

Balbach ~ Comparative strength of various concrete tunnel section



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SUPPLEMENTARY
MATERIAL
IN BACK OF BOOK

Photomount
Multibinders
Gaylord Bros., Inc.
Makers
SYRACUSE, N.Y.

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This thesis was contributed by

Mr. E. Balbach

under the date indicated by the department
stamp, to replace the original which was
destroyed in the fire of March 5, 1916.

T H E S I S.

C O M P A R A T I V E S T R E N G T H O F V A R I O U S
C O N C R E T E T U N N E L S E C T I O N S.

E. Balbach

A.R. Carter

1904



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THESIS

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The building of tunnels has been practiced for ages; but although many different shapes and various materials have been used in their construction, no tests have ever been made to ascertain which shape is the stronger. With this object in view our tests were conducted.

No matter of such a nature being available for reference we were obliged to make our own assumptions and trust that they were correct. In the first place, we assumed that if we constructed some small tunnels of various common shapes and proportioned them as near as possible like full sized sections and loaded them to destruction the same relative result would be obtained as by crushing full sized sections. Four different shapes were then made, namely: a section with perpendicular sides and semi-circular arch; one section of horse-shoe shape, semi-circular arch; another with horse-shoe for inside and straight on outside, semi-circular arch; and one perpendicular on inside and slanting on outside, so as to make the base thicker. (See Blue Print)

To mould these sections forms were made of galvanized iron and wood. Ribs of wood were sawed out to the shape desired and the sheet iron nailed on these. A form of the inside and one for the outside were made and the concrete was rammed in between these and allowed to set. The inside mould was then

forced out and the outside mould sprung off. The tunnels were made two feet long and three of each kind were made. The composition consisted of three (3) parts of common sand, passed through a one-fourth ($1/4$ ") inch mesh sieve to one part of Portland cement from Jonesville, Michigan. About 10% of water was used.

The intention was then to break these at the same age but owing to the limited time at our disposal this could not be done. They were, therefore, all broken in one week, with the age varying from five weeks to nine weeks. They were all allowed to set dry.

Some concrete beams were also made; one consisting of a block 6"x11"x2" with straight sides and one of the same dimensions with arched sides. Thirteen of these were made, seven (7) of the former and six (6) of the latter, the composition being the same as for the tunnels. The molds were made of wood.

In breaking the tunnels the attempt was made to approach natural conditions as near as possible. A special machine was constructed for this purpose, consisting of a compound lever and acting on the principle of a nut cracker. A photograph of the machine in operation is included in this report. The upper lever is a 6"x6"x14ft. with a lever arm of 12-1/2 ft. The lower lever is an 8"x10"x12ft. with a lever arm 10 ft., all

