Comparing LTV and ARMCO Magnetic Steel

Jean-François Ostiguy
AD/Accelerator Physics

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Motivation

More than twenty years ago, the Main Ring dipole magnets were built using specialty magnetic steel supplied by ARMCO. Prototypes of the new Main Injector dipole magnets were therefore built using sample quantities of steel procured from ARMCO. The prototypes have been extensively measured and shown to meet all field quality requirements. To supply the magnet steel in production quantities, five vendores were in competition: ARMCO and LTV, C. Itoh (representing Kawasaki), Mitsui (Nippon), and Tempel (Inland). The contract was awarded to the lowest bidder, LTV.

Although the LTV steel meets all specifications on coercivity and permeability, its properties are slightly different from the ARMCO product. This is not surprising at all since absolute magnetic properties are known to be sensitive to mechanical stress, chemical composition, heat treatment etc.

Figure [1] and [2] show respectively a comparison between the magnetization curves for the LTV and ARMCO products at low and high excitations. The LTV steel clearly has a lower saturation magnetization. All other factors being equal, one expects magnets built with LTV steel to exhibit lower field at high current than magnets built with ARMCO steel. This has been confirmed experimentally.

Since all dipole magnets generally are excited by a common current bus, magnet to magnet field strength reproducibility at a given current is an important consideration. The object of this note is to demonstrate our ability to make quantitative predictions and identify features of the magnetization curve that should be closely monitored to avoid unacceptable variations in the magnetic field strength and distribution.

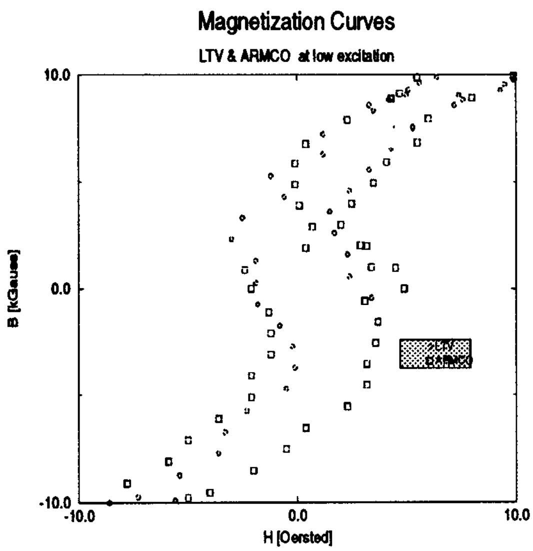

Figure 1: *Measured magnetization curves for ARMCO and LTV magnet steel in the low excitation region. It is difficult to establish which steel has the highest anhysteretic permeability.*

Results

Magnetization curves for both LTV and ARMCO steel have been measured by Advanced Materials Corporation of Pittsburgh, Pennsylvania up to approximately 500 Oersted. Complete measurement results are included as an appendix to this note. Figure [1] shows the magnetization curves for both materials at low field; there is considerable uncertainty in the permeability and the coercivity (on the order of 1-2 Oersted on the graph) for $H < 10$ Oersted. Figure [2] shows the same magnetization curves, this time in the high field region. The LTV steel clearly has a lower saturation magnetization, and consequently, a slightly lower permeability at high field.

To predict the strength of a dipole magnet, the following equation, based on a simple application of the integral form of Ampere's law is often used (MKS units):

$$H = \frac{NI}{g + \frac{\mathcal{L}}{\mu_r}} \simeq \frac{NI}{g}\left[1 - \frac{\mathcal{L}}{\mu_r g}\right] \qquad (1)$$

Here g is the total gap, NI is the total magnetomotive force in Ampere-turns, $\mathcal{L}$

