THE MAGNETISM OF TUNGSTEN STEEL.

by

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SCOPE OF THE RESEARCH.

This paper records a research into the magnetic properties, especially those of residual magnetism and coercive force, of steel alloys containing varying percentages of tungsten. The solution of each of the following problems was aimed at:-

1. The effect of the temperature of quenching on the residual magnetic properties.

2. The effect of vibration on a tungsten steel permanent magnet.

3. The effect of steaming a tungsten steel magnet.

4. The effect of maximum field on residual magnetism and coercive force.

5. The effect of varying percentages of tungsten on the magnetism of steel.

COMPOSITIONS OF STEELS USED.

The specimens used were supplied by Sir. W.G. Armstrong, Whitworth & Co. Ltd., and were about 20 cms. long and 0·75 cms. diameter. There percentage compositions were as follows:-

TABLE 1. ANALYSIS OF TUNGSTEN STEELS USED

SPECIMEN	TUNGSTEN	CARBON	MANGANESE
A.	2·88	0·44	0·24
B.	5·85	0·43	0·26
C.	8·73	0·43	0·26
D.	11·65	0·43	0·26

Steels of the same composition were used by Miss Moir,*

(*M.B. Moir, Phil. Mag., 28, 1914, 738 - 748.)

in certain tests made on steels quenched from 900°C.

The Gray - Ross Magnetometer† was employed for testing

(†J.G. Gray & A.D. Ross, Proc. Roy. Soc. Edin., 29, 1909, 182)

purposes, and Du Bois' Demagnetising Factors‡ employed,

(‡Du Bois, The Magnetic Circuit in Theory and Practice)

for the calculation of the net field acting on each specimen.

ALLOY A. (2·88% TUNGSTEN.)

I. EFFECT OF TEMPERATURE OF QUENCHING.

Specimen A1 was taken through a hysteresis cycle in each of the following states:-

(a) as received (R)

(b) After quenching from 700° (Q700°)

(c) " " " 750° (Q750°)

(d) " " " 800° (Q800°)

(e) " " " 850° (Q850°)

(f) " " " 900° (Q900°)

The maximum field experienced in each cycle was about 150 c.g.s units. The residual magnetism (I_r) and the coercive force (H_c) corresponding to this field are shown in Table 2:-

TABLE 2. EFFECT OF TEMPERATURE OF QUENCHING 2·88% TUNGSTEN STEEL.

Condition	I_r	H_c	$I_r \times H_c$	H_c/I_r
R	573	12·0	6900	·021
Q700°	675	20·2	13600	·030
Q750°	670	35·4	23700	·053
Q800°	665	38·9	25900	·058
Q850°	672	37·0	24900	·055
Q900°	674	36·4	24500	·054

Before each cycle was taken, the specimen was thoroughly magnetised and demagnetised, in order to remove any sensitive state* following on the thermal treatment.

(*J.G. Gray and A.D. Ross. On a Sensitive State induced in Magnetic Materials by Thermal Treatment. Proc. Roy. Soc. Edin. 28, 1908, 239 - 615)

The residual magnetism (I_r) given here represents the magnetism remaining in the specimen when the net field, including the field of the specimen itself, had been reduced to zero.

Now a permanent magnet not only must be strongly magnetised (i.e. possess a large value for the residual magnetism I_r), but also must resist strongly any attempt to remove its magnetism (i.e., must give a large value for the coercive force H_c).

A good criterion, therefore, for a permanent magnet is that the produce $I_r \times H_c$ should be large. It has been suggested by Ashworth* that for a particular steel, a good measure

(*J.R. Ashworth, "Nature" 94, 1915, 506)

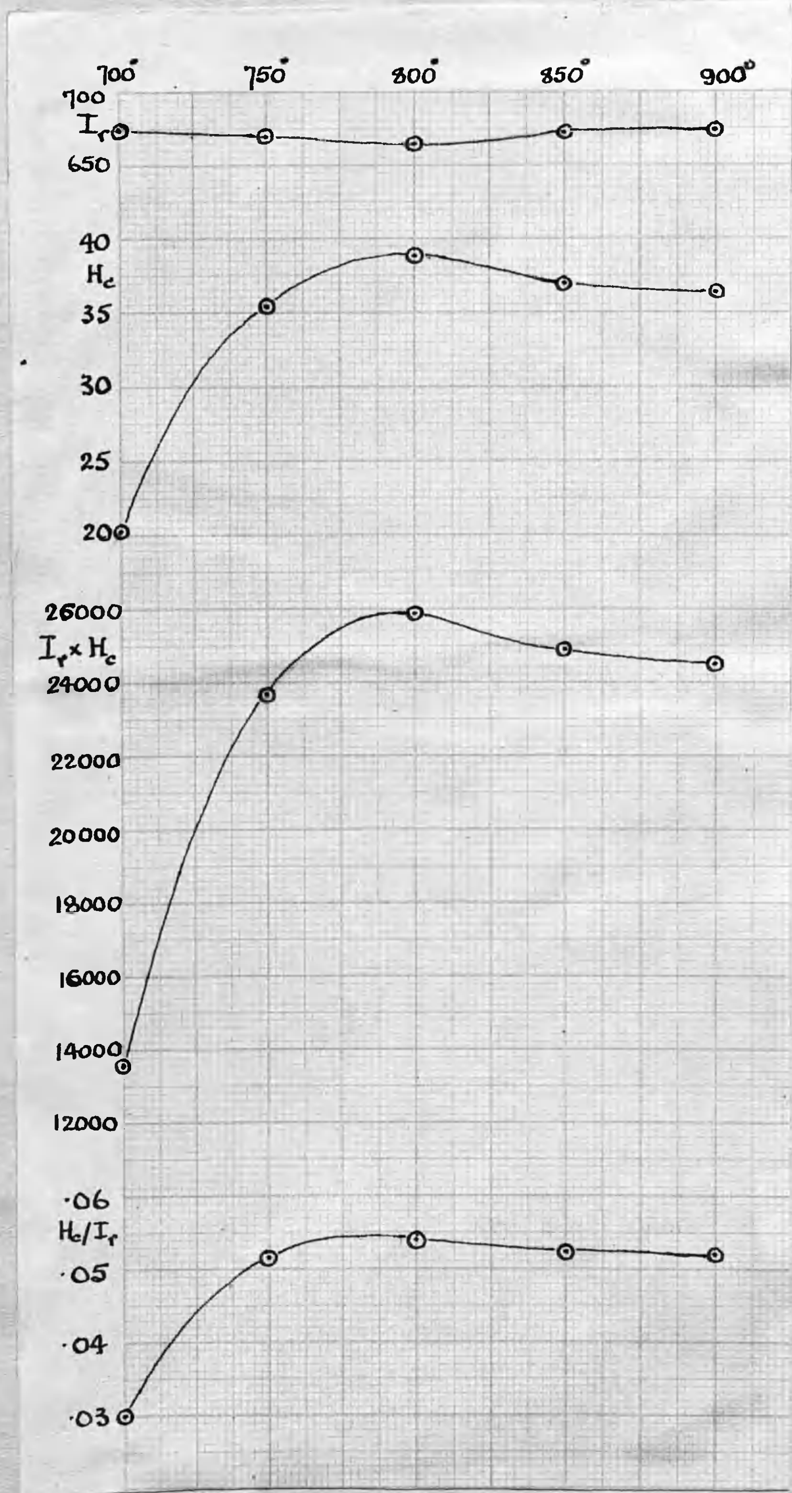
of the "permanence" of the magnetism should be the ratio of coercive force to residual magnetic intensity, that is, the ratio H_c/I_r. Thompson† later pointed out that this criterion must

(†S.P. Thompson, Proc. Phys. Soc. 27, 1915, 179 - 185)

not be used for the comparison of the residual magnetic properties of different steels, and that the safest criterion was a large value of the product $I_r \times H_c$ called the "remanence". In this paper the values of both permanence and remanence will be tabulated, and it will be seen that for a particular tungsten steel either criterion may be used, though permanence is probably the safer.

