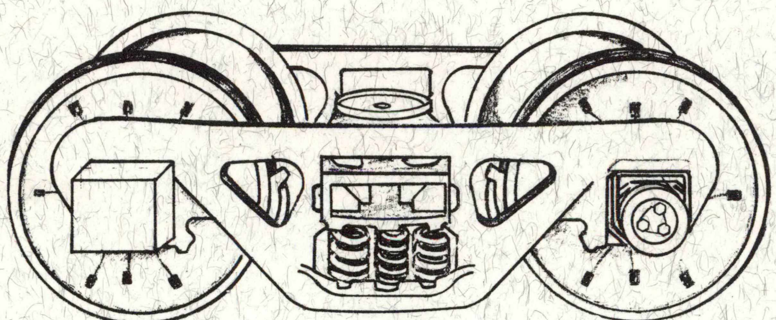
FRA-ORD&D-75-11 PB

INSTRUMENTATION FOR MEASURING FORCES ON WHEELS OF RAIL VEHICLES



MAY 1974

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Prepared for

U.S. DEPARTMENT OF TRANSPORTATION

FEDERAL RAILROAD ADMINISTRATION

OFFICE OF RESEARCH AND DEVELOPMENT

Washington, D.C. 20590

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TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FRA-ORD&D-75-11		

4. Title and Subtitle	5. Report Date
Instrumentation for Measurement of Forces on Wheels of Rail Vehicles	May 1974
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No. LT-328
9. Performing Organization Name and Address Association of American Railroads, Research and Test Department, Chicago, Illinois ENSCO, INC., 5408A Port Royal Rd., Springfield, Va. 22151	10. Work Unit No.
	11. Contract or Grant No. DOT-FR-20010
12. Sponsoring Agency Name and Address U.S. Department of Transportation Federal Railroad Administration Office of Research, Development & Demonstrations Washington, D.C.	13. Type of Report and Period Covered Project Engineering
	14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

The information in this report covers the procurement, development and testing of instrumentation designed to measure the dynamic forces and temperatures which are created in the wheels of a loaded rail vehicle truck.

The information contained herein is intended for use by scientific, research and engineering personnel who are involved in the measurement of dynamic loads of rail vehicle wheels.

17. Key Words	18. Distribution Statement
Instrumented Wheel Wheel Stresses Wheel Forces Force Measurement	Distribution Unlimited

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	103	

Form DOT F 1700.7 (8-69)

EXECUTIVE SUMMARY

The information in this report covers the procurement, development and testing of instrumentation designed to measure the dynamic forces and temperatures which are created in the wheels of a loaded rail vehicle truck. This report is comprised of three seperate documents which cover, chronologically, the original measurement requirements, design and calibration of wheel-mounted sensors, and the design and assembly of sensor data acquisition, data processing and data display hardware.

The Federal Railroad Administration initiated the activities covered herein by issuing a Task Statement (Section 1) which outlined the requirement for the instrumentation of 36-inch wheel sets. The wheel sets were then instrumented by the Association of American Railroads, who also provided calibration data relating wheel stress to measurement parameters (Section 2). ENSCO, INC. then fitted the instrumented wheels with appropriate instrumentation needed for data acquisition, signal conditioning and data display (Section 3). A final step will be taken by ENSCO, INC. to gather data applicable to the examination of wheel/rail interaction. This work will be described upon completion in an FRA report.

CONTENTS

SECTION 1

FEDERAL RAILROAD ADMINISTRATION'S TASK STATEMENT FOR THE DEVELOPMENT OF RAIL WHEEL INSTRUMENTATION

SECTION 1. TASK STATEMENT

Task Statement for the Instrumentation of 36" Railroad Car Wheel Sets to be Used for Measurement of Laterial and Vertical Forces at the Wheel/Rail Interface

I. BACKGROUND:

The Federal Railroad Administration wishes to procure two instrumented railroad car wheelsets. These wheelsets will be placed in a Barber S-2 freight car truck to obtain information related to the forces developed in the wheel-rail contract area under various loading conditions. Instrumentation electrical connections shall be made to slip ring assemblies and shall provide an essentially linear measurement of the magnitude of the vertical and lateral forces. The lateral force load measurement shall be continuous for 360° wheel rotation. The vertical force measurement shall be obtained instantaneously at least four times each wheel rotation.

II. SCOPE:

The contractor shall provide and instrument two wheelsets utilizing a two step process. The first being the application of a series of strain gages to identify points of maximum lateral and vertical load sensitivity. The second being the application of load gages at the experimentally determined critical points, calibration of the load gages and mounting of such wheel sets in the government furnished truck, including slip ring connections.

The vertical load package shall be such that the output from four sensors shall provide one vertical-load spike signal every ninety degrees (90°) of rotation when the sensor or sensors are directly along the line connecting the axle and the wheel/rail contact point.

The lateral load sensor package shall be such that the summation of six gage locations connected in a 360 ohm wheatstone bridge configuration will give a continuous strain signal representative of lateral loading.

III. MATERIALS TO BE FURNISHED:

1. Four rotating end cap type Timken roller bearings (6 1/2" X 12").

2. Four 20 contact Michigan Scientific slip ring assemblies.

3. Eight iron-copper thermocouples.

4. Four 36" cast steel multiple-wear wheels complying with AAR standard CK-36 design. Each wheel shall have an unbalance of less than 0.2 lbs. after machining.

5. Four slip ring adapters.

6. Four flexible couplings for slip rings.

7. Twenty-four or more SR-4 (A-7) exploratory strain gages (used to locate point of maximum sensitivity to loading).

8. Eighty (80) 1/4" Series 105 encapsulated polyimide backed strain gages (20 per wheel), wires, epoxy cement and glyptal waterproof protective coating.

9. Two roller bearing axles (63,000 lbs. capacity).

The above wheels, axle and roller bearings shall be mounted and placed in the Barbar S-2 freight car truck supplied by the Government.

IV. INFORMATION TO BE FURNISHED

The following information shall be furnished:

1. Wheel identification information.

2. Wheel plate profile drawing showing location of exploratory strain gages and final strain gage locations.

3. Exploratory calibration curves.

4. Wiring diagram for vertical and lateral load bridges.

5. Final calibration curves with listing of equipment (Visicorder, amplifiers, etc.) and calibration resistance values used in obtaining the calibration values.

6. Photographic documentation of all steps and processes.

V. WORK REQUIREMENTS:

Part I

A. The inner and outer web surfaces of the wheels shall be machined to the minimum web thickness for multi-wear wheels, as per AAR Standard wrought steel wheel design CK-36. The web surface shall be such that it assures proper application of the strain gage instrumentation. All wheel web profiles shall be finished to the same profile and web thickness which shall be documented.

B. To locate the points of maximum lateral and vertical load sensitivity on the web for all wheels, the contractor shall place the exploratory strain gages along a radial line through the axis of the wheel on the inner and outer web surface of one wheel; twelve or more strain gages shall be placed at intervals of approximately 1/2" in each web surface so as to cover most of the wheel plate except for the rim fillet area. Location of strain gages shall be graphically and pictorially documented.

1. A twenty ton vertical load, applied to the top of each roller bearing housing by hydraulic jack, shall be impressed on the taper line of the wheel tread (see Figure 1) and strain gage output monitored, recorded and documented. Determine the change in strain for each gage for every thirty (30) degrees of wheel rotation from 0° to 180°. Repeat for 5, 10, and 15 ton loads. All calibration test readings shall be made using a D.C. Signal Carrier System.

2. A twenty ton lateral load shall be applied to the wheel tread by a hydraulic jack placed at the end of the axle opposite the wheel to be calibrated. The strain gage output shall be monitored, recorded and documented. Determine the change in strain of each gage for every 30° of wheel rotation from 0° to 180°. Repeat for 5, 10, and 15 ton loads.

3. Simultaneously, a twenty ton vertical load and a twenty ton lateral load shall be applied as in the previous two paragraphs. The strain gage output shall be monitored, recorded and documented. Determine the change in strain of each gage for every 30 degrees of wheel rotation from 0° to 180°. Repeat for 5, 10, and 15 ton loads.

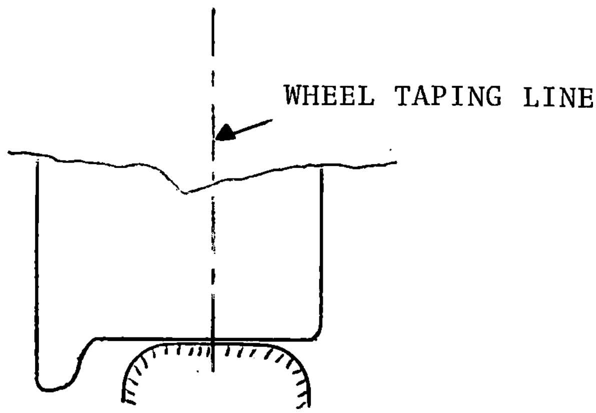
C. Prepare the following graphs for both inner and outer gage sets showing strain gage output versus strain gage location. The curves shall include:

(1) Corrected strain for each location due to the 20-ton lateral load at 0°, 30°, 60°, 90° and 180° wheel rotation. Corrected strain is the result of a vertical load correction applied to the values recorded during the lateral load test. This correction shall be equal to and have the opposite sign of the lateral strain gage reading caused by the application of the pure vertical load, used to restrain the wheel during the lateral load tests.

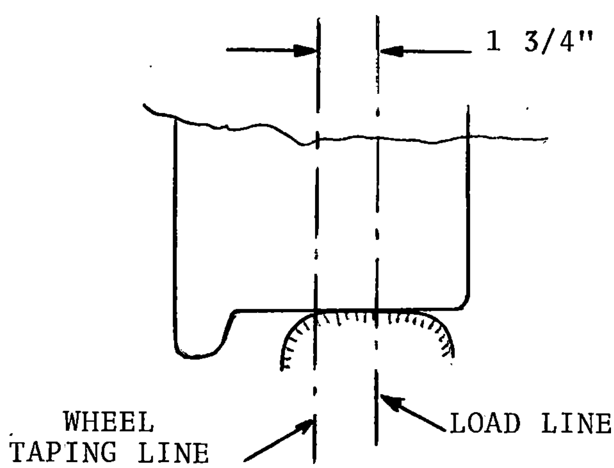
(2) Sum of corrected strain gage output values due to the 20 ton lateral load for wheel rotation positions of 0°, 60°, 120°, 180°, 240°, and 300°.

(3) Strain gage output values due to a vertical load of 20 tons at 0°, 30°, 60°, 90°, 180°, 270° wheel rotation.

(4) Sum of strain output values due to the 20 ton vertical load for wheel rotation positions of 0°, 60°, 120°, 180°, 240°, and 300°.



INITIAL LOAD POINT



ADDITIONAL LOAD POINT

LOADING POINTS

FIGURE 1

D. The 20 ton vertical and lateral loads shall be impressed on the wheel tread at the one additional point of wheel/rail contact defined in Figure 1, to determine sensitivity to loading point variation. Data shall be obtained per the requirements of Paragraph B and displayed per Paragraph C. Strain gage output curves for the two load points shall be compared and the load-point sensitivity of strain gage output determined and documented.

Part II

E. Establish in consultation with the FRA representative the final strain gage locations (for the 20 strain gages per wheel) from the strain value curves of Paragraph C in the following manner:

1. One set of four vertical load measurement gages are to be located in pairs 180° apart at that location on the wheel web face with maximum sensitivity to vertical loads where the change in strain due to the lateral load of 20 ton at 0° is equal to (and the same sign as) the value at 180°. The second set shall be 90° from the first.

2. The (twelve) lateral load measurement gages are to be located on the inside or outside face of the web such that maximum sensitivity is to lateral loads and with one every 60° at each of two distances from the axis of the wheel such that--

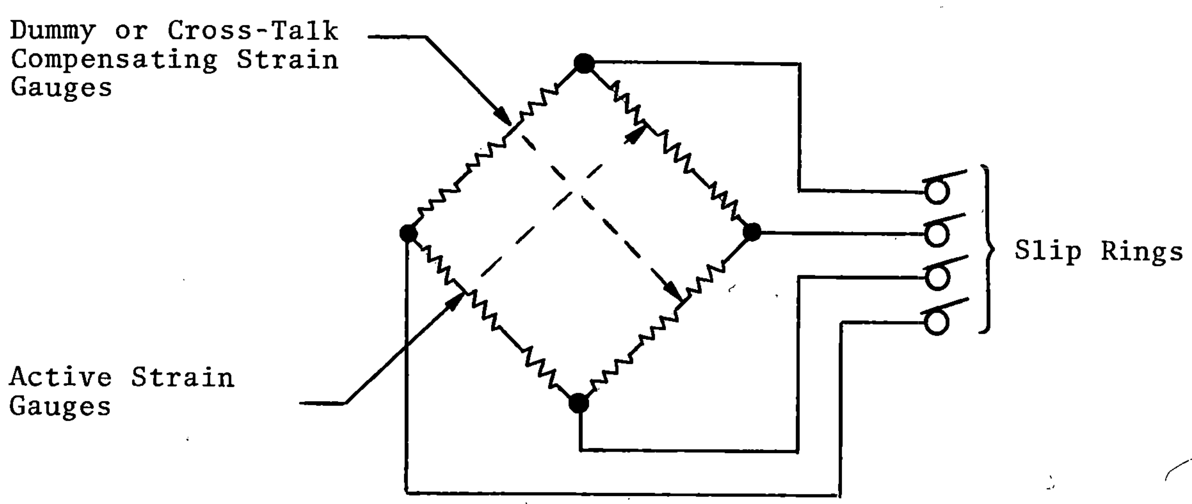
   a. The sum of the six 60° wheel rotation position strain values due to a 20 ton vertical load is the same at each distance from the wheel axis.

   b. The sum of the six 60° wheel rotation position values due to a 20 ton lateral load for the two distances from the wheel axis is a maximum (unlike signs add and like signs substract).

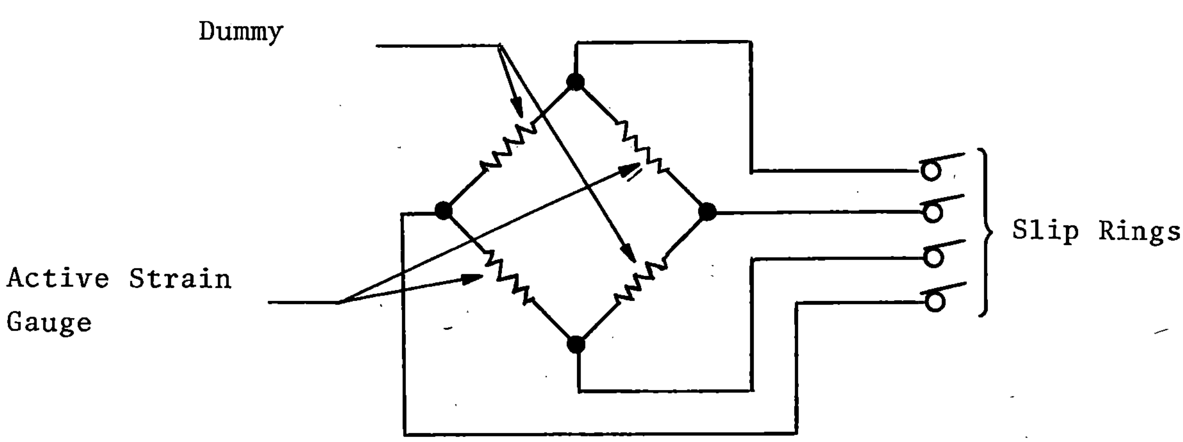
F. All strain gages shall be mounted with epoxy cement, and together with the connecting wires shall be waterproofed with several coats of "glyptal".

Two sets (per wheel) of four vertical load gages shall be wired to form a 120 ohm bridge and twelve lateral load gages (per wheel) shall be wired to form a 360 ohm bridge so as to obtain in each case the desired additive and subtractive effects (see Figure 2).

The strain gage wiring leads from each wheel shall enter the axle via a 3/8 inch hole drilled (to the center of the axle) between the bearing and continue out the end of the axle through another 3/8 inch hole drilled along the axle axis from the end of the axle taking care to avoid wire damage due to sharp corners. Twenty contact Michigan Scientific slip rings and adapters shall be assembled and mounted at each end of the axle.



Lateral Load 360 OHM
Wheatstone Bridge Configuration



Vertical Load 120 OHM
Wheatstone Bridge Configuration

Figure 2
Typical Wheatstone Bridge Configurations

G. Two iron copper thermocouples shall be attached to each wheel as shown in Figure 3 to monitor the web temperature. One shall be attached to the wheel web at the location of the lateral gages and one near the vertical load sensor. These thermocouple readings will be utilized to determine the magnitude of temperature corrections to loading values recorded during actual operating conditions.

H. The contractor shall then rotate each wheelset up to a maximum of 1000 rpm (corresponding to 108 m.p.h. ground speed) in a no-load condition. Variations in signal output shall be recorded.

I. Before final calibration, the contractor shall mount the wheel sets in the Barber S-2 truck. Final calibration shall involve both vertical and lateral load bridge output readings for one ton load increments up to the twenty ton lateral and twenty ton vertical loads (including the distributed truck weight), at the zero degree wheel rotation position and for every 30° of wheel rotation from 0° to 360° degrees.

J. The contractor shall recommend and specify types of recording and signal conditioning devices to be connected during FRA testing.

VI. SPECIAL PROVISIONS

1. The FRA may have a representative at the contractors facility to observe the installation and calibration of the wheel sets. The contractor shall provide the FRA representative with all information and assistance in documenting the procedures used in the instrumentation of a railroad wheel.

2. The task shall not be considered complete until contractor supplied documentation is presented to and satisfactorily reviewed by the FRA contract officer.

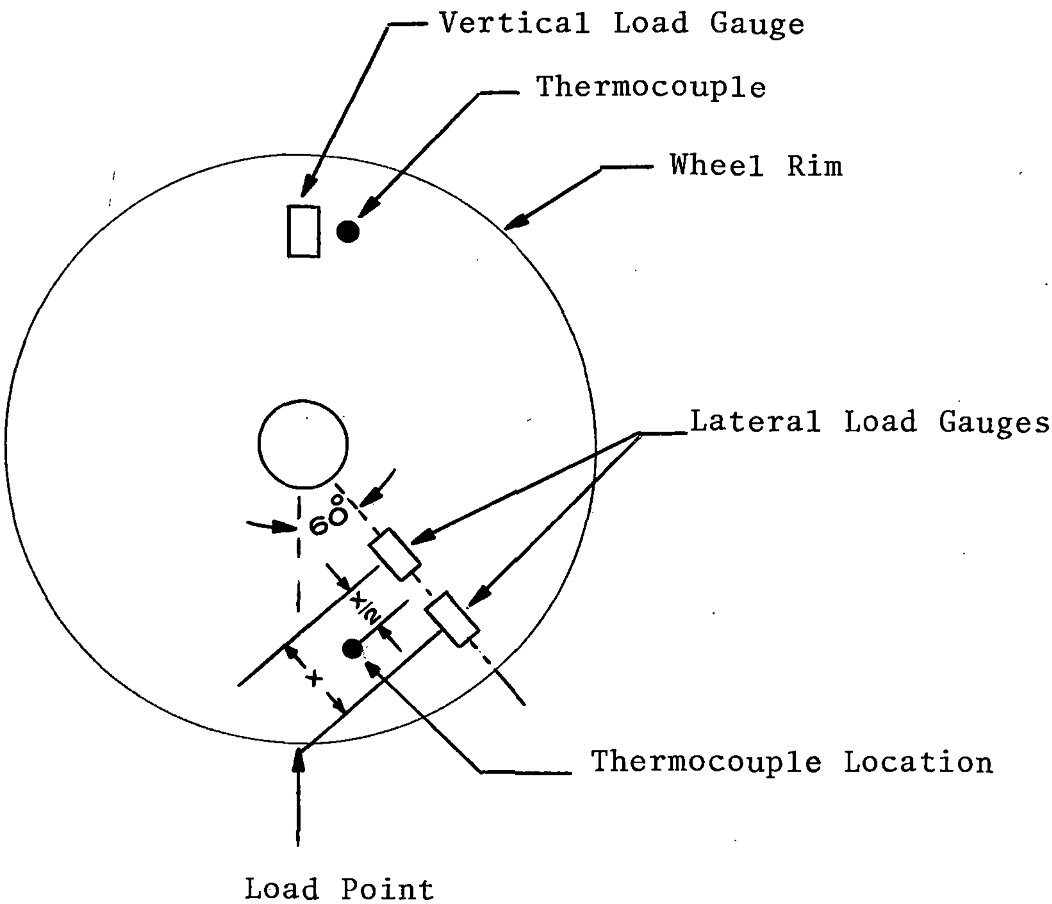


Figure 3

Appropriate Thermocouple Locations

SECTION 2

ASSOCIATION OF AMERICAN RAILROAD'S REPORT ON INSTRUMENTED WHEELS FOR MEASUREMENT OF VERTICAL AND LATERAL WHEEL FORCES

ASSOCIATION OF AMERICAN RAILROADS

RESEARCH AND TEST DEPARTMENT

REPORT NO. LT-328
(Project No. 71-S-71)

INSTRUMENTED WHEELS FOR MEASUREMENT OF VERTICAL AND LATERAL WHEEL FORCES

Prepared For
Federal Railway Administration
U. S. Department of Transportation

FRA Contract No. DOT-FR-20010

SEPTEMBER 1972

AAR RESEARCH CENTER
Chicago, Illinois

ASSOCIATION OF AMERICAN RAILROADS
RESEARCH AND TEST DEPARTMENT

NOV 13 1972

REPORT NO. LT-328
(Project No. 71-S-71)

INSTRUMENTED WHEELS FOR MEASUREMENT OF VERTICAL AND LATERAL WHEEL FORCES

INTRODUCTION

The Department of Transportation of the Federal Railroad Administration contracted the Association of American Railroads to furnish a fully assembled Barber S-2 100-ton freight car truck. The wheel sets were to be instrumented and calibrated to measure wheel forces and temperature. Each wheel was dynamically balanced to ten inch ounces and will carry five signal outputs. These outputs are a lateral wheel force signal, two vertical wheel force signals, and two wheel plate temperature signals. Slip rings attached to the ends of each axle transfer the electrical wheel measurements to signal conditioners and amplifiers.

ACKNOWLEDGMENTS

Calibration and instrumentation of the wheels and the acquisition of the Barber S-2 truck was under the general direction of R. F. Laskowski, Senior Electrical Engineer, who analyzed the data and prepared this report, assisted by H. H. Remington, Assistant Electrical Engineer, C. Stamper and F. Strozinski, Electronics Assistants. The Department of Transportation reimbursed the AAR for the work described in this report.

DESCRIPTION OF CALIBRATING EQUIPMENT

The test pad consisted of two 132 lb. rails, 10 ft. in length, placed on four 7 in. x 9 in. x 8 1/2 ft. oak ties that had eight roller bearing tie plates attached. The roller bearing tie plates reduced friction during lateral loading. Two 1-1/2 in. x 10 ft. rods spaced 6 ft. apart located just below the rail head, applied the lateral load by squeezing the rails against the wheel flanges. This load was controlled and maintained with two Simplex hydraulic rams of 50-ton capacity. Track gage was maintained after lateral loadings by returning the rails to 56 1/2 in. using a hand operated hydraulic jack of 10-ton capacity. Two 50-ton hydraulic Amsler jacks applied the vertical loads, and they were controlled and maintained by a pendulum dynamometer console.

EXPLORATORY PROCEDURE

Twenty four (24) SR-4 strain gages type FAP-25-12 were cemented to the inner and outer web plate surfaces of a CK-36 cast steel wheel No. 65584. They were spaced 1/2 in. apart on a radial axis extending from the hub fillet toward the wheel rim. Strain output data from vertical and lateral loads were analyzed and graphed to select the sensitive positions necessary for full bridge measurement of these loads. A 20-ton vertical load was applied to the top of each roller bearing housing (maintaining standard track gage) while changes in strain were recorded for each of the 24 gages, every 30° of wheel rotation from 0° to 300°. Changes in strain readings were also recorded for each gage during the lateral loadings in similar fashion to the vertical loadings. The lateral and vertical loads were applied in 10,000 lb. increments. Tables 1 through 9 contain the strain readings of the exploratory gages and their respective outputs under load. These data were used to plot curves for each exploratory gage. They appear in Fig. 1 and Fig. 2. These curves are the corrected strains resulting from a vertical load correction applied to the values recorded during lateral loading, as per paragraph 6.3.1, page 4, of the schedule under work requirements.

Fig. 3 contains a family of curves that are useful in selecting the sensitive positions for full bridge placement of strain gages. Curve V.T. is the algebraic strain output for each gage on the outer wheel plate, from a 20-ton vertical load at angular wheel positions of 0°, 60°, 120°, 180°, 240° and 300°. L.T. is the curve resulting from the 15-ton lateral load, for each gage with the vertical load correction at 0°, 60°, 120°, 180°, 240° and 300°. L at 0° is the 15-ton lateral load for each gage with the wheel in the 0° position, and L at 180° with the wheel in the 180° position respectively. V at 0° is the strain output with 20-ton vertical load applied when the wheel is at 0° and V at 180° with the wheel at 180°. The radial axis of exploratory gages with the wheel at 180° is between the rail and roller bearing housing.

Referring to the V.T. curve at gage positions No. 3 and 8.85 they read -50 micro-in./in. These same positions located on the L.T. curve (15-ton lateral load summation of six angular wheel positions) yield +305 micro-in./in. at No. 3 and -355 micro-in./in at No. 8.85. If six strain gages are placed 60° apart radially at position No. 3 and at position No. 8.85, and wired into the Wheatstone bridge configuration of Fig. 4 we have zero output due to the vertical loading and 660 micro-in./in. output from the lateral loading. However, since three gages are used in each bridge leg, the total lateral strain is reduced by one third, resulting in 220 micro-in./in. To select the vertical sensitive position we find the point of intersection of curves L at 0° and L at 180° at position No. 7.35. V at 0° at this position reads +43 micro-in./in. and -225 micro-in./in. on the V at 180° curve. The vertical bridge configuration of Fig. 4 reveals a zero output from lateral loads but 2 (-225-(43)) = -536 micro-in./in. output from a 20-ton vertical load. Since a pair of gages are placed at gage position 7.35 and another pair 180° apart radially in adjacent legs of a Wheatstone bridge, we realize -536 micro-in./in. and +536 micro-in./in. spike signal outputs each wheel revolution. The additional vertical channel designated V_2 is not shown in Fig. 4. Gages 1 and 2 are located at 90° and gages 3 and 4 at 270°.

CALIBRATION OF FULLY ASSEMBLED TRUCK

A photographic target slide graduated in 30° sectors was focused on the outer plate of each wheel to mark the lateral radii of positions No. 3 and 8.85 as per Fig. 4. The vertical radii at position 7.35 were located at 0° and 180° for channel V_1 and at 90° and 270° for channel V_2. Twenty Micro-Measurement strain gages type EA-06-250AF-120 with option "W" were cemented to each wheel using "M-M" type AE-10 epoxy with room temperature curing. Photographs illustrating this technique of gage application have been submitted to Ensco Inc. representatives. Two iron-constantan thermocouples were soldered to the wheel as requested and are labeled (0° offset) and (180° offset). They are located adjacent to the strain gages of channel V_1. Scotchflex No. 700 adhesive backed "lo-profile" cable completed the bridge circuits as shown in Fig. 4.

The wheel set was returned to the test pad and subjected to 20 tons of vertical and 15 tons of lateral load. After confirmation of data, the remaining three wheels were strain gaged. The Barber S-2 truck was assembled employing a D-5 spring group consisting of seven outer, six inner springs having double side springs with friction blocks. The truck assembly was placed on the test pad and loaded dynamically for 20,000 cycles. The dynamic load varied between 20 K lb. to 160 K lb. This procedure was inaugurated to insure against friction block hang up during the static calibration loading.

Final calibration was performed in 5 K lb. increments of vertical and lateral loads. Tables 10 through 33 contain the strain readings and microstrain outputs for given loads, from which the strain output-wheel rotation curves were plotted for each wheel. These curves are shown in Figs. 6 through 9. The load column labeled Vertical Load K lb./Jack lists eight loadings from 10 K lb. to 80 K lb./jack. The 5 K lb./wheel relates to the first loading of 10 K lb./jack or a total of 20 K lb., resulting in 5 K lb./wheel. Included is the Lateral Load K lb. total, again the 5 K lb./wheel only relates to the first loading of 10 K lb., which is for two wheel sets. The column labeled Diff. Micro-in./in.is the change in strain from the zero reading appearing on the bottom and the reading opposite the load increment under the individual wheel channel columns.

An additional point of wheel/rail loading was introduced to determine variations in sensitivity. Track gage of the test pad was adjusted to 60 in. resulting in 1 3/4 in. off the taping line per wheel and loaded vertically in 10 K lb. increments. An average strain output of the four wheels was used for channels V_1 and V_2, and their curves are illustrated in Fig. 5.

In addition to load-strain calibrations each wheel set was rotated at a ground speed of 76 mph in a no-load condition. A variation in signal output was noted. This is probably due to centrifugal force(see references) and varies exponentially with the speed. The variation in signal output is shown in the Appendix.

References:

1. Rushing, F. C., "Determination of Stresses in Rotating Discs of Conical Profile," Trans. ASME, Vol. 53, p 91, 1931.
2. Hodkinson, B, "Rotating Discs of Conical Profile, Engineering, Vol. 115, p 1, 1923

R. J. Laskowski

Senior Electrical Engineer

Approved:

J. E. Britton

Manager of Tests

APPENDIX

TABLE 1

EXPLORATORY STRAIN DATA UNDER VERTICAL AND LATERAL WHEEL LOADINGS

WHEEL NO. 65584

GAGE NO.		VERTICAL LOAD IN K LBS/WHEEL 10		20		30		40		0° 0	LATERAL LOAD IN K LBS/WHEEL 10		20		30	
		RDG	DIFF	RDG	DIFF	RDG	DIFF	RDG	DIFF	RDG	RDG	DIFF	RDG	DIFF	RDG	DIFF
Outer Plate	1	1628	39	1650	61	1670	81	1706	117	1589	1572	- 17	1453	- 64	1394	-195
	2	2255	37	2284	66	2325	107	2368	150	2218	2142	- 76	2044	-126	1950	-268
	3	1678	38	1718	78	1760	120	1801	161	1640	1543	- 97	1439	-201	1328	-312
	4	1738	38	1780	80	1822	122	1865	165	1700	1602	- 98	1491	-209	1378	-322
	5	626	34	662	70	699	107	736	144	592	512	- 80	424	-168	339	-253
	6	2377	26	2402	51	2434	83	2456	105	2351	2305	- 46	2241	-110	2190	-161
	7	1424	12	1436	24	1451	39	1474	62	1412	1396	- 16	1368	- 44	1342	- 70
	8	199	-	204	05	216	17	212	13	199	196	- 03	197	- 02	205	06
	9	1848	01	1838	-09	1837	-10	1827	- 20	1847	1874	27	1896	49	1935	88
	10	1510	-11	1500	-21	1492	-29	1470	- 51	1521	1564	43	1611	90	1651	130
	11	1718	-15	1700	-33	1682	-51	1664	- 69	1733	1790	57	1840	107	1906	173
	12	1536	-22	1512	-46	1495	-63	1478	- 80	1558	1612	54	1677	119	1730	172
Inner Plate	13	916	-19	897	-38	880	-55	862	- 73	935	1007	72	1080	145	1148	207
	14	868	-18	844	-42	818	-68	804	- 82	886	972	86	1064	178	1142	256
	15	2200	-26	2168	-58	2137	-89	2106	-120	2226	2324	98	2430	204	2526	300
	16	1946	-27	1912	-61	1880	-93	1845	-128	1973	2078	105	2188	215	2290	317
	17	764	-24	734	-54	706	-82	676	-112	788	874	86	970	182	1056	268
	18	788	-20	766	-42	742	-66	718	- 90	808	874	66	948	140	1012	204
	19	2502	-14	2486	-30	2470	-46	2452	- 64	2516	2564	48	2616	100	2658	142
	20	1130	-07	1121	-16	1112	-25	1105	- 32	1137	1164	27	1193	56	1216	79
	21	770	-	768	-02	766	-04	764	- 06	770	776	06	782	12	786	16
	22	1272	07	1278	13	1286	21	1292	37	1265	1255	- 10	1242	- 23	1228	- 37
	23	1412	12	1425	25	1440	40	1454	54	1400	1374	- 26	1342	- 58	1312	- 88
	24	882	14	900	32	918	50	938	70	868	830	- 38	785	- 83	746	-122

DIFF Column expressed in microinches per inch.

TABLE 2

EXPLORATORY STRAIN DATA UNDER VERTICAL AND LATERAL WHEEL LOADINGS

WHEEL NO. 65584

30°

GAGE NO.		VERTICAL LOAD IN K LBS/WHEEL 10 RDG	DIFF	20 RDG	DIFF	30 RDG	DIFF	40 RDG	DIFF	0 RDG	LATERAL LOAD IN K LBS/WHEEL 10 RDG	DIFF	20 RDG	DIFF	30 RDG	DIFF
Outer Plate	1	1606	24	1630	48	1655	73	1680	98	1582	1530	-55	1457	-125	1396	-186
	2	2234	31	2265	62	2296	93	2327	124	2203	2135	-68	2039	-164	1957	-246
	3	1646	34	1682	70	1718	106	1754	142	1612	1534	-78	1424	-188	1333	-279
	4	1700	36	1736	72	1773	109	1811	147	1664	1586	-78	1480	-184	1386	-278
	5	604	30	637	63	670	96	702	128	574	513	-61	420	-154	342	-232
	6	2369	22	2395	48	2418	71	2443	96	2347	2306	-41	2240	-107	2184	-163
	7	1422	15	1434	27	1451	44	1468	64	1407	1390	-17	1351	- 56	1322	- 85
	8	200	06	204	10	210	16	215	21	194	198	04	186	- 08	180	- 14
	9	1846	-02	1843	-05	1840	-08	1837	- 11	1848	1871	23	1884	36	1898	50
	10	1508	-10	1500	-18	1490	-28	1480	- 38	1518	1552	34	1586	68	1620	102
	11	1727	-07	1708	-26	1695	-39	1682	- 52	1734	1840	106	1820	86	1860	126
	12	1544	-11	1530	-25	1511	-44	1498	- 57	1555	1646	91	1673	118	1701	146
Inner Plate	13	926	-12	908	-30	890	-48	876	- 62	938	1000	62	1070	132	1130	192
	14	874	-14	854	-34	832	-56	810	- 78	888	960	72	1044	156	1114	226
	15	2208	-22	2181	-49	2156	-74	2130	-100	2230	2310	80	2410	120	2497	267
	16	1958	-25	1930	-53	1901	-82	1875	-108	1983	2068	85	2170	187	2260	277
	17	774	-21	749	-46	724	-71	698	- 97	795	864	69	953	158	1032	237
	18	791	-18	770	-39	750	-59	730	- 79	809	864	55	934	125	996	187
	19	2502	-10	2486	-26	2472	-40	2456	- 56	2512	2554	42	2605	93	2648	136
	20	1129	-07	1121	-15	1113	-23	1105	- 31	1136	1161	25	1188	52	1214	78
	21	766	-	765	-01	764	-02	762	- 04	766	775	09	784	18	790	24
	22	1270	06	1274	10	1280	16	1287	23	1264	1258	-06	1250	-14	1240	- 24
	23	1411	11	1422	22	1433	33	1445	45	1400	1381	-19	1353	-47	1328	- 72
	24	882	12	895	25	913	43	928	58	870	843	-27	803	-67	768	-102

DIFF Column expressed in microinches per inch.