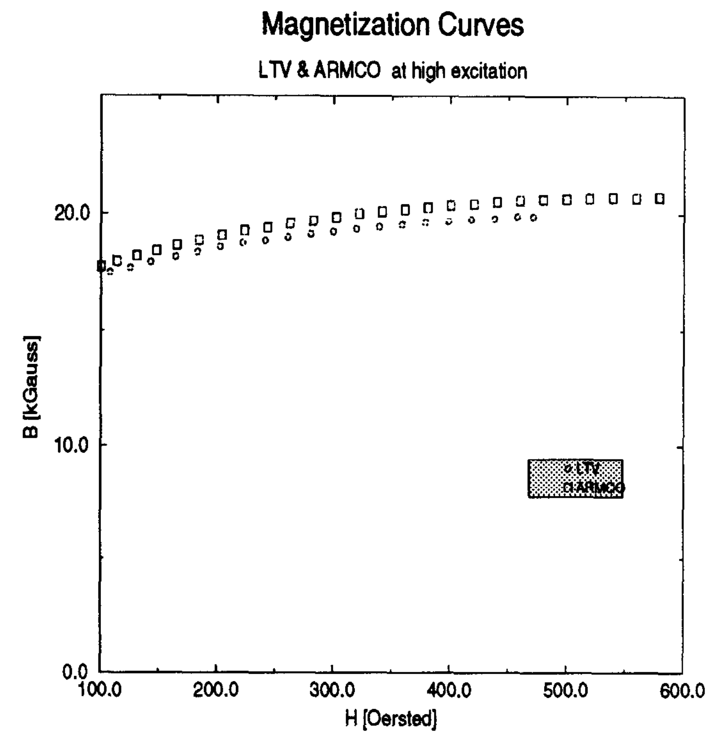

Figure 2: *Measured magnetization curves for ARMCO and LTV magnet steel in the high excitation region. The LTV steel clearly has a lower saturation magnetization.*

is the path length in steel and μ_r is the relative permeability. A small variation in permeability $\Delta\mu_r/\mu_r << 1$ results in a change in strength

$$\frac{\Delta H}{H} = \frac{\mathcal{L}}{g}\frac{\Delta\mu_r}{\mu_r^2} \tag{2}$$

For the MI magnet at $I = 500$ A, $H \simeq 0.5$ O and $\mu_r \simeq 1500$. With $\mathcal{L}/g \simeq 30$, a factor of 2 change in μ would result in a change of 1% in the field. At maximum current ($I = 9500$ A), $\mu_r \simeq 100$ and a variation of 1% in permeability results in a 0.3% change in field [1].

This simple model works fairly well, but does not account for non-uniform saturation of the pole, which determines the field harmonics. Magnetostatic calculations

[1] The permeabilities used here are for the pole region, which is the most saturated region. The permeability is much higher outside the pole region, so the predicted variations should be interpreted as upper bounds.

were therefore performed using the finite element code PE2D from Vector Fields Inc. Scalar (anhysteretic) versions of the magnetization curves were produced from the measurement data. These curves are shown in figure [3], the corresponding permeabilities are shown in figure [4]. Results of the calculations are summarized in figurcs [5], [6] and tablc [1].