The following graphs give the variation of I_r, H_c, $I_r \times H_c$, and H_c/I_r with the temperature of quenching:-

FIGURE 1. EFFECT OF TEMPERATURE OF QUENCHING 2·88% TUNGSTEN STEEL.



It will be seen that the residual magnetism (I_r) does not vary much for the range of temperatures taken; if this were taken as the sole criterion, the quenching temperature of 800° would probably be avoided owing to the small minimum there in the I_r - curve. The coercive force (H_c), however, rises rapidly for quenching temperatures up to 800°, after which it falls gradually, so that the remanence ($I_r \times H_c$) and the permanence $\left(\frac{H_c}{I_r}\right)$ have also maxima in the neighbourhood of 800°, and this may be taken as approximately the best temperature for quenching this particular steel(2·88 % Tungsten). These results form a striking example of the importance of consideration of the variation of H_c with quenching temperature.

11. EFFECT OF VIBRATION ON A PERMANENT MAGNET.

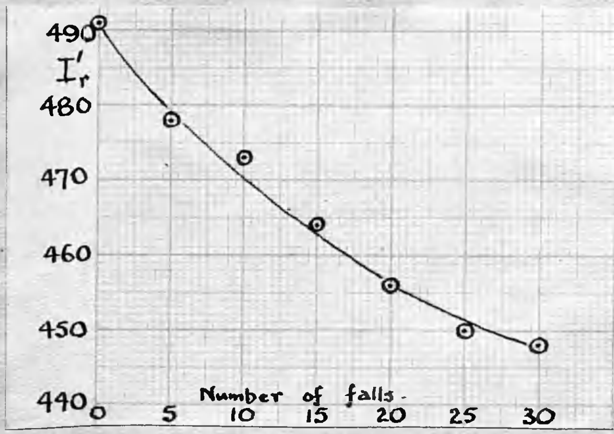
Specimen A 2 was quenched at the optimum temperature of 800°, and after being tested and magnetised, by a field of about 200 cgs. units, was put through a series of vibration tests. The vibrations were initially small; the specimen was dropped vertically on one end through a height of one foot on to a stone floor, and was caught on the rebound. In this way the specimen underwent a definite treatment that could be repeated exactly. The apparent residual magnetism (I_r') in the specimen was measured after each vibration. The apparent residual magnetism (I_r') is that in the specimen when no external magnetic field is acting.

The internal field due to the residual magnetism in the steel is still, however, unbalanced. This field is negative compared with the magnetism, and has a value, for these specimens, of about 20 cgs. units. The residual magnetism (I_r) corresponding to a zero field acting on the specimen is obtained from the plotted hysteresis cycle (See p. 4 above). I_r has a larger value than I'_r, since I'_r corresponds to a negative field of about 20 cgs. units. In the shock tests, I'_r alone can be studied. The results are put in tabular form in Table 3, and are also graphed in figure 2:-

TABLE 3. EFFECT OF VIBRATION ON 2·88% TUNGSTEN STEEL.

NUMBER OF FALLS.	I'_r	DECREASE IN I'_r for 5 falls.
0	491	-
5	478	13
10	473	5
15	464	9
20	456	8
25	450	6
30	448	2

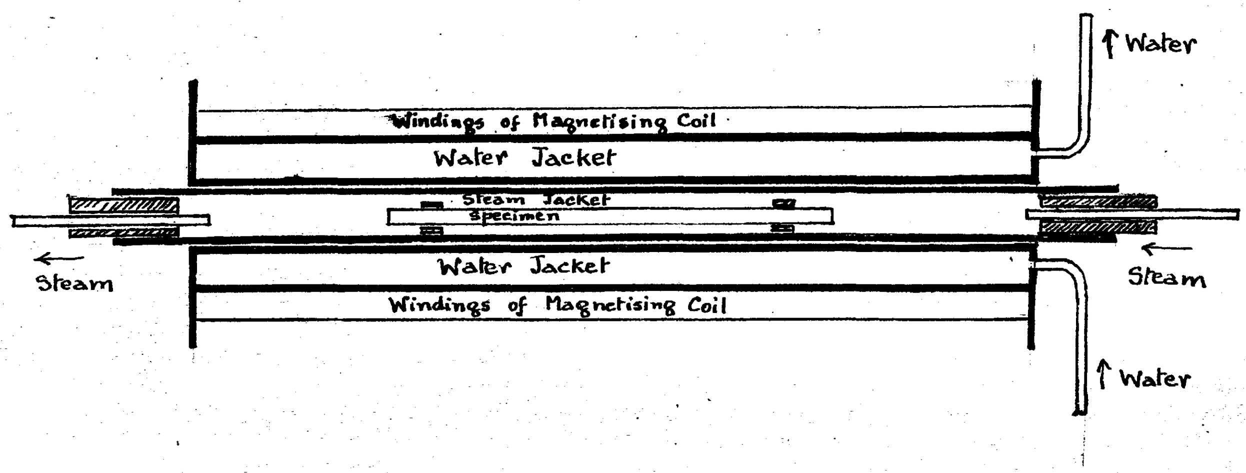
FIGURE 2. EFFECT OF VIBRATION ON 2·88% TUNGSTEN STEEL.



It will be seen that each small shock removes a portion of the magnetism of the steel, the amount removed by each successive treatment becoming gradually less. The steel is losing its temporary residual magnetism, and is tending to reach a truly permanent magnetic state. It is well known that magnets intended to be used as permanent magnets in the binnacles of ships compasses, or as control magnets in recording instruments, must before being put into use, undergo some process of maturing in order to remove this temporary residual magnetism. The small shocks considered in the previous paragraph were of the same order as the shocks the magnet might undergo when in use as a binnacle magnet or as a control magnet. A fairly thorough series of shocks was now given to the specimen and the value of I'_r was found on test to have been reduced from 448 units to 404 units. This treatment when repeated reduced this only slightly, to 399, so that a steady state of permanent residual magnetism had practically been reached. Thus the permanent residual magnetism was only about 80% of the initial residual magnetism, the remaining 20% being removable by shock.

In order to make certain that the specimen had not been distorted in any way by the shocks, a hysteresis cycle was now taken. For the same maximum field it gave I_r' as 491, exactly the same value as before. Thus the loss of magnetism due to the shocks was not due in any way to distortion of the specimen, nor change in the magnetic properties of the steel. The specimen with a value of 491, for I_r', was left magnetised, and after 15 days the value had dropped to 443. The effect of vibration is therefore not to alter the magnetic properties of the steel, but merely to remove the temporary portion of the residual magnetism; permanent magnets should therefore be magnetised <u>before</u>, and not after, being subjected to shock.

FIGURE 3. DIAGRAM OF STEAMING ARRANGEMENT.