TABLE 3

EXPLORATORY STRAIN DATA UNDER VERTICAL AND LATERAL WHEEL LOADINGS

WHEEL NO. 65584

60°

GAGE NO.		VERTICAL LOAD IN K LBS/WHEEL									LATERAL LOAD IN K LBS/WHEEL						
		10		20		30		40		0	10		20		30	
		RDG	DIFF	RDG	DIFF	RDG	DIFF	RDG	DIFF	RDG	RDG	DIFF	RDG	DIFF	RDG	DIFF
Outer Plate	1	1598	18	1614	34	1631	51	1647	67	1580	1547	-33	1506	- 74	1471	-109
	2	2222	20	2244	42	2266	64	2288	86	2202	2155	-47	2098	-104	2051	-151
	3	1633	26	1657	50	1684	77	1710	103	1607	1553	-54	1485	-122	1430	-177
	4	1686	25	1712	51	1740	79	1768	107	1661	1604	-57	1535	-126	1478	-183
	5	594	22	620	48	644	72	670	98	572	520	-52	458	-114	406	-166
	6	2363	20	2383	40	2404	61	2423	80	2343	2310	-33	2260	- 83	2216	-127
	7	1420	16	1433	29	1450	46	1462	58	1404	1379	-25	1344	- 60	1313	- 91
	8	200	08	207	15	214	22	222	30	192	181	-11	165	- 27	148	- 44
	9	1848	02	1848	02	1850	04	1850	04	1846	1848	02	1848	02	1845	- 01
	10	1518	-02	1514	-06	1511	-09	1506	-14	1520	1530	10	1542	22	1546	26
	11	1730	-04	1725	-09	1719	-15	1712	-22	1734	1750	16	1765	31	1773	39
	12	1553	-07	1547	-13	1534	-26	1528	-32	1560	1580	20	1601	41	1610	50
Inner Plate	13	937	-07	927	-17	917	-27	908	-36	944	978	34	1018	74	1044	100
	14	881	-09	871	-19	858	-32	846	-44	890	933	43	981	91	1016	126
	15	2220	-14	2204	-30	2187	-47	2170	-64	2234	2280	46	2340	106	2383	149
	16	1970	-16	1954	-32	1935	-51	1917	-69	1986	2040	56	2101	115	2146	160
	17	784	-14	768	-30	751	-47	736	-62	798	844	46	894	96	936	138
	18	800	-10	786	-24	773	-37	759	-51	810	848	38	891	81	927	117
	19	2508	-07	2498	-17	2488	-27	2478	-37	2515	2545	30	2578	63	2606	91
	20	1134	-04	1126	-12	1122	-16	1115	-23	1138	1156	18	1180	42	1197	59
	21	768	-	768	-	766	-02	764	-04	768	775	07	784	16	792	24
	22	1270	03	1274	07	1277	10	1280	13	1267	1265	-02	1263	-04	1264	-03
	23	1410	06	1418	14	1425	21	1434	30	1404	1393	-11	1380	-24	1371	-33
	24	882	10	890	18	902	30	912	40	872	856	-16	834	-38	818	-54

DIFF Column expressed in microinches per inch.

TABLE 4

EXPLORATORY STRAIN DATA UNDER VERTICAL AND LATERAL WHEEL LOADINGS

WHEEL NO. 65584

90°

GAGE NO.		VERTICAL LOAD IN K LBS/WHEEL 10 RDG	DIFF	20 RDG	DIFF	30 RDG	DIFF	40 RDG	DIFF	0 RDG	LATERAL LOAD IN K LBS/WHEEL 10 RDG	DIFF	20 RDG	DIFF	30 RDG	DIFF
Outer Plate	1	1584	04	1589	09	1592	12	1595	15	1580	1586	06	1592	12	1604	24
	2	2208	06	2216	10	2220	14	2227	21	2202	2206	04	2210	08	2220	18
	3	1614	06	1626	18	1634	26	1644	36	1608	1604	-04	1604	-04	1608	-04
	4	1670	09	1680	19	1691	30	1702	41	1661	1654	-07	1650	-11	1651	-10
	5	580	11	592	23	604	35	617	48	569	560	-09	546	-23	539	-30
	6	2355	11	2366	22	2378	34	2392	48	2344	2326	-18	2309	-35	2291	-53
	7	1415	09	1427	21	1439	33	1451	45	1406	1384	-22	1354	-52	1327	-79
	8	198	07	208	17	216	25	226	35	191	173	-18	146	-45	122	-69
	9	1851	05	1857	11	1864	18	1868	22	1846	1831	-15	1807	-39	1786	-62
	10	1523	05	1526	08	1532	14	1534	16	1518	1507	-11	1483	-35	1460	-58
	11	1739	03	1745	09	1748	12	1750	14	1736	1718	-18	1691	-45	1663	-73
	12	1563	01	1564	02	1564	02	1568	04	1562	1551	-11	1527	-35	1502	-60
Inner Plate	13	945	01	949	05	950	06	950	06	944	934	-10	917	-27	895	-49
	14	892	02	892	02	894	04	894	04	890	884	-06	868	-22	845	-45
	15	2234	-	2234	-	2233	-01	2233	-01	2234	2225	-09	2208	-26	2185	-49
	16	1986	-02	1985	-03	1984	-04	1983	-05	1988	1981	-07	1968	-20	1946	-42
	17	797	-01	794	-04	793	-05	791	-07	798	797	-01	788	-10	775	-23
	18	807	-03	805	-05	804	-06	801	-09	810	813	03	810	-	803	-07
	19	2516	-	2514	-02	2513	-03	2510	-06	2516	2522	06	2523	07	2521	05
	20	1138	-01	1136	-03	1136	-03	1135	-04	1139	1146	07	1150	11	1152	13
	21	770	-	771	01	770	-	772	02	770	775	05	780	10	783	13
	22	1270	02	1272	04	1274	06	1277	09	1268	1273	05	1280	12	1286	18
	23	1407	05	1412	10	1416	14	1420	18	1402	1408	06	1412	10	1418	16
	24	876	02	882	08	886	12	891	17	874	877	03	880	06	882	08

DIFF Column expressed in microinches per inch.

TABLE 5

EXPLORATORY STRAIN DATA UNDER VERTICAL AND LATERAL WHEEL LOADINGS

WHEEL NO. 65584

120°

GAGE NO.		VERTICAL LOAD IN K LBS/WHEEL 10		20		30		40		0	LATERAL LOAD IN K LBS/WHEEL 10		20		30	
		RDG	DIFF	RDG	DIFF	RDG	DIFF	RDG	DIFF	RDG	RDG	DIFF	RDG	DIFF	RDG	DIFF
Outer Plate	1	1567	-15	1554	-28	1540	-42	1528	-54	1582	1635	53	1707	125	1778	196
	2	2189	-17	2172	-34	2154	-52	2138	-68	2206	2270	64	2356	150	2447	241
	3	1594	-20	1578	-36	1561	-53	1546	-68	1614	1678	64	1766	152	1856	242
	4	1647	-20	1630	-37	1612	-55	1598	-69	1667	1724	57	1806	139	1890	223
	5	560	-16	547	-29	536	-40	525	-51	576	612	36	666	90	722	146
	6	2339	-11	2334	-16	2326	-24	2320	-30	2350	2360	10	2380	30	2405	55
	7	1407	-03	1407	-03	1410	-	1411	01	1410	1394	-16	1379	-31	1369	- 41
	8	197	03	200	06	204	10	210	16	194	168	-26	135	-59	105	- 89
	9	1853	06	1860	13	1868	21	1875	28	1847	1812	-35	1766	-81	1722	-125
	10	1534	10	1542	18	1553	29	1566	42	1524	1482	-42	1417	-107	1363	-161
	11	1753	16	1766	29	1780	43	1795	58	1737	1690	-47	1615	-122	1550	-187
	12	1576	16	1603	43	1606	46	1620	60	1560	1508	-52	1441	-119	1380	-180
Inner Plate	13	954	12	968	26	981	39	994	52	942	874	-68	782	-160	692	-250
	14	906	16	923	33	941	51	960	70	890	813	-77	710	-180	605	-285
	15	2250	18	2270	38	2290	58	2310	78	2232	2142	-90	2026	-196	1907	-325
	16	2006	21	2028	43	2050	65	2072	87	1985	1898	-87	1781	-204	1664	-321
	17	816	20	834	38	853	57	872	76	796	727	-69	632	-164	535	-261
	18	824	15	838	29	855	46	870	61	809	758	-51	690	-119	616	-193
	19	2528	12	2540	24	2552	36	2564	48	2516	2482	-34	2434	-82	2384	-132
	20	1147	08	1154	15	1164	25	1172	33	1139	1122	-17	1096	-43	1068	- 71
	21	774	04	779	09	785	15	790	20	770	765	-05	756	-14	744	- 26
	22	1270	-02	1274	06	1278	10	1277	09	1268	1277	09	1281	13	1284	16
	23	1402	-04	1402	-04	1402	-04	1402	-04	1406	1418	12	1436	30	1452	46
	24	870	-06	868	-08	868	-08	865	-11	876	890	14	916	40	940	66

DIFF Column expressed in microinches per inch.

TABLE 6

EXPLORATORY STRAIN DATA UNDER VERTICAL AND LATERAL WHEEL LOADINGS

WHEEL NO. 65584

150°

GAGE NO.		VERTICAL LOAD IN K LBS/WHEEL									LATERAL LOAD IN K LBS/WHEEL						
		10		20		30		40		0	10		20		30	
		RDG	DIFF	RDG	DIFF	RDG	DIFF	RDG	DIFF	RDG	RDG	DIFF	RDG	DIFF	RDG	DIFF
Outer Plate	1	1548	-32	1512	- 68	1481	- 99	1446	-134	1580	1717	137	1808	228	1922	342
	2	2161	-45	2116	- 90	2071	-135	2028	-178	2206	2374	167	2492	286	2641	435
	3	1558	-54	1508	-104	1456	-156	1408	-204	1612	1786	174	1907	295	2063	451
	4	1603	-57	1550	-110	1492	-168	1436	-224	1660	1821	161	1936	276	2080	420
	5	516	-50	466	-100	412	-154	358	-208	566	676	110	758	192	862	296
	6	2300	-40	2257	- 83	2212	-128	2166	-174	2340	2388	44	2428	88	2483	143
	7	1375	-30	1348	- 57	1319	- 86	1290	-115	1405	1394	- 11	1397	- 08	1400	- 05
	8	174	-20	156	- 38	137	- 57	120	- 74	194	145	- 49	118	- 76	100	- 94
	9	1841	-05	1836	- 10	1830	- 16	1824	- 22	1846	1774	- 72	1729	-117	1675	-171
	10	1530	06	1536	12	1546	22	1554	30	1524	1433	- 91	1370	-154	1298	-226
	11	1772	32	1778	38	1797	57	1813	73	1740	1640	-100	1568	-172	1486	-256
	12	1611	43	1630	62	1647	79	1660	92	1568	1470	- 98	1397	-171	1314	-254
Inner Plate	13	970	32	982	40	1002	60	1014	72	942	763	- 79	643	-299	498	-444
	14	921	29	948	56	974	82	996	104	892	688	-204	550	-342	388	-504
	15	2270	32	2302	64	2334	96	2368	130	2238	2000	-238	1845	-393	1650	-588
	16	2030	39	2068	77	2105	114	2140	149	1991	1752	-239	1592	-399	1396	-595
	17	836	34	872	70	906	104	942	140	802	605	-197	470	-332	310	-492
	18	848	30	876	58	908	90	940	122	818	668	-150	563	-255	436	-382
	19	2546	23	2570	47	2596	73	2616	93	2523	2411	-112	2334	-189	2245	-278
	20	1158	16	1173	31	1187	45	1200	58	1142	1072	- 70	1020	-122	964	-178
	21	780	10	785	15	792	22	800	30	770	731	- 39	704	- 66	676	- 94
	22	1267	-01	1265	- 03	1260	- 08	1256	-12	1268	1254	- 14	1246	- 22	1240	- 28
	23	1391	-12	1380	- 23	1365	- 38	1352	-51	1403	1409	06	1418	15	1428	25
	24	854	-18	835	- 37	816	- 56	798	-74	872	890	18	912	40	934	62

DIFF Column expressed in microinches per inch.

TABLE 7

EXPLORATORY STRAIN DATA UNDER VERTICAL AND LATERAL WHEEL LOADINGS

WHEEL NO. 65584

180°

GAGE NO.		VERTICAL LOAD IN K LBS/WHEEL 10		20		30		40		0	LATERAL LOAD IN K LBS/WHEEL 10		20		30	
		RDG	DIFF	RDG	DIFF	RDG	DIFF	RDG	DIFF	RDG	RDG	DIFF	RDG	DIFF	RDG	DIFF
Outer Plate	1	1547	-41	1506	- 82	1466	-122	1428	-160	1588	1703	115	1850	262	1980	392
	2	2158	-58	2102	-114	2045	-171	1992	-224	2216	2358	142	2548	332	2719	503
	3	1552	-70	1482	-288	1414	-356	1349	-273	1622	1770	148	1966	344	2144	522
	4	1589	-77	1510	-156	1428	-238	1349	-317	1666	1793	127	1977	311	2143	477
	5	490	-54	406	-138	328	-216	232	-312	544	624	80	758	214	878	334
	6	2264	-57	2188	-133	2110	-211	2024	-297	2321	2346	45	2413	92	2476	155
	7	1340	-66	1278	-128	1218	-188	1160	-246	1406	1384	- 22	1391	- 15	1400	- 06
	8	139	-55	94	-100	50	-144	06	-188	194	136	- 58	98	- 96	68	-126
	9	1812	-33	1785	- 60	1758	- 87	1732	-113	1845	1772	- 73	1702	-143	1642	-203
	10	1506	-14	1494	- 26	1482	- 38	1469	- 51	1520	1434	- 86	1344	-176	1264	-256
	11	1732	-06	1732	- 06	1746	08	1740	02	1738	1656	- 82	1552	-186	1460	-278
	12	1574	14	1567	07	1574	14	1577	17	1560	1476	- 84	1372	-188	1288	-272
Inner Plate	13	948	12	958	22	972	36	986	50	936	770	-166	586	-250	420	-516
	14	902	14	924	36	948	60	968	80	888	698	-190	485	-403	291	-597
	15	2250	27	2280	57	2310	87	2338	115	2223	2005	-218	1762	-461	1538	-685
	16	2012	34	2048	70	2088	110	2118	140	1978	1762	-216	1507	-471	1280	-698
	17	826	30	860	64	891	95	928	132	796	615	-181	402	-394	214	-582
	18	838	25	866	53	892	79	925	112	813	671	-142	502	-311	352	-461
	19	2534	17	2555	38	2577	60	2596	79	2517	2406	-111	2282	-235	2174	-343
	20	1143	09	1154	20	1163	29	1170	36	1134	1058	- 76	974	-160	896	-238
	21	761	-03	756	- 08	748	- 16	743	- 21	764	708	- 56	658	-106	613	-151
	22	1242	-14	1220	- 46	1202	- 64	1179	- 87	1266	1228	- 38	1202	- 64	1184	- 82
	23	1360	-42	1321	- 81	1284	-118	1247	-155	1402	1376	- 26	1370	- 32	1370	- 32
	24	818	-46	768	- 96	720	-144	664	-200	864	845	- 21	857	- 07	868	04

DIFF Column expressed in microinches per inch.

TABLE 8

EXPLORATORY STRAIN DATA UNDER VERTICAL AND LATERAL WHEEL LOADINGS

WHEEL NO. 65584

240°

GAGE NO.		VERTICAL LOAD IN K LBS/WHEEL 10		20		30		40		0	LATERAL LOAD IN K LBS/WHEEL 10		20		30	
		RDG	DIFF	RDG	DIFF	RDG	DIFF	RDG	DIFF	RDG	RDG	DIFF	RDG	DIFF	RDG	DIFF
Outer Plate	1	1572	-13	1559	-26	1545	-40	1531	-54	1585	1634	49	1694	109	1742	157
	2	2200	-16	2182	-34	2165	-51	2148	-68	2216	2279	63	2353	137	2415	199
	3	1606	-19	1587	-48	1568	-57	1550	-75	1625	1690	65	1772	147	1836	211
	4	1652	-18	1635	-35	1619	-51	1602	-68	1670	1728	58	1796	126	1853	183
	5	538	-12	526	-24	514	-36	504	-46	550	590	40	636	86	673	123
	6	2326	-04	2319	-11	2314	-16	2310	-20	2330	2344	14	2361	31	2371	41
	7	1414	-02	1411	-05	1412	-04	1408	-08	1416	1412	-04	1406	- 10	1400	- 16
	8	210	07	214	11	219	16	224	21	203	176	-27	146	- 57	116	- 87
	9	1863	09	1874	20	1883	29	1894	40	1854	1816	-38	1767	- 87	1725	-129
	10	1540	12	1552	24	1562	34	1577	49	1528	1484	-44	1426	-102	1387	-141
	11	1752	08	1764	20	1774	30	1786	42	1744	1704	-40	1646	- 98	1601	-143
	12	1582	16	1590	24	1604	38	1621	55	1566	1520	-46	1469	- 97	1422	-144
Inner Plate	13	960	19	973	32	978	37	992	51	941	890	-51	808	-133	750	-191
	14	911	21	926	36	941	51	960	70	890	828	-62	738	-152	674	-226
	15	2248	14	2266	32	2286	52	2306	72	2234	2150	-84	2056	-178	1980	-254
	16	2018	32	2026	40	2044	58	2064	78	1986	1905	-81	1810	-176	1736	-250
	17	820	16	836	32	853	49	870	66	804	740	-64	662	-142	601	-203
	18	834	15	848	29	860	41	876	57	819	772	-47	716	-103	673	-146
	19	2530	11	2542	13	2554	35	2565	46	2519	2490	-29	2450	- 69	2426	- 93
	20	1150	13	1154	17	1160	23	1170	33	1137	1123	-14	1104	- 33	1090	- 47
	21	775	03	775	03	780	08	788	16	772	766	-06	762	- 10	760	- 12
	22	1274	0	1276	02	1278	04	1283	09	1274	1280	06	1288	14	1294	20
	23	1414	03	1410	-01	1408	-03	1410	-01	1411	1424	13	1444	33	1455	44
	24	872	-04	870	-07	868	-08	868	-08	876	890	14	915	39	936	60

DIFF Column expressed in microinches per inch.

TABLE 9

EXPLORATORY STRAIN DATA UNDER VERTICAL AND LATERAL WHEEL LOADINGS

WHEEL NO. 65584

300°

GAGE NO.		VERTICAL LOAD IN K LBS/WHEEL 10		20		30		40		0	LATERAL LOAD IN K LBS/WHEEL 10		20		30	
		RDG	DIFF	RDG	DIFF	RDG	DIFF	RDG	DIFF	RDG	RDG	DIFF	RDG	DIFF	RDG	DIFF
Outer Plate	1	1610	19	1626	35	1644	53	1663	72	1591	1551	-40	1500	- 91	1455	-136
	2	2245	24	2266	45	2290	69	2312	91	2221	2168	-53	2102	-119	2042	-176
	3	1654	26	1680	52	1706	68	1731	103	1628	1572	-56	1498	-130	1432	-193
	4	1702	31	1728	57	1757	86	1784	113	1671	1612	-59	1534	-137	1464	-205
	5	580	26	606	52	630	76	656	102	554	502	-52	434	-120	375	-175
	6	2354	21	2375	42	2395	62	2414	81	2333	2294	-39	2244	- 89	2198	-132
	7	1431	14	1444	27	1456	39	1470	53	1417	1397	-20	1370	- 47	1345	- 70
	8	213	09	220	16	228	24	234	30	204	195	- 9	181	- 23	169	- 33
	9	1856	02	1858	04	1860	06	1861	07	1854	1856	02	1858	04	1860	06
	10	1535	05	1535	05	1520	-10	1518	- 12	1530	1546	16	1562	32	1573	43
	11	1734	-08	1725	-17	1717	-25	1708	- 34	1742	1770	28	1802	60	1816	76
	12	1600	28	1554	-18	1547	-25	1529	- 43	1572	1596	24	1622	50	1655	72
Inner Plate	13	944	-04	931	-17	927	-21	905	- 43	948	1000	52	1045	97	1082	136
	14	893	-01	876	-18	861	-33	845	- 49	894	950	56	1015	121	1064	166
	15	2231	-03	2207	-27	2189	-45	2170	- 64	2234	2300	66	2368	134	2430	190
	16	1976	-14	1956	-34	1934	-56	1914	- 76	1990	2057	67	2182	142	2196	204
	17	796	-14	778	-32	758	-52	737	- 73	810	865	55	930	120	988	178
	18	817	-09	802	-24	785	-41	767	- 59	826	872	46	928	102	973	147
	19	2519	-06	2512	-13	2496	-29	2484	- 41	2525	2564	39	2602	77	2637	113
	20	1144	-02	1138	-08	1128	-18	1119	- 27	1146	1167	21	1194	48	1216	71
	21	778	01	777	-	773	-04	768	- 09	777	788	11	804	27	812	37
	22	1286	08	1294	16	1294	16	1291	13	1278	1278	-	1278	-	1272	- 08
	23	1432	14	1446	28	1440	22	1450	32	1418	1404	-14	1388	- 30	1372	- 44
	24	892	14	910	32	913	35	922	44	878	860	-18	835	- 43	812	- 65

DIFF Column expressed in microinches per inch.

TABLE 10
CALIBRATION DATA
FULLY ASSEMBLED BARBER S-2 TRUCK WITH TWO WHEEL SETS

	WHEEL 65594 @ 0°						WHEEL 65495 @ 0°					
Vertical Load K lbs./Jack (5K Lbs./Wheel)	Channel 0°+ V1 180°- Reading	Diff. Micro "/"	Channel 90°- V2 270°+ Reading	Diff. Micro "/"	Chan. Lat. Rdg.	Diff. Micro "/"	Channel 0°+ V1 180°- Reading	Diff. Micro "/"	Channel 90°+ V2 270°+ Reading	Diff. Micro "/"	Chan. Lat. Rdg.	Diff. Micro "/"
10	-4299	77	-2924	02	-6041	- 02	-3881	75	-2867	- 03	-6044	- 08
20	-4231	145	-2922	04	-6045	- 06	-3816	140	-2870	- 06	-6048	- 12
30	-4165	211	-2921	05	-6046	- 07	-3750	206	-2874	- 10	-6050	- 14
40	-4100	276	-2921	05	-6048	- 09	-3684	272	-2878	- 14	-6052	- 16
50	-4034	342	-2922	04	-6050	- 11	-3620	336	-2881	- 17	-6056	- 20
60	-3969	407	-2922	04	-6051	- 12	-3555	401	-2885	- 21	-6059	- 23
70	-3905	471	-2922	04	-6053	- 14	-3488	468	-2888	- 24	-6061	- 25
80	-3848	526	-2922	04	-6054	- 15	-3430	526	-2891	- 27	-6063	- 27
Lateral Load K lbs. Total (5K Lbs./Wheel) + 10K Vertical												
10	-4315	61	-2924	02	-6000	39	-3896	60	-2860	04	-6000	36
20	-4328	48	-2922	04	-5952	87	-3908	48	-2850	14	-5952	84
30	-4338	38	-2920	06	-5912	127	-3914	42	-2842	22	-5910	126
40	-4350	26	-2922	04	-5866	173	-3921	35	-2834	30	-5868	168
50	-4362	14	-2923	03	-5825	214	-3978	28	-2826	38	-5827	209
60	-4375	-	-2921	05	-5783	256	-3936	20	-2818	46	-5785	251
0	-4376		-2926		-6039		-3956		-2864		-6036	

TABLE 11
CALIBRATION DATA
FULLY ASSEMBLED BARBER S-2 TRUCK WITH TWO WHEEL SETS

	WHEEL 65594 @ 30°						WHEEL 65495 @ 30°					
Vertical Load K lbs./Jack (5K Lbs./Wheel)	Channel 0°+ V1 180°- Reading	Diff. Micro "/"	Channel 90°- V2 270°+ Reading	Diff. Micro "/"	Chan. Lat. Rdg.	Diff. Micro "/"	Channel 0°+ V1 180°- Reading	Diff. Micro "/"	Channel 90°+ V2 270°+ Reading	Diff. Micro "/"	Chan. Lat. Rdg.	Diff. Micro "/"
10	-4361	39	-2938	- 10	-6044	- 02	-3930	44	-2882	- 10	-6044	- 08
20	-4326	74	-2948	- 20	-6047	- 05	-3892	82	-2892	- 20	-6045	- 09
30	-4294	106	-2961	- 33	-6050	- 08	-3852	122	-2904	- 32	-6047	- 11
40	-4260	140	-2972	- 44	-6050	- 08	-3814	160	-2912	- 40	-6049	- 13
50	-4227	173	-2984	- 56	-6052	- 10	-3777	197	-2924	- 52	-6050	- 14
60	-4193	207	-2996	- 68	-6053	- 11	-3738	236	-2934	- 62	-6053	- 17
70	-4160	240	-3007	- 79	-6055	- 13	-3700	274	-2945	- 73	-6052	- 16
80	-4128	272	-3018	- 90	-6056	- 14	-3662	312	-2954	- 82	-6053	- 17
Lateral Load K lbs. Total (5K Lbs./Wheel) + 10K Vertical												
10	-4378	22	-2930	- 02	-5999	43	-3942	32	-2868	04	-5999	37
20	-4387	13	-2926	02	-5967	75	-3950	24	-2857	15	-5960	76
30	-4398	02	-2916	12	-5918	124	-3960	14	-2844	28	-5914	122
40	-4410	-10	-2908	20	-5874	168	-3968	06	-2834	38	-5878	158
50	-4422	-22	-2900	28	-5830	212	-3974	-	-2826	46	-5840	196
60	-4433	-33	-2895	33	-5794	248	-3980	- 06	-2818	54	-5800	236
0	-4400		-2928		-6042		-3974		-2872		-6036	

TABLE 12
CALIBRATION DATA
FULLY ASSEMBLED BARBER S-2 TRUCK WITH TWO WHEEL SETS

	WHEEL 65594 @ 60°						WHEEL 65495 @ 60°					
Vertical Load K lbs./Jack (5K Lbs./Wheel)	Channel 0°+ V1 180°- Reading	Diff. Micro "/"	Channel 90°- V2 270°+ Reading	Diff. Micro "/"	Chan. Lat. Rdg.	Diff. Micro "/"	Channel 0°+ V1 180°- Reading	Diff. Micro "/"	Channel 90°+ V2 270°+ Reading	Diff. Micro "/"	Chan. Lat. Rdg.	Diff. Micro "/"
10	-4385	15	-2974	- 44	-6046	- 06	-3985	- 11	-2931	- 41	-6044	- 06
20	-4376	24	-3012	- 82	-6049	- 09	-3995	- 21	-2970	- 80	-6045	- 07
30	-4366	34	-3042	-112	-6052	- 12	-4007	- 33	-3009	-119	-6047	- 09
40	-4355	45	-3074	-144	-6054	- 14	-4018	- 44	-3048	-158	-6048	- 10
50	-4344	56	-3116	-186	-6057	- 17	-4030	- 56	-3087	-197	-6050	- 12
60	-4335	65	-3164	-234	-6060	- 20	-4040	- 66	-3126	-236	-6052	- 14
70	-4326	74	-3203	-273	-6063	- 23	-4050	- 76	-3164	-274	-6053	- 15
80	-4317	83	-3237	-307	-6026	- 26	-4060	- 86	-3200	-310	-6054	- 16
Lateral Load K lbs. Total (5K Lbs./Wheel) + 10K Vertical												
10	-4387	13	-2966	- 36	-5997	43	-3965	09	-2915	- 25	-6001	37
20	-4391	09	-2960	- 30	-5956	84	-3968	06	-2901	- 11	-5959	79
30	-4395	05	-2955	- 25	-5904	136	-3972	02	-2891	- 01	-5916	122
40	-4399	01	-2952	- 22	-5866	174	3973	01	-2878	12	-5878	160
50	-4406	-06	-2942	- 12	-5829	211	3978	- 04	-2860	30	-5837	201
60	-4410	-10	-2938	- 08	-5790	250	3982	- 08	-2849	41	-5793	245
0	-4400		-2930		-6040		-3974		-2890		-6038	

TABLE 13
CALIBRATION DATA
FULLY ASSEMBLED BARBER S-2 TRUCK WITH TWO WHEEL SETS

	WHEEL 65594 @ 90^0						WHEEL 65495 @ 90^0					
Vertical Load K lbs./Jack (5K Lbs./Wheel)	Channel 0^0+ V1 180^0- Reading	Diff. Micro "/"	Channel 90^0- V2 270^0+ Reading	Diff. Micro "/"	Chan. Lat. Rdg.	Diff. Micro "/"	Channel 0^0+ V1 180^0- Reading	Diff. Micro "/"	Channel 90^0+ V2 270^0+ Reading	Diff. Micro "/"	Chan. Lat. Rdg.	Diff. Micro "/"
10	-4397	04	-3030	- 75	-6042	- 04	-3977	- 03	2964	- 70	-6042	- 09
20	-4398	03	-3099	-144	-6046	- 08	-3978	- 04	3030	-136	-6044	- 06
30	-4398	03	-3165	-210	-6048	- 10	-3980	- 06	3096	-202	-6045	- 07
40	-4398	03	-3232	-277	-6050	- 12	-3980	- 06	3160	-266	-6046	- 08
50	-4399	02	-3300	-345	-6052	- 14	-3982	- 08	3227	-233	-6048	- 10
60	-4400	01	-3368	-413	-6055	- 17	-3984	- 10	3294	-300	-6051	- 13
70	-4401	02	-3433	-478	-6057	- 19	-3986	- 12	3359	-365	-6052	- 14
80	-4401	01	-3492	-537	-6058	- 20	-3986	- 12	3416	-522	-6054	- 16
Lateral Load K lbs. Total (5K Lbs./Wheel) + 10K Vertical												
10	-4396	04	-3026	- 71	-5994	44	-3970	04	-2957	- 63	-6001	37
20	-4394	06	-3019	- 64	-5951	81	-3965	09	-2950	- 56	-5956	82
30	-4392	08	-3014	- 59	-5904	134	-3962	12	-2944	- 50	-5916	122
40	-4389	11	-3008	- 53	-5854	184	-3958	16	-2940	- 46	-5877	161
50	-4390	10	-3000	- 45	-5807	231	-3954	20	-2934	- 40	-5831	207
60	-4386	14	-3000	- 45	-5767	271	-3952	22	-2930	- 36	-5789	249
0	-4400		-2955		-6038		-3974		-2894		-6038	

TABLE 14
CALIBRATION DATA
FULLY ASSEMBLED BARBER S-2 TRUCK WITH TWO WHEEL SETS

	WHEEL 65594 @ 120°						WHEEL 65495 @ 120°					
Vertical Load K lbs./Jack (5K Lbs./Wheel)	Channel 0°+ V1 180°- Reading	Diff. Micro "/"	Channel 90°- V2 270°+ Reading	Diff. Micro "/"	Chan. Lat. Rdg.	Diff. Micro "/"	Channel 0°+ V1 180°- Reading	Diff. Micro "/"	Channel 90°+ V2 270°+ Reading	Diff. Micro "/"	Chan. Lat. Rdg.	Diff. Micro "/"
10	-4421	- 11	-2970	- 40	-6041	- 01	-3987	- 12	-2919	- 39	-6039	- 01
20	-4431	- 21	-3009	- 79	-6043	- 03	-3997	- 22	-2958	- 78	-6041	- 03
30	-4441	- 31	-3048	-118	-6044	- 04	-4008	- 33	-2998	-118	-6042	- 04
40	-4451	- 41	-3088	-158	-6047	- 07	-4019	- 44	-3036	-156	-6045	- 07
50	-4462	- 52	-3126	-196	-6049	- 09	-4029	- 54	-3076	-196	-6047	- 09
60	-4472	- 62	-3158	-228	-6050	- 10	-4042	- 67	-3114	-234	-6052	- 14
70	-4481	- 71	-3197	-267	-6049	- 09	-4053	- 78	-3153	-273	-6053	- 15
80	-4493	- 83	-3247	-317	-6049	- 09	-4062	- 87	-3189	-309	-6055	- 17
Lateral Load K lbs. Total (5K Lbs./Wheel) + 10K Vertical												
10	-4429	- 19	-2962	- 32	-6005	35	-3995	- 20	-2908	- 28	-6003	35
20	-4417	- 07	-2960	- 30	-5957	83	-3986	- 11	-2897	- 17	-5962	76
30	-4412	- 02	-2959	- 29	-5910	130	-3977	- 02	-2888	- 08	-5918	120
40	-4402	08	-2954	- 24	-5861	179	-3968	07	-2880	-	-5879	159
50	-4394	16	-2950	- 20	-5825	225	-3959	16	-2873	07	-5836	202
60	-4381	29	-2948	- 18	-5775	265	-3949	26	-2867	13	-5793	245
0	-4410		-2930		-6040		-3975		-2880		-6038	

TABLE 15
CALIBRATION DATA
FULLY ASSEMBLED BARBER S-2 TRUCK WITH TWO WHEEL SETS

	WHEEL 65594 @ 150°						WHEEL 65495 @ 150°					
Vertical Load K lbs./Jack (5K Lbs./Wheel)	Channel 0°+ V1 180°- Reading	Diff. Micro "/"	Channel 90°- V2 270°+ Reading	Diff. Micro "/"	Chan. Lat. Rdg.	Diff. Micro "/"	Channel 0°+ V1 180°- Reading	Diff. Micro "/"	Channel 90°+ V2 270°+ Reading	Diff. Micro "/"	Chan. Lat. Rdg.	Diff. Micro "/"
10	-4459	- 45	-2930	- 06	-6039	01	-4029	- 45	-2871	- 04	-6041	- 01
20	-4500	- 86	-2938	- 14	-6043	- 03	-4065	- 81	-2878	- 11	-6043	- 03
30	-4538	- 124	-2946	- 22	-6046	- 06	-4102	-118	-2885	- 18	-6046	- 06
40	-4578	- 164	-2954	- 30	-6048	- 08	-4140	-156	-2892	- 25	-6047	- 07
50	-4618	- 204	-2962	- 38	-6050	- 10	-4176	-192	-2898	- 31	-6049	- 09
60	-4658	- 244	-2972	- 48	-6054	- 14	-4215	-231	-2908	- 41	-6054	- 14
70	-4698	- 284	-2979	- 55	-6057	- 17	-4252	-268	-2914	- 47	-6056	- 16
80	-4734	- 320	-2987	- 63	-6058	- 18	-4285	-301	-2920	- 53	-6058	- 18
Lateral Load K lbs. Total (5K Lbs./Wheel) + 10K Vertical												
10	-4446	- 32	-2929	- 05	-6002	38	-4013	- 29	-2876	- 09	-6004	36
20	-4431	- 17	-2928	- 04	-5954	86	-3997	- 13	-2878	- 11	-5957	83
30	-4416	- 02	-2924	-	-5908	132	-3982	02	-2880	- 13	-5915	125
40	-4398	16	-2920	04	-5856	184	-3969	15	-2882	- 15	-5876	164
50	-4382	32	-2919	03	-5806	234	-3954	30	-2884	- 17	-5830	210
60	-4370	44	-2918	06	-5768	272	-3940	44	-2888	-21	-5784	256
0	-4414		-2924		-6040		-3984		-2867		-6040	