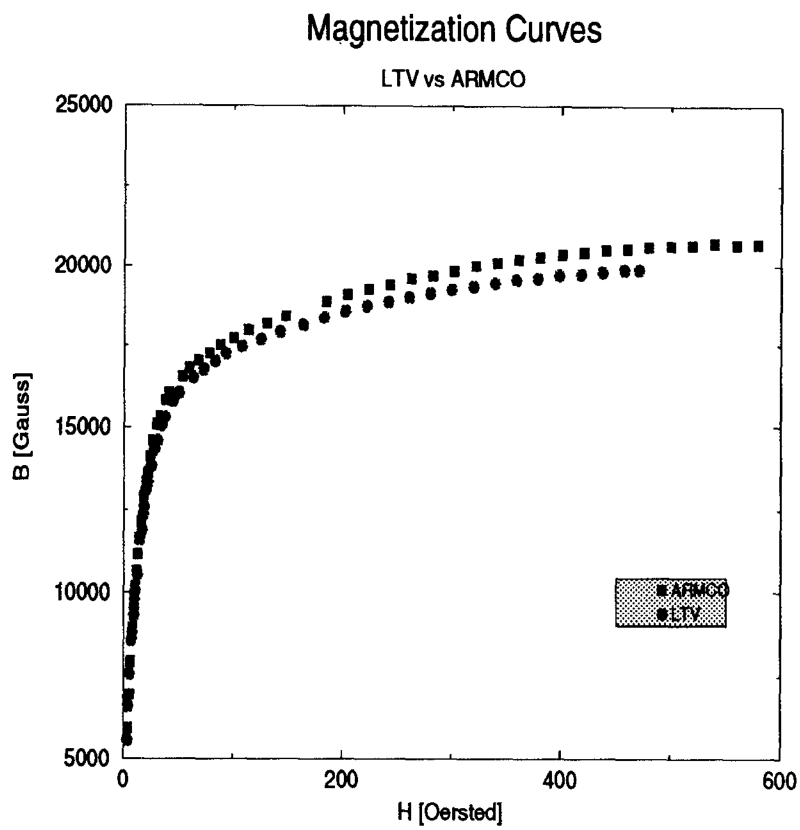

Figure 3: *Magnetization curves used for magnetostatic calculations.*

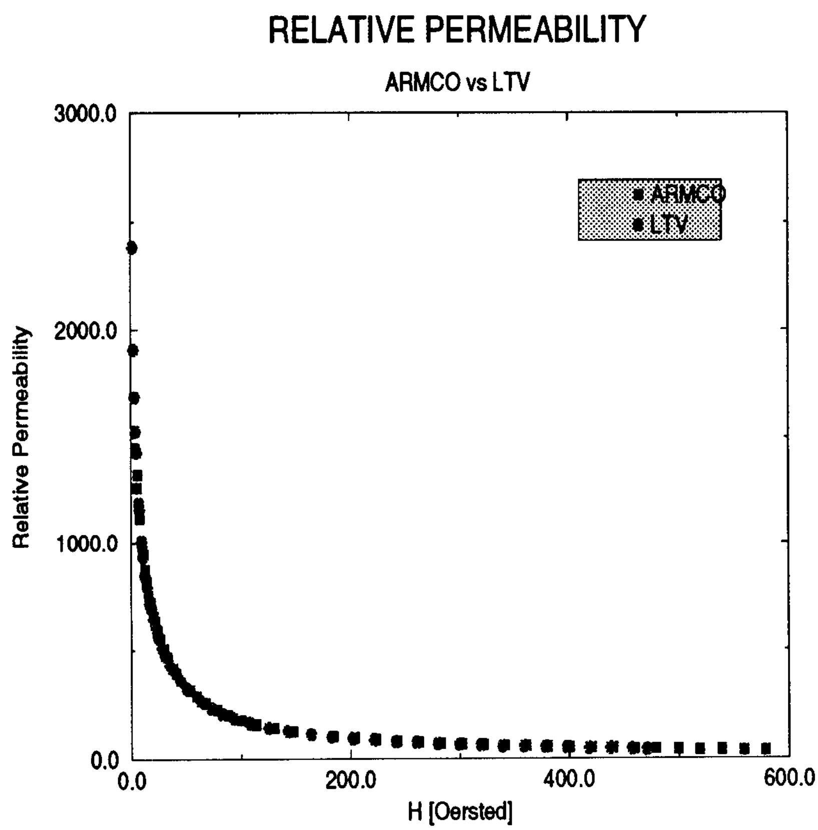

Figure 4: *Magnetic permeabilities corresponding to the curves in figure [3].*

