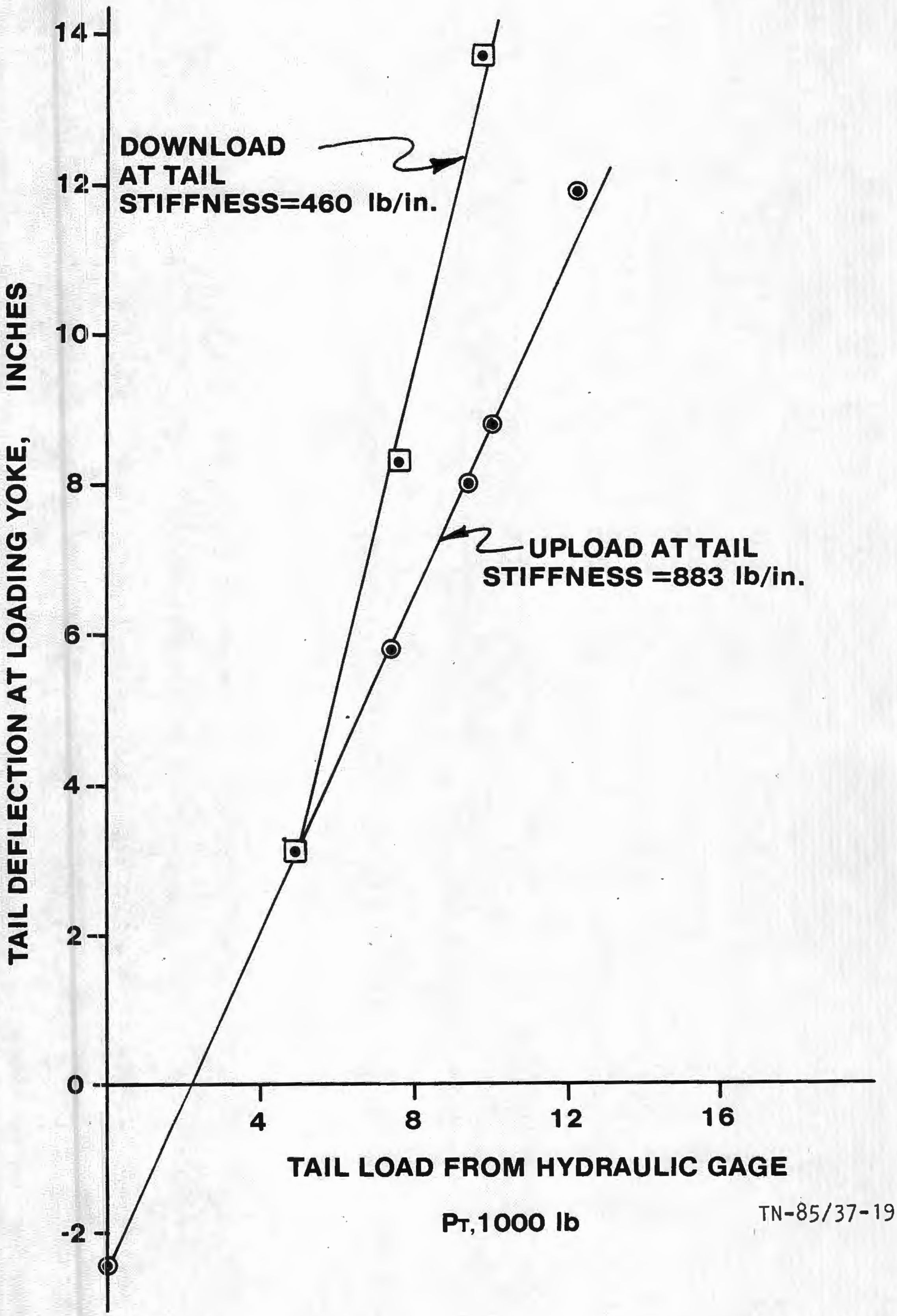
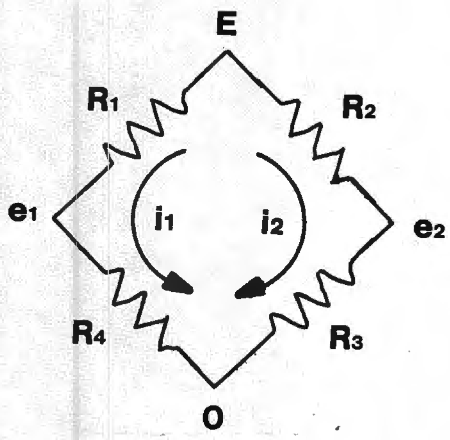


FIGURE 19. TAIL YOKE DEFLECTION VERSUS HYDRAULIC GAGE UP AND DOWN LOAD

APPENDIX



$$e_1 = E - R_1 i_1$$

$$e_2 = E - R_2 i_2$$

$$i_1 = \frac{E}{R_1 + R_4}, \quad l_2 = \frac{E}{R_2 + R_3}$$

For longitudinal (vertical) bending: $R_1 = R_3$ and $R_2 = R_4$

Therefore $i_1 = i_2 = i = \frac{E}{R_1 + R_2}$

e out $= e = e_2 - e_1 = i\,(R_1 - R_2)$

$$\frac{e}{E} = \frac{R_1 - R_2}{R_1 + R_2} = \frac{R+\Delta R-R-\Delta R_2}{2R+\Delta R_1+\Delta R_2} = \frac{G\,\epsilon_1 - G\,\epsilon_2}{2 + G\,\epsilon_1 + G\,\epsilon_2}$$

where $G = \frac{\Delta R/R}{\epsilon\,(\mu in/in)}$ and at $G = 2$

$$\frac{e}{E} = \frac{\epsilon_1 - \epsilon_2}{1 + \epsilon_1 + \epsilon_2}$$