111. EFFECT OF STEAMING A PERMANENT MAGNET.

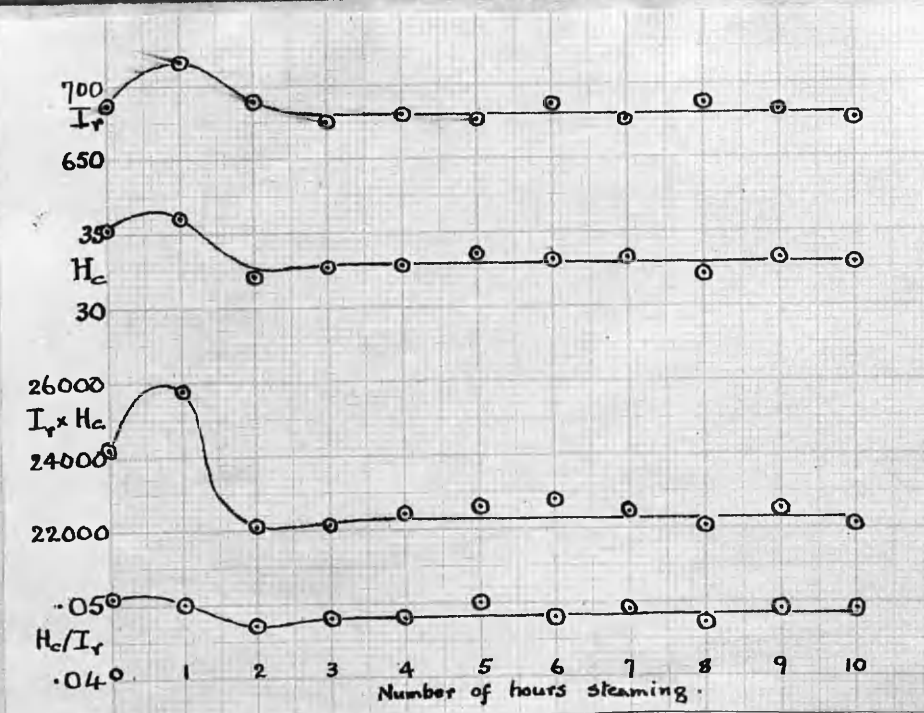
Arrangements were now made so that the specimen could be maintained for any definite period at a temperature of 100°C, while remaining in its position in the magnetometer. The sectional diagram in figure 3 shows the arrangement. The specimen was placed within a brass steam jacket; this was contained within a magnetising coil furnished with an internal tube thro' which water could be passed in order to keep the coil cool. The specimen thus remained in the same position throughout all the tests.

The specimen, after having been quenched from the optimum temperature of 800°C, was placed in the magnetising coil, throughly magnetised and demagnetised in order to remove any sensitive state and a hysteresis cycle taken. The specimen was steamed for an hour, allowed to cool, demagnetised, and a second cycle taken. The process was continued for a total of ten separate hours steaming. Complete hysteresis cycles were taken in all cases, the maximum field being as nearly the same as possible, 200 cgs. units. The effect of steaming on the residual magnetism and coercive force is shown in the table, and by the graphs:-

TABLE 3. EFFECT OF STEAMING 2·88% TUNGSTEN STEEL.

	Number of hours' steaming, 0	1	2	3	4	5	6	7	8	9	10
I_r	686·	716	690	675	680	676	686	676	686	681	675
H_c	35·3	36·0	32·1	32·7	32·9	33·5	33·2	33·2	32·1	33·1	32·8
$I_r \times H_c$	24200	25800	22100	22100	22400	22600	22800	22400	22000	22500	22100
H_c / I_r	·051	·050	·047	·048	·048	·050	·048	·049	·047	·049	·049

FIGURE 4. EFFECT OF STEAMING 2·88% TUNGSTEN STEEL.



It will be seen that the initial effect of steaming is to increase slightly both the residual magnetism and the coercive force; but the second hour's steaming reduces both below their initial values to what are practically steady values. There is an initial increase in $I_r \times H_c$, followed by a decrease, while H_c/I_r decreases slightly during the first two hours. Thus the effect of prolonged steaming is to reduce I_r, by about 1%, and to decrease H_c by about 6%; the permanence $I_r \times H_c$ has been decreased by about 7% and the remanence H_c/I_r by about 6%.

111. A. EFFECT OF VIBRATIONS ON THE STEAMED MAGNET.

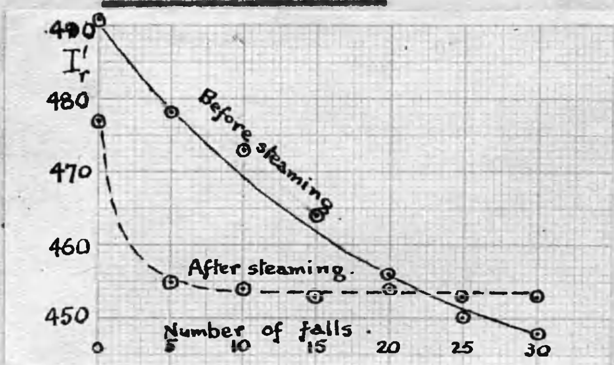
The vibration tests were as before; the results for small vibrations are given in table 4.

TABLE 4. EFFECT OF SMALL VIBRATIONS ON STEAMED 2·88% TUNGSTEN STEEL.

Number of Falls	I'_r	Decrease in I'_r for 5 falls.
0	477	
5	455	22
10	454	1
15	453	1
20	454	- 1
25	453	1
30	453	0

The apparent residual magnetism before the steaming was 491; steaming reduced the value of this for the same maximum field to 477. The first few knocks reduced it further to 455, after which small vibrations had little or no effect. Thus for ordinary small vibrations on a permanent magnet made of this steel, steaming, followed by a slight vibration, after magnetisation, is a distinct success, the specimen reaching amuch more permanent magnetic condition than before the steaming. A comparison of the effects of small vibrations before and after steaming is given in the figure:-

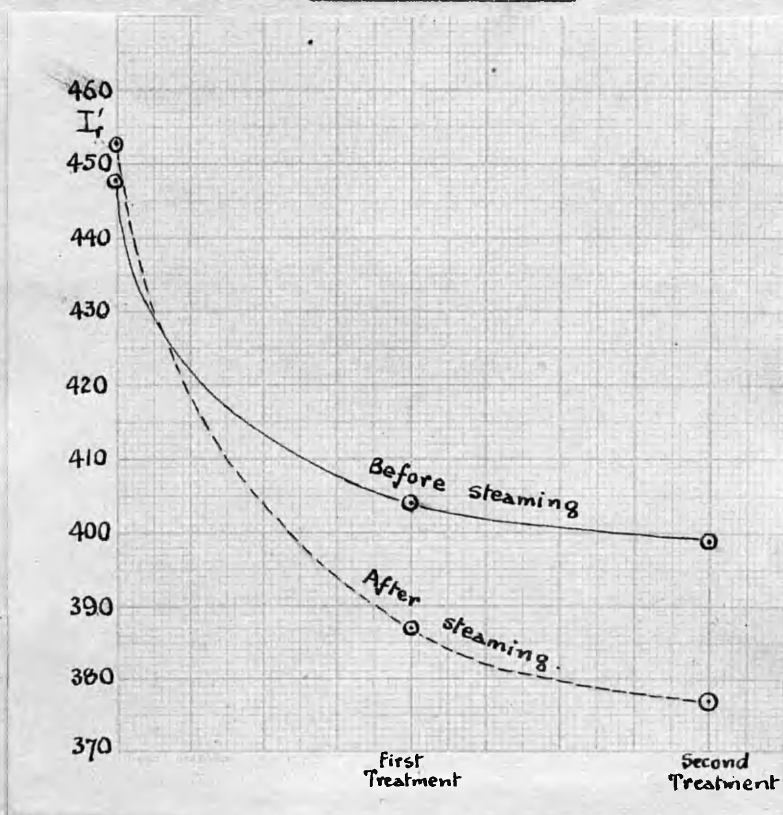
FIGURE 5. EFFECT OF SMALL VIBRATIONS ON STEAMED AND UNSTEAMED 2·88% TUNGSTEN STEEL.



The effect of steaming in creating a permanent condition in the steel is very noticeable.

The effect of large vibrations is quite the opposite. For the steamed specimen, the first treatment reduced the value of I'_r from 453 to 387, a change of 66 units, and the second treatment reduced it to 377, a change of 10 units, the corresponding changes in the unsteamed specimen being 44 and 5. The graph shows the comparison:-

FIGURE 6. EFFECT OF LARGE VIBRATIONS ON STEAMED AND UNSTEAMED 2·88% TUNGSTEN STEEL.



Apparently, therefore, steaming makes this steel more of a truly permanent magnet for small vibrations, but reduces the permanent nature of the magnet for violent vibrations.