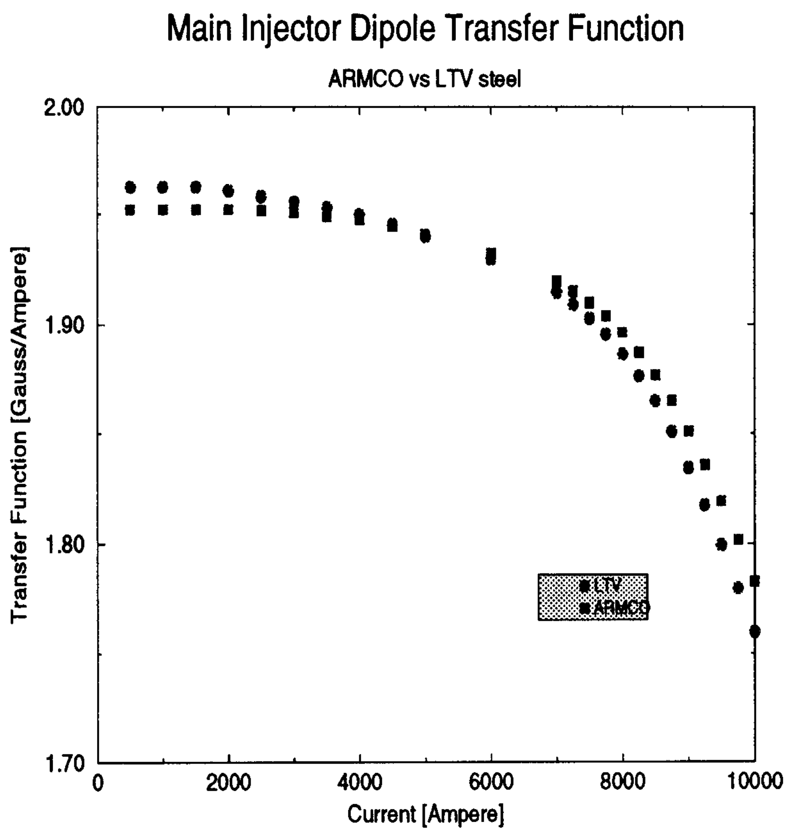

Figure 5: *Calculated transfer function for the MI dipole magnet.*

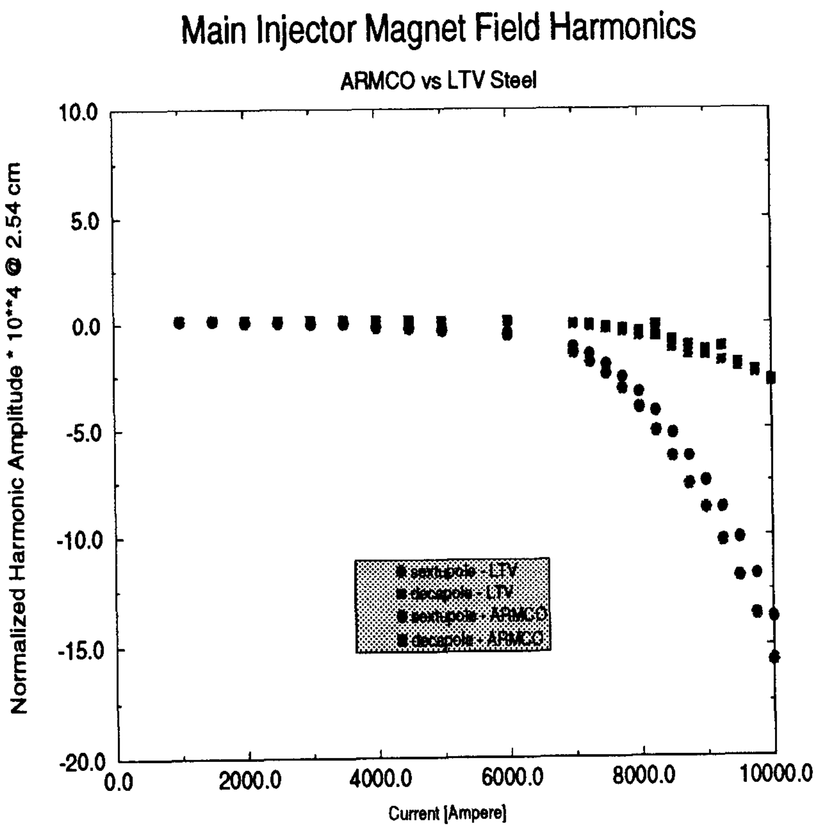

Figure 6: *Calculated harmonic contents of the field as a function of the excitation current.*