TABLE 16

CALIBRATION DATA

FULLY ASSEMBLED BARBER S-2 TRUCK WITH TWO WHEEL SETS

	WHEEL 65594 @ 180°						WHEEL 65495 @ 180°					
Vertical Load K lbs./Jack (5K Lbs./Wheel)	Channel 0°+ V1 180°- Reading	Diff. Micro "/"	Channel 90°- V2 270°+ Reading	Diff. Micro "/"	Chan. Lat. Rdg.	Diff. Micro "/"	Channel 0°+ V1 180°- Reading	Diff. Micro "/"	Channel 90°+ V2 270°+ Reading	Diff. Micro "/"	Chan. Lat. Rdg.	Diff. Micro "/"
10	-4495	- 70	-2924	- 04	-6042	- 02	-4065	- 69	-2862	01	-6048	- 07
20	-4562	-137	-2922	- 02	-6047	- 07	-4133	-137	-2861	02	-6052	- 11
30	-4630	-205	-2920	-	-6052	- 12	-4200	-204	-2859	04	-6055	- 14
40	-4698	-273	-2918	02	-6054	- 14	-4266	-270	-2858	05	-6060	- 19
50	-4764	-339	-2918	02	-6059	- 19	-4334	-338	-2855	08	-6063	- 22
60	-4828	-403	-2916	04	-6062	- 22	-4401	-405	-2853	10	-6067	- 26
70	-4892	-467	-2915	05	-6064	- 24	-4468	-472	-2851	12	-6070	- 29
80	-4952	-524	-2914	06	-6068	- 28	-4530	-536	-2850	13	-6072	- 31
Lateral Load K lbs. Total (5K Lbs./Wheel) + 10K Vertical												
10	-4495	- 70	-2922	- 02	-6006	34	-4059	- 63	-2872	- 09	-6005	36
20	-4481	- 56	-2924	- 04	-5959	81	-4046	- 50	-2878	- 15	-5961	80
30	-4471	- 46	-2929	- 09	-5910	130	-4038	- 42	-2886	- 23	-5918	123
40	-4460	- 35	-2930	- 10	-5860	180	-4030	- 34	-2891	- 28	-5879	162
50	-4450	- 25	-2932	- 12	-5815	225	-4024	- 28	-2897	- 34	-5835	206
60	-4440	- 15	-2932	- 12	-5772	268	-4017	- 21	-2901	- 38	-5795	246
0	-4425		-2920		-6040		-3996		-2863		-6041	

TABLE 17 -

CALIBRATION DATA

FULLY ASSEMBLED BARBER S-2 TRUCK WITH TWO WHEEL SETS

	WHEEL 65594 @ 210°						WHEEL 65495 @ 210°					
Vertical Load K lbs./Jack (5K Lbs./Wheel)	Channel 0°+ V1 180°- Reading	Diff. Micro "/"	Channel 90°- V2 270°+ Reading	Diff. Micro "/"	Chan. Lat. Rdg.	Diff. Micro "/"	Channel 0°+ V1 180°- Reading	Diff. Micro "/"	Channel 90°+ V2 270°+ Reading	Diff. Micro "/"	Chan. Lat. Rdg.	Diff. Micro "/"
10	-4441	- 33	-2906	11	-6038	- 01	-4020	- 36	-2850	12	-6038	- 01
20	-4475	- 67	-2895	22	-6041	- 04	-4056	- 72	-2840	22	-6041	- 04
30	-4507	- 99	-2885	32	-6042	- 06	-4092	-108	-2828	34	-6042	- 05
40	-4538	-130	-2872	45	-6042	- 05	-4130	-146	-2818	44	-6042	- 05
50	-4572	-164	-2864	53	-6046	- 09	-4166	-182	-2809	53	-6046	- 09
60	-4604	-196	-2852	65	-6047	- 10	-4202	-218	-2797	65	-6045	- 08
70	-4634	-226	-2841	76	-6046	- 09	-4240	-256	-2786	76	-6046	- 09
80	-4666	-258	-2831	86	-6046	- 09	-4273	-289	-2778	84	-6046	- 09
Lateral Load K lbs. Total (5K Lbs./Wheel) + 10K Vertical												
10	-4432	- 24	-2914	03	-6002	35	-4014	- 30	-2862	-	-6002	35
20	-4416	- 08	-2924	- 07	-5953	84	-4001	- 17	-2874	-12	-5956	81
30	-4404	04	-2933	- 16	-5906	131	-3993	- 09	-2886	-24	-5915	122
40	-4392	16	-2942	- 25	-5860	177	-3986	- 02	-2895	-33	-5882	155
50	-4380	28	-2950	- 33	-5812	225	-3978	06	-2905	-41	-5839	198
60	-4370	38	-2955	- 38	-5775	262	-3972	12	-2914	-52	-5795	242
0	-4408		-2917		-6037		-3984		-2862		-6037	

TABLE 18

CALIBRATION DATA

FULLY ASSEMBLED BARBER S-2 TRUCK WITH TWO WHEEL SETS

	WHEEL 65594 @ 240°						WHEEL 65495 @ 240°					
Vertical Load K lbs./Jack (5K Lbs./Wheel)	Channel 0°+ V1 180°- Reading	Diff. Micro "/"	Channel 90°- V2 270°+ Reading	Diff. Micro "/"	Chan. Lat. Rdg.	Diff. Micro "/"	Channel 0°+ V1 180°- Reading	Diff. Micro "/"	Channel 90°+ V2 270°+ Reading	Diff. Micro "/"	Chan. Lat. Rdg.	Diff. Micro "/"
10	-4408	- 10	-2866	42	-6042	- 03	-3979	- 08	-2816	40	-6040	- 01
20	-4418	- 20	-2829	79	-6047	- 08	-3989	- 18	-2781	75	-6044	- 05
30	-4425	- 27	-2793	115	-6049	- 10	-3998	- 27	-2746	110	-6046	- 07
40	-4434	- 36	-2756	152	-6054	- 15	-4006	- 35	-2710	146	-6049	- 10
50	-4442	- 44	-2718	190	-6056	- 17	-4016	- 45	-2676	180	-6051	- 12
60	-4450	- 52	-2680	228	-6059	- 20	-4024	- 53	-2640	216	-6054	- 15
70	-4460	- 62	-2642	266	-6060	- 21	-4031	- 60	-2605	251	-6057	- 18
80	-4469	- 71	-2606	302	-6064	- 25	-4042	- 71	-2570	286	-6059	- 20
Lateral Load K lbs. Total (5K Lbs./Wheel) + 10K Vertical												
10	-4398	-	-2884	24	-6006	33	-3980	- 09	-2830	26	-6000	- 39
20	-4392	06	-2895	13	-5960	79	-3977	- 06	-2844	12	-5960	79
30	-4386	12	-2912	-04	-5915	124	-3974	- 03	-2856	-	-5920	119
40	-4378	20	-2928	- 20	-5870	169	-3972	- 01	-2868	- 12	-5884	155
50	-4370	28	-2942	- 34	-5826	213	-3968	03	-2884	- 28	-5842	197
60	-4364	34	-2956	- 48	-5786	253	-3966	05	-2898	- 42	-5800	239
0	-4398		-2908		-6039		-3971		-2856		-6039	

TABLE 19
CALIBRATION DATA
FULLY ASSEMBLED BARBER S-2 TRUCK WITH TWO WHEEL SETS

	WHEEL 65594 @ 270°						WHEEL 65495 @ 270°					
Vertical Load K lbs./Jack (5K Lbs./Wheel)	Channel 0°+ V1 180°- Reading	Diff. Micro "/"	Channel 90°- V2 270°+ Reading	Diff. Micro "/"	Chan. Lat. Rdg.	Diff. Micro "/"	Channel 0°+ V1 180°- Reading	Diff. Micro "/"	Channel 90°+ V2 270°+ Reading	Diff. Micro "/"	Chan. Lat. Rdg.	Diff. Micro "/"
10	-4395	02	-2820	71	-6035	03	-3964	08	-2769	70	-6038	- 06
20	-4395	02	-2754	137	-6038	-	-3963	09	-2702	137	-6042	- 10
30	-4394	03	-2687	204	-6040	-02	-3963	09	-2635	204	-6043	- 11
40	-4394	03	-2618	273	-6040	-02	-3961	11	-2568	271	-6044	- 12
50	-4392	05	-2550	341	-6042	-04	-3961	11	-2502	337	-6044	- 12
60	-4392	05	-2484	407	-6042	-04	-3960	12	-2435	404	-6046	- 14
70	-4391	06	-2420	471	-6042	-04	-3960	12	-2370	470	-6047	- 15
80	-4392	05	-2358	533	-6044	-06	-3959	13	-2306	534	-6048	- 16
Lateral Load K lbs. Total (5K Lbs./Wheel) + 10K Vertical												
10	-4398	01	-2832	59	-5993	45	-3975	-03	-2775	64	-5993	- 39
20	-4397	-	-2845	46	-5960	78	-3979	-07	-2786	53	-5950	82
30	-4396	01	-2857	34	-5917	121	-3982	-10	-2794	45	-5913	119
40	-4394	03	-2872	19	-5874	164	-3987	-15	-2800	39	-5874	158
50	-4394	03	-2882	09	-5834	204	-3988	-16	-2806	33	-5834	198
60	-4391	06	-2894	-03	-5792	246	-3990	-18	-2814	25	-5792	240
0	-4397		-2891		-6038		-3972		-2839		-6032	

TABLE 20

CALIBRATION DATA

FULLY ASSEMBLED BARBER S-2 TRUCK WITH TWO WHEEL SETS

	WHEEL 65594 @ 300°						WHEEL 65495 @ 300°					
Vertical Load K lbs./Jack (5K Lbs./Wheel)	Channel 0°+ V1 180°- Reading	Diff. Micro "/"	Channel 90°- V2 270°+ Reading	Diff. Micro "/"	Chan. Lat. Rdg.	Diff. Micro "/"	Channel 0°+ V1 180°- Reading	Diff. Micro "/"	Channel 90°+ V2 270°+ Reading	Diff. Micro "/"	Chan. Lat. Rdg.	Diff. Micro "/"
10	-4371	39	-2919	11	-6041	- 01	-3937	38	-2868	12	-6039	- 01
20	-4331	79	-2909	21	-6045	- 05	-3900	75	-2857	23	-6041	- 03
30	-4293	117	-2900	30	-6048	- 08	-3862	113	-2845	35	-6043	- 05
40	-4254	156	-2888	42	-6049	- 09	-3824	151	-2834	46	-6044	- 06
50	-4216	194	-2878	52	-6051	- 11	-3786	189	-2824	56	-6046	- 08
60	-4176	234	-2867	63	-6054	- 14	-3749	226	-2812	68	-6048	- 10
70	-4138	272	-2856	74	-6056	- 16	-3711	264	-2801	79	-6050	- 12
80	-4100	310	-2846	84	-6058	- 18	-3674	301	-2784	96	-6052	- 14
Lateral Load K lbs. Total (5K Lbs./Wheel) + 10K Vertical												
10	-4390	20	-2906	24	-6012	38	-3978	-03	-2909	- 29	-6003	35
20	-4401	09	-2918	12	-5957	83	-3989	-14	-2898	- 18	-6064	74
30	-4408	02	-2930	-	-5909	131	-4001	-26	-2888	- 08	-6020	118
40	-4417	-07	-2939	-09	-5862	178	-4008	- 33	-2881	- 01	-5977	161
50	-4432	-22	-2947	-17	-5820	220	-4015	- 40	-2872	08	-5938	200
60	-4446	-36	-2950	-20	-5782	258	-4022	- 47	-2869	11	-5898	240
0	-4410		-2930		-6040		-3975		-2880		-6038	

TABLE 21
CALIBRATION DATA
FULLY ASSEMBLED BARBER S-2 TRUCK WITH TWO WHEEL SETS

	WHEEL 65594 @ 330°						WHEEL 65495 @ 330°					
Vertical Load K lbs./Jack (5K Lbs./Wheel)	Channel 0°+ V1 180°- Reading	Diff. Micro "/"	Channel 90°- V2 270°+ Reading	Diff. Micro "/"	Chan. Lat. Rdg.	Diff. Micro "/"	Channel 0°+ V1 180°- Reading	Diff. Micro "/"	Channel 90°+ V2 270°+ Reading	Diff. Micro "/"	Chan. Lat. Rdg.	Diff. Micro "/"
10	-4352	44	-2913	10	-6034	01	-3936	42	-2859	08	-6034	- 04
20	-4312	84	-2904	19	-6035	-	-3903	75	-2849	18	-6035	- 05
30	-4276	120	-2895	28	-6036	-01	-3872	106	-2841	26	-6036	- 06
40	-4239	157	-2887	36	-6036	-01	-3838	140	-2832	35	-6038	- 08
50	-4200	196	-2878	45	-6036	-01	-3806	172	-2824	43	-6038	- 08
60	-4164	232	-2871	52	-6035	-	-3773	205	-2815	52	-6040	- 10
70	-4129	267	-2862	61	-6035	-	-3739	239	-2806	61	-6042	- 12
80	-4092	304	-2853	70	-6035	-	-3710	268	-2798	69	-6042	- 12
Lateral Load K lbs. Total (5K Lbs./Wheel) + 10K Vertical												
10	-4366	30	-2921	02	-5999	36	-3954	24	-2856	11	-5990	40
20	-4376	20	-2925	-02	-5960	75	-3964	14	-2857	10	-5954	76
30	-4389	07	-2932	- 09	-5918	117	-3977	01	-2858	09	-5910	120
40	-4403	-07	-2938	- 15	-5872	163	-3989	- 11	-2859	08	-5872	158
50	-4416	-20	-2943	- 20	-5827	208	-4000	- 22	-2859	08	-5834	196
60	-4426	-30	-2950	- 27	-5788	247	-4006	- 28	-2861	06	-5798	232
0	-4396		-2923		-6035		-3978		-2867		-6030	

TABLE 22
CALIBRATION DATA
FULLY ASSEMBLED BARBER S-2 TRUCK WITH TWO WHEEL SETS

	WHEEL 65164 @ 0^o						WHEEL 65584 @ 0^o					
Vertical Load K lbs./Jack (5K Lbs./Wheel)	Channel 0^o+ V1 180^o- Reading	Diff. Micro "/"	Channel 90^o- V2 270^o+ Reading	Diff. Micro "/"	Chan. Lat. Rdg.	Diff. Micro "/"	Channel 0^o+ V1 180^o- Reading	Diff. Micro "/"	Channel 90^o+ V2 270^o+ Reading	Diff. Micro "/"	Chan. Lat. Rdg.	Diff. Micro "/"
10	045	78	1300	02	4965	-05	-235	73	1646	01	5321	-01
20	108	141	1300	02	4964	-06	-173	135	1646	01	5317	-05
30	173	206	1301	03	4965	-05	-109	199	1648	03	5316	-06
40	238	271	1300	02	4961	-09	-045	263	1648	03	5312	-10
50	302	335	1301	03	4960	-10	023	331	1649	04	5312	-10
60	367	400	1301	03	4959	-11	087	395	1651	06	5313	-09
70	431	464	1302	04	4960	-10	153	461	1652	07	5315	-07
80	496	529	1306	08	4957	-13	214	522	1653	08	5312	-10
Lateral Load K lbs. Total (5K Lbs./Wheel) + 10K Vertical												
10	030	63	1298	-	5013	43	-242	66	1645	-	5360	38
20	021	54	1295	-03	5060	90	-244	64	1643	-02	5405	83
30	014	47	1290	-08	5100	130	-246	62	1640	-05	5447	125
40	007	40	1291	-07	5141	171	-246	62	1640	-05	5491	169
50	-003	36	1288	-10	5182	212	-248	60	1638	-07	5530	208
60	-013	46	1284	-14	5235	265	-251	57	1636	-09	5573	249
0	-033		1298		4970		-308		1645		5322	

TABLE 23
CALIBRATION DATA
FULLY ASSEMBLED BARBER S-2 TRUCK WITH TWO WHEEL SETS

	WHEEL 65164 @ 30°						WHEEL 65584 @ 30°					
Vertical Load K lbs./Jack (5K Lbs./Wheel)	Channel 0°+ V1 180°- Reading	Diff. Micro "/"	Channel 90°- V2 270°+ Reading	Diff. Micro "/"	Chan. Lat. Rdg.	Diff. Micro "/"	Channel 0°+ V1 180°- Reading	Diff. Micro "/"	Channel 90°+ V2 270°+ Reading	Diff. Micro "/"	Chan. Lat. Rdg.	Diff. Micro "/"
10	-002	33	1283	-12	4970	-05	-306	33	1623	-10	5312	-01
20	35	70	1274	-21	4971	-04	-272	67	1614	-19	5310	-03
30	71	106	1264	-31	4970	-05	-238	101	1606	-27	5310	-03
40	106	141	1257	-38	4971	-04	-205	134	1598	-35	5310	-03
50	143	178	1247	-48	4970	-05	-170	169	1591	-42	5311	-02
60	180	215	1237	-58	4971	-04	-134	205	1583	-50	5312	-01
70	215	250	1229	-66	4971	-04	-101	238	1573	-60	5313	-
80	250	285	1219	-76	4970	-05	-064	275	1566	-67	5312	-01
Lateral Load K lbs. Total (5K Lbs./Wheel) + 10K Vertical												
10	-016	19	1288	21	5016	41	-310	29	1624	-09	5351	38
20	-030	05	1289	21	5061	86	-312	27	1625	-08	5391	78
30	-044	-09	1295	27	5110	135	-316	23	1623	-10	5439	126
40	-055	-20	1300	20	5146	171	-320	19	1625	-08	5479	166
50	-067	-32	1301	21	5186	211	-324	15	1625	-08	5520	207
60	-079	-44	1305	15	5224	249	-327	12	1624	-09	5553	240
0	-035		1295		4975		-339		1633		5313	

TABLE 24
CALIBRATION DATA
FULLY ASSEMBLED BARBER S-2 TRUCK WITH TWO WHEEL SETS

	WHEEL 65164 @ 60°						WHEEL 65584 @ 60°					
Vertical Load K lbs./Jack (5K Lbs./Wheel)	Channel 0°+ V1 180°- Reading	Diff. Micro "/"	Channel 90°- V2 270°+ Reading	Diff. Micro "/"	Chan. Lat. Rdg.	Diff. Micro "/"	Channel 0°+ V1 180°- Reading	Diff. Micro "/"	Channel 90°+ V2 270°+ Reading	Diff. Micro "/"	Chan. Lat. Rdg.	Diff. Micro "/"
10	053	13	1256	- 39	4964	- 06	-300	10	1600	- 45	5319	- 01
20	066	26	1218	- 77	4964	- 06	-291	19	1557	- 88	5320	-
30	079	39	1179	-116	4963	- 07	-281	29	1516	-129	5319	- 01
40	093	53	1143	-152	4963	- 07	-271	39	1477	-168	5320	-
50	107	67	1105	-190	4962	- 08	-260	50	1443	202	5321	01
60	120	80	1066	-229	4963	- 07	-250	60	1400	-245	5321	01
70	133	93	1027	-268	4963	- 07	-241	69	1365	-280	5322	02
80	145	105	993	-302	4964	- 06	-233	77	1333	-312	5320	-
Lateral Load K lbs. Total (5K Lbs./Wheel) + 10K Vertical												
10	041	01	1266	-29	5009	39	-315	-05	1610	-35	5357	37
20	034	-06	1275	-20	5048	78	-311	-01	1615	-30	5395	75
30	027	-13	1283	-12	5091	121	-310	-	1620	-25	5434	114
40	029	-21	1291	-04	5129	159	-306	04	1626	-19	5476	156
50	012	-28	1299	04	5169	199	-303	07	1634	-11	5519	199
60	05	-35	1306	11	5208	238	-300	10	1642	-03	5557	237
0	40		1295		4970		-310		1645		5320	

TABLE 25

CALIBRATION DATA

FULLY ASSEMBLED BARBER S-2 TRUCK WITH TWO WHEEL SETS

	WHEEL 65164 @ 90°						WHEEL 65584 @ 90°					
Vertical Load K lbs./Jack (5K Lbs./Wheel)	Channel 0°+ V1 180°- Reading	Diff. Micro "/"	Channel 90°- V2 270°+ Reading	Diff. Micro "/"	Chan. Lat. Rdg.	Diff. Micro "/"	Channel 0°+ V1 180°- Reading	Diff. Micro "/"	Channel 90°+ V2 270°+ Reading	Diff. Micro "/"	Chan. Lat. Rdg.	Diff. Micro "/"
10	-049	04	1195	-69	4975	-03	-354	-	1534	- 72	5315	01
20	-047	06	1128	-136	4973	-05	-355	-01	1468	-138	5313	-01
30	-044	09	1062	-202	4974	-04	-355	-01	1405	-201	5313	-01
40	-042	11	996	-268	4970	-08	-357	-03	1340	-266	5313	-01
50	-040	13	927	-337	4968	-10	-358	-04	1275	-331	5311	-03
60	-038	15	858	-406	4969	-09	-357	-03	1209	-397	5312	-02
70	-034	19	792	-472	4968	-10	-358	-04	1145	-461	5311	-03
80	-032	21	726	-538	4967	-11	-359	-05	1080	-526	5313	-01
Lateral Load K lbs. Total (5K Lbs./Wheel) + 10K Vertical												
10	-060	-07	1203	- 61	5017	39	-353	01	1538	- 68	5351	37
20	-066	-13	1210	- 54	5064	86	-349	05	1538	- 68	5390	76
30	-074	-21	1218	- 46	5116	138	-349	05	1540	- 66	5433	119
40	-080	-27	1228	- 36	5151	173	-349	05	1544	- 62	5477	163
50	-085	-32	1238	- 26	5194	216	-345	09	1550	- 56	5520	206
60	-093	-40	1250	- 14	5238	260	-346	08	1556	- 50	5557	243
0	-053		1264		4978		-354		1606		5314	

TABLE 26
CALIBRATION DATA
FULLY ASSEMBLED BARBER S-2 TRUCK WITH TWO WHEEL SETS

	WHEEL 65164 @ 120°						WHEEL 6 5164 @ 120°					
Vertical Load K lbs./Jack (5K Lbs./Wheel)	Channel 0°+ V1 180°- Reading	Diff. Micro "/"	Channel 90°- V2 270°+ Reading	Diff. Micro "/"	Chan. Lat. Rdg.	Diff. Micro "/"	Channel 0°+ V1 180°- Reading	Diff. Micro "/"	Channel 90°+ V2 270°+ Reading	Diff. Micro "/"	Chan. Lat. Rdg.	Diff. Micro "/"
10	056	11	1259	-39	4973	-02	-322	-12	1606	-39	5319	-01
20	061	21	1219	-79	4971	-04	-333	-23	1569	-76	5320	-
30	076	31	1180	-118	4968	-07	-345	-35	1531	-114	5318	-02
40	085	40	1139	-159	4967	-08	-355	-45	1494	-151	5316	-04
50	095	50	1099	-199	4965	-10	-366	-56	1457	-188	5317	-03
60	105	60	1060	-238	4964	-11	-377	-67	1419	-226	5318	-02
70	116	71	1021	-277	4962	-13	-388	-78	1382	-263	5317	-03
80	125	80	983	-315	4961	-14	-398	-88	1346	-299	5319	-01
Lateral Load K lbs. Total (5K Lbs./Wheel) + 10K Vertical												
10	026	-19	1277	-21	5015	40	-319	-09	1619	-26	5358	38
20	026	-19	1295	-03	5056	81	-318	-08	1618	-27	5395	75
30	022	-23	1309	11	5097	122	-318	-08	1621	-24	5438	118
40	026	-19	1319	21	5134	159	-320	-10	1627	-18	5482	162
50	025	-20	1327	29	5177	202	-319	-09	1631	-14	5524	204
60	029	-16	1338	40	5215	240	-319	-09	1632	-13	5563	243
0	045		1298		4975		-310		1645		5320	

TABLE 27
CALIBRATION DATA
FULLY ASSEMBLED BARBER S-2 TRUCK WITH TWO WHEEL SETS

	WHEEL 65164 @ 150°						WHEEL 65584 @ 150°					
Vertical Load K lbs./Jack (5K Lbs./Wheel)	Channel 0°+ V1 180°- Reading	Diff. Micro "/"	Channel 90°- V2 270°+ Reading	Diff. Micro "/"	Chan. Lat. Rdg.	Diff. Micro "/"	Channel 0°+ V1 180°- Reading	Diff. Micro "/"	Channel 90°+ V2 270°+ Reading	Diff. Micro "/"	Chan. Lat. Rdg.	Diff. Micro "/"
10	-098	- 38	1282	-14	4972	- 06	-406	- 46	1626	-10	5314	- 01
20	-128	- 68	1270	-26	4970	- 08	-438	- 78	1615	-21	5313	- 02
30	-158	- 98	1258	-38	4970	- 08	-472	-112	1606	-30	5313	- 02
40	-188	-128	1246	-50	4969	- 09	-508	-148	1596	-40	5312	- 03
50	-218	-158	1234	-62	4966	- 12	-542	-182	1585	-51	5311	- 04
60	-249	-189	1222	-74	4965	- 13	-577	-217	1576	-60	5309	- 06
70	-276	-216	1210	-86	4964	- 14	-611	-251	1565	-71	5308	- 07
80	-306	-246	1198	-98	4961	- 17	-645	-285	1555	-81	5308	- 07
Lateral Load K lbs. Total (5K Lbs./Wheel) + 10K Vertical												
10	-096	- 36	1292	-04	5020	42	-394	- 34	1632	-04	5346	31
20	-094	- 34	1300	-04	5067	89	-390	- 30	1637	01	5387	72
30	-092	- 32	1309	13	5113	135	-383	- 23	1643	07	5430	115
40	-090	- 30	1315	19	5154	176	-380	- 20	1650	14	5475	160
50	-085	- 25	1321	25	5202	224	-372	- 12	1654	18	5520	205
60	-081	- 21	1328	32	5248	270	-365	- 05	1656	20	5560	245
0	-060		1296		4978		-360		1636		5315	

TABLE 28
CALIBRATION DATA
FULLY ASSEMBLED BARBER S-2 TRUCK WITH TWO WHEEL SETS

	WHEEL 65164 @ 180°						WHEEL 65584 @ 180°					
Vertical Load K lbs./Jack (5K Lbs./Wheel)	Channel 0°+ V1 180°- Reading	Diff. Micro "/"	Channel 90°- V2 270°+ Reading	Diff. Micro "/"	Chan. Lat. Rdg.	Diff. Micro "/"	Channel 0°+ V1 180°- Reading	Diff. Micro "/"	Channel 90°+ V2 270°+ Reading	Diff. Micro "/"	Chan. Lat. Rdg.	Diff. Micro "/"
10	-148	- 69	1295	-05	4972	- 05	-440	- 67	1641	01	5315	-
20	-214	-135	1293	-07	4970	- 07	-507	-134	1641	01	5311	- 04
30	-278	-199	1292	-08	4966	- 11	-570	-197	1641	01	5307	- 08
40	-341	-262	1289	-11	4965	- 12	-634	-261	1640	-	5305	- 10
50	-406	-327	1286	-14	4960	- 17	-700	-327	1640	-	5301	- 14
60	-470	-391	1282	-18	4958	- 19	-766	-393	1640	-	5300	- 15
70	-534	-455	1280	-20	4957	- 20	-829	-456	1640	-	5300	- 15
80	-602	-526	1280	-20	4954	- 23	-896	-523	1640	-	5298	- 17
Lateral Load K lbs. Total (5K Lbs./Wheel) + 10K Vertical												
10	-147	- 68	1300	-	5018	41	-437	- 64	1640	-	5340	25
20	-147	- 68	1303	03	5062	85	-432	- 59	1642	02	5383	68
30	-145	- 66	1305	05	5108	131	-433	- 60	1643	03	5426	111
40	-146	- 67	1308	08	5149	172	-430	- 57	1646	06	5472	157
50	-144	- 65	1310	10	5194	217	-426	- 53	1647	07	5514	199
60	-138	- 59	1312	12	5232	255	-426	- 53	1648	08	5552	237
0	-079		1300		4977		-373		1640		5315	

TABLE 29

CALIBRATION DATA

FULLY ASSEMBLED BARBER S-2 TRUCK WITH TWO WHEEL SETS

	WHEEL 65164 @ 210°						WHEEL 65584 @ 210°					
Vertical Load K lbs./Jack (5K Lbs./Wheel)	Channel 0°+ V1 180°- Reading	Diff. Micro "/"	Channel 90°- V2 270°+ Reading	Diff. Micro "/"	Chan. Lat. Rdg.	Diff. Micro "/"	Channel 0°+ V1 180°- Reading	Diff. Micro "/"	Channel 90°+ V2 270°+ Reading	Diff. Micro "/"	Chan. Lat. Rdg.	Diff. Micro "/"
10	-112	- 54	1309	10	4977	01	-394	- 34	1655	17	5316	02
20	-154	- 96	1316	17	4975	-01	-428	- 68	1666	28	5313	-01
30	-198	-130	1323	24	4974	-02	-463	-103	1675	37	5312	-02
40	-240	-172	1330	31	4973	-03	-497	-137	1685	47	5312	-02
50	-283	-215	1338	39	4970	-06	-532	-172	1695	57	5310	-04
60	-324	-256	1341	42	4970	-06	-566	-206	1704	66	5310	-04
70	-366	-298	1348	49	4968	-08	-603	-243	1713	75	5310	-04
80	-410	-342	1356	57	4968	-08	-640	-280	1723	85	5310	-04
Lateral Load K lbs. Total (5K Lbs./Wheel) + 10K Vertical												
10	-105	- 37	1304	05	5014	38	-390	- 30	1649	11	5343	29
20	-100	- 32	1300	01	5064	88	-385	- 25	1646	08	5389	75
30	-094	- 26	1295	-04	5106	130	-380	- 20	1643	05	5430	116
40	-090	- 22	1292	-07	5142	166	-374	- 14	1640	02	5471	157
50	-085	- 17	1288	-11	5184	208	-369	- 09	1637	- 01	5513	199
60	-080	- 12	1284	-15	5223	247	-369	- 09	1631	- 07	5550	236
0	-068		1299		4976		-360		1638		5314	

TABLE 30

CALIBRATION DATA

FULLY ASSEMBLED BARBER S-2 TRUCK WITH TWO WHEEL SETS

	WHEEL 65164 @ 240°						WHEEL 65584 @ 240°					
Vertical Load K lbs./Jack (5K Lbs./Wheel)	Channel 0°+ V1 180°- Reading	Diff. Micro "/"	Channel 90°- V2 270°+ Reading	Diff. Micro "/"	Chan. Lat. Rdg.	Diff. Micro "/"	Channel 0°+ V1 180°- Reading	Diff. Micro "/"	Channel 90°+ V2 270°+ Reading	Diff. Micro "/"	Chan. Lat. Rdg.	Diff. Micro "/"
10	-065	- 13	1341	34	4972	- 04	-358	- 10	1689	40	5311	- 01
20	-078	- 26	1370	63	4970	- 06	-366	- 18	1725	76	5309	- 03
30	-090	- 38	1398	92	4968	- 08	-377	- 29	1760	111	5306	- 06
40	-103	- 51	1427	120	4966	- 10	-387	- 39	1796	147	5305	- 07
50	-117	- 65	1457	150	4964	- 12	-397	- 49	1833	184	5304	- 08
60	-130	- 78	1488	181	4962	- 14	-405	- 57	1869	220	5303	- 09
70	-142	- 90	1516	209	4959	- 17	-416	- 68	1904	255	5302	- 10
80	-155	-103	1548	241	4958	- 18	-425	- 77	1942	293	5300	- 12
Lateral Load K lbs. Total (5K Lbs./Wheel) + 10K Vertical												
10	-056	- 04	1330	23	5018	42	-357	- 09	1682	33	5350	38
20	-051	01	1319	12	5057	81	-354	- 06	1678	29	5388	76
30	-046	06	1308	01	5098	122	-352	- 04	1672	23	5428	116
40	-040	12	1298	-09	5135	159	-350	- 02	1667	18	5470	158
50	-035	17	1285	-22	5178	202	-348	-	1660	11	5511	199
60	-030	22	1272	-35	5219	243	-348	-	1651	02	5550	238
0	-052		1307		4976		-348		1649		5312	

TABLE 31
CALIBRATION DATA
FULLY ASSEMBLED BARBER S-2 TRUCK WITH TWO WHEEL SETS

	WHEEL 65164 @ 270°						WHEEL 65584 @ 270°					
Vertical Load K lbs./Jack (5K Lbs./Wheel)	Channel 0°+ V1 180°- Reading	Diff. Micro "/"	Channel 90°- V2 270°+ Reading	Diff. Micro "/"	Chan. Lat. Rdg.	Diff. Micro "/"	Channel 0°+ V1 180°- Reading	Diff. Micro "/"	Channel 90°+ V2 270°+ Reading	Diff. Micro "/"	Chan. Lat. Rdg.	Diff. Micro "/"
10	-050	02	1392	66	4976	-04	-340	05	1732	68	5314	- 05
20	-053	-01	1456	130	4975	-05	-338	07	1796	132	5314	- 05
30	-056	-04	1521	195	4976	-04	-338	07	1858	194	5313	- 06
40	-060	-08	1587	261	4976	-04	-338	07	1922	258	5314	- 05
50	-063	-11	1654	328	4976	-04	-339	06	1986	322	5312	- 07
60	-066	-14	1720	394	4977	-03	-338	07	2052	388	5312	- 07
70	-070	-18	1781	455	4978	-02	-338	07	2114	450	5312	- 07
80	-073	-21	1846	520	4976	-04	-338	07	2180	526	5316	- 03
Lateral Load K lbs. Total (5K Lbs./Wheel) + 10K Vertical												
10	-050	02	1382	56	5020	40	-348	-03	1728	64	5358	39
20	-046	06	1370	44	5061	81	-348	-03	1722	58	5393	74
30	-042	10	1362	36	5102	122	-350	-05	1720	56	5432	113
40	-037	15	1354	28	5140	160	-353	-08	1720	56	5476	157
50	-032	20	1344	18	5176	196	-354	-09	1715	51	5515	196
60	-030	22	1330	04	5225	245	-356	-11	1710	46	5553	234
0	-052		1326		4980		-345		1664		5319	

TABLE 32
CALIBRATION DATA
FULLY ASSEMBLED BARBER S-2 TRUCK WITH TWO WHEEL SETS

	WHEEL 65164 @ 300°						WHEEL 65584 @ 300°					
Vertical Load K lbs./Jack (5K Lbs./Wheel)	Channel 0°+ V1 180°- Reading	Diff. Micro "/"	Channel 90°- V2 270°+ Reading	Diff. Micro "/"	Chan. Lat. Rdg.	Diff. Micro "/"	Channel 0°+ V1 180°- Reading	Diff. Micro "/"	Channel 90°+ V2 270°+ Reading	Diff. Micro "/"	Chan. Lat. Rdg.	Diff. Micro "/"
10	059	09	1340	40	4973	- 02	-298	12	1684	39	5324	04
20	068	18	1380	80	4974	- 01	-287	23	1724	79	5320	-
30	077	27	1419	119	4974	- 01	-276	34	1763	118	5318	- 02
40	086	36	1460	160	4975	-	-265	45	1803	158	5318	- 02
50	096	46	1499	199	4976	01	-253	57	1841	196	5316	- 04
60	106	56	1539	239	4975	-	-242	68	1880	235	5316	- 04
70	114	64	1579	279	4977	02	-231	79	1920	275	5316	- 04
80	120	70	1619	319	4977	02	-222	88	1959	314	5316	- 04
Lateral Load K lbs. Total (5K Lbs./Wheel) + 10K Vertical												
10	059	09	1329	29	5017	42	-298	12	1675	30	5348	38
20	051	01	1321	21	5063	88	-302	08	1670	25	5396	76
30	048	-02	1315	15	5111	136	-305	05	1665	20	5440	120
40	044	-06	1311	11	5151	176	-310	-	1661	16	5483	163
50	040	-10	1307	07	5190	215	-313	-03	1655	10	5525	205
60	038	-12	1304	04	5227	252	-316	-06	1654	09	5560	240
0	050		1300		4975		-310		1645		5320	

TABLE 33
CALIBRATION DATA
FULLY ASSEMBLED BARBER S-2 TRUCK WITH TWO WHEEL SETS

	WHEEL 65164 @ 330°						WHEEL 65584 @ 330°					
Vertical Load K lbs./Jack (5K Lbs./Wheel)	Channel 0°+ V1 180°- Reading	Diff. Micro "/"	Channel 90°- V2 270°+ Reading	Diff. Micro "/"	Chan. Lat. Rdg.	Diff. Micro "/"	Channel 0°+ V1 180°- Reading	Diff. Micro "/"	Channel 90°+ V2 270°+ Reading	Diff. Micro "/"	Chan. Lat. Rdg.	Diff. Micro "/"
10	-024	34	1314	13	4981	-01	-304	47	1642	06	5323	-01
20	002	60	1328	27	4983	-03	-267	84	1652	16	5324	-
30	026	84	1341	40	4982	-	-231	120	1661	25	5324	-
40	053	111	1355	54	4982	-	-196	155	1670	34	5323	-01
50	077	135	1369	68	4982	-	-159	192	1678	42	5323	-01
60	103	161	1382	81	4983	01	-122	229	1686	50	5324	-
70	127	185	1395	94	4984	02	-085	266	1696	60	5323	-01
80	154	212	1410	109	4984	02	-049	302	1704	68	5324	-
Lateral Load K lbs. Total (5K Lbs./Wheel) + 10K Vertical												
10	-034	24	1299	-02	5027	45	-317	34	1640	04	5354	30
20	-038	20	1292	-09	5062	80	-320	31	1636	-	5390	66
30	-044	14	1283	-18	5105	123	-326	25	1634	-02	5432	108
40	-051	07	1277	-24	5140	158	-333	18	1629	-06	5478	154
50	-058	-	1269	-32	5178	196	-340	11	1626	-10	5520	196
60	-065	-07	1264	-37	5217	235	-349	02	1626	-10	5558	234
0	-058		1301		4982		-351		1636		5324	

TABLE 34

CALIBRATION RESISTANCE

WHEEL NUMBER	V1	V2	LATERAL
65594	114,000 OHMS	113,000 OHMS	700,000 OHMS
65584	115,000 OHMS	115,000 OHMS	754,000 OHMS
65495	113,000 OHMS	114,000 OHMS	743,000 OHMS
65164	114,000 OHMS	115,000 OHMS	720,000 OHMS

A Budd portable strain indicator, Model P-350, and a Shallcross decade potentiometer were used to obtain the calibration resistances for the above numbered wheels.