IV. EFFECT OF MAXIMUM FIELD ON RESIDUAL MAGNETISM & COERCIVE FORCE.

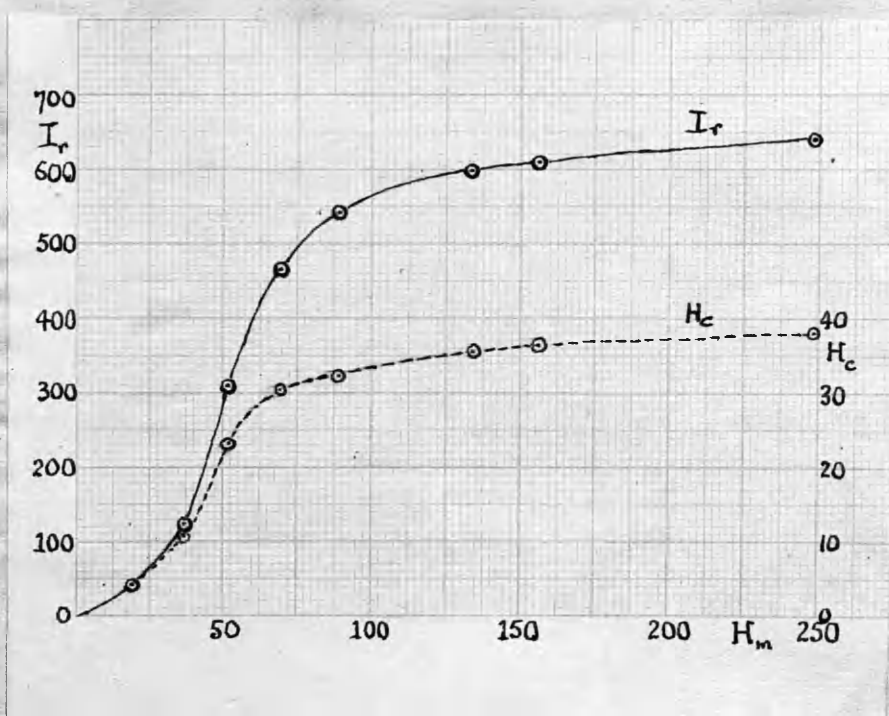
A third specimen of this material was quenched at 800°, magnetised and demagnetised to remove any sensitive state due to the thermal treatment, and then put thro' a series of hysteresis cycles to determine the effect of the maximum field on I_r and H_c. The specimen remained in the magnetometer during all the cycles, and was demagnetised after each. The values obtained were as follows:-

TABLE 5. EFFECT OF MAXIMUM FIELD ON PERMANENT MAGNETISM OF 2·88% TUNGSTEN STEEL.

Maximum Field H_m	Intensity of Magnetisation I	Residual Magnetism I_r	Coercive Force H_c.
19·3	140	41	4·4
36·9	329	123	10·9
52·0	585	310	23·1
69·8	769	465	30·2
89·8	923	540	32·3
133·5	1095	599	35·6
156·1	1154	610	36·4
249·1	1195	640	38·0

I_r and H_c are plotted against H_m in Figure 7.

FIGURE 7. EFFECT OF MAXIMUM FIELD ON PERMANENT MAGNETISM OF 2.88% TUNGSTEN STEEL.



There is little general difference in the curves. Both I_r and H_c increase rapidly for values of the maximum field H_m between 20 and 70, and then proceed slowly to limiting values. During this rapid increase, a great proportion of the increase in I_r remains in the specimen as residual magnetism. This is better seen from Table 6, in which the values of the quantities H_c, I_r, I have been tabulated for equal steps of 25 c.g.s. units of H:-

TABLE 6. PERMANENT MAGNETISM OF 2·88% TUNGSTEN STEEL.

H_m	I	H_c	I_r	dI	dH_c	dI_r	$\frac{dI_r}{dI}$	$I_r x H_c$	$d(I_r H_c)$
0	0	0	0	184	6·0	68	·37	0	400
25	184	6·0	68	243	15·6	216	·89	400	5700
50	427	21·6	284	283	9·3	208	·73	6100	9100
75	710	30·9	492	230	2·3	72	·31	15200	3500
100	940	33·2	564	87	1·8	30	·3	18700	2100
125	1027	35·0	594	44	1·2	15	·3	20800	1200
150	1071	36·2	609	41	0·5	10	·2	22000	700
175	1112	36·7	619	32	0·5	7	·2	22700	600
200	1144	37·2	626	30	0·4	7	·2	23300	500
225	1174	37·6	633	22	0·4	7	·3	23800	500
250	1196	38·0	640					24300	

As H_m rises from 0 to 25, 37% of the intensity of magnetism induced remains, when the field is withdrawn, as residual magnetism; for the change of H_m from 25 to 50, 89% remains; in the next interval 73% remains, the percentage falling quickly to 30%, ~~then about 20%~~, which remains the approximate steady value for changes in H_m above the value 100 units for H_m. The rate of change of I_r with H_m reaches a maximum about the value 50 units of H_m: the rate of change of H_c with H_m reaches a maximum somewhat earlier. If we consider changes in the product $I_r \times H_c$, we find a maximum between $H_m = 50$ and $H_m = 75$ when $I_r \times H_c$ is increasing by about 360 units per unit change in H_m. The increase in $I_r \times H_c$ decreases rapidly beyond this maximum until H_m reaches a value of about 150 units, after which $I_r \times H_c$ increases slowly and steadily by about 20 units per unit change of H_m. There would seem to be little use, therefore, in increasing the maximum field beyond about 150 c.g.s.units.

ALLOY B. 5·85% TUNGSTEN.

I. EFFECT OF TEMPERATURE OF QUENCHING.

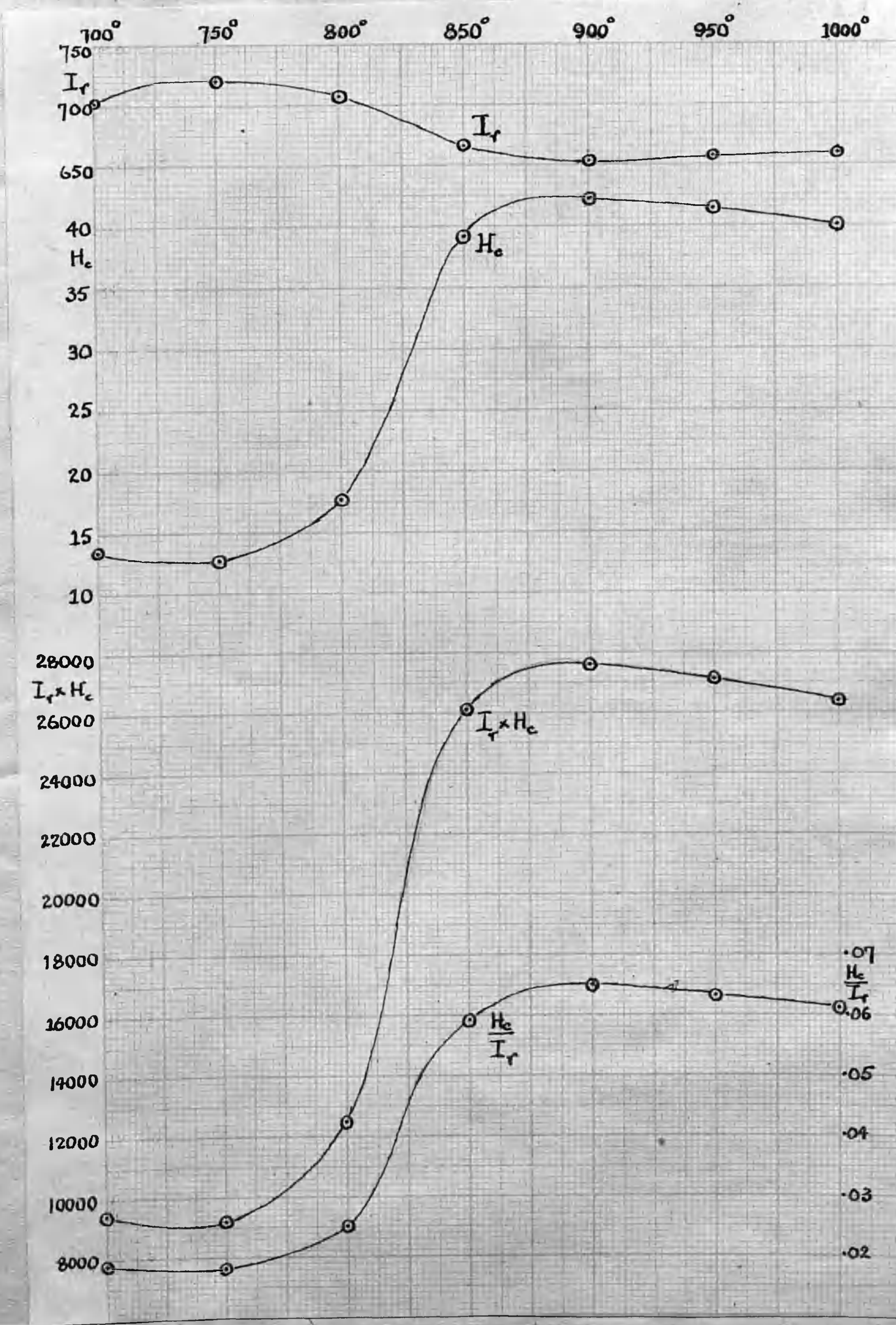
The first specimen of this, the second alloy, was tested, as in the case of the previous alloy, for the best quenching temperature. The results are shown in table 7, and graphed in figure 8.