		LTV				ARMCO			
	I	B	B/I	6-pole	10-pole	B	B/I	6-pole	10-pole
1	500	981.268	1.962536			976.05	1.95210	0.13383	0.16094
2	1000	1962.49	1.962490	0.17470	0.16719	1952.09	1.95209	0.14126	0.16166
3	1500	2943.29	1.962193	0.15614	0.16731	2928.08	1.95205	0.14744	0.16366
4	2000	3921.21	1.960605	0.05185	0.16437	3903.87	1.95194	0.13832	0.16289
5	2500	4894.31	1.957724	0.03127	0.14879	4879.06	1.95162	0.10678	0.15888
6	3000	5865.53	1.955176	0.01880	0.16860	5852.3	1.95077	-0.00722	0.16903
7	3500	6834.43	1.952694	-0.00494	0.15371	6821.76	1.94907	0.00804	0.16358
8	4000	7798.29	1.949573	-0.17478	0.15255	7789.34	1.94734	-0.14807	0.13795
9	4500	8752.66	1.945035	-0.23749	0.14742	8750.61	1.94444	-0.16711	0.14494
10	5000	9698.8	1.939760	-0.32488	0.14000	9704.48	1.94090	-0.24341	0.13832
11	6000	11573.4	1.928900	-0.57015	0.09190	11590.8	1.93180	-0.48806	0.11745
12	7000	13399.3	1.914186	-1.4362	-0.04617	13434.1	1.91916	-1.15100	-0.01388
13	7250	13839.8	1.908937	-1.8828	-0.15196	13882.3	1.91480	-1.49676	-0.07864
14	7500	14271.7	1.902893	-2.4421	-0.25480	14323.3	1.90978	-1.98876	-0.16340
15	7750	14690.1	1.895497	-3.1563	-0.43345	14754.3	1.90378	-2.59614	-0.29342
16	8000	15092.9	1.886613	-4.0596	-0.67026	15170.8	1.89635	-3.33664	-0.43725
17	8250	15481.5	1.876545	-5.1390	-0.09327	15570.8	1.88737	-4.23201	-0.64967
18	8500	15849.6	1.864658	-6.3490	-1.21050	15953.3	1.87686	-5.25521	-0.84371
19	8750	16195.7	1.850937	-7.6618	-1.50952	16318.1	1.86492	-6.33665	-1.09230
20	9000	16519.9	1.834344	-8.73497	-1.52420	16659.5	1.85106	-7.50316	-1.33371
21	9250	16825.7	1.817610	-10.2396	-1.83294	16980.2	1.83570	-8.73437	-1.16132
22	9500	17107.3	1.799347	-11.8900	-2.09368	17283.6	1.81932	-10.160	-1.93967
23	9750	17364.0	1.780071	-13.6657	-2.41094	17566.7	1.80171	-11.804	-2.30960
24	10000	17568.0	1.760050	-15.7000	-2.85339	17832.2	1.78322	-13.8021	-2.75191

Table 1: Summary of the magnetostatic calculations.

As expected from the simple model, calculations show that the field of a magnet assembled with LTV laminations is approximately 1% weaker than for magnet assembled with ARMCO laminations at maximum excitation (9500 A). This is consistent with experiment. The calculations predict a stronger field in the LTV magnet at low excitations. This is not the case experimentally and is most likely the result of the very high uncertainty in the measured values of μ for $H < 10$ Oersted[2]. Finally, the calculations predict no significant difference in field quality for magnets produced with the two different steels.

Conclusions

- The impact of the differences in magnetic properties between the LTV and ARMCO steel is well understood.
- To keep magnet-to-magnet integrated field strength variations below 1 part in a 1000, the relative permeability should not vary by more than 5% at low field ($H < 10$ O, $\mu \leq 1500$) and by more than a percent at high excitation ($H > 100$ O, $\mu \leq 200$).
- As long as
  1. all magnets are built from batches of steel procured from the same vendor
  2. there are no batch-to-batch modification in the steel fabrication process
  3. the laminations are properly sorted

  there should be no difficulty in matching the integrated strength of MI dipole magnets to within a part in a 1000.

Appendix

The following tables are measurements performed by Advanced Material Corporation in December 1994.

[2]For the scalar magnetization curves used in the calculations, the permeability of the LTV steel was indeed higher than for the ARMCO steel at $H \simeq 0.5$ Oersted.