Calibration resistances are to be shunted across A and B (Black and Green) and B and C (Green and Red) respectively.

Calibration resistors should be precision resistors with a tolerance of 1% or less or a precision resistance decade box.

Calibration resistances were found by shunting, as mentioned above, at the Slip Ring. However, it is more convenient to calibrate at the amplifier. This can accurately be done by allowing for line loss in the cable.

TABLE 35

WHEEL 65594

(LATERAL BRIDGE)*

Speed MPH	Strain Rdg. Microinches/Inch	Difference
76	5872	91
70	5856	75
60	5836	55
50	5820	39
40	5805	24
30	5794	13
20	5786	5
10	5782	1
0	5781	0

WHEEL 65584

(LATERAL BRIDGE)*

76	-6382	91
70	-6398	75
60	-6416	57
50	-6434	39
40	-6447	26
30	-6458	15
20	-6465	8
10	-6471	2
0	-6473	0

*Due to bridge configuration of vertical gages no change in output signal was recorded.

TABLE 36

WHEEL 65164

(LATERAL BRIDGE)*

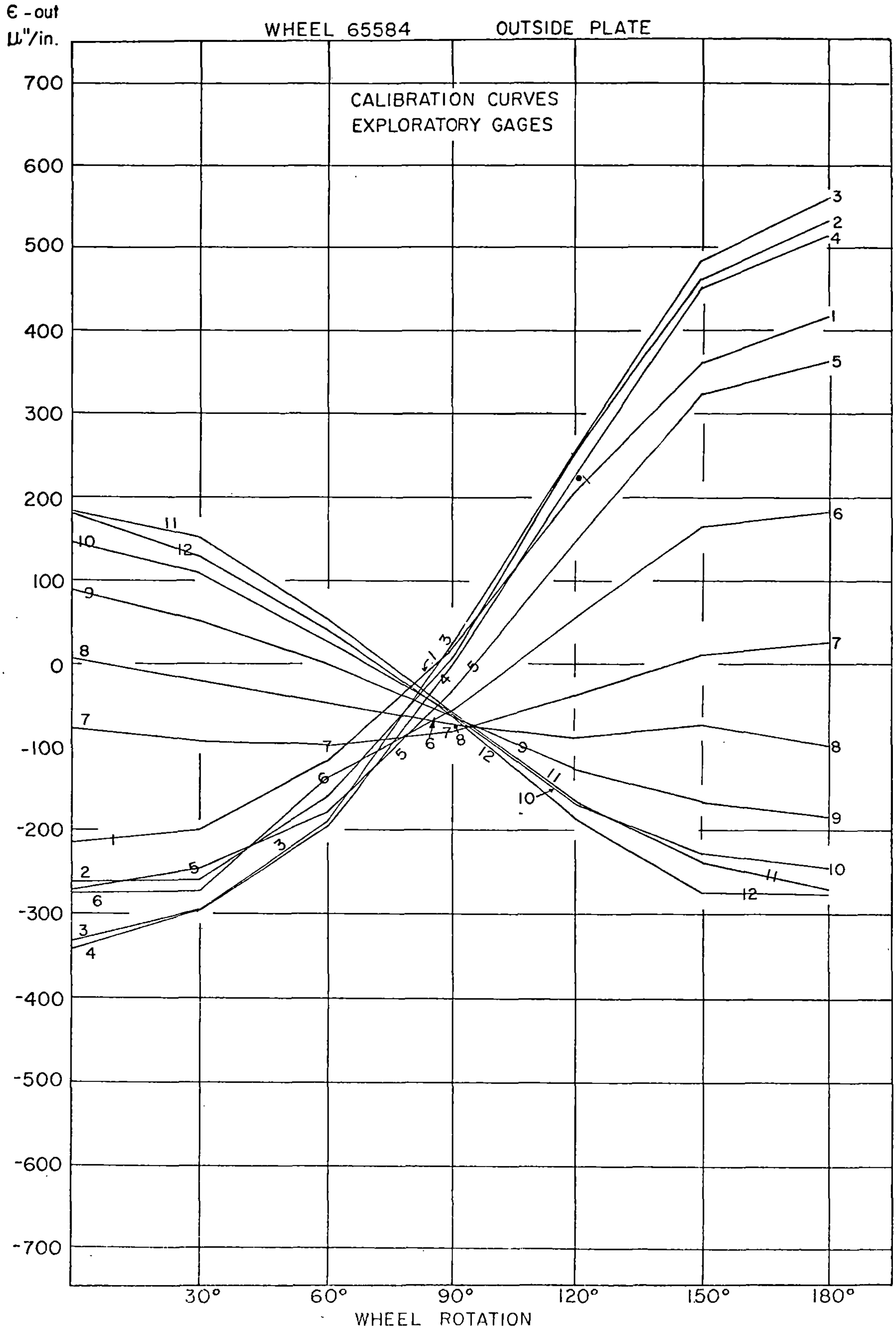
Speed MPH	Strain Rdg. Microinches/Inch	Difference
76	5057	87
70	5044	74
60	5022	52
50	5001	31
40	4987	17
30	4982	12
20	4975	5
10	4970	0
0	4970	0

WHEEL 65495

(LATERAL BRIDGE)*

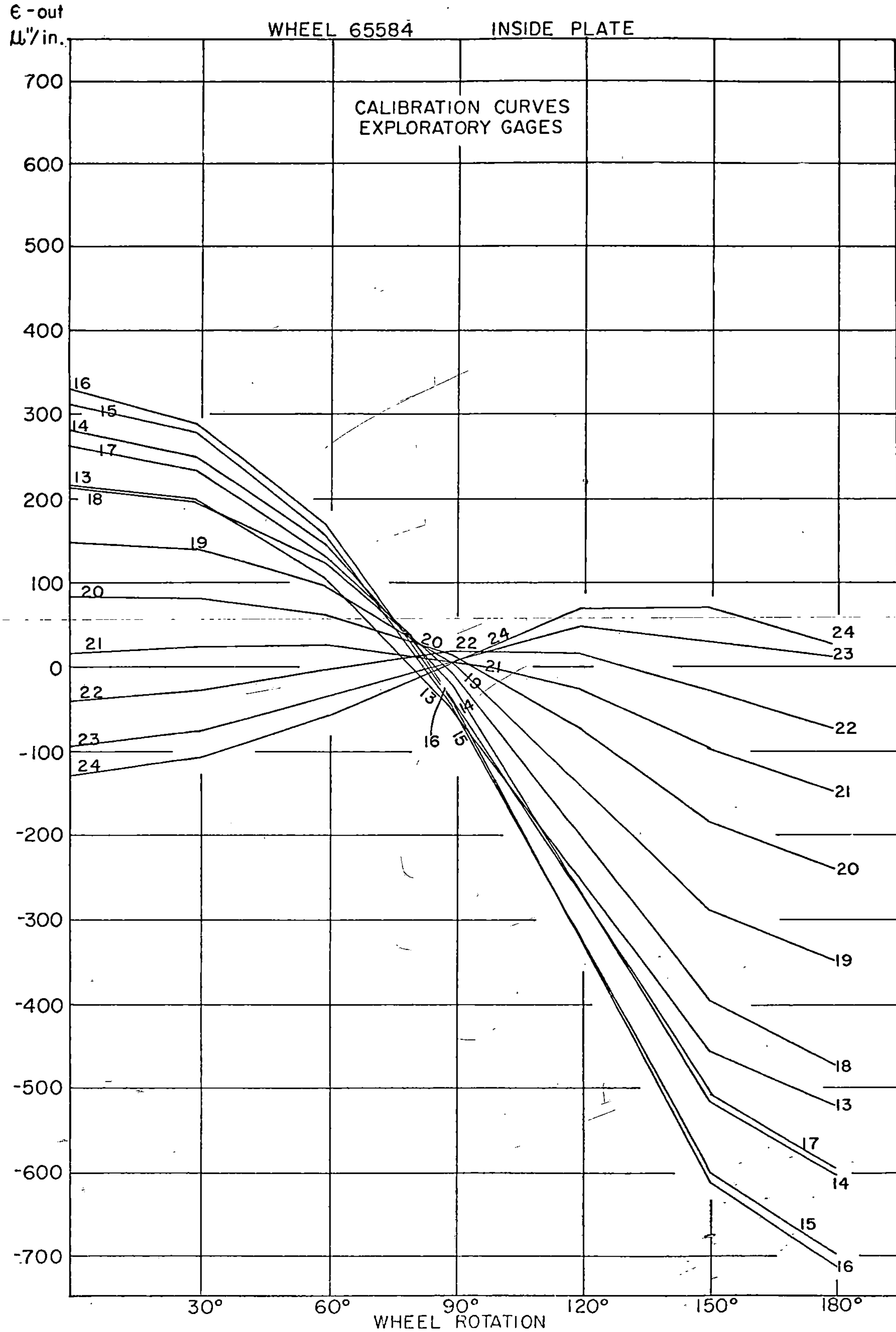
76	3286	86
70	3273	73
60	3252	52
50	3236	36
40	3222	22
30	3212	12
20	3204	4
10	3200	0
0	3200	0

*Due to bridge configuration of vertical gages no change in output signal was recorded.



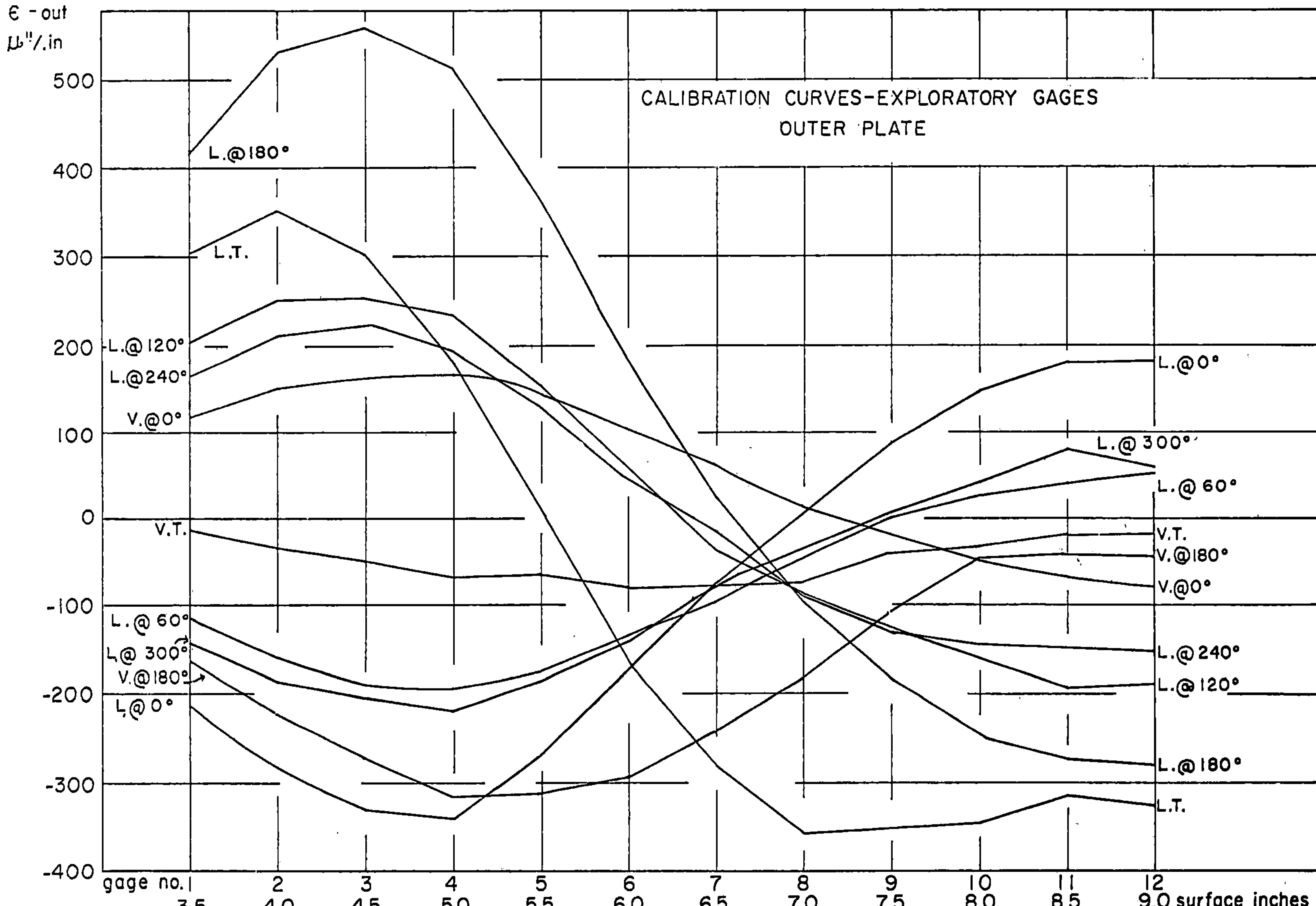
ε - out
μ"/in.
WHEEL 65584
OUTSIDE PLATE
CALIBRATION CURVES
EXPLORATORY GAGES
700
600
500
400
300
200
100
0
-100
-200
-300
-400
-500
-600
-700
30°
60°
90°
120°
150°
180°
WHEEL ROTATION

FIGURE 1



WHEEL 65584
INSIDE PLATE
CALIBRATION CURVES
EXPLORATORY GAGES
ε - out
μ"/in.
700
600
500
400
300
200
100
0
-100
-200
-300
-400
-500
-600
-700
30°
60°
90°
120°
150°
180°
WHEEL ROTATION
16
15
14
17
13
18
19
20
21
22
23
24

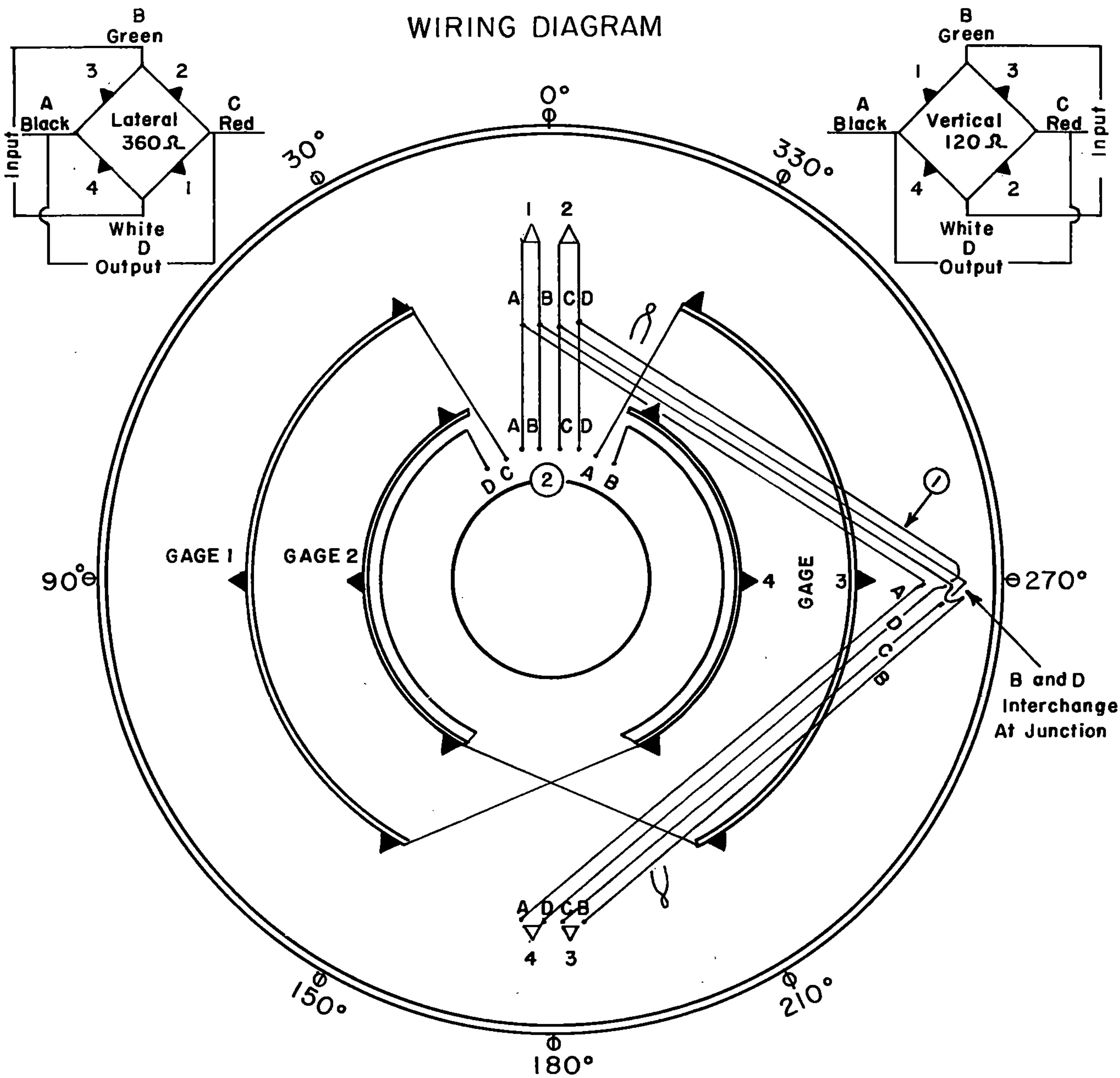
FIGURE 2



ε - out
μ"/.in
500
400
300
200
100
0
-100
-200
-300
-400
CALIBRATION CURVES-EXPLORATORY GAGES
OUTER PLATE
L.@180°
L.T.
L.@120°
L.@240°
V.@0°
V.T.
L.@60°
L.@300°
V.@180°
L.@0°
L.@0°
L.@300°
L.@60°
V.T.
V.@180°
V.@0°
L.@240°
L.@120°
L.@180°
L.T.
gage no. 1 2 3 4 5 6 7 8 9 10 11 12
3.5 4.0 4.5 5.0 5.5 6.0 6.5 7.0 7.5 8.0 8.5 9.0 surface inches from hub

FIGURE 3

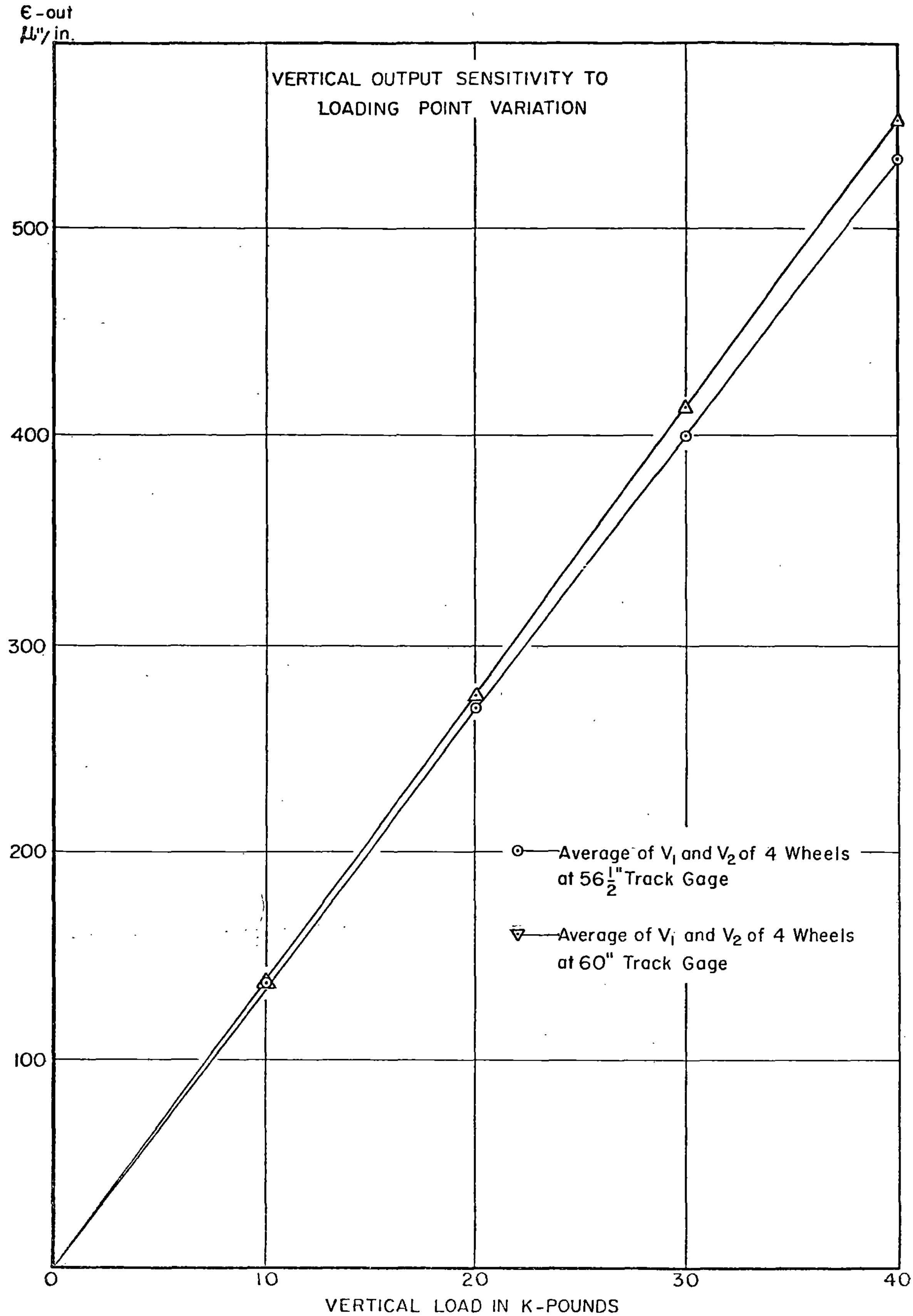
WIRING DIAGRAM



△ Vertical Gages 180° Apart-120Ω Bridge.
▲ Lateral Gages 60° Apart-360Ω Bridge.
(1) 4 Conductor Flat Cable #26 Wire Scotch-Flex #700.
(2) Mates With 4 Conductor Shielded Hook-Up Wire Through Axle.
⊃∘ Iron Constantan Thermocouples (Two)

NOTE: V2 @ 90° & 270° Not Shown - Identical to V1.

FIGURE 4



ε-out
μ"/in.
VERTICAL OUTPUT SENSITIVITY TO
LOADING POINT VARIATION
500
400
300
200
100
0
10
20
30
40
Average of V1 and V2 of 4 Wheels
at 56½" Track Gage
Average of V1 and V2 of 4 Wheels
at 60" Track Gage
VERTICAL LOAD IN K-POUNDS

FIGURE 5

WHEEL 65594

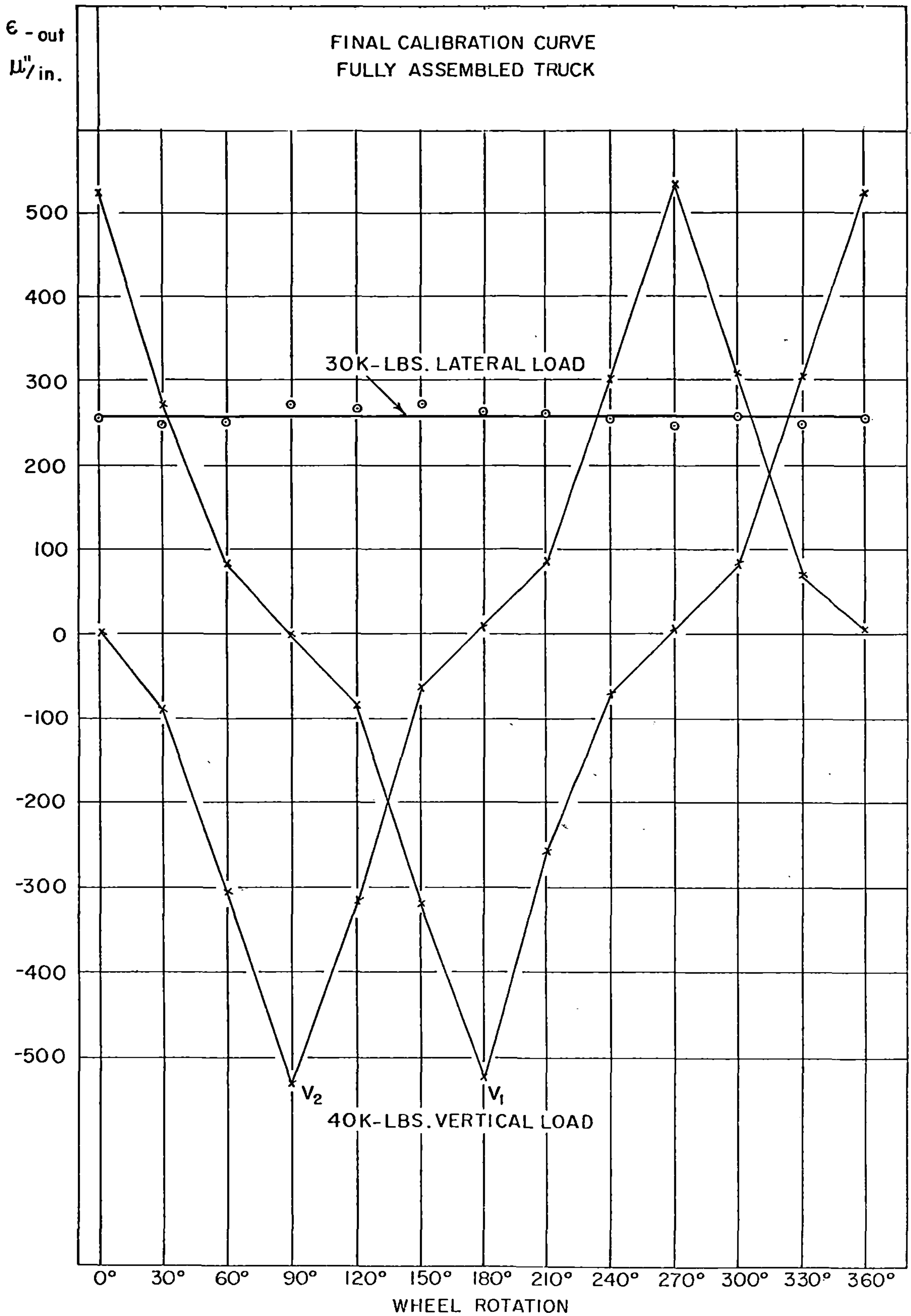


FIGURE 6

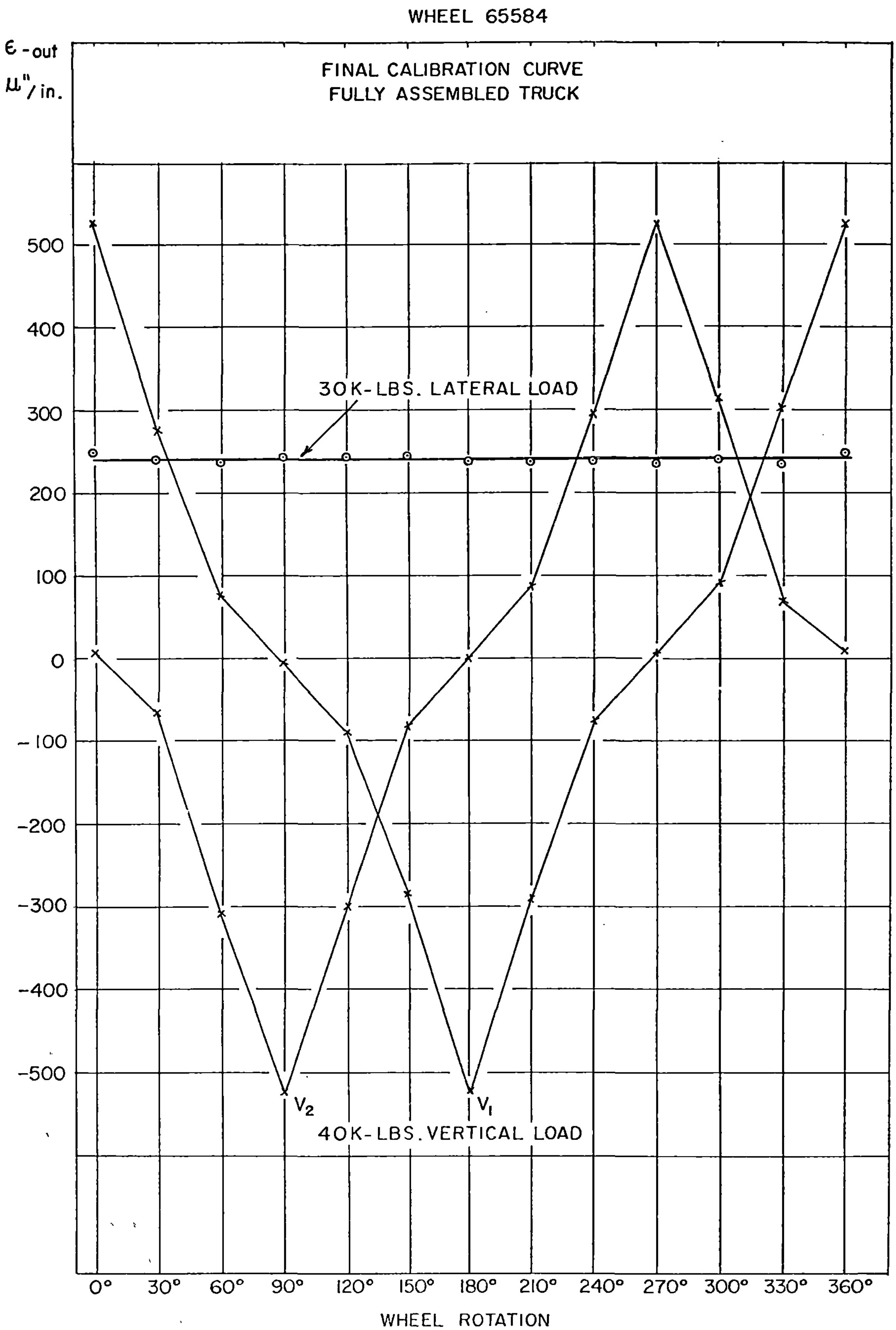

WHEEL 65584
ε - out
μ"/in.
FINAL CALIBRATION CURVE
FULLY ASSEMBLED TRUCK
500
400
300
200
100
0
-100
-200
-300
-400
-500
30K-LBS. LATERAL LOAD
V2
V1
40K-LBS. VERTICAL LOAD
0°
30°
60°
90°
120°
150°
180°
210°
240°
270°
300°
330°
360°
WHEEL ROTATION