TABLE 7. EFFECT OF TEMPERATURE OF QUENCHING 5·85% TUNGSTEN STEEL.

Condition	I_r	H_c	$I_r \times H_c$	H_c/I_r.
R	653	14·0	9100	·021
Q700	702	13·5	9500	·019
Q750	720	12·8	9200	·018
Q800	708	17·7	12500	·025
Q850	666	39·2	26100	·059
Q900	654	42·2	27600	·065
Q950	656	41·3	27100	·063
Q1000	659	40·0	26400	·061

Examination of these results shows the necessity for consideration of H_c as well as I_r. If the latter alone were considered, the best temperature of quenching would be 750°; but the value of coercive force for this case is low. The maximum value for the coercive force is obtained with a quenching temperature of 900°, and the maximum value of the permanence at the same temperature. The sudden drop in I_r and the large increase in H_c between the quenchings from 800° and 850° point to a transformation taking place in the steel between

FIGURE 8. EFFECT OF TEMPERATURE OF QUENCHING 5.85% TUNGSTEN STEEL.



these temperatures. It was decided to use a quenching temperature of at least 900°.

11. EFFECT OF VIBRATION.

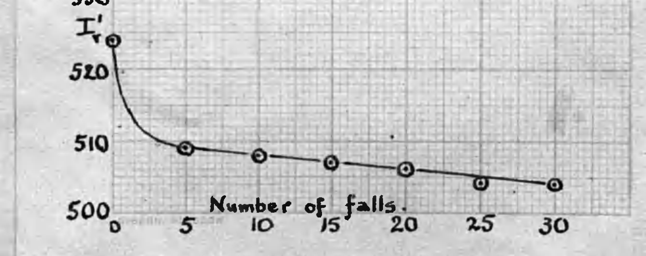
A second specimen was quenched from 900°, put into a cyclic condition in the usual way by thorough magnetisation and demagnetisation, and tested. The value of I_r was 698, of H_c 42·2, the residual magnetism being somewhat higher than that of the first specimen of this alloy under the same condition, when I_r was 654, H_c 42·2. The specimen was now subjected to a series of shocks, as for the first alloy. The figures obtained were

TABLE 8. EFFECT OF SMALL VIBRATIONS ON RESIDUAL MAGNETISM OF 5·85% TUNGSTEN STEEL.

Number of falls	I'_r	Decrease in I'_r for 5 falls.
0	524	-
5	509	15
10	508	1
15	507	1
20	506	1
25	504	2
30	504	0

These figures are graphed below:-

FIGURE 9. EFFECT OF SMALL VIBRATIONS ON RESIDUAL MAGNETISM OF 5·85% TUNGSTEN STEEL.



As in the case of the 3% tungsten alloy, and in fact if all magnetic specimens tested, shock removes a portion of the residual magnetism. In this, the 6% tungsten alloy, the first five falls remove the greatest part of this temporary residual magnetism, subsequent shocks having small effect. The behaviour of the two alloys, 3% and 6% tungsten, under vibration tests, is thus not quite alike; for in the case of the 3% alloy, shocks after the first five have a quite appreciable effect. This point is easily seen by comparison of the two curves in figures 2 and 9.

A thorough vibration reduced I_r' for the 6% alloy from 504 to 438, and the treatment repeated reduced this latter figure only slightly, to 433.

These results, therefore, show that the 6% alloy is more easily brought into a stable condition for slight shocks than is the 3% alloy.

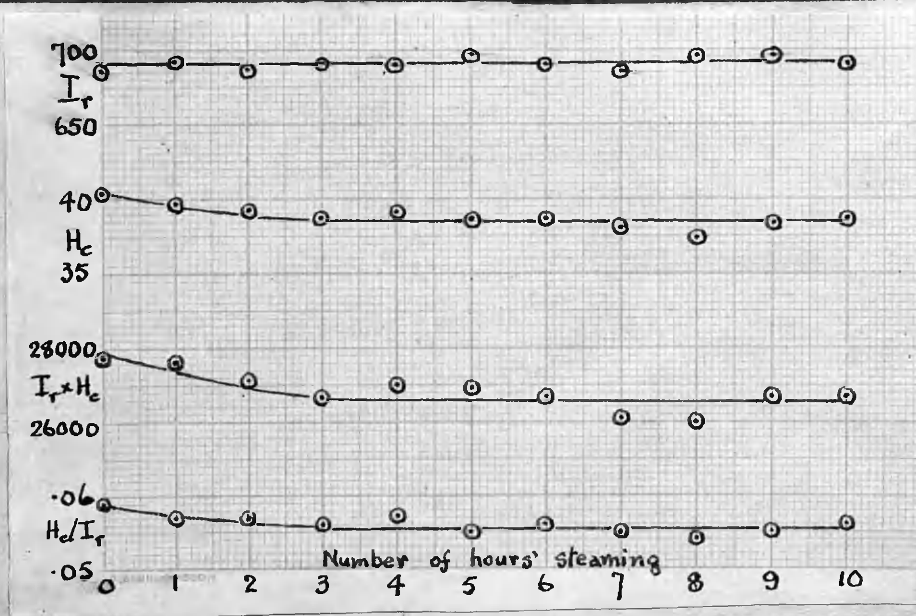
111. EFFECT OF STEAMING 5·85% TUNGSTEN STEEL.

The effect of steaming this alloy is shown by the following table and graphs:-

TABLE 9. EFFECT OF STEAMING 5·85% TUNGSTEN STEEL.

	Number of hours' steaming.										
	0	1	2	3	4	5	6	7	8	9	10
I_r	686	693	687	690	690	696	691	686	696	696	690
H_c	40·5	39·8	39·4	38·7	39·1	38·6	38·6	38·0	37·4	38·3	38·7
$I_r \times H_c$	27800	27600	27100	26700	27000	26900	26700	26100	26000	26700	26700
H_c / I_r	·059	·057	·057	·056	·057	·055	·056	·055	·054	·055	·056

FIGURE 10. EFFECT OF STEAMING 5·85% TUNGSTEN STEEL.



These are indications of a slight drop in the coercive force, and therefore in the permanence and remanence of the steel, after one or two hour's' steaming; further steaming has no appreciable effect on I_r and H_c.

111.A. EFFECT OF VIBRATING STEAMED 5·85% TUNGSTEN STEEL.