LTV Steel											
H [Oersted] vs B [kGauss]											
	H	B		H	B		H	B		H	B
1	3.4	-0.42	61	398.2	19.72	121	-10.8	-10.75	181	-23.6	-14.09
2	2.4	0.58	62	417.9	19.77	122	-11.6	-11.00	182	-21.3	-13.85
3	2.3	1.58	63	437.6	19.82	123	-12.5	-11.25	183	-19.9	-13.60
4	1.7	2.58	64	457.3	19.89	124	-12.8	-11.51	184	-18.6	-13.35
5	1.5	3.58	65	470.9	19.90	125	-13.7	-11.76	185	-17.3	-13.11
6	2.4	4.58	66	67.3	16.63	126	-15.0	-12.01	186	-16.0	-12.86
7	3.3	5.58	67	58.9	16.39	127	-16.3	-12.26	187	-15.1	-12.62
8	4.3	6.58	68	51.4	16.14	128	-16.2	-12.51	188	-13.8	-12.37
9	5.3	7.57	69	46.2	15.89	129	-17.5	-12.76	189	-12.4	-12.12
10	7.2	8.57	70	41.9	15.65	130	-18.8	-13.01	190	-11.2	-11.88
11	7.6	8.82	71	37.8	15.40	131	-20.2	-13.26	191	-10.8	-11.63
12	7.4	9.07	72	34.1	15.15	132	-22.0	-13.51	192	-9.9	-11.38
13	9.3	9.31	73	32.2	14.90	133	-23.7	-13.76	193	-10.4	-11.14
14	9.5	9.56	74	29.5	14.65	134	-25.5	-14.01	194	-9.5	-10.89
15	9.9	9.80	75	26.8	14.40	135	-26.4	-14.26	195	-8.7	-10.64
16	10.8	10.05	76	24.5	14.15	136	-28.1	-14.51	196	-7.8	-10.40
17	11.6	10.30	77	22.8	13.90	137	-30.4	-14.76	197	-7.0	-10.15
18	12.5	10.54	78	21.1	13.65	138	-32.3	-14.94	198	-5.6	-9.90
19	13.3	10.79	79	19.7	13.40	139	-34.5	-15.19	199	-7.5	-10.51
20	13.3	11.04	80	18.5	13.15	140	-38.4	-15.43	200	-7.0	-10.26
21	14.9	11.38	81	17.2	12.90	141	-42.1	-15.68	201	-5.5	-10.02
22	14.8	11.62	82	15.4	12.65	142	-47.4	-15.93	202	-5.0	-9.77
23	16.6	11.87	83	15.6	12.40	143	-52.2	-16.18	203	-4.0	-9.53
24	17.5	12.12	84	13.8	12.15	144	-59.1	-16.42	204	-2.0	-8.53
25	17.8	12.36	85	12.4	11.90	145	-68.1	-16.66	205	-0.5	-7.54
26	18.2	12.61	86	11.6	11.65	146	-78.9	-16.91	206	0.4	-6.54
27	19.0	12.86	87	11.7	11.39	147	-89.3	-17.15	207	2.3	-5.55
28	20.4	13.10	88	10.4	11.14	148	-104.4	-17.38	208	3.2	-4.55
29	22.2	13.35	89	10.6	10.89	149	-118.9	-17.62	209	3.2	-3.56
30	23.5	13.59	90	9.8	10.64	150	-134.7	-17.86	210	3.6	-2.56
31	24.8	13.84	91	8.5	10.39	151	-152.3	-18.09	211	3.7	-1.56
32	26.1	14.09	92	7.2	10.14	152	-174.6	-18.32	212	3.1	-0.57
33	28.0	14.33	93	6.4	9.89	153	-200.9	-18.55	213	4.9	-0.00
34	30.8	14.58	94	5.6	9.64	154	-224.3	-18.78	214	3.4	0.99
35	32.6	14.82	95	5.1	9.31	155	-243.9	-18.91	215	2.9	1.99
36	34.9	15.07	96	5.0	9.06	156	-263.6	-19.04			
37	37.2	15.31	97	4.2	8.81	157	-283.1	-19.21			
38	40.9	15.56	98	3.3	8.56	158	-302.9	-19.30			
39	44.6	15.80	99	3.5	8.30	159	-322.6	-19.41			
40	50.3	16.04	100	1.2	7.30	160	-342.3	-19.50			
41	56.1	16.28	101	1.2	6.30	161	-362.1	-19.59			
42	63.3	16.52	102	-1.2	5.30	162	-381.8	-19.69			
43	73.0	16.76	103	-0.6	4.29	163	-401.7	-19.73			
44	83.0	17.00	104	-2.5	3.29	164	-421.5	-19.80			
45	93.0	17.24	105	-3.0	2.29	165	-441.4	-19.82			
46	107.7	17.47	106	-1.9	1.29	166	-461.2	-19.89			
47	125.0	17.70	107	-1.9	0.28	167	-481.0	-19.93			
48	142.6	17.93	108	-1.8	-0.72	168	-500.9	-19.98			
49	163.9	18.15	109	-0.8	-1.73	169	-520.9	-19.96			
50	182.9	18.38	110	-0.2	-2.73	170	-540.8	-20.00			
51	202.3	18.59	111	-0.1	-3.73	171	-560.7	-20.01			
52	221.7	18.75	112	-0.5	-4.74	172	-580.6	-20.06			
53	241.3	18.88	113	-2.3	-5.74	173	-600.6	-20.04			
54	260.8	19.02	114	-3.3	-6.74	174	-44.5	-15.80			
55	280.4	19.14	115	-3.6	-7.74	175	-39.4	-15.56			
56	299.9	19.27	116	-5.4	-8.75	176	-36.2	-15.32			
57	319.5	19.37	117	-7.3	-9.75	177	-32.9	-15.07			
58	339.2	19.46	118	-8.6	-10.00	178	-30.1	-14.83			
59	358.8	19.55	119	-9.6	-10.25	179	-27.7	-14.58			
60	378.5	19.63	120	-10.9	-10.50	180	-25.9	-14.34			