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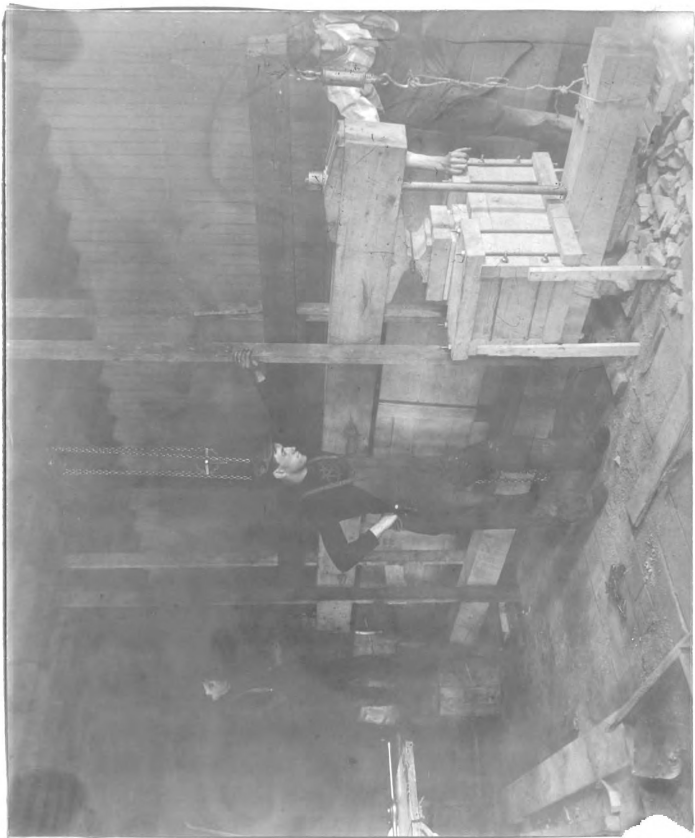
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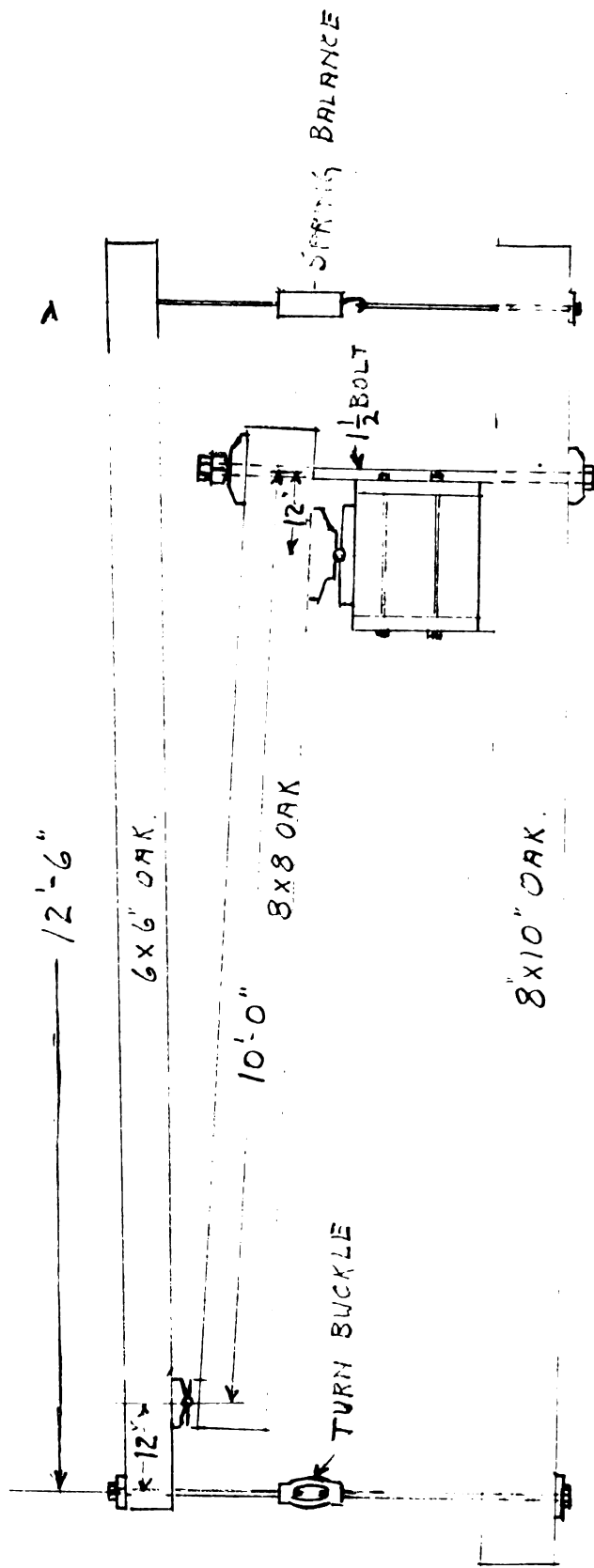
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of oak. The combined leverage was then $12-1/2 \times 10 = 125$. A spring balance was attached at the end of the upper lever as shown and the pressure on the tunnel thus ascertained. The bearings were made as small as possible with safety so as to minimize the friction. Cast iron plates were bolted on the timbers in order to prevent the crushing of the wood. (See Photograph and Blue Print.)

A wooden box was constructed in which the tunnels were placed for testing. A layer of sand, about $1-1/2"$, was placed in the bottom of the box and the tunnel placed upright on this. The box was then completely filled with sand, making about two inches ($2"$) of sand over the top of the tunnel. The box was completely closed over with the exception of one square foot in the top through which the pressure was applied. Dry sand was used. A pressure applied through this opening would then distribute through the sand to the sides and practically the same condition be produced as in actual practice.