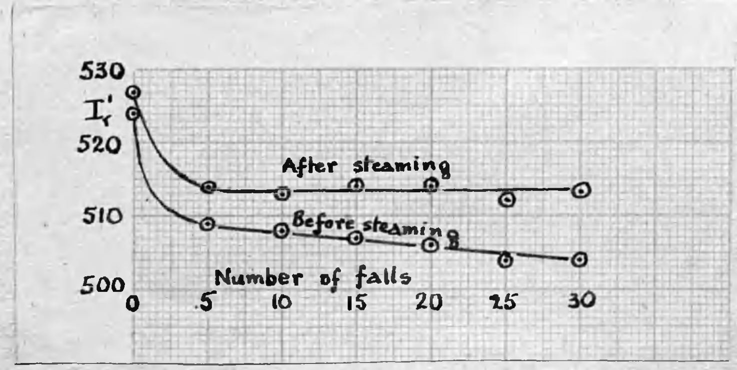
As before, the steamed magnet was dropped on one end from a height of one foot, and the apparent residual magnetism measured for every fifth fall. The readings obtained were as follows:-

TABLE 10. EFFECT OF VIBRATING STEAMED 5·85% TUNGSTEN STEEL.

Number of Falls.	I'_r	Decrease in I'_r for 5 falls.
0	527	--
5	514	13
10	513	1
15	514	-1
20	514	0
25	512	2
30	513	-1

The apparent residual magnetism is thus unchanged after the first few falls; these results are compared graphically in figure 11, with those obtained from the specimen in the unsteamed state:-

FIGURE 11. EFFECT OF VIBRATION ON 5·85% TUNGSTEN STEEL PERMANENT MAGNET.



It will be seen that while the residual magnetism is ~~greater~~ the same in the unsteamed specimen ~~than~~ as in the specimen after steaming, for the same maximum field, nevertheless the magnetism of the steamed material is slightly less liable to change by slight shocks than the unsteamed material. This difference is less marked in this, the 6% W alloy, than in the 3% alloy.

Large vibrations reduced I_r' from 513 to 438, and the treatment repeated reduced this slightly further to 430 steaming having apparently but little if any, effect in preparing the magnetic properties of the material against heavy shocks.

ALLOY C. (8·72% TUNGSTEN)

1. EFFECT OF TEMPERATURE OF QUENCHING.

The values of I_r and H_c for specimen C1. for a series of quenching temperatures are shown in table 11 - - :-

TABLE 11. EFFECT OF QUENCHING 8·72% TUNGSTEN STEEL.

Condition	I_r	H_c	$I_r \times H_c$	H_c/I_r
R	775	19·3	15000	0·025
Q700	851	18·3	15600	0·022
Q 750	836	18·7	15600	0·022
Q 800	798	19·0	15200	0·024
Q 870	655	35·8	23400	0·055
Q 900	628	44·3	27800	0·071
Q 950	630	44·0	27700	0·070
Q 1000	611	42·1	25700	0·070

The initial heating to 700°, had a softening effect on the specimen, shown by an increase in I_r and decrease in H_c, and therefore a decrease in H_c/I_r. This softening is not shown by $I_r \times H_c$; and this suggests that for a particular specimen, the ratio H_c/I_r is the better criterion of the permanent magnetic properties of a steel. The magnetic properties are only slightly affected by quenching from 750° and from 800°, but the quenching from 870° brings about a marked hardening, which is increased by subsequent quenching from 900°.

Quenching from 950° causes little change, quenching from 1000° decreases I_r and H_c. The best temperature of quenching is thus between 900° and 950°, a decided transformation taking place in the neighbourhood of 850°.

11. EFFECT OF VIBRATING 8·72% TUNGSTEN STEEL.

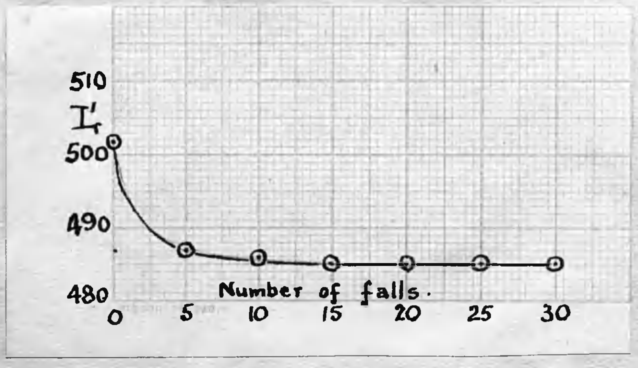
A second specimen was quenched from 950°, magnetised and demagnetised, and finally tested. It gave values of 581 for I_r, 41·5 for H_c, the corresponding values for the first specimen of the same alloy being 630 and 44·0. Vibration tests were carried out as before, the following being the results:-

TABLE 12. EFFECT OF VIBRATING 8·72% TUNGSTEN STEEL.

Number of Falls.	I'_r	Decrease in I'_r for 5 falls.
0	502	-
5	487	15
10	486	1
15	485	1
20	485	0
25	485	0
30	485	0

These results are graphed below:-

FIGURE 12. EFFECT OF VIBRATING 8·72% TUNGSTEN STEEL.



The first few knocks bring the specimen into a fairly constant state, further knocks of the same intensity having no effect. Thus if such an alloy is to be used as a permanent magnet, a few knocks of a moderate intensity are sufficient to bring its magnetism into a constant condition. Larger knocks, however remove more of the magnetism. A thorough vibration reduced I'_r for this specimen from 485 to 442, and this value fell to 433 when the treatment had been repeated.

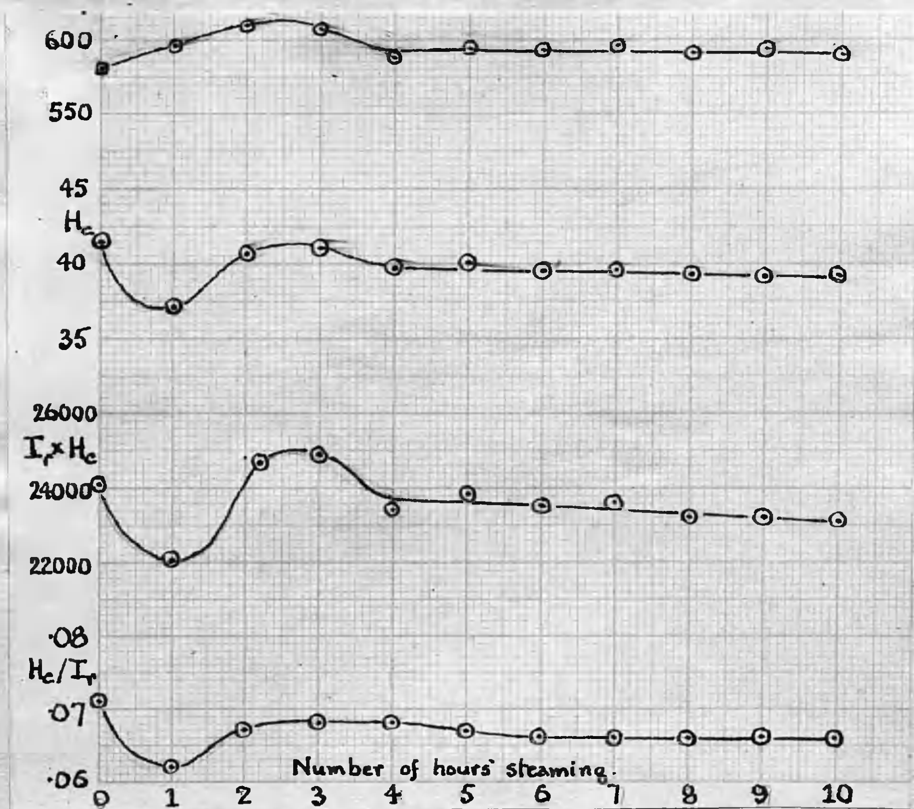
111. EFFECT OF STEAMING 8·72% TUNGSTEN STEEL.