Table 2: *Magnetization curve data for the LTV steel.*

ARMCO Steel											
H [Oersted] vs B [kGauss]											
	H	B		H	B		H	B		H	B
1	4.5	0.96	61	459.8	20.56	121	-12.4	-11.53	181	-25.4	-14.93
2	3.2	1.96	62	479.6	20.61	122	-13.8	-11.78	182	-23.5	-14.69
3	2.0	2.96	63	499.5	20.63	123	-15.5	-12.03	183	-22.1	-14.44
4	2.5	3.96	64	519.3	20.66	124	-16.0	-12.28	184	-20.2	-14.20
5	3.5	4.95	65	539.1	20.71	125	-16.5	-12.53	185	-18.3	-13.95
6	4.1	5.95	66	559.1	20.67	126	-17.1	-12.78	186	-17.4	-13.71
7	5.5	6.94	67	578.9	20.70	127	-19.1	-13.03	187	-16.9	-13.46
8	6.0	7.94	68	81.1	17.37	128	-20.1	-13.28	188	-15.4	-13.22
9	8.0	8.93	69	70.2	17.11	129	-21.1	-13.53	189	-14.4	-12.97
10	9.9	9.93	70	60.5	16.86	130	-21.5	-13.78	190	-13.3	-12.73
11	10.4	10.17	71	51.5	16.62	131	-23.3	-14.03	191	-12.8	-12.48
12	10.8	10.42	72	44.7	16.38	132	-24.8	-14.28	192	-12.3	-12.23
13	11.3	10.66	73	39.0	16.13	133	-26.8	-14.53	193	-11.8	-11.99
14	11.3	10.91	74	34.7	15.88	134	-28.3	-14.78	194	-10.9	-11.74
15	12.8	11.16	75	31.7	15.64	135	-29.8	-15.03	195	-9.9	-11.49
16	13.8	11.40	76	30.3	15.39	136	-32.2	-15.28	196	-9.0	-11.25
17	14.3	11.65	77	26.9	15.14	137	-34.6	-15.53	197	-8.3	-11.00
18	14.9	11.89	78	24.5	14.89	138	-38.0	-15.75	198	-7.5	-10.76
19	15.9	12.14	79	23.6	14.64	139	-41.4	-16.00	199	-7.5	-10.51
20	16.5	12.39	80	21.6	14.39	140	-46.2	-16.24	200	-7.0	-10.26
21	17.4	12.63	81	20.1	14.14	141	-52.4	-16.49	201	-5.5	-10.02
22	18.0	12.88	82	19.2	13.89	142	-59.6	-16.73	202	-5.0	-9.77
23	19.0	13.12	83	18.1	13.64	143	-68.8	-16.98	203	-4.0	-9.53
24	20.5	13.37	84	17.1	13.39	144	-79.0	-17.22	204	-2.0	-8.53
25	21.5	13.62	85	15.7	13.14	145	-90.6	-17.46	205	-0.5	-7.54
26	23.0	13.86	86	15.3	12.89	146	-103.5	-17.70	206	0.4	-6.54
27	24.0	14.11	87	14.3	12.64	147	-117.9	-17.93	207	2.3	-5.55