The pressure due to the weight of the levers alone was determined as follows: A Buffalo scale was placed at some distance from the crushing point and a lever placed so as to reach under the pressure point and supported a short distance beyond. The machine lever was then allowed to rest upon this small lever and the turn-buckle on the machine drawn up until





ARRANGEMENT OF LEVERS.

the upper lever just balanced. The scales then read 770#. The lever arm of the scale was 7 ft. 9-3/4 in. and that of the pressure arm was 4-1/2 in. Therefore $770 \times 7' 9\text{-}3/4'' \div 4\text{-}1/2'' = 16940\#$, the constant of the machine. This is somewhat smaller than the theoretical constant for some of the power is consumed in friction. The load on the tunnel then will be the reading of the spring balance $\times 125 \div$ the constant of the machine. In this way the breaking loads were determined in each case. The machine was designed for 50000# but this pressure was not reached. The following table gives a record of the results. (See Table 1)

Description of Fracture.

No. 1 was not full length, one end being broken off but it was tested. It broke very easily, requiring but 10# pressure on the lever. After uncovering, it was found to be completely fractured, the arch crushed in and the sides and bottom broken into small pieces. No. 2 was sound and after uncovering was found to have the entire arch crushed in; the sides and bottom were but slightly cracked. No. 3 was sound and after uncovering was found to have the arch crushed entire length and the sides slightly cracked but standing. The bottom was cracked but little.

Table No. 1.

LOG OF RESULTS.

No.	Date Made	Date Broken	Age	Shape	Weight	Spring Reading	Total π Pressure
1	April 6	May 16	5 Wk. 5 Da.	Fig. 1	50#	10#	17290
2	March 18	May 16	8 Wk. 3 Da.	Fig. 1	49.6	130	32290
3	March 16	May 19	9 Wk. 1 Da.	Fig. 1	51	120	<u>31040</u>
						Average	31665
4	March 18	May 17	8 Wk. 4 Da.	Fig. 2	55.4	115	30415
5	April 6	May 18	6 Wk.	Fig. 2	54.6	67	24415
6	March 16		Fractured	Fig. 2	--	--	--
						Average	27415
7	April 9	May 18	5 Wk. 4 Da.	Fig. 3	58.8	125	31665
8	April 12	May 19	5 Wk. 2 Da.	Fig. 3	59.3	85	26665
9	April 13	May 17	4 Wk. 6 Da.	Fig. 3	60.8	135	<u>32915</u>
						Average	30415
10	April 9	May 17	5 Wk. 3 Da.	Fig. 4	57.3	117	30665
11	April 12	May 19	5 Wk. 2 Da.	Fig. 4	56.4	132	32540
12	April 13	May 18	5 Wk.	Fig. 4	58	105	<u>29165</u>
						Average	30790
Constant = 16040#							

π Total pressure = scale reading x 125 + constant (16040#)