The same specimen was now steamed in one hour intervals, and tested after each hour, at room temperature; the table and graphs show the results:-

TABLE 13. EFFECT OF STEAMING 8·72% TUNGSTEN STEEL.

	Number of hours' steaming.										
	0	1	2	3	4	5	6	7	8	9	10
I_r	581	596	610	607	588	595	594	596	591	594	590
H_c	41·5	37·1	40·6	41·0	39·8	40·0	39·5	39·6	39·3	39·1	39·2
$I_r \times H_c$	24100	22100	24800	24900	23400	23800	23500	23600	23200	23200	23100
H_c/I_r	·071	·062	·067	·068	·068	·067	·066	·066	·066	·066	·066

FIGURE 13. EFFECT OF STEAMING 8·72% TUNGSTEN STEEL.



The initial steaming seems to soften the material slightly, but after about four hours' steaming the material is in a fairly stable state; and further steaming has no appreciable effect on the residual magnetism and coercive force.

111 A. EFFECT OF VIBRATING STEAMED 8·72% TUNGSTEN STEEL.

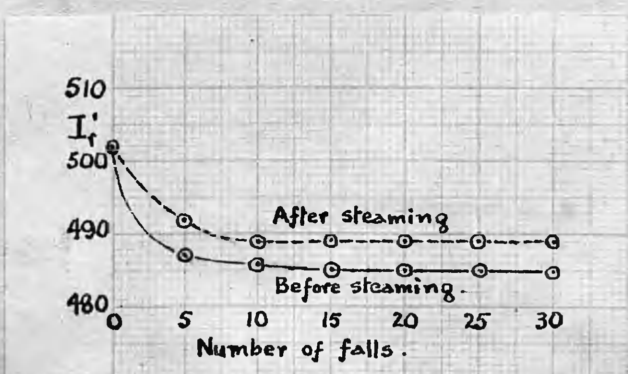
Vibration tests were now carried out on the steamed specimen, and the following results were obtained:-

TABLE 14. EFFECT OF VIBRATING STEAMED 8·72% TUNGSTEN STEEL.

Number of Falls	I'_r	Decrease in I'_r for 5 falls.
0	502	-
5	492	10
10	489	3
15	489	0
20	489	0
25	489	0
30	489	0

These figures are plotted in the graph below, and the graph for the specimen in the unsteamed condition has been added for comparison:-

FIGURE 14. EFFECT OF VIBRATING 8·72% TUNGSTEN STEEL.



The effect of steaming is negligible, there being only a small increase in stability, if any, due to the steaming. More violent vibrations reduced I'_r from 489 to 426, and finally to 422, the reducation for the unsteamed specimen being from 485 to 442 and 433. The specimen after steaming is thus, for heavy vibrations, less stable than before.

ALLOY D (11·65% TUNGSTEN)

1. EFFECT OF TEMPERATURE OF QUENCHING 11·65% TUNGSTEN STEEL.

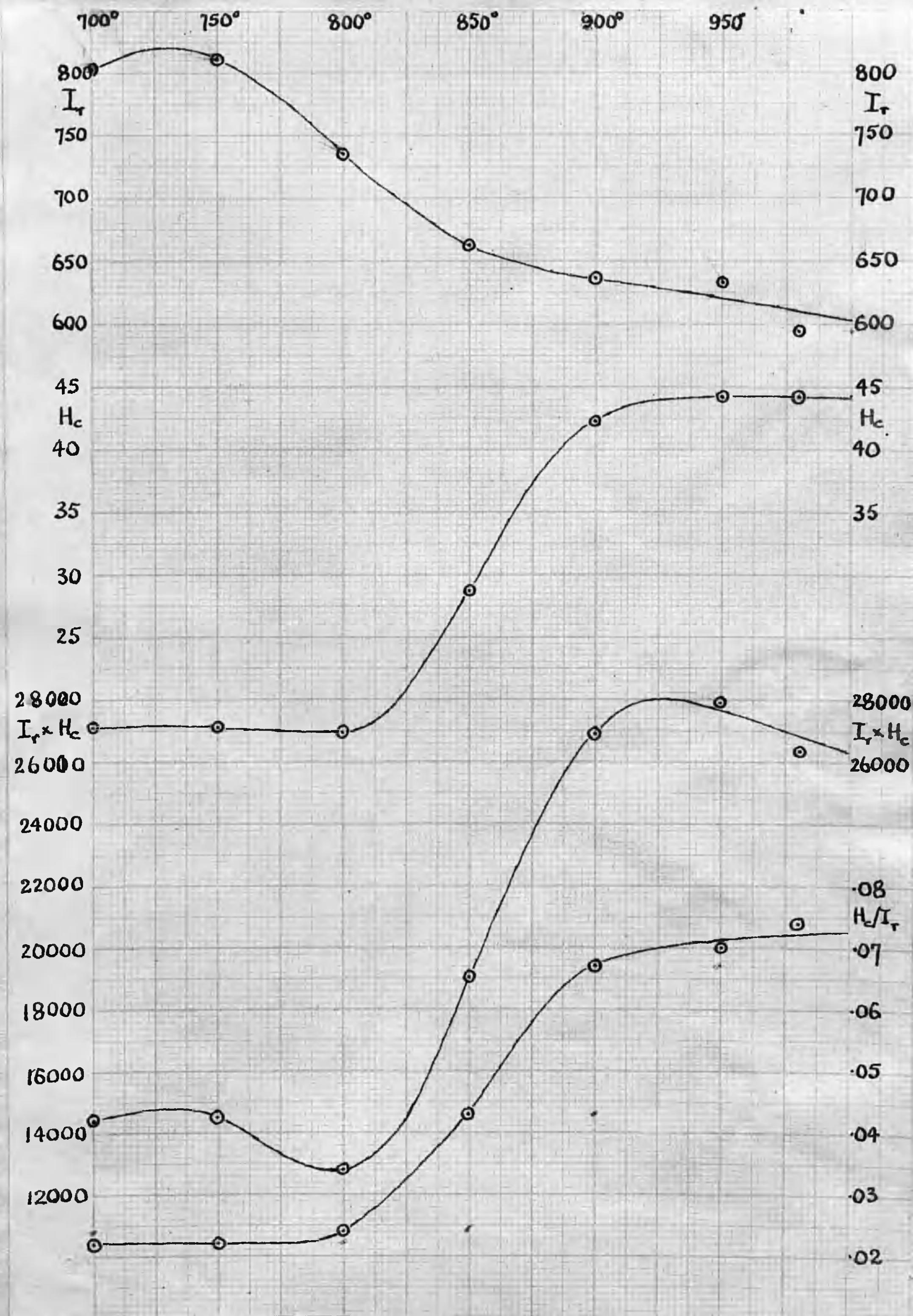
A specimen of this alloy was tested as received; quenched from 700° and tested, quenched from 750° and tested, and so on, and the values of I_r and H_c read off from the graphs of the hysteresis cycle. The results obtained are given in table 15:-

TABLE 15. EFFECT OF TEMPERATURE OF QUENCHING 11·65% TUNGSTEN STEEL.

Condition	I_r	H_c	$I_r x H_c$	H_c/I_r
R	750	18·3	13700	·024
Q700°	803	17·9	14400	·022
Q750	810	17·9	14500	·022
Q800	735	17·4	12800	·024
Q850	662	28·7	19000	·043
Q900	636	42·3	26900	·067
Q950	632	44·1	27900	·070
Q980	594	44·2	26300	·074

These results are graphed in figure 15:-

FIGURE 15. EFFECT OF TEMPERATURE OF QUENCHING 11·65% TUNGSTEN STEEL.