FIGURE 7

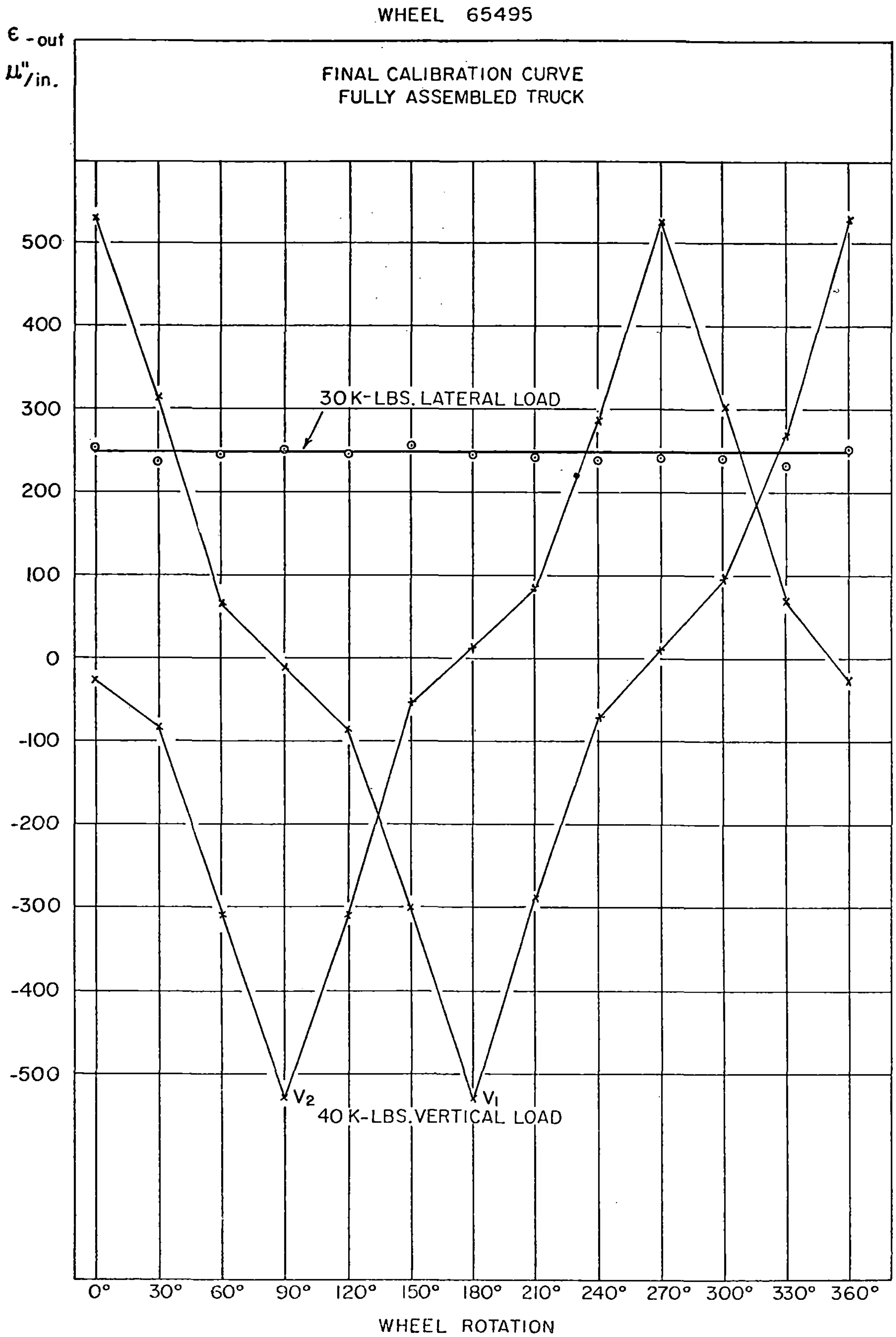

WHEEL 65495
ε -out
μ"/in.
FINAL CALIBRATION CURVE
FULLY ASSEMBLED TRUCK
500
400
300
200
100
0
-100
-200
-300
-400
-500
30 K-LBS. LATERAL LOAD
V2
V1
40 K-LBS. VERTICAL LOAD
0°
30°
60°
90°
120°
150°
180°
210°
240°
270°
300°
330°
360°
WHEEL ROTATION

FIGURE 8

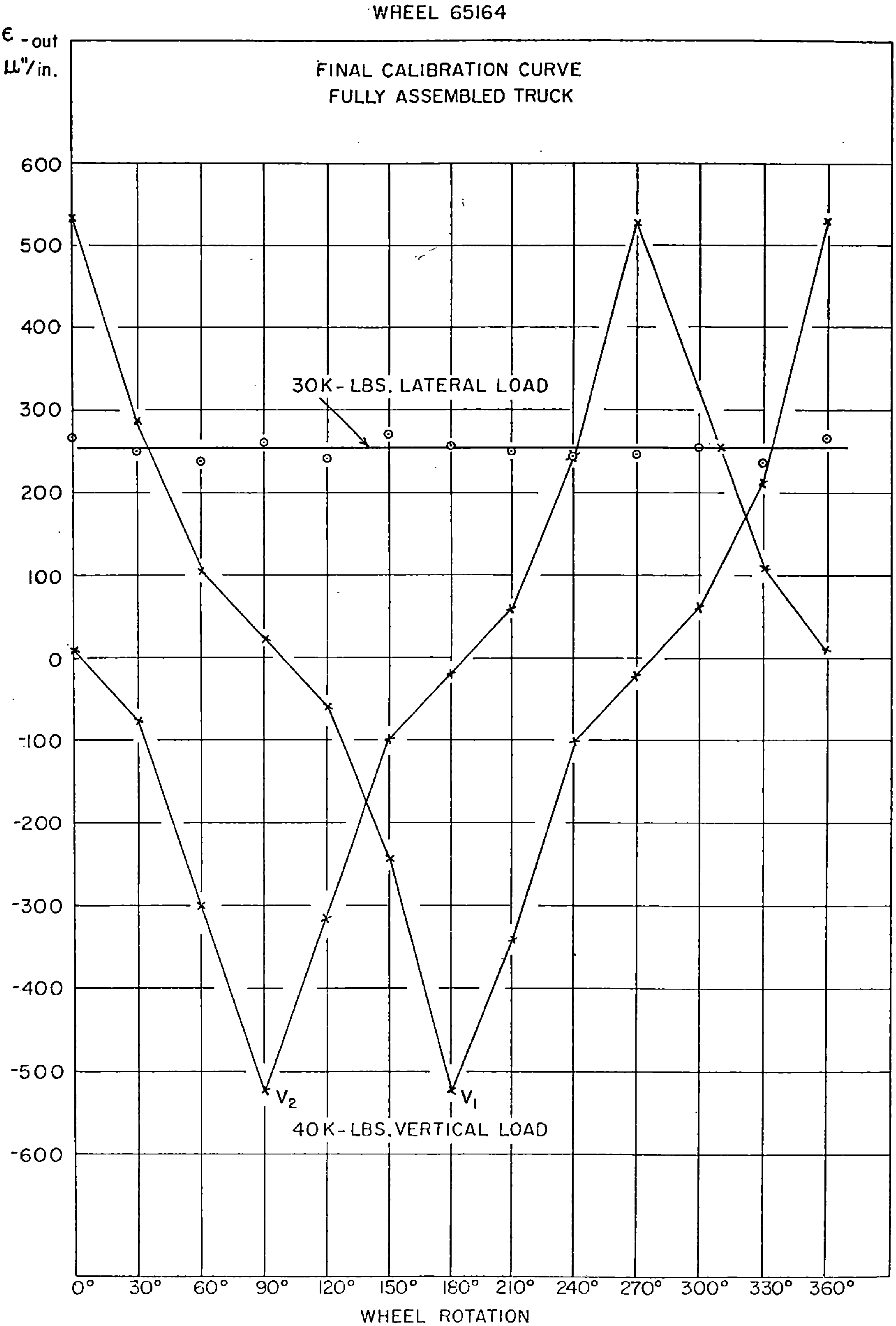
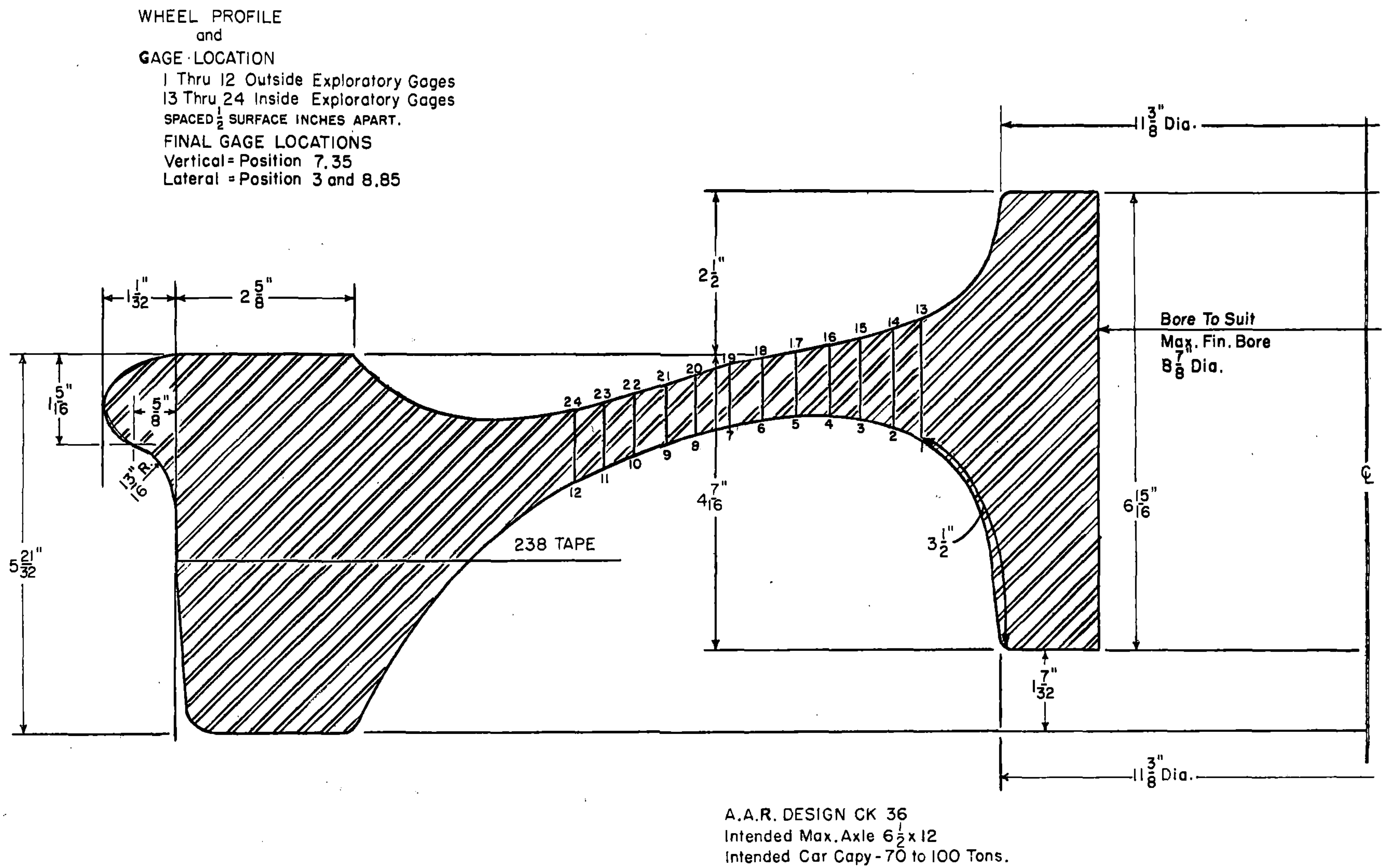

WHEEL 65164
ε - out
μ"/in.
FINAL CALIBRATION CURVE
FULLY ASSEMBLED TRUCK
600
500
400
300
200
100
0
-100
-200
-300
-400
-500
-600
30K-LBS. LATERAL LOAD
V_2
V_1
40K-LBS. VERTICAL LOAD
0°
30°
60°
90°
120°
150°
180°
210°
240°
270°
300°
330°
360°
WHEEL ROTATION

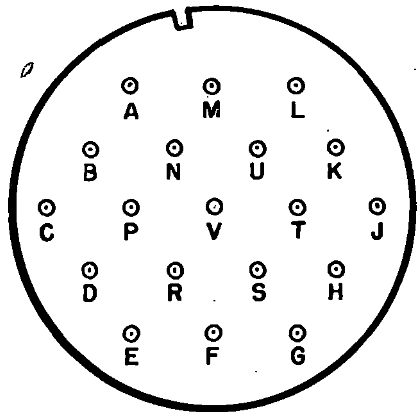
FIGURE 9



WHEEL PROFILE
and
GAGE LOCATION
1 Thru 12 Outside Exploratory Gages
13 Thru 24 Inside Exploratory Gages
SPACED 1/2 SURFACE INCHES APART.
FINAL GAGE LOCATIONS
Vertical = Position 7.35
Lateral = Position 3 and 8.85
1 1/32"
2 5/8"
1 5/16"
5/8"
13/16" R.
5 21/32"
2 1/2"
4 7/16"
238 TAPE
3 1/2"
11 3/8" Dia.
Bore To Suit
Max. Fin. Bore
8 7/8" Dia.
6 15/16"
1 7/32"
11 3/8" Dia.
A.A.R. DESIGN CK 36
Intended Max. Axle 6 1/2 x 12
Intended Car Capy - 70 to 100 Tons.

FIGURE 10

CONNECTOR WIRING DIAGRAM



BOTTOM VIEW

AXLE END MALE CONNECTOR

VERTICAL I (0°-180°)
A ⟶ Black
B ⟶ Green
C ⟶ Red
D ⟶ White
E ⟶ Shield

VERTICAL II (90°-270°)
F ⟶ Black
G ⟶ Green
H ⟶ Red
J ⟶ White
K ⟶ Shield

LATERAL
L ⟶ Black
M ⟶ Green
N ⟶ Red
P ⟶ White
R ⟶ Shield

THERMOCOUPLE (0° OFFSET)
S ⟶ Red (Minus)
T ⟶ White (Plus)

THERMOCOUPLE (180° OFFSET)
U ⟶ Red (Minus)
V ⟶ White (Plus)