' Made of Wabash Portland Cement

• Only Nos. 2 and 3 were used to get average of Fig. 1

Fig. 1 - Horse-shoe

Fig. 2 - Straight Outside and Inside

Fig. 3 - Straight Inside Slant Outside

Fig. 4 - Straight Outside Horse-shoe Inside

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100	101	102	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118	119	120	121	122	123	124	125	126	127	128	129	130	131	132	133	134	135	136	137	138	139	140	141	142	143	144	145	146	147	148	149	150	151	152	153	154	155	156	157	158	159	160	161	162	163	164	165	166	167	168	169	170	171	172	173	174	175	176	177	178	179	180	181	182	183	184	185	186	187	188	189	190	191	192	193	194	195	196	197	198	199	200	201	202	203	204	205	206	207	208	209	210	211	212	213	214	215	216	217	218	219	220	221	222	223	224	225	226	227	228	229	230	231	232	233	234	235	236	237	238	239	240	241	242	243	244	245	246	247	248	249	250	251	252	253	254	255	256	257	258	259	260	261	262	263	264	265	266	267	268	269	270	271	272	273	274	275	276	277	278	279	280	281	282	283	284	285	286	287	288	289	290	291	292	293	294	295	296	297	298	299	300	301	302	303	304	305	306	307	308	309	310	311	312	313	314	315	316	317	318	319	320	321	322	323	324	325	326	327	328	329	330	331	332	333	334	335	336	337	338	339	340	341	342	343	344	345	346	347	348	349	350	351	352	353	354	355	356	357	358	359	360	361	362	363	364	365	366	367	368	369	370	371	372	373	374	375	376	377	378	379	380	381	382	383	384	385	386	387	388	389	390	391	392	393	394	395	396	397	398	399	400	401	402	403	404	405	406	407	408	409	410	411	412	413	414	415	416	417	418	419	420	421	422	423	424	425	426	427	428	429	430	431	432	433	434	435	436	437	438	439	440	441	442	443	444	445	446	447	448	449	450	451	452	453	454	455	456	457	458	459	460	461	462	463	464	465	466	467	468	469	470	471	472	473	474	475	476	477	478	479	480	481	482	483	484	485	486	487	488	489	490	491	492	493	494	495	496	497	498	499	500	501	502	503	504	505	506	507	508	509	510	511	512	513	514	515	516	517	518	519	520	521	522	523	524	525	526	527	528	529	530	531	532	533	534	535	536	537	538	539	540	541	542	543	544	545	546	547	548	549	550	551	552	553	554	555	556	557	558	559	560	561	562	563	564	565	566	567	568	569	570	571	572	573	574	575	576	577	578	579	580	581	582	583	584	585	586	587	588	589	590	591	592	593	594	595	596	597	598	599	600	601	602	603	604	605	606	607	608	609	610	611	612	613	614	615	616	617	618	619	620	621	622	623	624	625	626	627	628	629	630	631	632	633	634	635	636	637	638	639	640	641	642	643	644	645	646	647	648	649	650	651	652	653	654	655	656	657	658	659	660	661	662	663	664	665	666	667	668	669	670	671	672	673	674	675	676	677	678	679	680	681	682	683	684	685	686	687	688	689	690	691	692	693	694	695	696	697	698	699	700	701	702	703	704	705	706	707	708	709	710	711	712	713	714	715	716	717	718	719	720	721	722	723	724	725	726	727	728	729	730	731	732	733	734	735	736	737	738	739	740	741	742	743	744	745	746	747	748	749	750	751	752	753	754	755	756	757	758	759	760	761	762	763	764	765	766	767	768	769	770	771	772	773	774	775	776	777	778	779	780	781	782	783	784	785	786	787	788	789	790	791	792	793	794	795	796	797	798	799	800	801	802	803	804	805	806	807	808	809	810	811	812	813	814	815	816	817	818	819	820	821	822	823	824	825	826	827	828	829	830	831	832	833	834	835	836	837	838	839	840	841	842	843	844	845	846	847	848	849	850	851	852	853	854	855	856	857	858	859	860	861	862	863	864	865	866	867	868	869	870	871	872	873	874	875	876	877	878	879	880	881	882	883	884	885	886	887	888	889	890	891	892	893	894	895	896	897	898	899	900	901	902	903	904	905	906	907	908	909	910	911	912	913	914	915	916	917	918	919	920	921	922	923	924	925	926	927	928	929	930	931	932	933	934	935	936	937	938	939	940	941	942	943	944	945	946	947	948	949	950	951	952	953	954	955	956	957	958	959	960	961	962	963	964	965	966	967	968	969	970	971	972	973	974	975	976	977	978	979	980	981	982	983	984	985	986	987	988	989	990	991	992	993	994	995	996	997	998	999	1000	1001	1002	1003	1004	1005	1006	1007	1008	1009	1010	1011	1012	1013	1014	1015	1016	1017	1018	1019	1020	1021	1022	1023	1024	1025	1026	1027	1028	1029	1030	1031	1032	1033	1034	1035	1036	1037	1038	1039	1040	1041	1042	1043	1044	1045	1046	1047	1048	1049	1050	1051	1052	1053	1054	1055	1056	1057	1058	1059	1060	1061	1062	1063	1064	1065	1066	1067	1068	1069	1070	1071	1072	1073	1074	1075	1076	1077	1078	1079	1080	1081	1082	1083	1084	1085	1086	1087	1088	1089	1090	1091	1092	1093	1094	1095	1096	1097	1098	1099	1100	1101	1102	1103	1104	1105	1106	1107	1108	1109	1110	1111	1112	1113	1114	1115	1116	1117	1118	1119	1120	1121	1122	1123	1124	1125	1126	1127	1128	1129	1130	1131	1132	1133	1134	1135	1136	1137	1138	1139	1140	1141	1142	1143	1144	1145	1146	1147	1148	1149	1150	1151	1152	1153	1154	1155	1156	1157	1158	1159	1160	1161	1162	1163	1164	1165	1166	1167	1168	1169	1170	1171	1172	1173	1174	1175	1176	1177	1178	1179	1180	1181	1182	1183	1184	1185	1186	1187	1188	1189	1190	1191	1192	1193	1194	1195	1196	1197	1198	1199	1200	1201	1202	1203	1204	1205	1206	1207	1208	1209	1210	1211	1212	1213	1214	1215	1216	1217	1218	1219	1220	1221	12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No. 4 was sound and after uncovering was found in same condition as No. 3.