28	25.0	14.35	88	12.5	12.39	148	-134.7	-18.17	208	3.2	-4.55
29	26.5	14.60	89	12.0	12.14	149	-149.2	-18.40	209	3.2	-3.56
30	28.6	14.84	90	11.0	11.88	150	-166.3	-18.64	210	3.6	-2.56
31	29.9	15.09	91	10.0	11.63	151	-188.3	-18.87	211	3.7	-1.56
32	32.8	15.33	92	10.0	11.38	152	-210.7	-19.10	212	3.1	-0.57
33	35.4	15.58	93	8.9	11.13	153	-232.4	-19.33	213	4.9	0.00
34	38.2	15.82	94	8.5	10.88	154	-252.2	-19.47	214	3.4	0.99
35	41.2	16.06	95	7.0	10.63	155	-271.9	-19.61	215	2.9	1.99
36	46.5	16.31	96	6.5	10.38	156	-291.6	-19.77			
37	53.4	16.54	97	6.5	10.13	157	-311.3	-19.90			
38	59.2	16.79	98	5.5	9.88	158	-331.1	-20.02			
39	67.9	17.02	99	4.7	9.13	159	-350.9	-20.12			
40	77.5	17.26	100	4.3	8.87	160	-370.7	-20.19			
41	88.2	17.50	101	2.3	7.88	161	-390.5	-20.31			
42	100.2	17.73	102	0.4	6.88	162	-410.4	-20.36			
43	113.6	17.97	103	-0.1	5.88	163	-430.2	-20.45			
44	130.7	18.20	104	-0.1	4.87	164	-450.1	-20.50			
45	147.8	18.42	105	0.1	3.87	165	-470.0	-20.55			
46	165.1	18.65	106	0.7	2.87	166	-489.9	-20.60			
47	184.5	18.88	107	0.4	1.87	167	-509.8	-20.65			
48	204.0	19.09	108	-2.4	0.87	168	-529.8	-20.65			
49	223.5	19.28	109	-2.1	0.00	169	-549.7	-20.68			
50	243.1	19.42	110	-1.3	-1.11	170	-569.8	-20.67			
51	262.7	19.61	111	-1.2	-2.11	171	-589.7	-20.69			
52	282.3	19.72	112	-1.2	-3.11	172	-609.7	-20.70			
53	302.0	19.85	113	-2.1	-4.11	173	-63.6	-16.87			
54	321.6	20.01	114	-2.1	-5.11	174	-55.2	-16.63			
55	341.3	20.10	115	-3.6	-6.11	175	-47.0	-16.39			
56	361.0	20.20	116	-5.0	-7.11	176	-41.7	-16.15			
57	380.8	20.27	117	-5.9	-8.11	177	-36.5	-15.91			
58	400.5	20.36	118	-7.8	-9.11	178	-32.7	-15.67			
59	420.3	20.43	119	-10.2	-10.11	179	-29.2	-15.42			
60	440.0	20.51	120	-12.2	-11.11	180	-26.8	-15.18			

Table 3: *Magnetization curve data for ARMCO steel.*