FIGURE 11

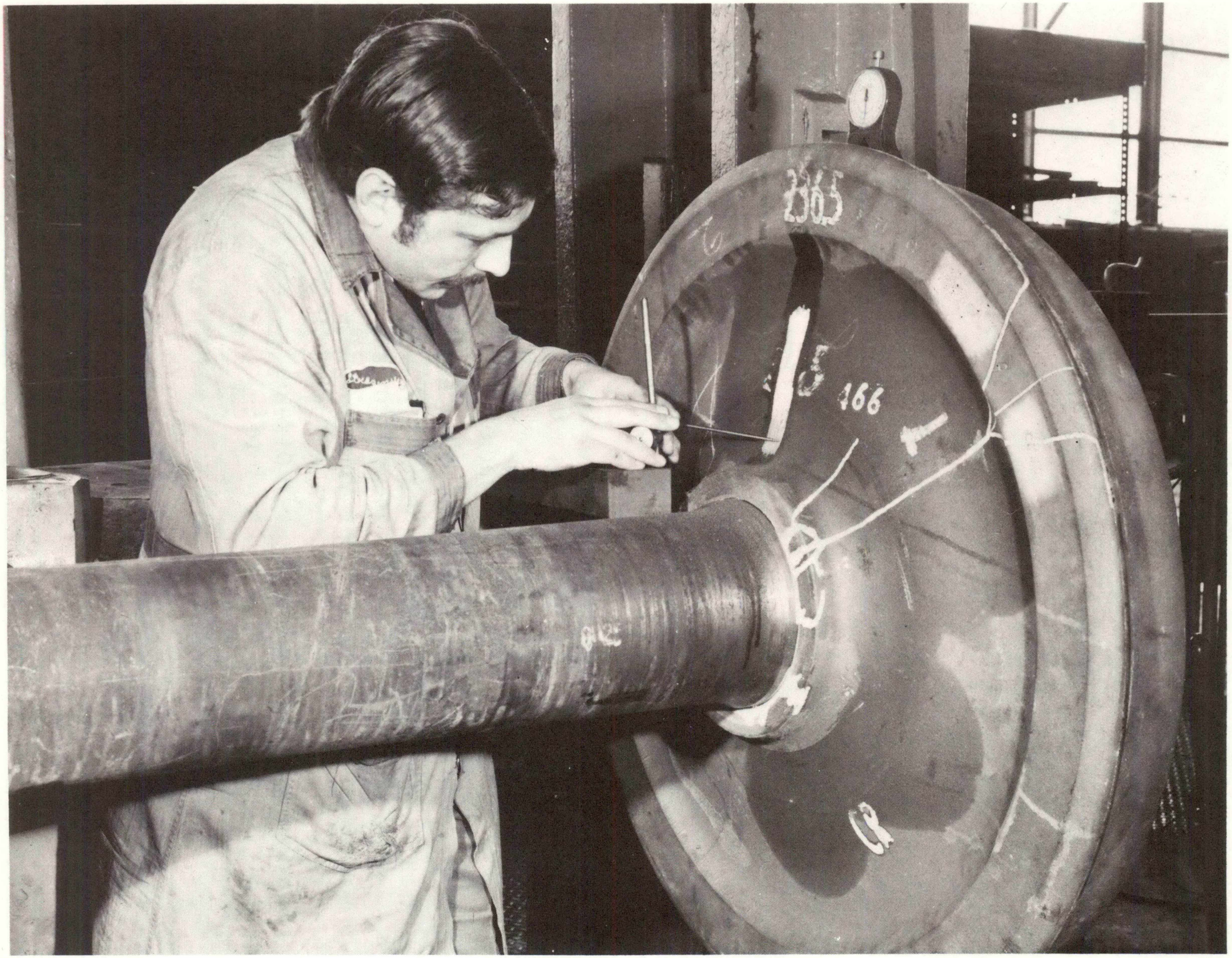


PHOTO 1 - WHEEL LAYOUT FOR EXPLORATORY GAGES

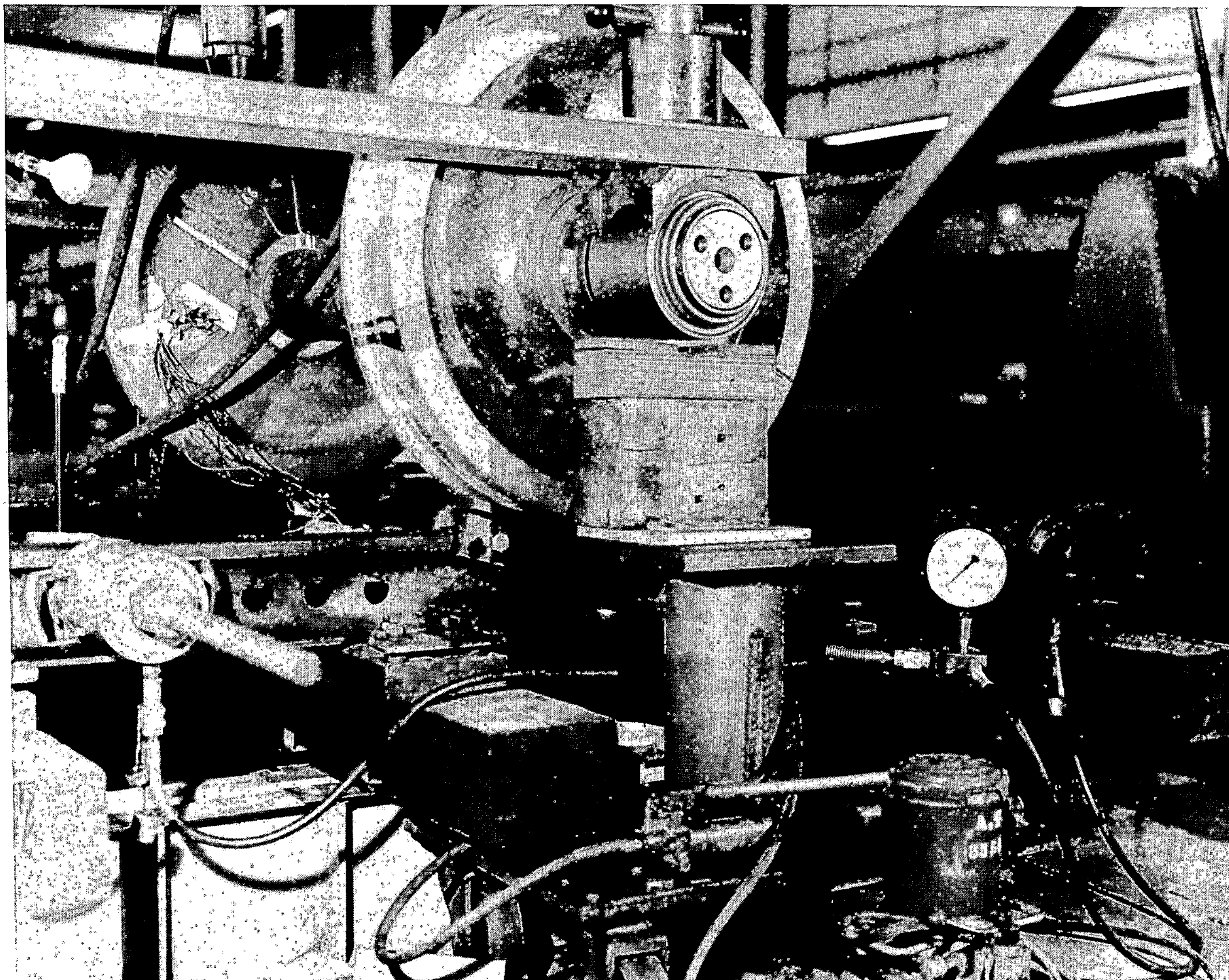


PHOTO 2 - LOADING APPARATUS - EXPLORATORY STRAIN GAGE CALIBRATION

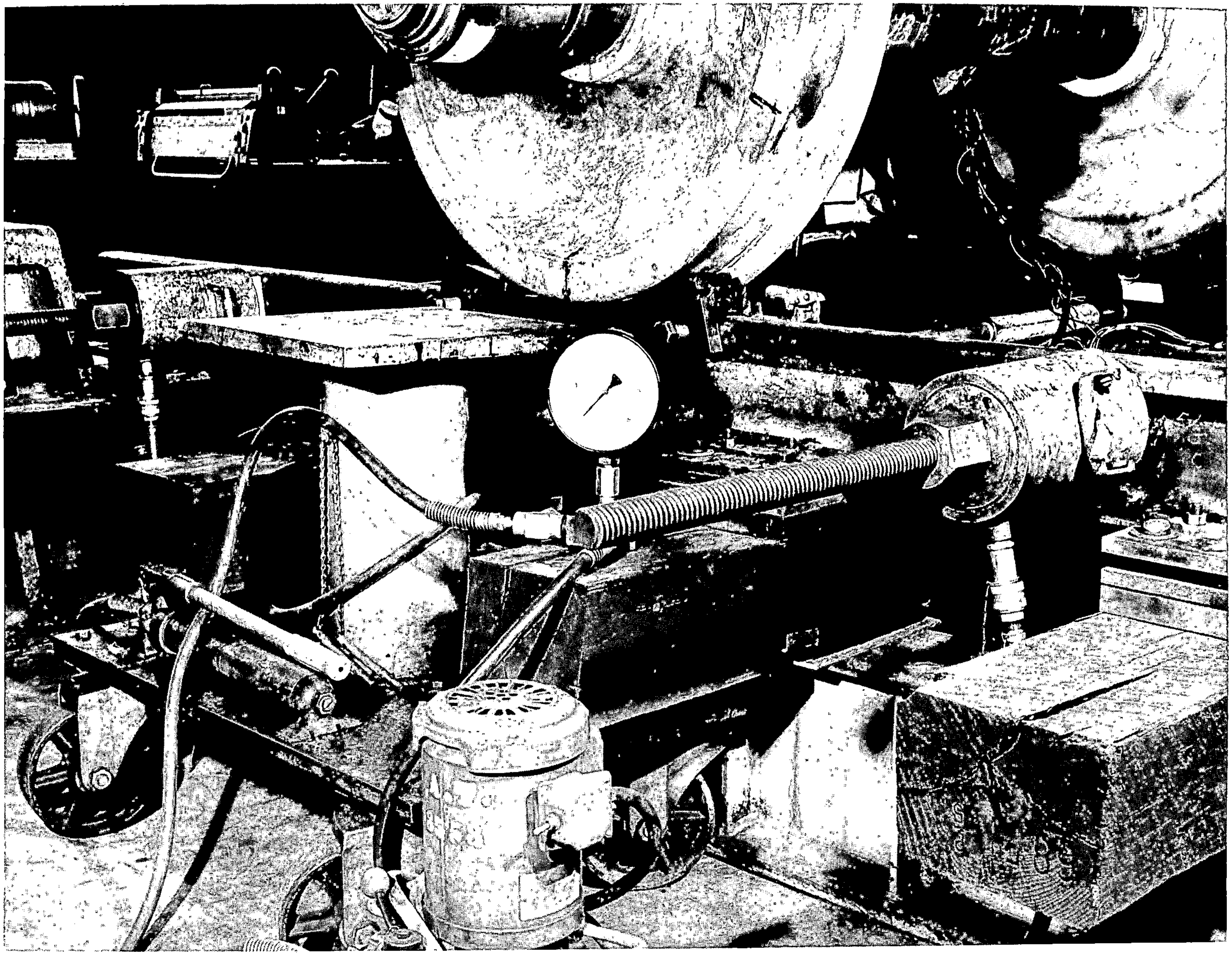


PHOTO 3 - LOADING APPARATUS SHOWING SIMPLEX JACKS
USED TO APPLY LATERAL LOAD

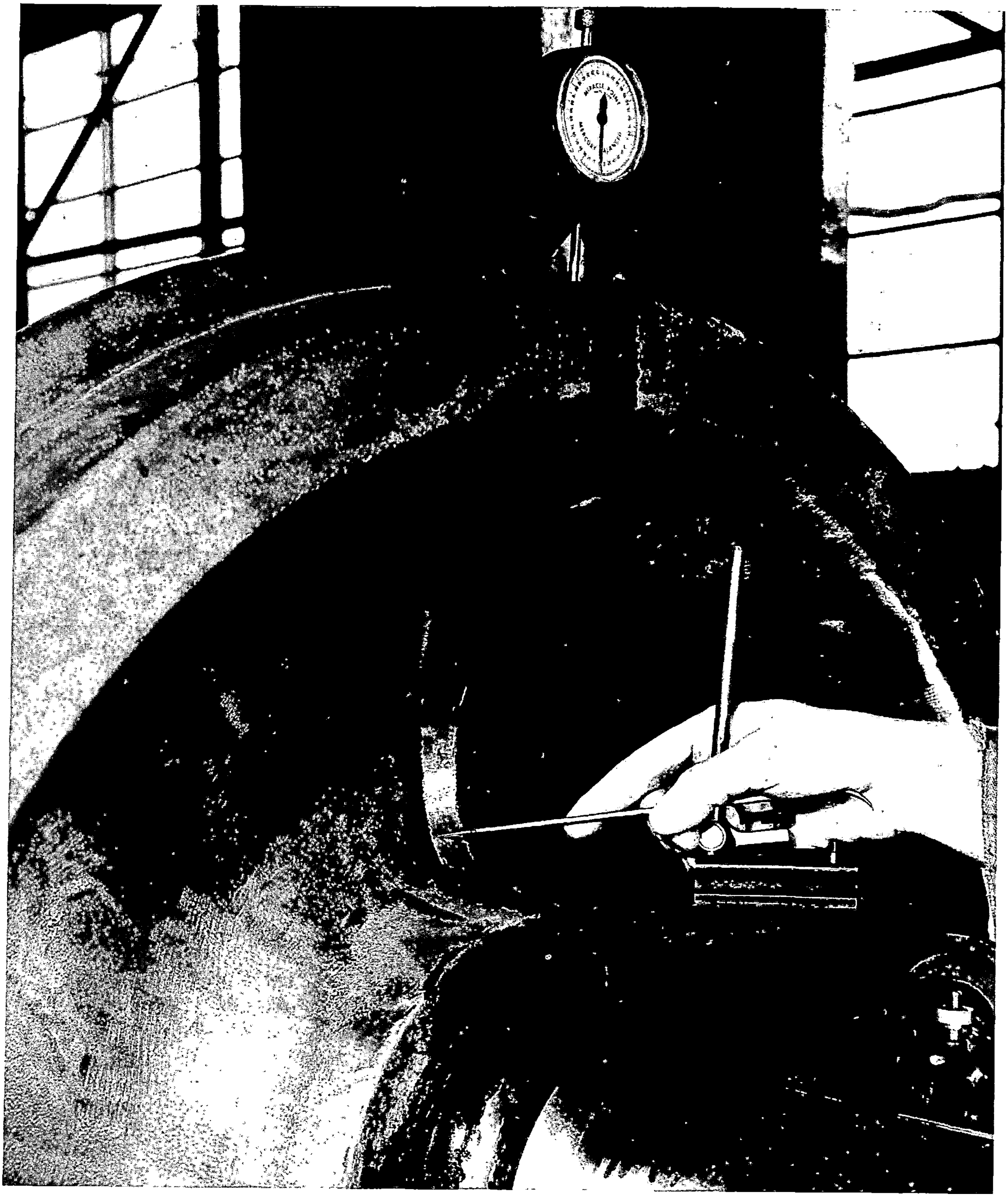


PHOTO 4 - WHEEL LAYOUT FOR FINAL STRAIN GAGING

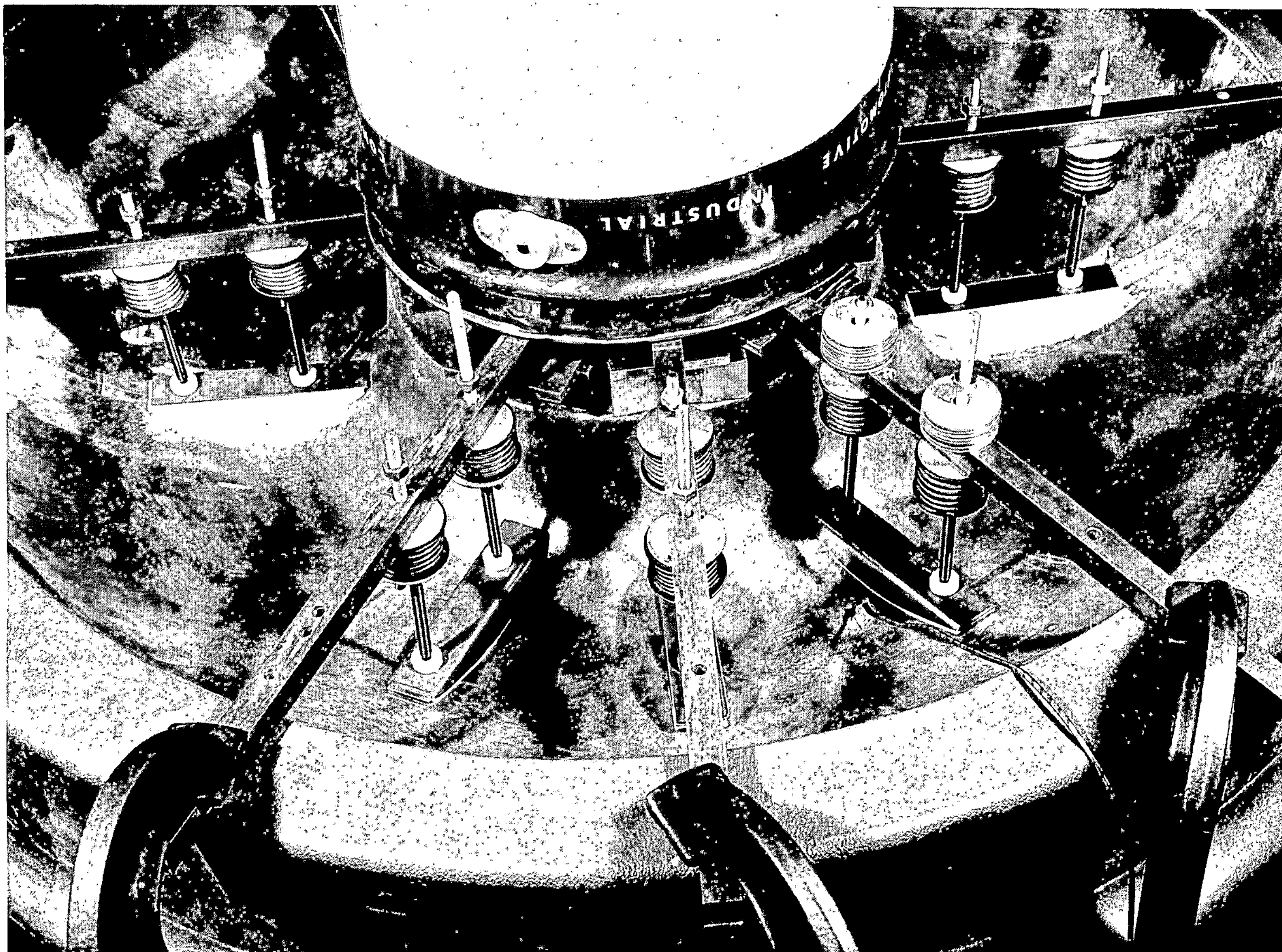


PHOTO - 5 STRAIN GAGING AND CLAMPING OPERATION

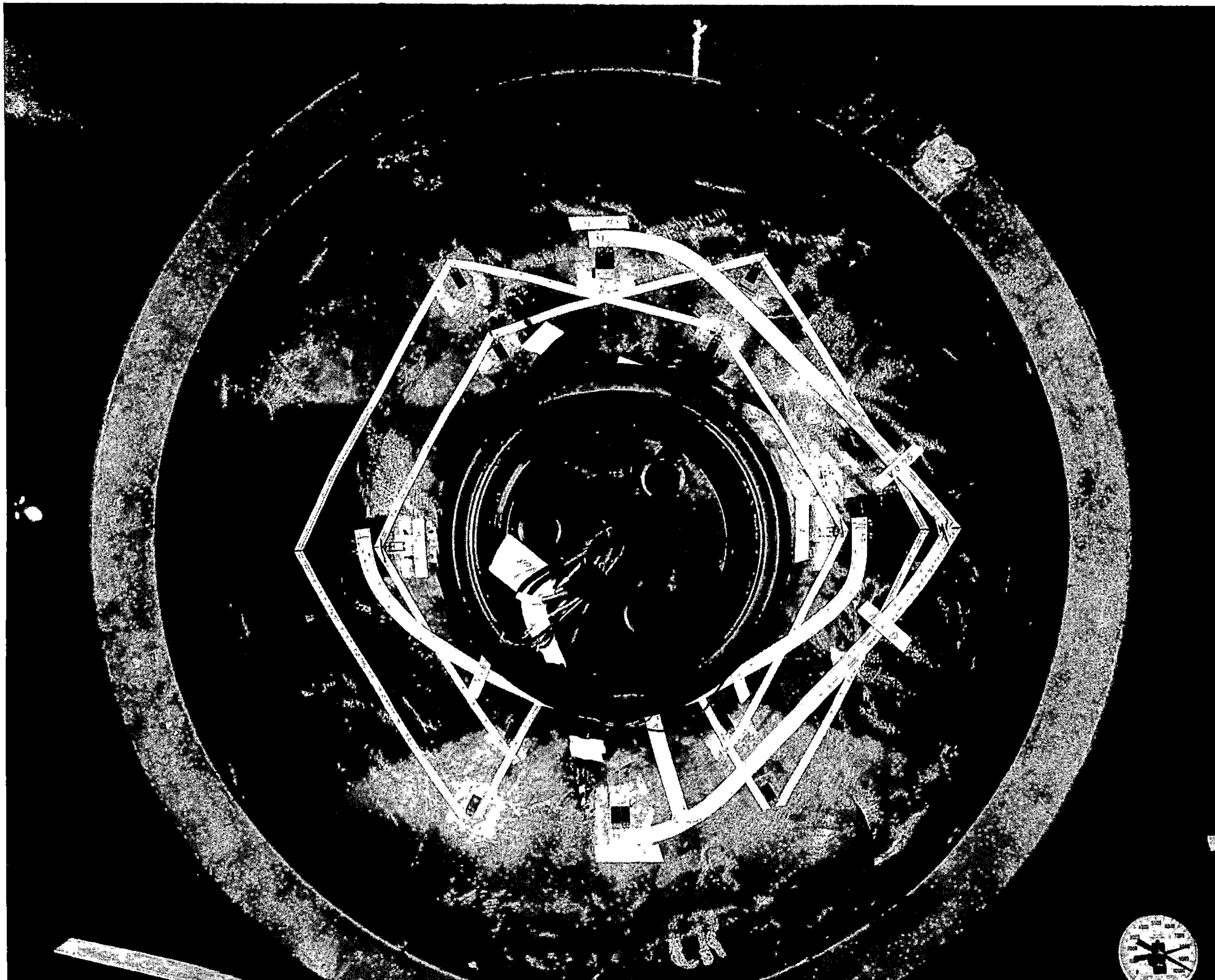


PHOTO 6 - STRAIN GAGE AND THERMOCOUPLE LOCATION AND WIRING

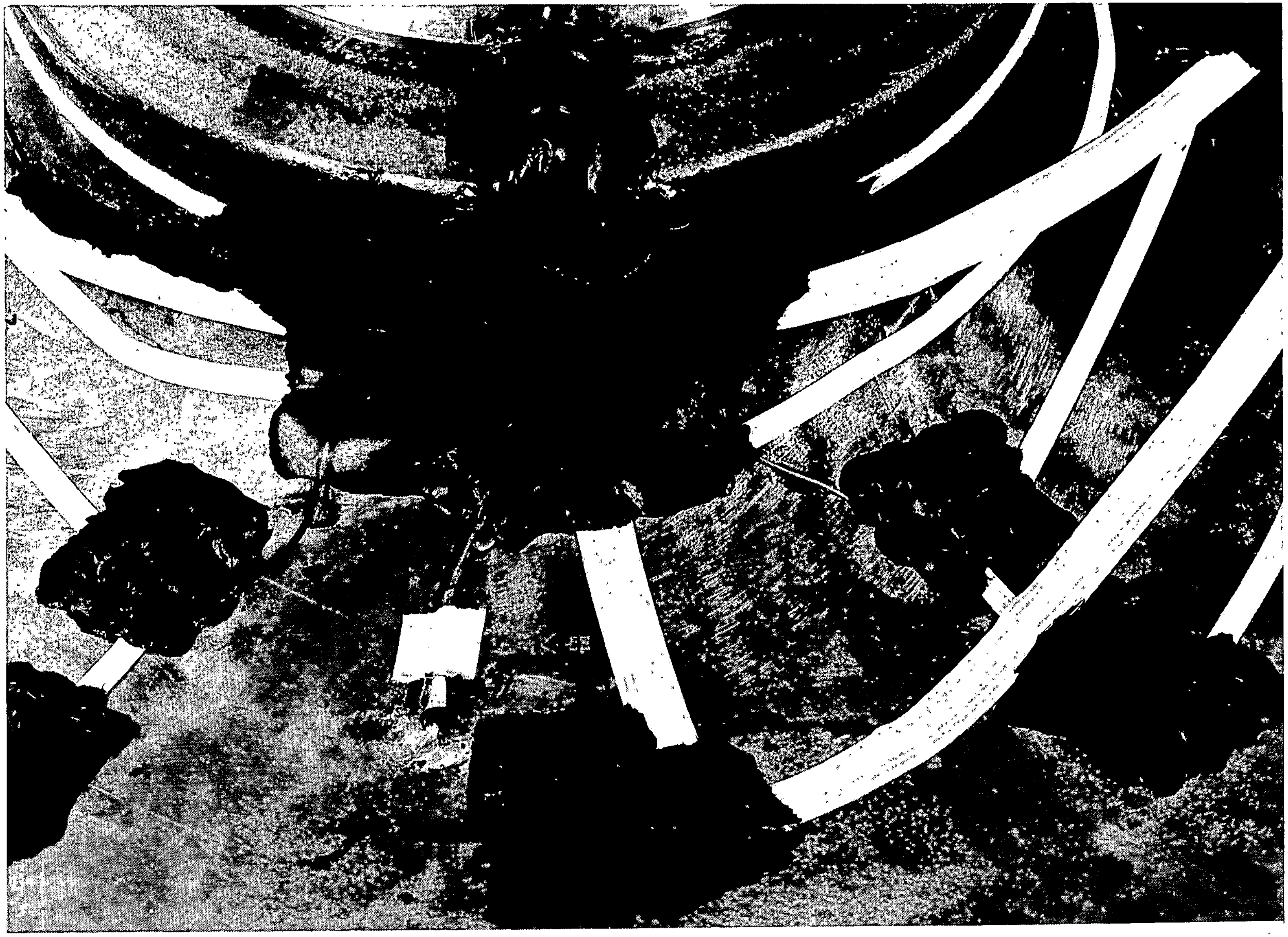


PHOTO 7 - APPLICATION OF SEALING AND DIELECTRIC COMPOUND

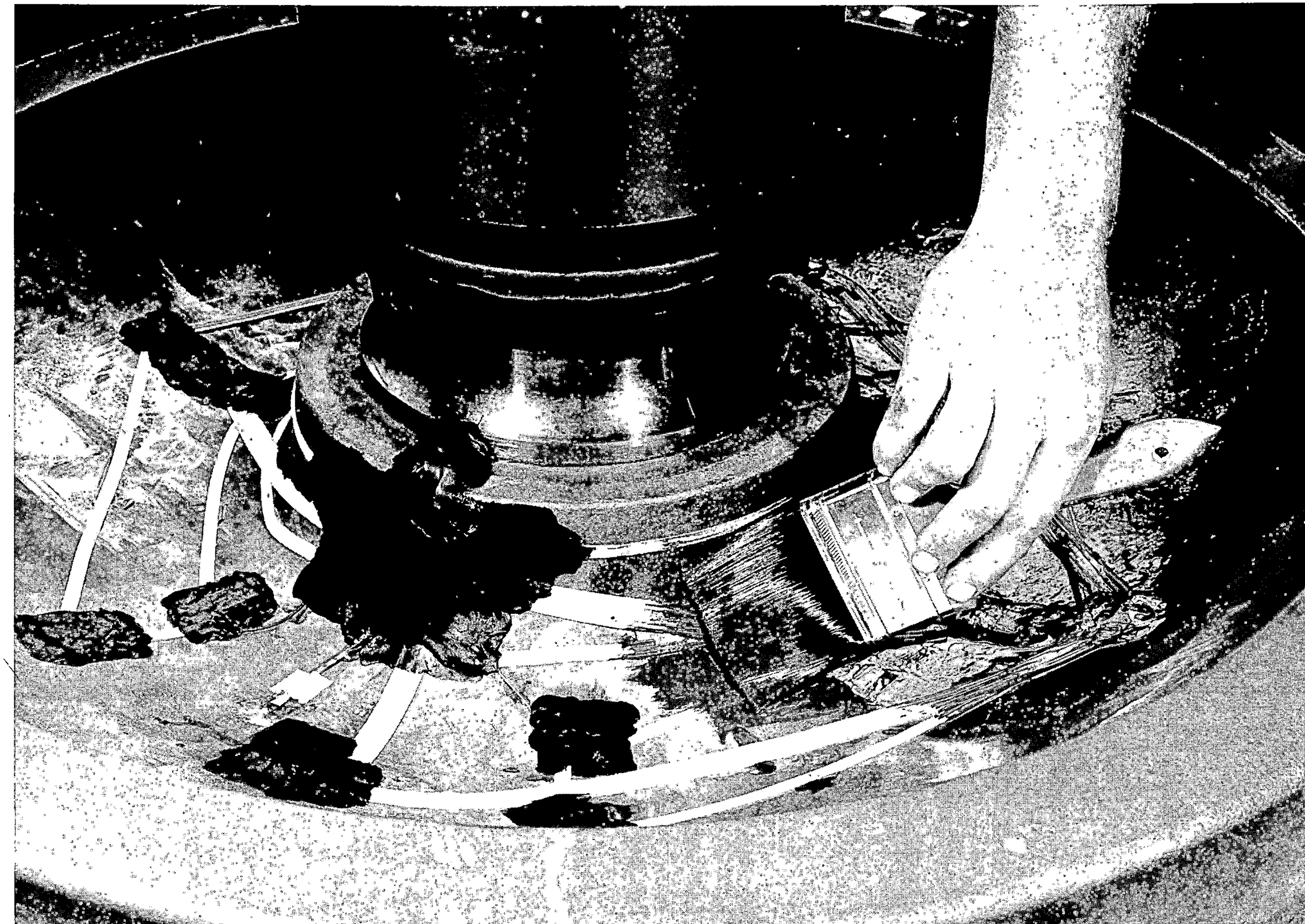


PHOTO 8 - WATERPROOFING OPERATION -
APPLICATION OF GLYPTAL AND SEALING AND DIELECTRIC COMPOUND

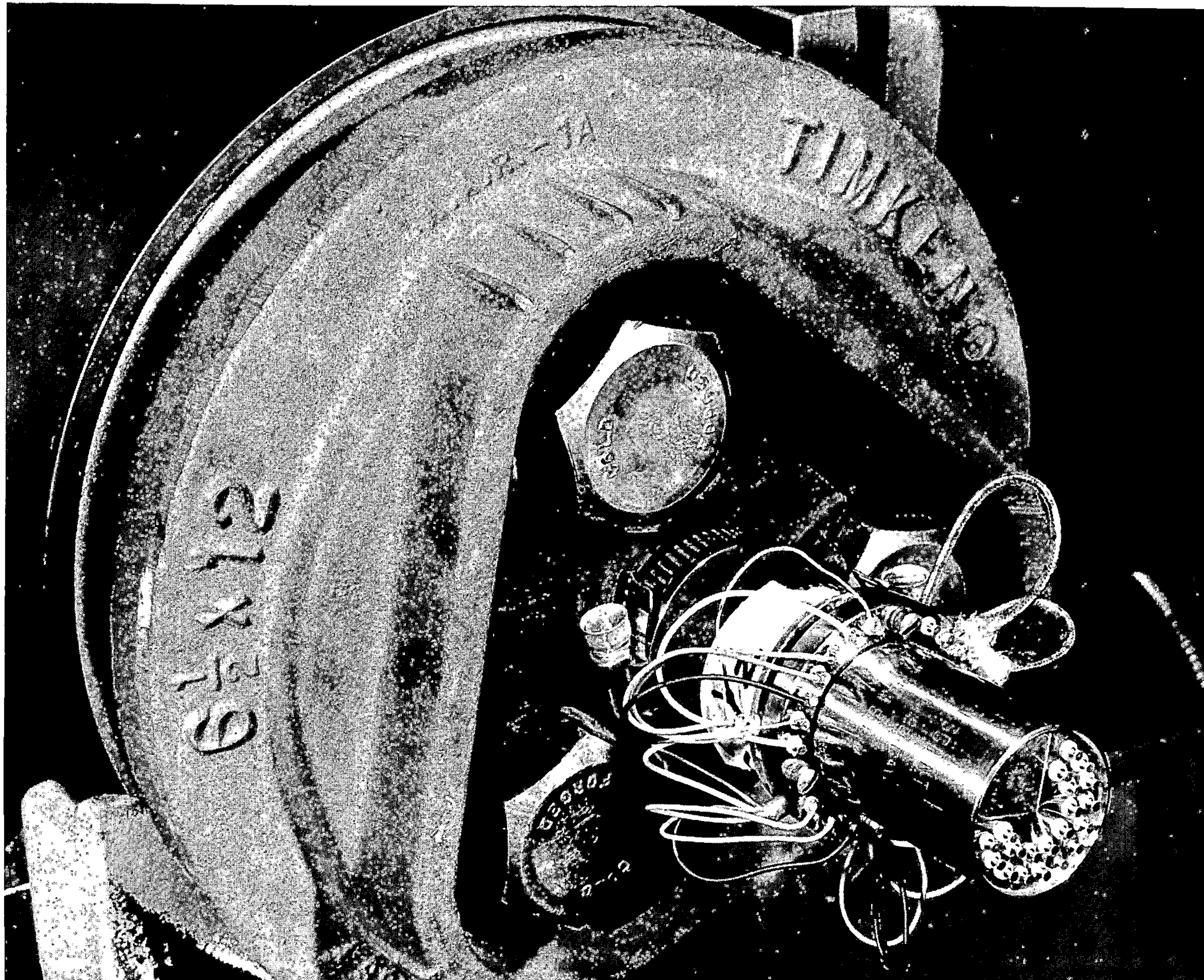


PHOTO 9 - PRELIMINARY SLIP RING HOOK-UP

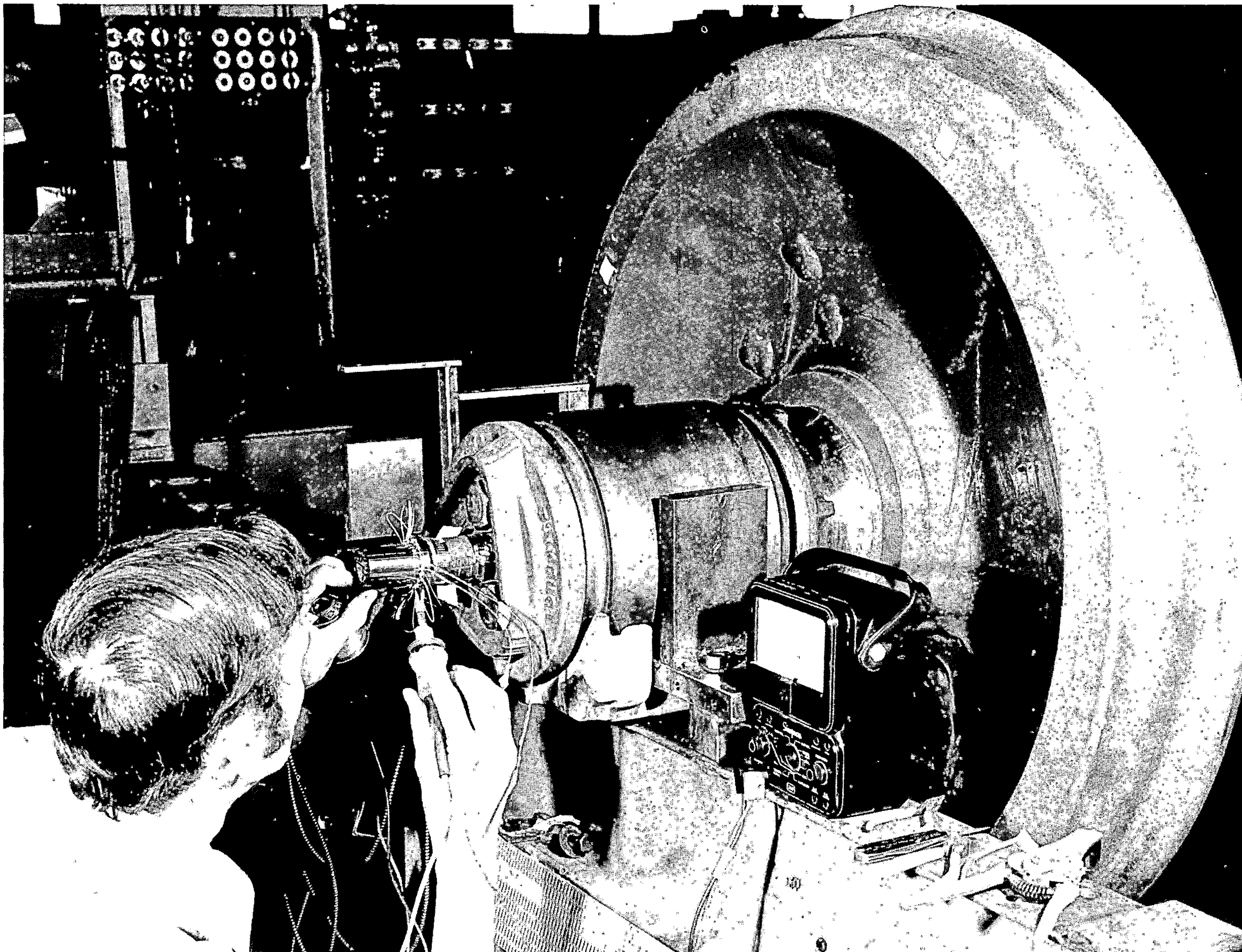


PHOTO 10 - INSTALLATION OF SLIP-RING ASSEMBLY

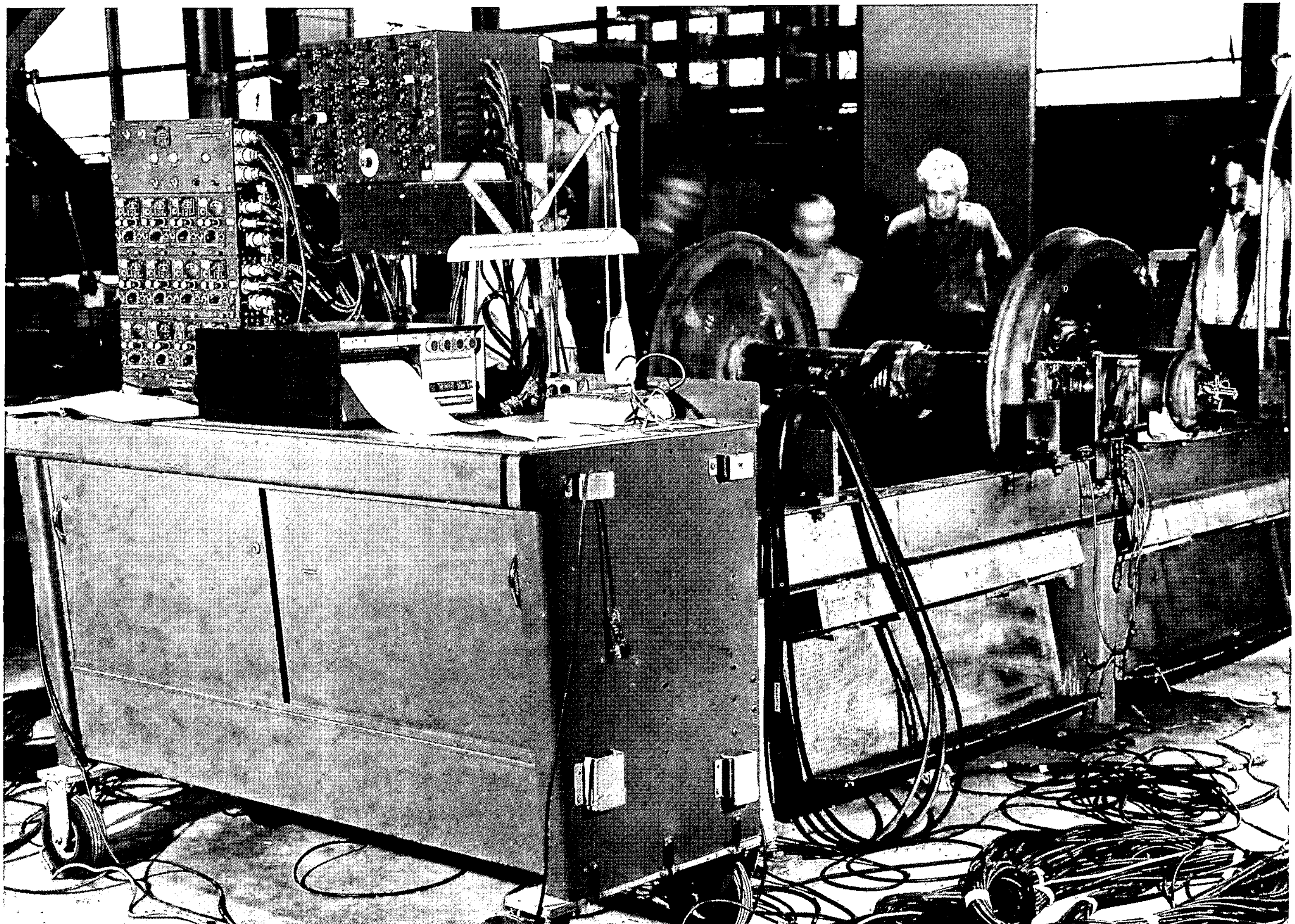


PHOTO 11 - TEST FIXTURE FOR WHEEL ROTATION AND HONEYWELL INSTRUMENTATION USED TO MONITOR VERTICAL AND LATERAL GAGES ON WHEEL SET

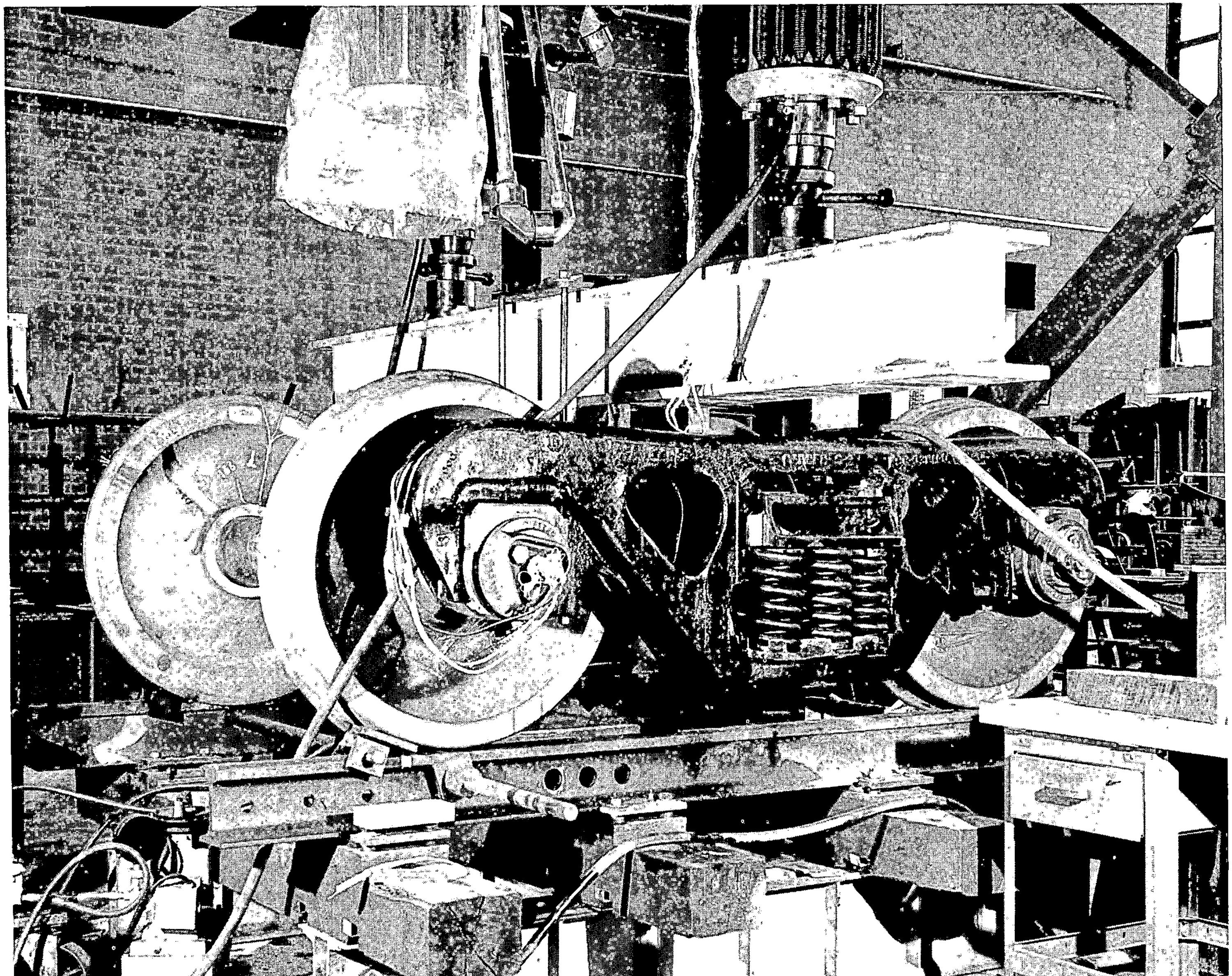


PHOTO 12 - FULLY ASSEMBLED TRUCK IN LOADING APPARATUS

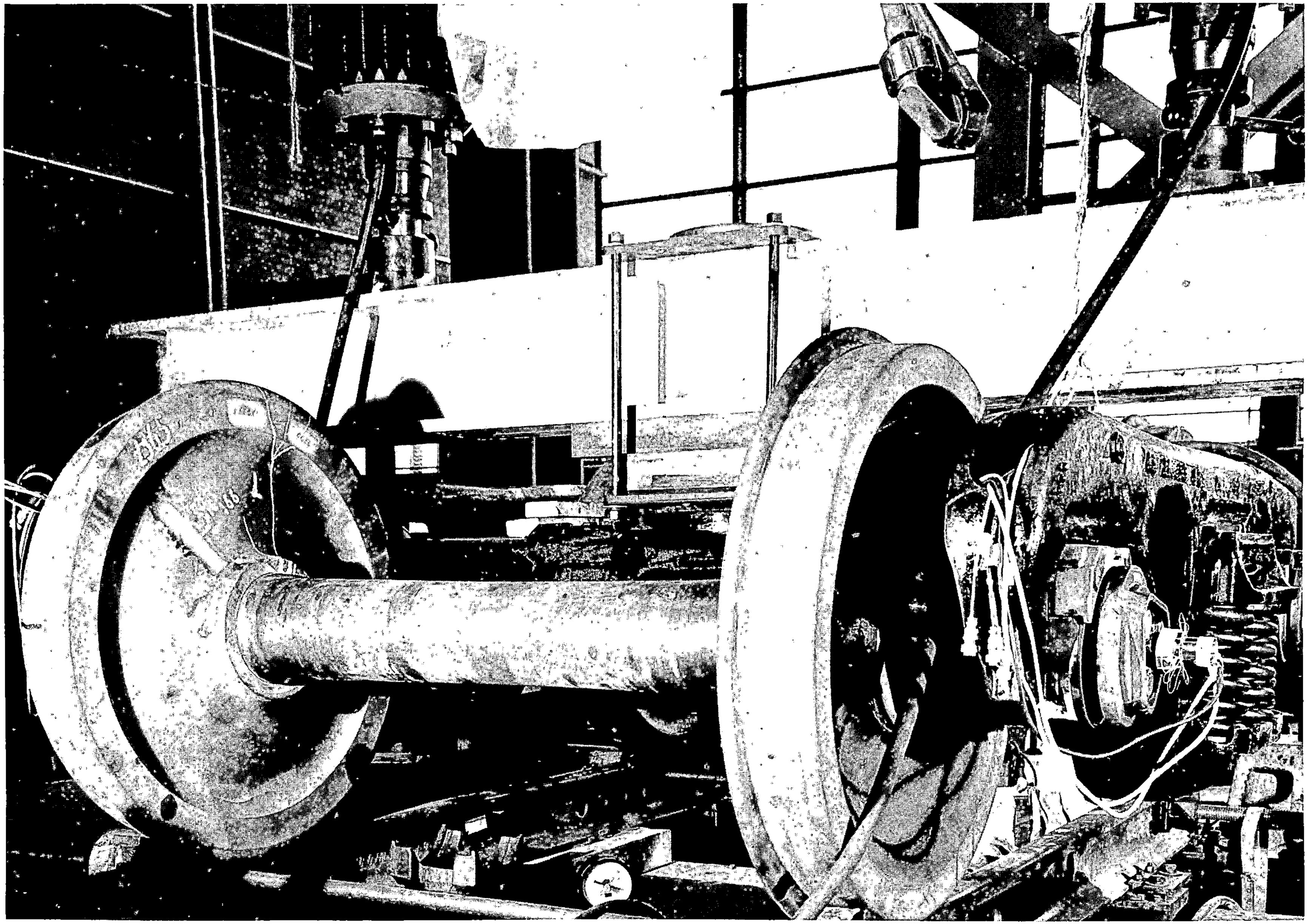


PHOTO 13 - LOADING APPARATUS - FINAL CALIBRATION OF FULLY ASSEMBLED TRUCK

EQUIPMENT RECOMMENDATION

It is recommended that the signal conditioning and recording equipment be of the following nature:

1. Any high quality D. C. type strain gage amplifier employing a differential input. A differential input is favorable due to the fact that one can operate several amplifiers from a single power supply.

2. Any high quality regulated D. C. power supply capable of delivering ± 50 volts D. C. with a regulation of 0.01% + 1 milli-volt and ripple of 250 micro-volts RMS. It is favorable to use D. C. signal conditioning equipment that incorporates built-in power supplies for each individual channel.

3. Any high quality light beam recording oscillograph employing electrically damped galvanometers having a frequency response of 200 hertz or higher.

Listed below are a few of the many companies that are capable of supplying high quality strain gage instrumentation:

Honeywell

Gould, Inc.

Bell and Howell

Hewlett-Packard

BLH Electronics

Kepco

Dana Laboratories

LIST OF INSTRUMENTATION USED IN THE CALIBRATION PROCESS OF FRA WHEEL SETS

Budd P-350 Strain Indicators

Shallcross Resistance Decade Box

Honeywell Signal Amplifiers Type 1-113B and Associated Power Supply and Oscillator

Honeywell 1508 Visicorder

Honeywell M-1000 Galvanometers

REFERENCES

- Rushing, F.C., "Determination of Stresses in Rotating Discs of Conical Profile," Trans. ASME, Vol. 53, p 91, 1931.
- Hodkinson, B, "Rotating Discs of Conical Profile", Engineering, Vol. 115, p 1, 1923.

DETERMINATION OF STRESSES IN ROTATING DISKS OF CONICAL PROFILE

In this paper a determination is made of the accuracy of stress-distribution curves obtained by the application of Donath's "Sum and Difference Curves" to rotating disks of conical profiles.

ROTATING disks of conical profiles (Fig. 1) are used rather extensively on account of their economy in the use of material and the facility with which they are produced. A rotating disk in which the stress is equally distributed is relatively thick near the axis and thin at the rim; the variation in the thickness of such a disk is not constant, however, and it is difficult to machine the sides to the exact shape. Since a conical profile approximates the profile necessary for equal stress distribution, and since a disk with straight sides is easily machined, such a disk is commonly used.

In calculating the stresses in conical disks, use is made of approximate methods whose accuracies have never been determined. One of the most extensively used approximate methods is an application of Donath's "Sum and Difference Curves."[3]

Fortunately, an exact method of calculating stresses in conical-profiled disks has been published by Mr. H. M. Martin.[4] The chief purpose of the present paper is to determine, with the use of Mr. Martin's exact method, the accuracy of the results obtained by the approximate application of Donath's "Sum and Difference Curves" to disks of conical profiles. In accomplishing this purpose, it is deemed desirable to include here a brief description of the derivation of each method, together with an example of its application; followed by a comparison of results obtained by the application of the two methods to a wide variety of shapes and sizes of conical disks.

Notation

x = radial distance from the axis
y = thickness of the disk at the distance x
σ_r = radial stress in pounds per square inch
σ_t = tangential stress in pounds per square inch
μ = mass density of material of the disk
ω = angular velocity of rotation
$\frac{1}{\nu}$ = Poisson's ratio
ξ = radial displacement at the end of radius x
R = radius at which extended sides would meet
D = $2R$
Y = thickness at center if sides were extended to center
N = revolutions per minute
z = x/R
P = $(1-z)\sigma_r$
Q = $(1-z)\sigma_t$
u = ωx
S = $\sigma_t + \sigma_r$
D = $\sigma_t - \sigma_r$
T = stress that would be produced in ring at radius R due to the centrifugal force of the ring.

Martin's Exact Method

Mr. Martin, in his paper, derived a differential equation covering the stress distribution in a rotating disk of conical profile. This derivation can be accomplished by applying the principle of equilibrium and the theory of elasticity to a particle in the disk. Applying the principle of equilibrium to a particle in a disk gives

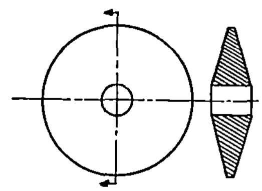


Fig. 1 Disk of Conical Profile

$$\frac{d(xy\sigma_r)}{dx} - y\sigma_t + \mu\omega^2x^2y = 0. \quad [1]$$

Applying the theory of elasticity to a particle in a disk gives the following pair of relations:

$$\left.\begin{aligned} \sigma_r &= \frac{E}{1-\nu^2}\left(\frac{d\xi}{dx} + \nu\frac{\xi}{x}\right) \\ \sigma_t &= \frac{E}{1-\nu^2}\left(\nu\frac{d\xi}{dx} + \frac{\xi}{x}\right) \end{aligned}\right\} \quad \ldots\ldots\ldots\ldots [2]$$

The following compatability equation can be obtained by eliminating ξ in Equation [2]:

$$\frac{d\sigma_t}{dx} - \nu\frac{d\sigma_r}{dx} = (1+\nu)\frac{\sigma_r - \sigma_t}{x} \ldots\ldots\ldots\ldots [3]$$

By combining Equations [1] and [3], eliminating σ_t between them, and by making the following changes in coordinates, namely,

$$x = Rz$$
$$y = Y(1-z)$$
$$P = \sigma_r(1-z), \text{ and}$$
$$Q = \sigma_t(1-z),$$

the following differential equation is obtained:[5]

$$z(1-z)\frac{d^2P}{dz^2} + (3-2z)\frac{dP}{dz} + (1-\nu)P + (3+\nu)Tz(1-z)^2 = 0 \ldots [4]$$

In deriving this differential equation, the following useful relations were found:

$$Q = P + z\frac{dP}{dz} + \mu\omega^2R^2(1-z)$$

$$T = 2 \times 10^{-6}D^2N^2$$

A complete solution of Equation [4] gives

$$P = P_1 + P_2 + P_3$$

where P_3 is the particular solution and

---

[1] The material presented in this paper was used in a thesis by the author for an M.S. degree from the University of Pittsburgh.

[2] Westinghouse Electric & Manufacturing Co. Mr. Rushing was born in 1906 in Runge, Texas, where he lived until he entered the University of Texas in 1924. He received a B.S. degree from this university in 1928, and became an employee of the Westinghouse Elec. & Mfg. Co. shortly thereafter. As an employee of this company, he was permitted to take the design training course, which enabled him to attend the University of Michigan during the Summer session of 1929 and to receive also some graduate credit from the University of Pittsburgh. He received an M.S. degree from the University of Pittsburgh in 1930. At the present time he is in the design section of the Industrial Motor Engineering Department of the Westinghouse Company.