No. 5 was also sound but after applying the load the arch was found crushed in, also one side; the other side remained standing but cracked, the bottom also cracked.

No. 6 was dropped by accident and fractured and so could not be tested.

No. 7 was sound but after test was found with the arch crushed in as in the others. The sides were badly broken but still standing. The bottom was slightly cracked.

No. 8 was in good condition and after test showed the arch completely crushed in. The sides and bottom were but slightly broken.

No. 9 was perfectly sound but after load was supplied showed arch badly crushed in with the sides and bottom in fairly good condition.

No. 10 was sound and after test showed arch crushed in with the sides and bottom but slightly cracked.

No. 11 was in good condition before test but afterwards showed complete crushing in of the arch and extensive fracture of the sides and bottom.

No. 12 was perfect before the test and afterwards showed the arch crushed in as far as the springing line. The

rest of the walls and bottom were very slightly injured.

General Conclusions:-

In every case the tunnel failed by crushing in the arch a little above the springing line. The sides in some cases were quite extensively broken and in others showed but few cracks. In nearly every case the bottom held together well and was fractured but slightly.

Taking the average load of the three tunnels of the same shape we find the horse-shoe shape to be the strongest. This shape was the lightest weight indicating that less material was necessary for construction. This would perhaps be offset by the greater difficulty of construction. The only advantage that is obtained by Fig. 3 is the greater base area where heavy traffic is to take place in the tunnel. Fig. 4 does not give greater base area and besides has less room on the inside and uses more material.

If more tunnels of each variety had been made our results would have been more reliable. The difficulty of getting all tunnels alike makes the result more or less uncertain where the average is taken. For instance, in the test of Fig. 3, one test showed a low result whereas the other two showed high results. This may have been due to construction. Judging from the results as a whole, would say that there is no advantage in thickening the sides for ordinary conditions as most of the pressure seems to come on the arch above the springing line. Our conditions perhaps were not ideal for we had but two inches

(2") of sand above the highest point of the arch and the pressure was therefore greatest there. If the depth of sand had been greater better results would have been obtained, without doubt.

Breaking of Beams.

As before stated, beams of concrete were constructed of the shape of the sides of the tunnels Nos. 1 and 2 for the purpose of comparing their strength. In a tunnel the pressure from the load on the arch is sustained by the side walls. Also the lateral pressure of the earth on the sides must be sustained by the side walls of the tunnel. To obtain such loading a machine was designed to operate in conjunction with the Tinius Olsen testing machine in the M. A. C. laboratory. This consisted of a timber 6"x6"x6', on top of which was placed a casting supporting the two ends of the concrete beam. One of these supports was fixed rigidly and the other was mounted on rollers in order to reduce friction. This movable end was attached to a dynamometer consisting of a cylinder with a tight fitting piston, compressing oil. A screw pressed against the dynamometer and by turning the same the pressure in the dynamometer could be regulated. This machine was placed in the testing machine and the load brought directly over the beam.

All of the beams were broken with such double loading excepting one which was broken with a load only from the top.