[3] Developed by M. Donath in "Die Berechnung rotierender Scheiben und Ringe" (Berlin, G. Springer, 1912), and described by H. Hearle in "The Strength of Rotating Discs," *Engineering*, vol. cvi, Aug. 9, 1918, pp. 131–134.

[4] "Stress Distribution in Rotating Disks of Conical Profile," *Engineering*, vol. cxv, Jan., 1923, p. 1.

Contributed by the Applied Mechanics Division and presented at the Annual Meeting, New York, N. Y., Dec. 1 to 5, 1930, of The American Society of Mechanical Engineers.

[5] An error appeared in Mr. Martin's paper as published. In the last term of Equation [4], the factor $(3+\nu)$ was written and used as $(3-\nu)$.

$$P_1 = A\left(1 - \frac{0.7}{3}z - \frac{0.7}{3}\frac{1.3}{8}z^2 - \frac{0.7}{3}\frac{1.3}{8}\frac{5.3}{15}z^3 - - - - - -\right)$$

$$P_2 = B(1-z)^2\left[1 + \frac{5.3}{3}(1-z) + \frac{5.3}{3}\frac{11.3}{8}(1-z)^2 + \frac{5.3}{3}\frac{11.3}{8}\frac{19.3}{15}(1-z)^3 + + + + + +\right]$$

$$P_3 = T(0.13525 - 0.03156z - 0.34263z^2 + 0.23894z^3)$$

A and B being constants of integration.

Referring now to the change made in the coordinates, note that

$$\sigma_r = \frac{P_1 + P_2 + P_3}{(1-z)}$$

$$\sigma_t = \frac{Q_1 + Q_2 + Q_3}{(1-z)}$$

The use of this method is simplified by reducing the functions of z contained in P and Q to numerical form. This step is possible and practical since z varies only from zero to unity. Table 1 is the result of the introduction of numerical quantities in these functions.

Furthermore, since each of the terms in P and Q is divided by $(1 - z)$, this division can be made in Table 1, and Table 2 is established.

In order to fully explain the use of this method, it is applied to a specific example (Fig. 2).

Calculating the radius at which the extended sides will meet gives

$$R = 32.5 \text{ in.}$$

$$z_{hub} = \frac{5}{32.5} = 0.1538$$

$$z_{rim} = \frac{21.5}{32.5} = 0.6616$$

By graphical interpolation the following values for Table 2 are obtained for the boundary values of z:

z	p_1	q_1	p_2	q_2	p_3	q_3
0.1538	0.174	0.1743	1.632	1.568	—27.150	35.000
0.6616	0.120	0.1525	3.490	2.608	— 0.747	3.407

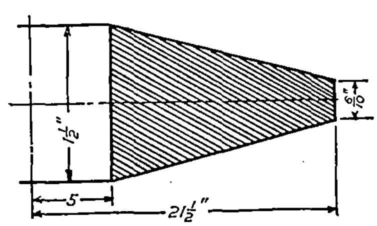


FIG. 2 EXAMPLE OF USE OF MARTIN'S METHOD
(Material of disk, steel; rim load, 8850 lb. per sq. in.; hub load, —710 lb. per sq. in.; speed, 3000 r.p.m.)

Substituting in the expression for T gives

$$T = 2 \times 10^{-6} \times 65^2 \times 3000^2 = 76{,}040$$

Since, according to the solution of the differential equation,

$$\sigma_r = Tp_1 + Ap_2 + Bp_3$$

and since the radial stresses on the rim and the hub are known, together with the above computed values of Table 2 for the rim and the hub,

$$8850 = 76{,}040 \times 0.12 + 3.490A + (-0.747)B$$

$$-710 = 76{,}040 \times 0.174 + 1.632A + (-27.15)B$$

Solving the two equations for A and B gives

$$A = 29.9 \quad \text{and} \quad B = 528$$

TABLE 1[1]

z	$P_1 = Ax$	$Q_1 = Ax$	$P_2 = Bx$	$Q_2 = Bx$	$P_3 = Tx$	$Q_3 = Tx$
0.00	1.00000	1.00000	∞	∞	0.1655	0.1655
0.05	.....	.....	—259.74	274.18		
0.10	0.97627	0.95214	— 59.957	69.549	0.1577	0.1555
0.15	.....	.....	— 24.380	31.065		
0.20	0.95170	0.90163	— 12.431	17.525	0.1434	0.1410
0.25	.....	.....	— 7,1497	11.159		
0.30	0.92616	0.84800	— 4.4597	7.6257	0.1233	0.1239
0.35	.....	.....	— 2.8517	5.5453		
0.40	0.89953	0.79059	— 1.8949	4.1494	0.1017	0.1043
0.45	.....	.....	— 1.2804	3.1844		
0.50	0.87163	0.72853	— 0.87163	2.4718	0.07799	0.0838
0.60	0.84220	0.66047	— 0.39950	1.5264	0.05423	0.0631
0.70	0.81091	0.58429	— 0.17011	0.93046	0.03280	0.0433
0.80	0.77723	0.49589	— 0.05943	0.52287	0.01611	0.0257
0.90	0.74021	0.38711	— 0.01205	0.22632	0.00442	0.0110
1.00	0.69702	0.20911	— 0.00000	0.00000	0.00000	0.0000

[1] Values of P_1, Q_1, P_2, Q_2 from Martin's paper.

TABLE 2[1]

	Stresses due to centrifugal forces		Stresses due to a pull of 1 lb. per inch run applied to knife edge forming periphery of disk		Stress coefficients due to an infinite pressure applied to interior of infinitely small hole in the center	
z	Radial $p_1 = Tx$	Tangential $q_1 = Tx$	Radial $p_2 = Ax$	Tangential $q_2 = Ax$	Radial $p_3 = Bx$	Tangential $q_3 = Bx$
0.00	0.1655	0.1655	1.435	1.435	∞	∞
0.05	0.1709	0.1695	1.497	1.475	—273.400	288.600
0.10	0.1753	0.1725	1.559	1.518	— 66.620	77.280
0.15	0.1782	0.1749	1.627	1.565	— 28.680	36.550
0.20	0.1794	0.1763	1.707	1.617	— 15.540	21.910
0.25	0.1784	0.1773	1.796	1.674	— 9.553	14.880
0.30	0.1761	0.1767	1.898	1.738	— 6.371	10.890
0.35	0.1734	0.1757	2.015	1.809	— 4.387	8.531
0.40	0.1694	0.1739	2.151	1.890	— 3.158	6.915
0.45	0.1635	0.1712	2.311	1.983	— 2.328	5.788
0.50	0.1560	0.1675	2.501	2.090	— 1.743	4.944
0.55	0.1465	0.1633	2.733	2.217	— 1.309	4.301
0.60	0.1355	0.1579	3.021	2.369	— 0.9988	3.816
0.65	0.1229	0.1525	3.390	2.556	— 0.7523	3.419
0.70	0.1094	0.1445	3.860	2.794	— 0.5670	3.102
0.75	0.0956	0.1370	4.559	3.111	— 0.4161	2.835
0.80	0.0805	0.1286	5.563	3.557	— 0.2971	2.614
0.85	0.0634	0.1193	7.263	4.276	— 0.1995	2.421
0.90	0.0442	0.1100	10.620	5.554	— 0.1203	2.263
0.95	0.0231	0.0976	20.645	8.890	— 0.0555	2.140
1.00	0.0000	0.0840	∞	∞	— 0.0000	2.051

[1] Values of p_2, q_2, p_3, q_3 taken from Martin's paper.

Having found A and B from known boundary conditions, the stresses can be found for any radius in the disk. Consider a case when $z = 0.2$; then x the radius $= 32.5 \times 0.2 = 6^1/_2$ in., and at $6^1/_2$ in. the stresses are:

$$\sigma_r = 76{,}040 \times 0.1795 + 29.9 \times 1.707 - 528 \times 15.54 = 5{,}500$$

$$\sigma_t = 76{,}040 \times 0.1833 + 29.9 \times 1.617 + 528 \times 21.9 = 25{,}600$$

The complete stress-distribution curves found in this manner are the exact stress curves in Fig. 8.

DONATH'S "SUM AND DIFFERENCE CURVES"

An approximate application of Donath's "Sum and Difference Curves" has been a popular method of determining stresses in rotating disks of variable cross-section. The "Sum and Difference" in this case means the sum and difference of stresses along a radius.

The sum and difference curves in this case are of course linked with the differential equation covering stresses in a rotating disk. If the values of σ_t and σ_r, Equation [2], are introduced in Equation [1] the following differential equation is obtained:

$$\frac{d^2\xi}{dx^2} + \left[\frac{d(\log_e y)}{dx} + \frac{1}{x}\right]\frac{d\xi}{dx} + \left[\frac{\nu}{x}\frac{d(\log_e y)}{dx} - \frac{1}{x^2}\right]\xi + \frac{(1-\nu)}{E}\mu\omega^2x^2 = 0 \ldots [5]$$

This equation differs from [4] only in its coordinates. Setting y equal to a constant in this equation, solving it for ξ, and placing the result in the expressions for σ_t and σ_r, Equation [2] gives the following well-known expressions for stresses in a rotating disk of uniform thickness:

$$\sigma_r = \frac{E}{1-\nu^2}\left[(3+\nu)Kx^2 + (1+\nu)b_1 - (1-\nu)b_2\frac{1}{x^2}\right]$$

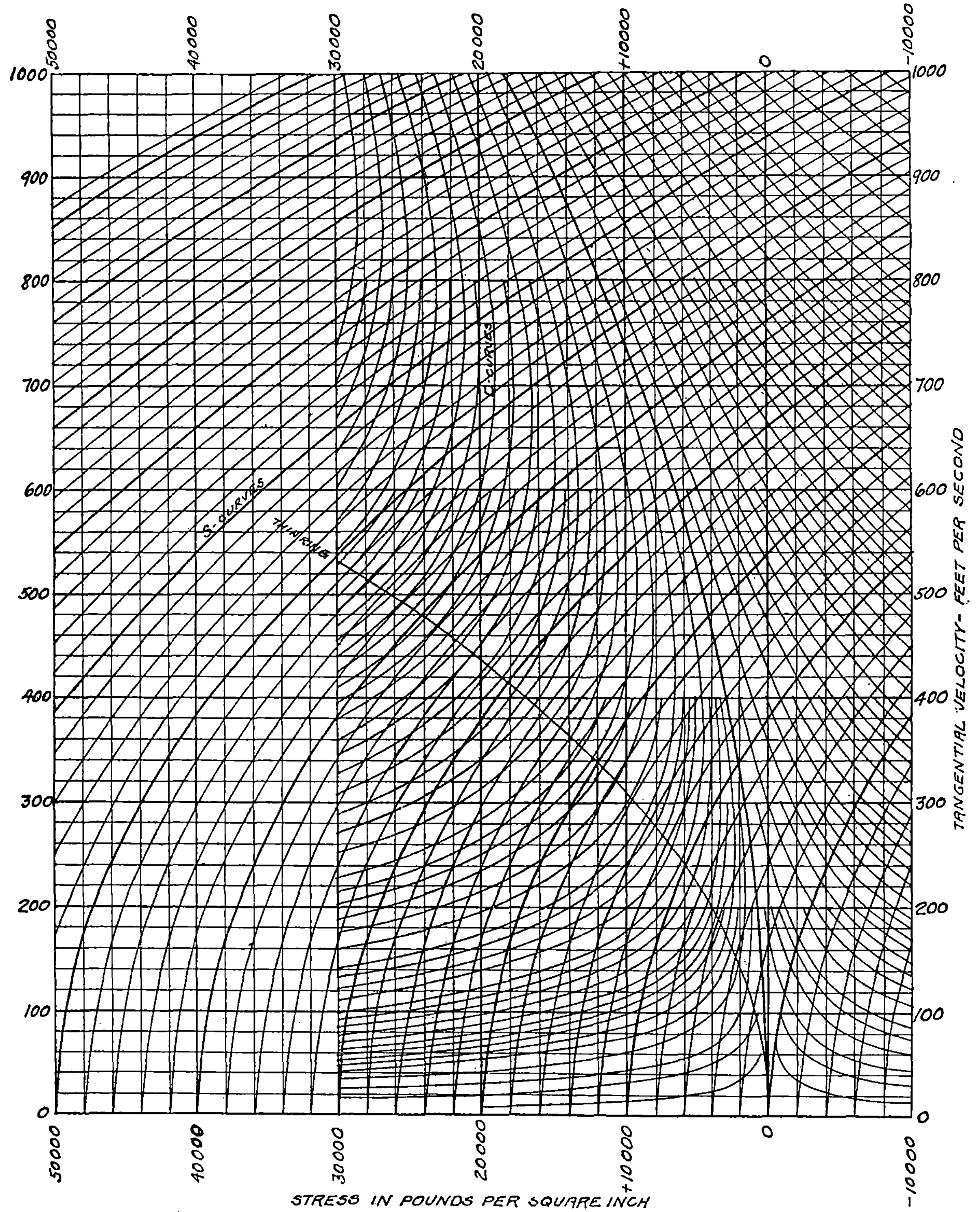


Fig. 3 Donath's "Sum and Difference" Curves of Tangential and Radial Stresses for Parallel-Sided Elastic Steel Disks

$$\sigma_t = \frac{E}{1 - \nu^2}\left[(1 + 3\nu)\,Kx^2 + (1 + \nu)b_1 + (1 - \nu)b_2\frac{1}{x^2}\right]$$

where $K = \dfrac{(1 - \nu^2)\mu\omega^2}{8E}$, and b_1 and b_2 are constants of integration.

Donath discovered that by adding and subtracting the expressions for σ_t and σ_r and letting

$$S = \sigma_t + \sigma_r$$
$$D = \sigma_t - \sigma_r$$
$$u = \omega x$$

the following relatively simple functions were obtained:

$$S = (1 + \nu)\frac{\mu}{2}\left[-u^2 + K_1\right]$$

$$D = (1 - \nu)\frac{\mu}{4}\left[u^2 + \frac{K_2}{u^2}\right]$$

These functions were plotted for a series of K's, Fig. 3, covering a field of stresses and speeds in which disks in practical use will fall.

The common method of applying these curves to a conical disk is to assume the disk to be divided into a number of disks of uniform thicknesses (Fig. 4).

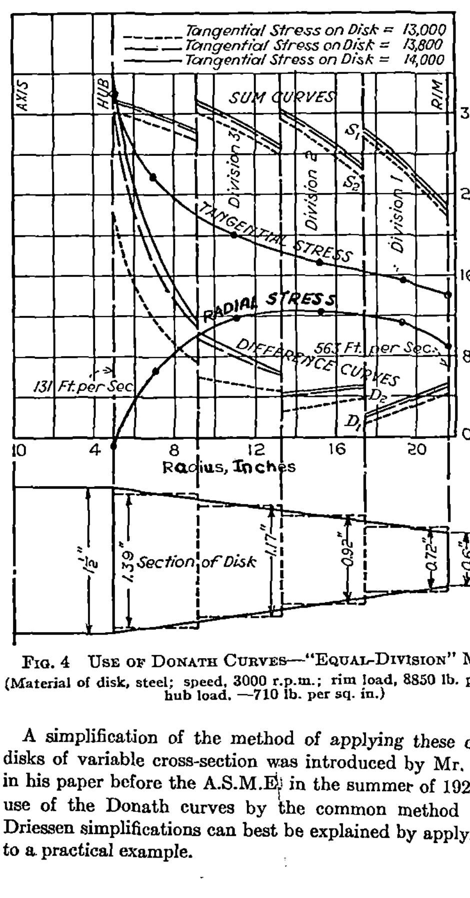


FIG. 4 USE OF DONATH CURVES—"EQUAL-DIVISION" METHOD
(Material of disk, steel; speed, 3000 r.p.m.; rim load, 8850 lb. per sq. in.; hub load. —710 lb. per sq. in.)

A simplification of the method of applying these curves to disks of variable cross-section was introduced by Mr. Driessen in his paper before the A.S.M.E. in the summer of 1928.[6] The use of the Donath curves by the common method with the Driessen simplifications can best be explained by applying them to a practical example.

Refer to the example represented in Fig. 4, assume the disk to be made up of four disks of uniform axial thicknesses and of equal radial thicknesses as shown. Since the tangential stress on the rim is not known, assume

$$\sigma_t \text{ for the rim} = 13{,}000 \text{ lb. per sq. in.}$$

then

$$S_{\text{rim}} = 13{,}000 + 8850 = 21{,}850$$
$$D_{\text{rim}} = 13{,}000 - 8850 = 4150$$

Having these values of S and D at the known rim speed locates the S- and D-curves applicable to this imaginary disk in Fig. 3. Transfer the S- and D-curves between the boundary speeds of this outer imaginary disk to Fig. 4.

Mr. Driessen's method of passing across a boundary by assuming that the tangential stress on either side of a boundary is the same and that the radial stress varies inversely as the thicknesses of the imaginary disks can be used at this point. He showed that

$$\Delta S = -0.65\left(1 - \frac{t_1}{t_2}\right)\left(S_1 - D_1\right)$$

$$\Delta D = 0.35\left(1 - \frac{t_1}{t_2}\right)\left(S_1 - D_1\right)$$

where ΔS and ΔD are the changes in S and D, t_1 is the thickness of the disk just passed, and t_2 the thickness of the disk being entered. In this case

$$\Delta S = -0.65\left(1 - \frac{0.72}{0.92}\right)\left(29{,}500 - 1500\right) = -3970$$

$$\Delta D = 0.35\left(1 - \frac{0.72}{0.92}\right)\left(29{,}500 - 1500\right) = 2140$$

Adding these increments to S_1 and D_1 gives S_2 and D_2, which are known values of S and D on the outer boundary of Division 2.

Following this procedure in crossing each of the imaginary disks, the S- and D-curves can be established across the entire radius of the disk. It happens in this case that the radial stress indicated at the hub by these curves is 5100, while the actual radial stress is known to be —710; this difference is an indication that the wrong tangential stress was assumed for the rim.

Assume another tangential stress of 13,800 for the rim, and establish the second set of S- and D-curves as are indicated in

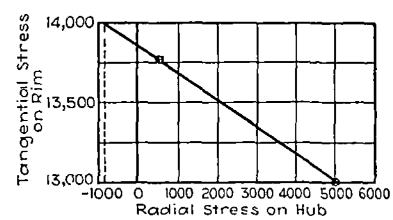


FIG. 5 RELATION BETWEEN RADIAL AND TANGENTIAL STRESSES ON HUB

Fig. 4. At the hub, this set of curves indicates a radial hub stress of 500, which is also incorrect.

At this point in the process, another one of Mr. Driessen's simplifications can be used. He showed that there was a direct relation between the radial stress on one boundary and the tangential stress on the opposite boundary. In this case the two assumed tangential rim stresses with their consequent radial hub stresses can be plotted as in Fig. 5. On this graph the tangential stress on the rim which will give a radial stress of —710 on the hub is indicated to be 14,000.

With this new value of tangential stress on the rim, the third set of S- and D-curves in Fig. 4 can be established.

[6] "A Simplified Method of Determining Stresses in Rotating Disks," M. G. Driessen, Trans. A.S.M.E., 1928.

Since the midpoint between the boundaries of each of the divisions is of the same thickness as the actual disk at that point, the values of S and D indicated at such points are assumed to be most accurate. Through these points the stress-distribution curves, Fig. 4, are established.

The stress-distribution curves obtained in this manner, as well as others obtained by using two and eight divisions of the disk, have been transferred to Fig. 8 where their relative accuracies can be obtained by comparing them to the exact stress-distribution curves.

One-Equivalent-Disk Method

Some experimentation with the application of Donath's curves has shown that there are other satisfactory methods of applying them. One of the methods involves the assuming of one equivalent disk of uniform thickness equal to the hub thickness of the conical disk for the conical disk. Also, it is assumed that the radial rim stress on this imaginary disk is equal to the radial rim stress of the conical disk decreased in a ratio of rim thickness to hub thickness of the conical disk. To this new disk apply Donath's curves just as they would be applied to a disk of uniform thickness. The stresses indicated by these curves at the hub and at the midpoint between the rim and the hub and the known stresses on the rim are used to construct the stress-distribution curves.

For a better explanation of this equivalent-disk method, consider an example (Fig. 6). Assume

$$\sigma_t \text{ for the rim } = 13{,}000$$

then

$$S_{\text{rim}} = \sigma_t + \sigma_r = 13{,}000 + 8850 = 21{,}850$$

$$D_{\text{rim}} = \sigma_t - \sigma_r = 13{,}000 - 8850 = 4150$$

Reducing the rim radial stress in a ratio of rim thickness to hub thickness gives the change in S and D by Mr. Driessen's method as

$$\Delta S = -0.65\left(21{,}850 - 4150\right)\left(1 - \frac{0.6}{1.5}\right) = -6900$$

$$\Delta D = 0.35\left(21{,}850 - 4150\right)\left(1 - \frac{0.6}{1.5}\right) = 3700$$

so $S_1 = 14{,}950$ and $D_1 = 7850$.

Locating these values of S and D on the Donath curve sheet at the rim speed establishes two curves which, when followed to the hub speed and transferred to Fig. 6, prove to be the correct ones since the indicated radial hub stress is the same as the actual hub stress. (σ_t for the rim was chosen correctly just by chance, otherwise other assumptions would have had to be made and Mr. Driessen's simplification would have been used if the second assumption had been incorrect.)

Refer to Fig. 8 for a comparison of the accuracy of this method with the exact stress curves and with the other approximate curves.

Two-Division Method

Experiment also shows that, by dividing the disk in the neighborhood of three-quarters of the distance from the hub to the rim, very satisfactory results can be obtained. With this method the S- and D-curves are established across the outer imaginary disk just as if the outer imaginary disk were of uniform thickness equal to the thickness of the rim. The boundary is crossed by assuming the indicated radial stress at the boundary to be decreased in a ratio of rim thickness to hub thickness of the conical disk. With the new values of S and D thus obtained the curves are established across the inner imaginary disk. The values of stress indicated at the rim and hub and at midpoint between the division and hub are taken as points through which to construct the stress-distribution curves.

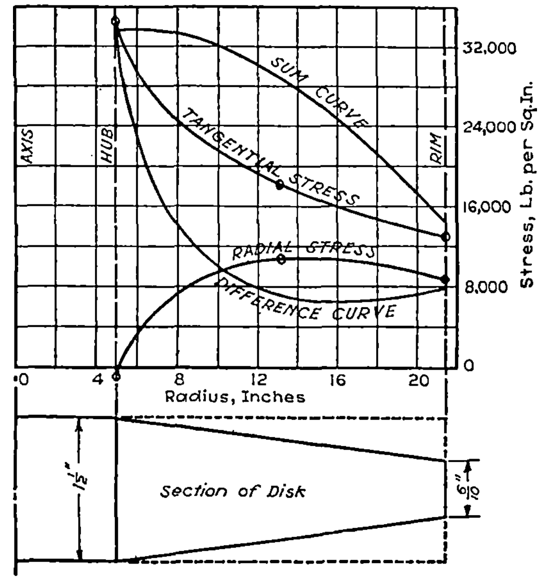


Fig. 6 Use of Donath Curves—"One Equivalent Disk" Method

(Material of disk, steel; speed, 3000 r.p.m.; rim load, 8850 lb. per sq. in.; hub load, —710 lb. per sq. in.)

For a better explanation of the use of this method, apply it to an example (Fig. 7).

The radius of the division which has been found to give the best results can be calculated from the following formula:

$$X = \sqrt{\frac{\dfrac{b^4}{4} + \dfrac{a^4}{12} - \dfrac{ab^3}{3}}{\dfrac{b^2}{2} + \dfrac{a^2}{2} - ab}}$$

where b = rim radius, and
a = hub radius

Assume

$$\sigma_t \text{ for the rim } = 13{,}250$$

then

$$S_{\text{rim}} = 13{,}250 + 8850 = 22{,}100$$

$$D_{\text{rim}} = 13{,}250 - 8850 = 4400$$

With these values of S and D, establish the S- and D-curves between the rim speed and the speed at the division.

Crossing the division by the use of Driessen's formulas gives

$$S_2 = 17{,}500$$

$$D_2 = 6{,}000$$

With these values of S and D, the curves are established across the inner part of the disk.

For a comparison of the accuracy of this method with other methods, refer to Fig. 8. Note that the three points obtained for the tangential-stress curve fall upon the exact tangential-stress-distribution curve.

Application to a Variety of Disks

Figs. 8, 9, 10, 11, and 12 show the comparisons of the results obtained by the various methods on a variety of disks. The variations in the examples included are the diameters and tapers. From study of these examples, the most accurate approximate method can be selected for general use.

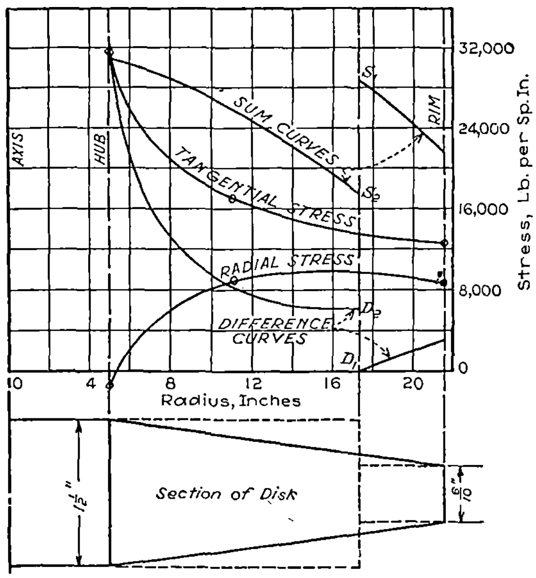


FIG. 7 USE OF DONATH CURVES—TWO-DIVISION METHOD
(Material of disk, steel; speed, 3000 r.p.m.; rim load, 8850 lb. per sq in.; hub load, —710 lb. per sq. in.)

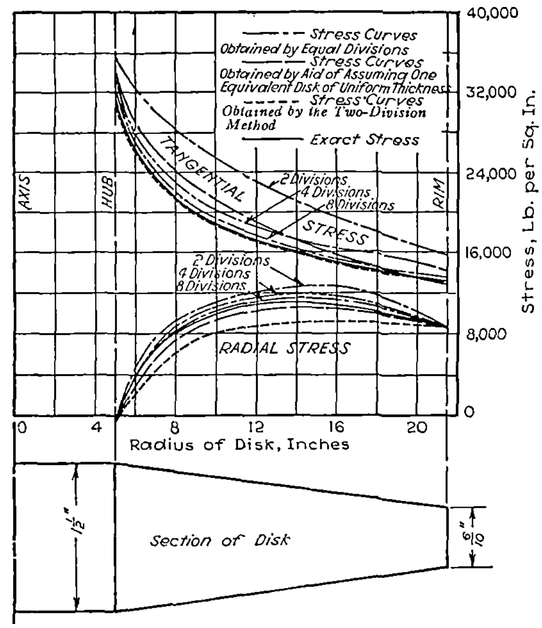


FIG. 8 COMPARISON OF RESULTS—LARGE DIAMETER, SMALL TAPER
(Material of disk, steel; speed, 3000 r.p.m.; rim load, 8850 lb. per sq. in.; hub load, —710 lb. per sq. in.)

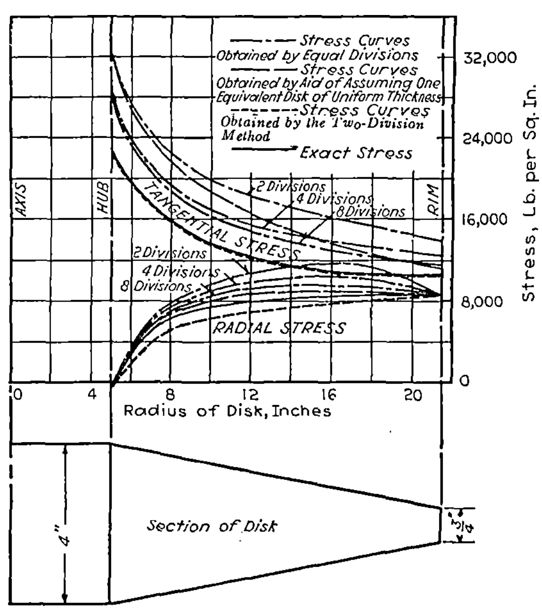


FIG. 9 COMPARISON OF RESULTS—LARGE DIAMETER, LARGE TAPER
(Material of disk, steel; speed, 3000 r.p.m.; rim load, 8850 lb. per sq. in.; hub load, —710 lb. per sq. in.)

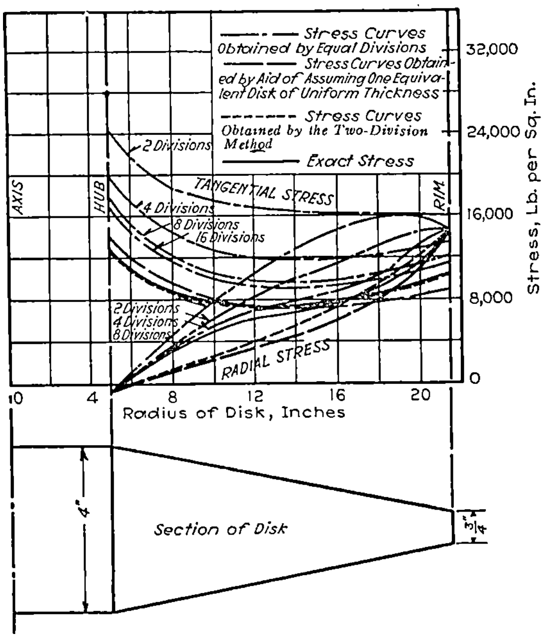


Fig. 10 Comparison of Results—Large Diameter, Large Taper

(Material of disk, steel; speed, 1500 r.p.m.; rim load, 15,000 lb. per sq. in.; hub load, —500 lb. per sq. in.)

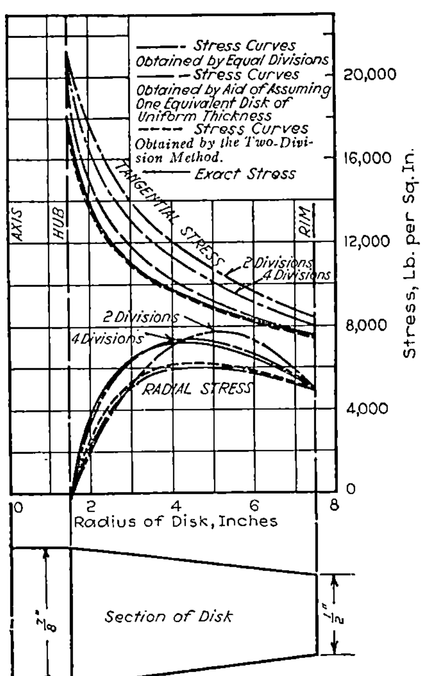


Fig. 11 Comparison of Results—Small Diameter, Small Taper

(Material of disk, steel; speed, 5000 r.p.m.; rim load, 5000 lb. per sq. in.; hub load, —500 lb. per sq. in.)

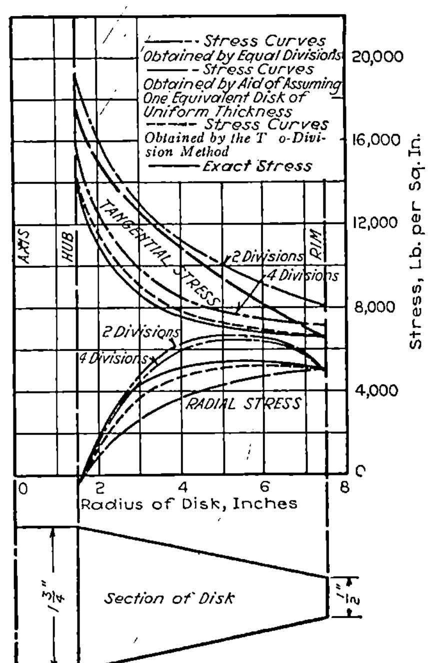


Fig. 12 Comparison of Results—Small Diameter, Large Taper

(Material of disk, steel; speed, 6000 r.p.m.; rim load, 5000 lb. per sq. in.; hub load, —500 lb. per sq. in.)

Results

One feature about the stress curves obtained by the equal-division method is that they are in all cases higher than the exact stress curves. The reason for this higher stress indication is apparent since, in any one of the imaginary disks used, Fig. 4, there is assumed to be some material added and some material dropped along the radius, the added material being at a larger radius than the corresponding dropped piece of material. Since the effect of material varies as the square of its radius, this added material more than compensates for the dropped material.

In the comparisons of results, the relative accuracies obtained by two, four, and eight divisions of the disk can be seen. One important feature of the stress distributions obtained in this manner is that the accuracy increases at a rapidly decreasing rate as the number of equal divisions increases. For this reason, four equal divisions give as good results as eight. In one case where there was a high rim load and large taper, eight equal divisions gave an appreciable increase in accuracy over four divisions; however, sixteen divisions were very little better than eight in that case.

The stress-distribution curves obtained by the equivalent-disk method are satisfactory except in a case where the disk has a large taper and is running at a high speed. This method, Fig. 6, assumes a disk with more material at the rim, but the midpoint between the two boundaries is the point at which the additional material will compensate for the lower radial stress at the rim. As can be seen in the comparison of results, this method gives good results in most cases; and the error is fortunately on the safe side. The reason it does not give satisfactory results for a disk of large taper and high speed is that the added material becomes more effective as the speed increases.

The "two-division" method is a successful method of assuming a decreased radial load at some point in the disk and adding material to compensate for it at some certain point. Having this method work satisfactorily on the variety of examples included in this paper is an indication that it will give good results in all cases.

The practical value of Mr. Driessen's "Simplified Method of Determining Stresses in Rotating Disks" has been determined in solving the examples included in this paper. It would seem on first sight that his method of determining a correct value of tangential stress to assume on the rim, after having assumed two values unsuccessfully, would be of great value in the use of Donath's curves. However, after having used these curves for a number of disks, the author has found that a person with some experience in their use can determine mentally the correct stress to assume. Due to the limited field which the published *S*- and *D*-curves cover, a person will usually have to assume several stresses before he can establish curves which will not run off the curve sheet before they reach the hub speed; and by the time he has found a tangential rim stress which will not cause the *D*-curve to run off the sheet before reaching the hub speed, he is able to determine mentally the correct stress value to assume.

This condition is caused by the nature of the difference curves. The value of D on the hub is affected greatly by a small change in the tangential stress on the rim, while the value of S on the hub under similar conditions is affected but a comparatively small amount. The value of Mr. Driessen's method would be increased by an increase in the field which the published *S*- and *D*-curves cover.

Mr. Driessen's formulas for use in crossing a boundary between two imaginary disks of uniform thicknesses are of great value, as these simple expressions eliminate the necessity of computing an extensive table for that purpose.

Conclusions and Recommendations

1 In applying the Donath curves by equal divisions along the radius of a disk, four equal divisions of the disk will be found to give satisfactory results.

2 By the method of assuming one equivalent disk of uniform thickness for a conical disk, results of satisfactory accuracy can be obtained for all disks except in cases where the speed is high and the taper large.

3 By the two-division method proposed in this paper, accurate results can always be obtained.

Discussion

A. L. Kimball.[7] The writer has read this paper with interest as one with some familiarity with methods of computing stresses in revolving turbine disks, though not having that intimate knowledge that comes from continued work in disk design.

The value of this paper consists primarily in an up-to-date review of the subject such as cannot be found in present literature without dipping into several sources. Although it cannot be said to contain a fundamentally new method, ingenious application of the Donath and Driessen methods have been made, particularly in separating a conical disk into two steps, as specified by the formula at the top of page 96. This should greatly shorten the labor of calculation of stress distribution in a variety of shapes of conical disks.

Apparently the equations at the bottom of page 94 and the top of page 95 refer to a different disk from that of Fig. 4, although the discussion following seems to refer to this figure.

The paper is clearly presented, and will be a useful reference to have at hand when brushing up on the subject of stress determination in revolving disks.

S. Timoshenko.[8] The idea of investigating the accuracy of the well-known Donath method by using an exact solution for disks of conical profile seems a very interesting one. A considerable amount of work has been done by the author in comparing the Donath method, using various numbers of divisions, with the exact method. It is very desirable to give this comparison in percentages. For certain cases it appears that an increase in the number of divisions does not improve the results, and the approximate method does not converge toward the exact solution. It would be a good idea to check the calculations for these cases. It is important, also, to check over the equations on the fourth page for ΔS and ΔD; the equations as they are printed are not correct. Possibly in some of the calculations the incorrect equations were used, so it will be well to look over these calculations.

M. G. Driessen.[9] So far as the writer knows, the author is the first to compute the widely used approximate Donath method for the calculation of these stresses in rotating disks of conical profile. His studies show clearly the magnitude of the error made in applying the sum and difference curves.

The author also introduced a simplification by which the calculation of conical disks can be shortened considerably. He divides the disk in two parts as the radius of gyration, so that the upper part is a cylindrical disk with a width equal to the width at the rim and the lower part also a cylindrical disk with a width equal to that of the hub. He also showed that this latter method is the best approximation for different kinds of conical disks. The author uses the following formula for the radius of gyration X:

$$X = \sqrt{\frac{\dfrac{b^4}{4} + \dfrac{a^4}{12} - \dfrac{ab^3}{3}}{\dfrac{b^2}{2} + \dfrac{a^2}{2} - ab}}$$

where b = rim radius
a = hub radius.

This formula is independent of the widths at rim and hub, and the writer would therefore ask the author if the radius of gyration is the same for a large and for a small taper.

Author's Closure

The author wishes to express his gratitude for the constructive criticism given this paper in the discussion.

The general equations to be used in evaluating ΔS and ΔD were not written correctly when the paper was first printed; also, in the numerical example where the equations for ΔS and ΔD were used, the expressions were not written correctly. These changes do not affect any of the results obtained because a careful check of the original calculations has been made and it has been found that the correct forms of the two above-mentioned equations were used at all times.

The dividing point for the "Two-Division Method" was originally called the Radius of Gyration in this paper; it was incorrectly named, however. Since Mr. Driessen has called this glaring fact to the author's attention, stress-distribution curves have been obtained by using the actual radius of gyration of the cross-section as a dividing point in the "Two-Division Method." But the results obtained were not nearly as satisfactory as those obtained by using the dividing point originally introduced in the paper. As the facts stand at the present time, when using the "Two-Division Method," the dividing point originally introduced in the paper gives better results than any other known point; so it would best remain as it is until another can possibly be found when the subject receives further investigation.

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ROTATING DISCS OF CONICAL PROFILE
By: B. Hodkinson

(Reprinted from "Engineering", Vol. 115, p1, 1923.)

As is well known, mathematicians have been unable to find exact expressions for the stresses in a rotating disc even when the latter is of the simplest possible form, that is to say, of constant thickness. Nevertheless, on certain assumptions which are at least approximately correct, it has been possible to determine, with an accuracy sufficient for the needs of the engineer, not merely the stresses in a disc of constant thickness, but also those arising in discs in which the thickness z at different radii can be expressed in the form

$$z = \frac{C}{r^a}$$

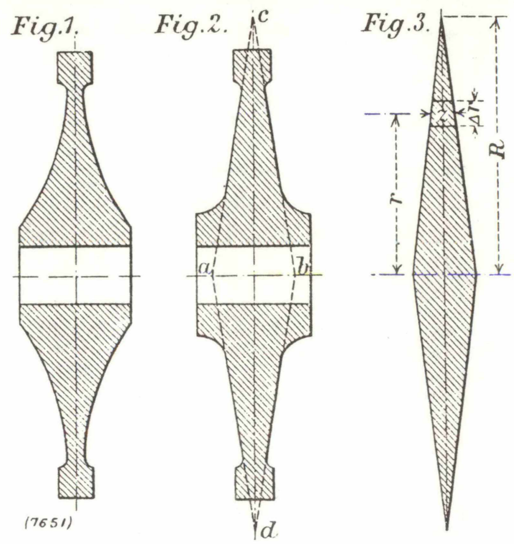
where r denotes the radius in question and C and a are numerical constants.

This problem appears to have been worked out in the first instance by Dr. de Laval, but his results were independently obtained by many later investigators, although they seem to have been first published by Professor Stodola. The formulæ thus obtained are of a type very inconvenient for practical use, but as was pointed out in ENGINEERING, the difficulty may be turned by adopting semigraphic methods of calculation, and the system then described has been subsequently still further developed by Mr. W. Knight, who computed and plotted many additional curves which were published in our issue of August 3, 1917. With the same assumptions as to the boundary conditions these diagrams necessarily yield the same results as the formulæ from which they are derived. This point seems to have been frequently overlooked, and naturally if one hypothesis is adopted in determining stresses from the diagrams and another in computing them from the original formulæ, discrepancies are bound to appear.

When the thickness of the disc varies according to the law $z = \frac{C}{r^a}$ the resultant profile is of the type represented in Fig. 1. The bounding curves are somewhat troublesome to machine, and accordingly there has been a tendency towards the adoption of straight-sided profiles such as is represented in Fig. 2. If the straight sides are produced, as indicated by the dotted lines, to cut the axes of rotation at a and b, and in the opposite directions to intersect at c and d, the disc included between these lines consists of two cones placed base to base, and if the stresses in this "generalised" form can be found, we can also deduce those in any practical form derived from it.

So far as the writer is aware no general solution for the stresses which arise in these conical discs has hitherto been published, although some nine or ten years ago an approximate arithmetical solution, which involved the solving of a number of simultaneous equations, appeared in the *Revue Mecanique*.

From the mathematical standpoint the general problem reduces itself to the determination of the stresses produced in the solid double cone d, a, c, b (represented in Fig. 2) by two different sets of forces, viz., (1) by the centrifugal forces acting alone, and (2) by the application of a load of say 1 lb. per inch run applied along the knife-edge forming the periphery. For the complete solution we also require to know the stresses which would be produced in the disc by an infinitely great pressure applied to the interior of an infinitely small hole drilled through



the disc at its centre. As this infinite pressure is applied over an infinitely small area, the stresses are finite everywhere save at the surface of the infinitely small hole.

If we can determine the stresses due to these three independent systems of loading we can deduce from them the stresses developed in any concentric annulus cut from this rotating disc, loaded at its periphery with blading and joined on to a hub at its inner periphery.

Let the outer diameter of the disc be 2 R (see Fig. 3), and let r be any other radius. Consider a thin ring at this radius of radial thickness Δr. Then if this ring were completely isolated and rotating, the tangential stress developed in it by the centrifugal forces is accurately given in lb. per square inch by the expression

$$t = 2\left(\frac{d}{10}\right)^2\left(\frac{\text{R.P.M.}}{100}\right)^2.$$

In this formula it is assumed that the material is steel* whilst d denotes the mean diameter of the thin ring expressed in inches.

The total tangential pull is equal to the stress t multiplied by the cross-section of the ring, that is to say, it is equal to $t\, z\, \Delta r$.

* For other materials the coefficient 2 should be increased or decreased in the ratio of the specific gravity of the material used to the specific gravity of steel.

Actually, the ring is not free, but forms part of the disc and is thus subjected to radial tensions on its inner and outer surfaces. Let us denote those on the inner surface by p where p is expressed in pounds per square inch. Then by the ordinary formula for the strength of boiler shells this load will produce a total tangential force on the ring equal to $p\,z\,r$. The stress p being a tension, the resultant tangential force in the ring will be a thrust. Coming next to the external periphery of the ring we note that $p\,z\,r$ is a function of r, hence, by Taylor's theorem, the total tangential force due to the tension applied to this outer periphery of the thin ring will be

$$p\,z\,r + \frac{d}{d\,r} \cdot (p\,z\,r)\,\Delta\,r + \text{terms}$$

involving higher power of $\Delta\,r$ which may be neglected when $\Delta\,r$ is small. This tangential force is obviously a tension. The total resultant tangential force on the ring is the algebraic sum of these three terms. If the resultant stress be denoted by q this resultant tangential force will be $q\,z\,\Delta\,r$, and we thus get the relation

$$q\,z\,\Delta\,r = t\,z\,\Delta\,r - p\,z\,r + p\,z\,r + \frac{\delta}{\delta\,r}\,(p\,z\,r)\,\Delta\,r$$

Whence

$$q\,z = \frac{d}{d\,r}\,(p\,z\,r) + t\,z \quad . \quad . \ (1)$$

This equation gives one relation between the radial stress p and the tangential stress q. It is convenient to replace t by $\frac{T\,r^2}{R^2}$, where T is equal to

$$2\left(\frac{D}{10}\right)^2\left(\frac{\text{R.P.M.}}{100}\right)^2,$$

D being the external diameter of the disc, *i.e.*, D = 2 R. Hence we get from (1)

$$q\,z = \frac{d}{d\,r}\,(p\,z\,r) + \frac{T}{R^2}\,r^2 z \quad . \quad . \quad . \ (2)$$

In the foregoing it has been assumed that the stresses p and q may without any very serious error be taken as uniformly distributed over the sections on which they act. This assumption is the usual one made by Professor Stodola and others, and even within the elastic limit the condition is approximately satisfied if the faces of the double cone do not make a large angle with each other. So far as the ultimate strength of the disc is concerned, the hypothesis is very nearly true, even if the angle between the faces be fairly large.

There are various ways of eliminating q from equation (2). Perhaps that least open to criticism is based on Castigliano's theorem. Every elastic structure when stressed acts as a spring, and in virtue of being in a state of stress has accordingly stored up in it a certain potential energy. By Castigliano's principle, the stresses always adjust themselves so that this "potential energy of strain" is a minimum, consistent with the equilibrium of the forces acting on the structure. One advantage of this principle is that it is often possible to see from general considerations that certain of the stresses will contribute little to this store of potential energy, whilst in the other cases what they do contribute will vary but little with any reasonably conceivable distribution of the remaining stresses. In both cases, accordingly we need take into consideration only these remaining stresses. In the present case these considerations do not arise as it has already been assumed that the only stresses with which we need concern ourselves are p and q. Let e be the radial strain at any point of the disc where the radial tension is p. Then the strain energy stored up in one cubic inch of the metal, due to the stress p, is $\frac{p\,e}{2}$. Similarly, if f be the tangential strain, the work stored up in one cubic inch, due to the stress q, is $\frac{q\,f}{2}$. Since the total volume of our thin ring is $2\,\pi\,r\,z\,d\,r$ cubic inches the total work stored in it is

$$2\,\pi\,r\,z\left(\frac{p\,e}{2} + \frac{q\,f}{2}\right)d\,r.$$

If $\frac{1}{m}$ denotes Poisson's ratio, we have

$$e = \frac{p}{E} - \frac{1}{m\,E}\,q$$

whilst

$$f = \frac{q}{E} - \frac{1}{m\,E}\,p.$$

Substituting these values for f and e we get for the work $d\,W$ stored in our elementary ring the expression

$$d\,W = \frac{\pi}{E} \cdot r\,z\left(p^2 - \frac{2\,p\,q}{m} + q^2\right)d\,r.$$

The work W stored up in the whole disc is found by integrating this between $r = 0$ and $r = R$. Whence

$$W = \frac{\pi}{E} \cdot \int_0^R \left(p^2 - \frac{2\,p\,q}{m} + q^2\right) r\,z\,d\,r \quad . \ (3)$$

and by Castigliano's principle this must be a minimum.

It is convenient to change the variable from r to x where $x = \frac{r}{R}$, so that $d\,r = R\,d\,x$. Then, if Z be the thickness of the disc at the centre, the thickness at any other point is given by $z = Z\,(1 - x)$. Making these substitutions in (2) gives

$$(1 - x)\,q = \frac{d}{dx}\,p\,(1 - x)\,x + T\,x^2\,(1 - x) \quad . \ (4)$$

whilst, ignoring certain constant coefficients, the integral in (3) reduces to

$$\int_0^1 \left(p^2 - \frac{2\,p\,q}{m} + q^2\right) x\,(1 - x)\,d\,x \quad . \ (5)$$

The mathematical work can be simplified by two further substitutions, viz., $P = (1 - x)\,p$ and $Q = (1 - x)\,q$. We thus get from (4)

$$Q = P + x\frac{d\,P}{d\,x} + T\,x^2\,(1 - x) \quad . \quad . \ (6)$$

whilst (5) becomes

$$\int_0^1 \left(P^2 - \frac{2\,P\,Q}{m} + Q^2\right)\frac{x}{1 - x}\,d\,x \quad . \quad . \ (7)$$

Let us denote the expression in the brackets by V. Then the calculus of variations shows us, that for this integral to be a minimum as required by Castigliano's theorem, we must have

$$\frac{x}{1 - x} \cdot \frac{d\,V}{d\,P} - \frac{d}{d\,x} \cdot \frac{x}{1 - x} \cdot \frac{d\,V}{d\,P'} = 0 \quad . \ (8)$$

Where P′ is "shorthand" for $\frac{d\,P}{d\,x}$.

obviously

$$\frac{d\,V}{d\,P} = 2\,P - \frac{2\,Q}{m} - \frac{2\,P}{m}\frac{d\,Q}{d\,P} + 2\,Q\frac{d\,Q}{d\,P}.$$

From equation (6) we see that $\frac{d\,Q}{d\,P} = 1$.

Again,

$$\frac{d\,V}{d\,P'} = -\frac{2\,P}{m}\frac{d\,Q}{d\,P'} + 2\,Q\frac{d\,Q}{d\,P'},$$

and from (6)

$$\frac{d\,Q}{d\,P'} = x.$$

Inserting these values and substituting for Q in (8) we finally arrive at the following differential equation for P—

$$\left(1 - \frac{1}{m}\right) \mathrm{P} + (3 - 2\,x) \frac{d\,\mathrm{P}}{d\,x} + x\,(x - 1) \frac{d^{\,2}\mathrm{P}}{d\,x^2}$$
$$+ \left(3 - \frac{1}{m}\right) \mathrm{T}\,x\,(1 - x)^2 = 0 \quad . \quad . \quad (9)$$

From the theory of differential equations we know that the complete solution of this equation consists of three parts, viz., any solution whatever which satisfies (9), plus two independent solutions of the "auxiliary" equation—

$$\left(1 - \frac{1}{m}\right) \mathrm{P} + (3 - 2\,x) \frac{d\,\mathrm{P}}{d\,x} + x\,(x - 1) \frac{d^{\,2}\mathrm{P}}{d\,x^2} = 0.$$

If we take Poisson's ratio as 0·3, this equation becomes—

$$0{\cdot}7\,\mathrm{P} + (3 - 2\,x) \frac{d\,\mathrm{P}}{d\,x} + x\,(x - 1) \frac{d^{\,2}\mathrm{P}}{d\,x^2} = 0 \quad (10)$$

Solutions of this can be found in the form of infinite series. One such solution, valid for all values of x between 0 and 1, is—

$$\mathrm{P}_1 = \mathrm{A}\left(1 - \frac{0{\cdot}7}{3} x - \frac{0{\cdot}7}{3} \cdot \frac{1{\cdot}3}{8} x^2 - \frac{0{\cdot}7}{3} \cdot \frac{1{\cdot}3}{8} \cdot \frac{5{\cdot}3}{15} x^3 - \&c.\right)$$

Here A is an arbitrary constant. We defer for the present the consideration of the physical significance of this solution, and thus merely note in passing that the radial stresses due to P_1 are equal to $\frac{\mathrm{P}_1}{1 - x}$.

The corresponding tangential stresses are equal to $\frac{\mathrm{Q}_1}{1 - x}$ where

$$\mathrm{Q}_1 = \mathrm{P}_1 + x \frac{d\,\mathrm{P}_1}{d\,x}.$$

A second independent solution of (10) is—

$$\mathrm{P}_2 = \mathrm{B}\,(1 - x)^2 \left(1 + \frac{5{\cdot}3}{3}(1 - x) + \frac{5{\cdot}3}{3} \cdot \frac{11{\cdot}3}{8}(1 - x)^2\right.$$
$$\left. + \frac{5{\cdot}3}{3} \cdot \frac{11{\cdot}3}{8} \cdot \frac{19{\cdot}3}{15}(1 - x)^3 + \&c.\right)$$

Here B is another arbitrary constant. This series is convergent for all values of x between 0 and 1, but becomes infinite when $x = 0$. The radial stress $\frac{\mathrm{P}_2}{1 - x}$ is that due to an infinite pressure applied to the interior of an infinitely small hole drilled through the centre of the disc. The corresponding tangential stress $\frac{\mathrm{Q}_2}{1 - x}$ is derived from the expression—

$$\mathrm{Q}_2 = \mathrm{P}_2 + x \frac{d\,\mathrm{P}_2}{d\,x}$$

The solution of the original equation (9) is easily derivable from P_1 or can be obtained directly by the usual symbolic methods, on changing the variable from x to θ where θ is defined by the relation $x = e^{\theta}$. Denoting the solution thus found by P_3 we have—

$$\mathrm{Q}_3 = \mathrm{P}_3 + x \frac{d\,\mathrm{P}_3}{d\,x} + \mathrm{T}\,.\,x^2\,(1 - x).$$

The stresses due to a combination of those corresponding to P_1 and P_3 are

$$p = \frac{\mathrm{C}\,\mathrm{P}_1 + \mathrm{P}_3}{1 - x}$$

and

$$q = \frac{\mathrm{C}\,\mathrm{Q}_1 + \mathrm{Q}_3}{1 - x}.$$

Here C denotes a constant, chosen so as to make $\mathrm{C}\,\mathrm{P}_1 + \mathrm{P}_3 = 0$ when $x = 1$. If we put $\mathrm{C}\,\mathrm{P}_1 + \mathrm{P}_3 = \phi$ and $\mathrm{C}\,\mathrm{Q}_1 + \mathrm{Q}_2 = \psi$, values of ϕ and ψ for different values of x are tabulated in Table I, together with corresponding values of P_1, P_2, and Q_1, Q_2. Both the series for P_1 and P_2 converge very slowly for certain values of x. In the first case the convergence is slow when x is nearly unity, and the second case the convergence is extremely slow when x is nearly zero. Fortunately, however, after some 50 terms have been directly computed an asymptotic recurrent series can be substituted for the remainder, and the sum of such a recurrent series can be expressed in a finite form. Advantage has been taken of this in computing some of the values printed in Table I. With the aid of this table the stresses in conical discs can be computed about as easily as they can in the case of a disc of uniform thickness.

TABLE I.

	P_1	Q_1	$-\mathrm{P}_2$	Q_2	$\phi = \mathrm{T}\,x$	$\psi = \mathrm{T}\,x$
0·0	1·00000	1·0000	—	—	0·13547	0·13547
0·05	—	—	259·74	2·7418	—	—
0·10	0·97627	0·95214	59·957	69·549	0·12913	0·12883
0·15	—	—	24·380	31·065	—	—
0·20	0·95170	0·90163	12·431	17·525	0·11736	0·12136
0·25	—	—	7·1497	11·159	—	—
0·30	0·92610	0·84790	4·4597	7·6257	0·10160	0·11280
0·35	—	—	2·8517	5·5453	—	—
0·40	0·89953	0·79060	1·8949	4·1494	0·083300	0·10350
0·45	—	—	1·2804	3·1844	—	—
0·50	0·87163	0·72853	0·87163	2·4718	0·063876	0·091357
0·60	0·84220	0·66047	0·39950	1·5264	0·044768	0·077927
0·70	0·81091	0·58400	0·17011	0·93046	0·026904	0·062332
0·80	0·77723	0·49618	0·059426	0·52287	0·013232	0·044278
0·90	0·74021	0·38668	0·012053	0·2263	0·0036193	0·022706
1·00	0·69702	0·20911	—	—	—	—

SECTION 3

ENSCO TECHNICAL DESCRIPTION OF RAIL WHEEL DATA ACQUISITION AND SIGNAL PROCESSING INSTRUMENTATION

RAIL WHEEL DATA ACQUISITION & SIGNAL PROCESSING INSTRUMENTATION
TECHNICAL DESCRIPTION

INTRODUCTION

The instrumented truck supplied by the Association of American Railroads to the Federal Railroad Administration of the U.S. Department of Transportation is instrumented with strain gauges and thermocouples mounted on the wheel plates for measuring wheel forces and temperatures. Each wheel contains sensors for measuring the following characteristics:

- One lateral wheel force
- Two vertical wheel forces
- Two wheel plate temperatures

The signals produced by these sensors, and the outputs of absolute angular position shaft encoders attached to each axle, are processed to derive the following wheel/rail parameters for each wheel:

- Lateral force
- Vertical force
- Plate temperature
- Lateral/Vertical Ratio
- Angle of rotation of each axle relative to the vertical
- Speed

Slip ring assemblies at the end of each axle transfer the wheel signals to cables which are connected to amplifiers and conditioning circuits.

DATA COLLECTION

Figure 1 shows a block diagram of the data collection system. The sensors on the instrumented wheel operate in conjunction with signal conditioning amplifiers which supply the necessary independent excitation, balancing, calibration and amplification of each bridge circuit.

The signals normally produced by the wheel force sensors are rotationally dependent; that is, their peak response occurs as the wheel rotates through a point where the sensor is positioned between the rail and wheel axle.

The Wheel Signal Processor (Figure 1) combines the two rotationally dependent signals from each wheel into a single rotationally independent signal. The Wheel Signal Processor also developes signals representing L/V ratio, speed, plus test and calibration signals. Signal conditioning amplifiers provide scale adjustments for the vertical and lateral force signals, and establish a sca;e factor which relates Volts to Klbs.

All signals available for recording are filtered by antialiasing filters which are bandpass limited to 100 Hz. The resulting siganls are suitable for digital data recording, at sample rates of approximately 300 Hz and above, and for connection to various analog recording equipment.

The two Channel Selectors shown in Figure 1 can select twelve channels of data simultaneously and in any combination for recording on two six-channel oscillographs.

The Channel Monitor contains a DC digital voltmeter and a selector switch for checking the zero and gain for each channel. A front panel test jack is also provided for observing the selected channel on an oscilloscope or other test instrument.

The digital recorder to be used is the FRA Dynamic Data Collection system which: samples each channel at a predetermined rate; digitizes the analog signals; and formats the data and records it on magnetic tape. This system also provides a means for playing back recorded data for display on the strip chart recorders and for off-line digital processing.

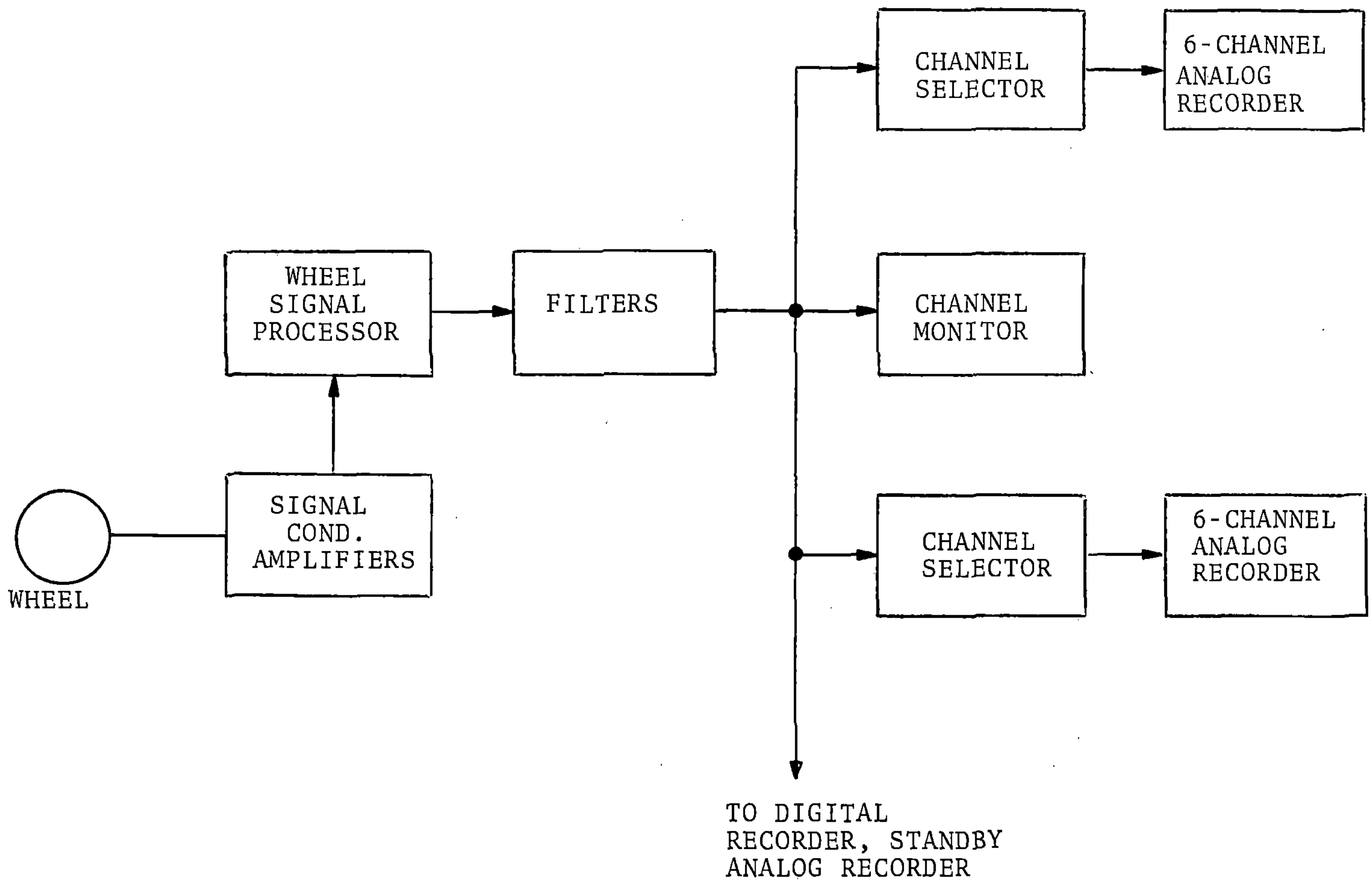


FIGURE 1. Block Diagram of Data Collection and Processing System

WHEEL SIGNAL PROCESSING

VERTICAL PROCESSING

The vertical wheel signal is developed from two identical strain-gauge bridges positioned so that their output signals are in space quadrature. Each bridge signal produces two zeros, one positive maximum, and one equal negative maximum per wheel revolution. Due to the quadrature relationship, one bridge is always available for an output when the other bridge is in or near a zero output position. These bridge elements are located so that very little vertical output signal is produced for lateral forces. Also, the vertical bridges do not produce outputs for an unloaded wheel when it is rotated at rates equivalent to a speed of 76 miles per hour.

As the instrumented truck moves along the track and the wheel rotates, the vertical output signal should be a constant voltage level scaled to represent the constant load on the wheel caused by the weight of the boxcar. This assumes speeds slow enough to produce no vertical accelerations. At higher speeds, the vertical signal should respond linearly to changing vertical forces produced in the wheel by the wheel and rail interactions. The vertical bridges as described above do not produce this type of signal directly. Additional signal processing is required to combine the two vertical signals into a single unipolar signal.

Figure 2 is a block diagram of the vertical wheel signal processer. The operation of the circuit is as follows: An absolute angular position shaft encoder is driven from the axle and is used to divide the wheel into 64 sectors. The output of the encoder provides 64 memory addresses (one per sector). A digital word (gain value) is stored at each memory address which sets the gain of the programmable gain amplifier A1. The other input to

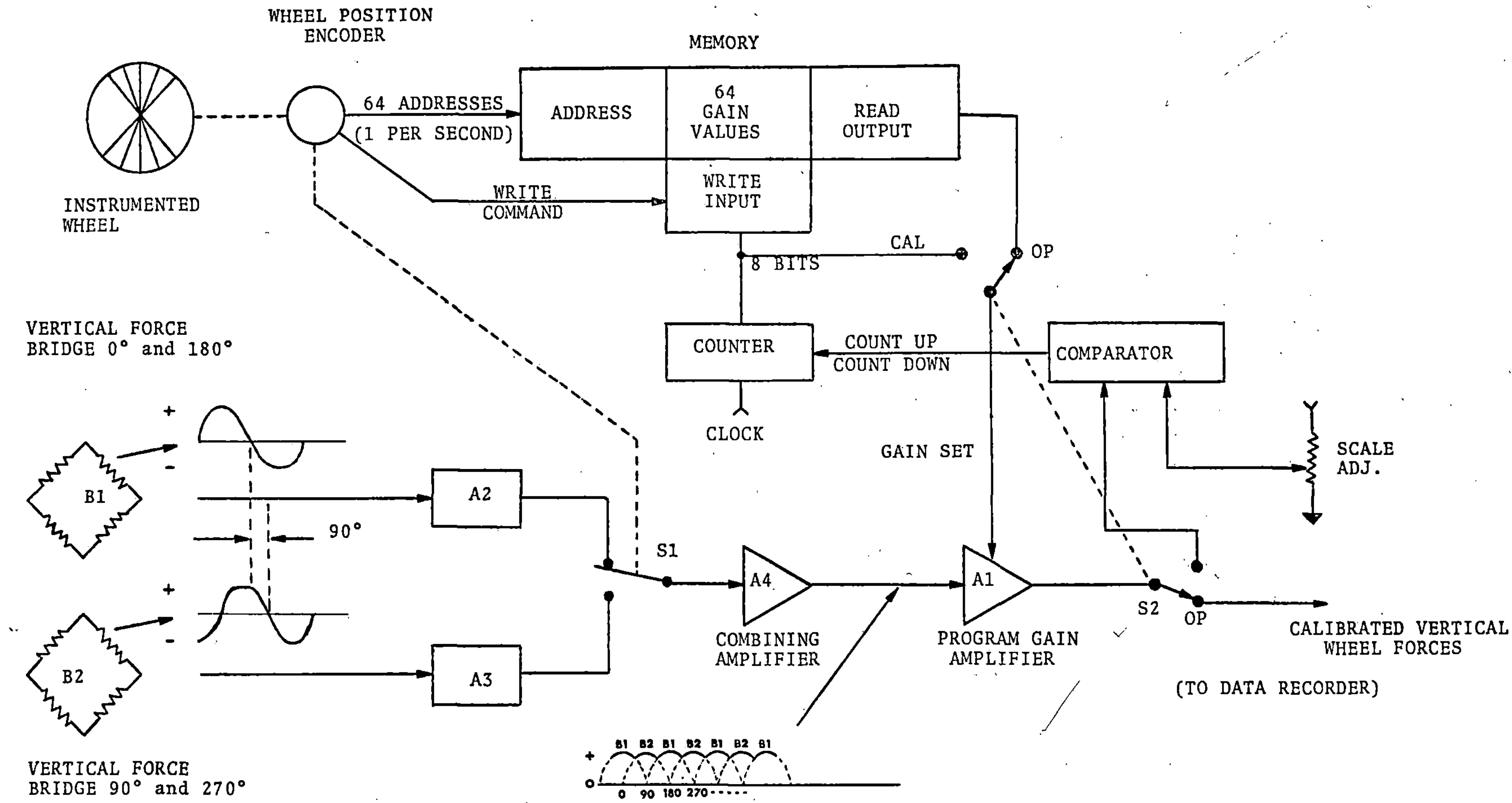


FIGURE 2. Block Diagram of Wheel Signal Processing Function.

the programmable gain amplifier is a combined signal from the two vertical bridges. Each bridge produces a bipolar signal similar to the signals shown at the inputs of A2 and A3 as the wheel rotates under constant load. The bridge signals are then rectified by precision full-wave rectifiers. A typical resultant waveform is shown at the output of A3.

A control signal is developed from the shaft encoder which operates switch S1. This switch selects the signal from B1 or B2 whenever the bridge sensor is within approximately 45° of its peak response position. Since the bridge outputs are 90° out of phase, switch S1 alternately selects B1 and B2 to produce the combined signal shown at the output of A4. This signal is produced by amplifier A1 where sixteen compensating gain values are provided between each minimum point. The gain values have been set to produce a constant scaled output voltage from A1 as the wheel rotates under constant load. Since the gain values for each wheel sector are fixed during calibration, the output of amplifier A1 changes linearly with changing wheel force signals caused by wheel and rail interaction under dynamic conditions.

Calibration of the vertical wheel signal is accomplished by placing switch S2 in the calibrate position and moving the truck through one wheel revolution. The scale factor adjustment, R1 is set to a value which produces a suitable scale factor. For example, if the empty weight of the vehicle is 62,000 lbs., this is equivalent to 7,750 lbs. per wheel. The voltage to the comparator is adjusted to 0.775 volts, and the scale factor will be 10,000 lbs. per volt. As the wheel rotates, the output of amplifier A1 is compared to the scale factor voltage. The comparator causes the counter to count to a digital gain value such that the gain of A1 is adjusted continuously to make its output analog wheel signal exactly equal to the scale factor voltage.

A write command signal, developed from the wheel position encoder, transfers the digital gain value from the counter into the memory when the center of each wheel sector contacts the rail. At the completion of one wheel revolution, the correct digital gain value for each sector will have been stored at the sector address in the memory. Returning S2 to the operate position inhibits any further writing into the memory and calibration is complete.

LATERAL FORCE SIGNALS

The lateral signals are developed in the bridge circuits to produce a nearly constant output as the wheel rotates under constant lateral loads. Final scaling amplifiers are provided to set a suitable scale factor. The lateral bridge circuits are calibrated by adjusting the signal conditioning amplifiers. A more accurate calibration of the lateral signals can be obtained on a section of superelevated track which is instrumented with precision load cells to determine the lateral force caused by the superelevated track.

Lateral-to-vertical force ratios (L/V) are developed for each wheel by analog dividers. The scale factor for these ratios is adjustable so that a L/V ratio of 1 can be set to full scale output between 1 and 10 volts. When the digital recording system is in use, L/V ratios can be calculated from the digital values of vertical and lateral forces.

Instrumentation for Measuring Forces on
Wheels of Rail Vehicles, 1974
US DOT, FRA