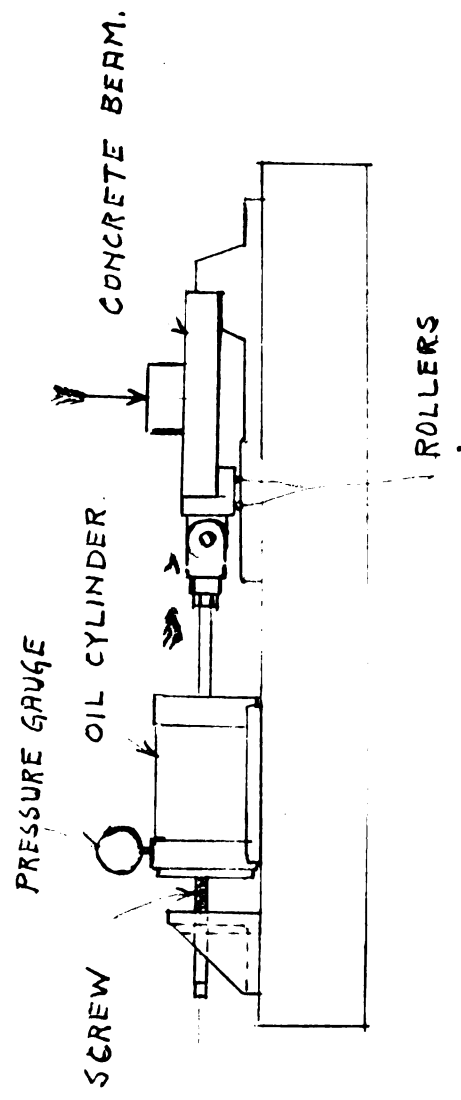
(See drawing for arrangement of machine.)

The diameter of the piston was 5" making an area of 19.635 sq. in. The area of the end of the beam was $2" \times 6" = 12$ sq. in. Therefore the end pressure per sq. in. on the beam was $\frac{19.635}{12}$ x gage reading. The beams were of different ages but one of each kind of the same age was selected to be broken with the same end pressure. In this way two of each kind were broken under 50# end pressure per sq. in. by the gage, two under 75# pressure per sq. in. and two under 100# pressure per sq. in. by the gage.

The load was applied at the center of the beam with a block 3"x5" and the results tabulated below. It will be seen that the one broken without end pressure sustained but a very small load compared with the others; also that the breaking load for all of the arched beams was greater than that for the straight beam with the exception of No. 12. This one was very weak and should not be considered in the results.

In every instance, the beam would first crack on the under side either parallel to the load or at an angle of 45°. After cracking, the load could be considerably increased before the beam would yield.

DEVICE FOR APPLYING END PRESSURE ON BEAMS,



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Table No. 11.

S T R A I G H T S I D E S.

NO.	Date Made	Date Broken	Age	Gage Reading	Total Pressure	End Balance Reading	Average of Two
1	April 6	May 28	7 Wk. 3 Da.	50#	9812.5#	2330#	_____
2	April 8	May 28	7 Wk. 1 Da.	50	9812.5	2350	2340#
3	April 9	May 28	7 Wk. 0 Da.	75	14720	3350	_____
4	April 11	May 28	6 Wk. 5 Da.	75	14720	3400	3375
5	April 15	May 28	6 Wk. 1 Da.	100	19625	3450	_____
6	April 16	May 28	6 Wk. 0 Da.	100	19625	3650	3550
7	April 12	May 28	6 Wk. 4 Da.	0	0	1200	1200
<u>E I R C U L A R</u>							
8	April 8	May 28	7 Wk. 1 Da.	50#	9812.5#	3200#	_____
9	April 16	May 28	6 Wk. 0 Da.	50	9812.5	2750	2975#
10	April 9	May 28	7 Wk. 0 Da.	75	14720	3610	_____
11	April 11	May 28	6 Wk. 5 Da.	75	14720	3540	3575
12	April 12	May 28	6 Wk. 4 Da.	100	19625	2990 ^x	
13	April 15	May 28	6 Wk. 1 Da.	100	19625	3900	3900

x This reading not used in comparison.

• Balance reading contains dead weight of the machine which was 120#.

~~CONFIDENTIAL~~

Wt A 56 p.2

[REDACTED]

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