It will be seen that between the temperatures of 750° and 950° a decided transformation takes place in the steel. Quenching from 800° shows a reduction in the value of I_r compared with the value when the specimen is quenched from 750°, but there is no decided increase in H_c until the temperature of quenching is raised to 850°. Quenching from 900° and 950° increases H_c further; quenching beyond 950° has no effect on H_c, but I_r is reduced. The temperature of 950° may therefore be taken as the best temperature for quenching this particular steel.

11. EFFECT OF VIBRATION ON 11·65% TUNGSTEN STEEL MAGNET.

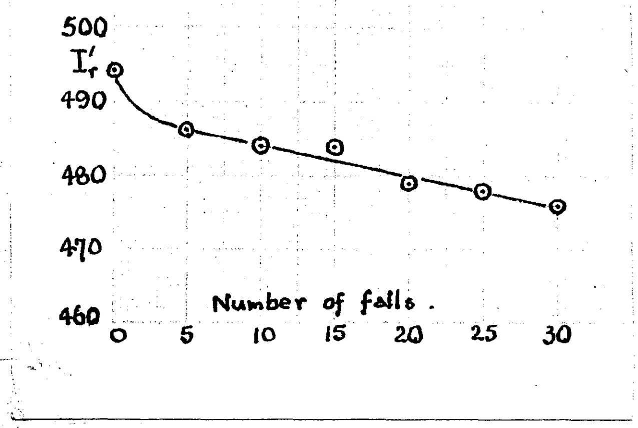
A Second specimen of this alloy (11·65% Tungsten) was quenched from 950°, put into a cyclic state by repeated magnetisation and demagnetisation, and tested. It gave values of 633 for I_r and 44·6 for H_c, the corresponding values for the first specimen being 632 and 44·1. Vibration tests were carried out as before, and gave the following results:-

TABLE 16. EFFECT OF VIBRATING 11·65% TUNGSTEN STEEL.

Number of falls	I'_r	Decrease in I'_r for 5 falls.
0	494	-
5	486	8
10	484	2
15	484	0
20	479	5
25	478	1
30	456	1

These figures are plotted on the graph below:-

FIGURE 16. EFFECT OF VIBRATING 11·65% TUNGSTEN STEEL.



The values of I_r' in these tests fell gradually with succeeding falls. A thorough vibration reduced I_r' further from 476 to 427; this treatment seemed to have brought I_r' to a nearly constant value, as after further similar treatment the value was 425.

This specimen was now put through a complete hysteresis cycle; I_r was read off as 637, H_c as 43·8, the values obtained in the cycle taken before the vibration tests were 633 and 44·6. I_r is thus unchanged; H_c seems to have dropped slightly.

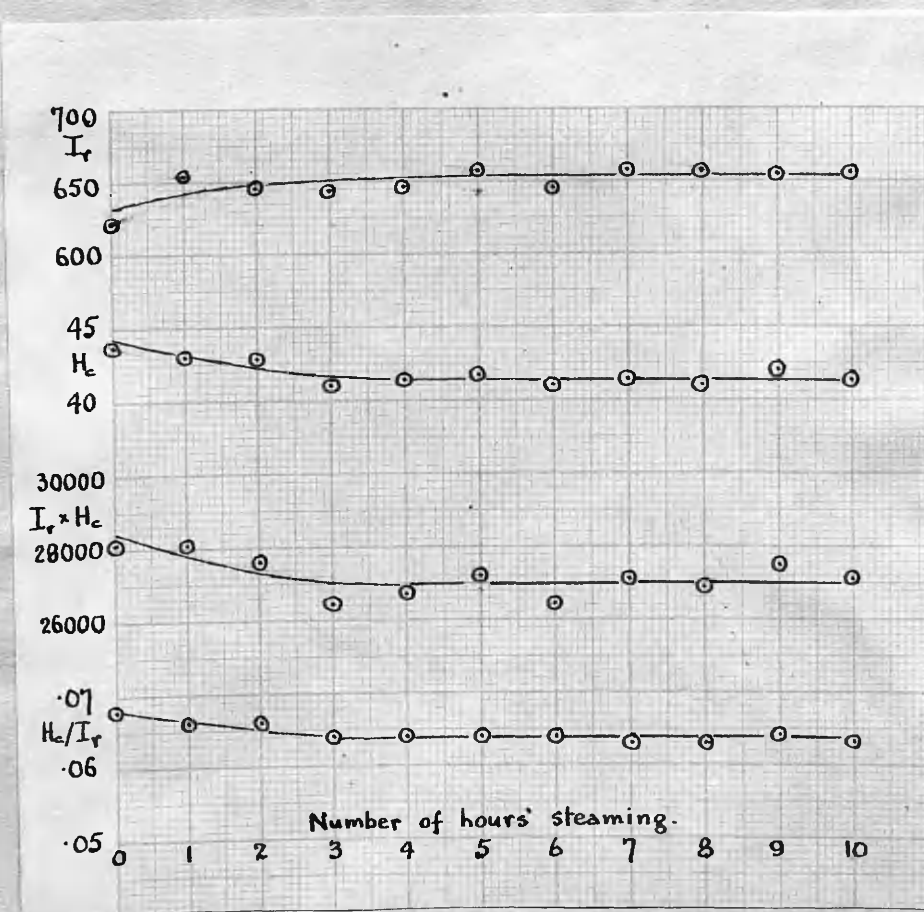
III. EFFECT OF STEAMING 11·65% TUNGSTEN STEEL.

Steaming tests were carried out as before. The results are given in table 17, and plotted in figure 17:-

TABLE 17. EFFECT OF STEAMING 11·65% TUNGSTEN STEEL.

	Number of hours' steaming.										
	0	1	2	3	4	5	6	7	8	9	10
I_r	642	654	645	644	646	653	645	657	656	654	655
H_c	43·7	43·0	42·8	41·0	41·4	41·7	41·0	41·3	41·0	42·0	41·4
$I_r \times H_c$	28100	28100	27600	26400	26700	27200	26400	27100	26900	27500	27100
H_c/I_r	·068	·066	·066	·064	·064	·064	·064	·063	·063	·064	·063

FIGURE 17. EFFECT OF STEAMING 11·65% TUNGSTEN STEEL.



With a few hours' steaming, I_r tends to increase slightly to a steady value, and H_e to decrease to a steady value, the changes being, however, comparatively small.

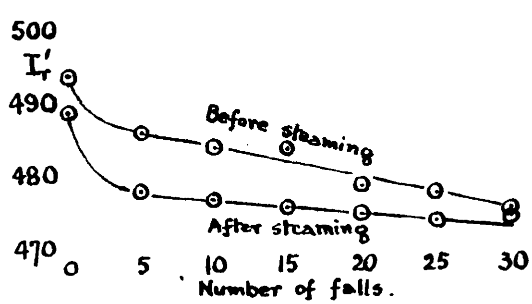
111A. EFFECT OF VIBRATION ON STEAMED 11·65% TUNGSTEN STEEL.

The vibration tests were repeated on the steamed specimen, which had already been subjected to vibration tests before steaming. The variation in I'_r is shown in table 18, and is compared with that of the unsteamed specimen in figure 18:-

TABLE 18. EFFECT OF VIBRATION ON STEAMED 11·65% TUNGSTEN STEEL.

Number of falls	I'_r	Decrease in I'_r for 5 falls.
0	489	-
5	478	12
10	477	1
15	476	1
20	475	1
25	474	1
30	475	-1

FIGURE 18. EFFECT OF VIBRATION ON 11·65% TUNGSTEN STEEL.



As in previous cases, the first few knocks remove a measurable amount of I'_r; thereafter there is little change. The steamed specimen is more stable for these small knocks, than the unsteamed specimen, but the difference is small. A thorough vibration reduced the value of I'_r from 475 to 425; the treatment repeated reduced it to 420. The total change due to heavy knocks is 55, compared with 51 in the unsteamed specimen. The difference is within the limits of experimental error.

Complete cycles taken before and after these vibration tests gave I_r and H_c 658 and 44·5 before the tests and 655 and 42·0 after the tests, so that ~~any permanent effect is small~~ there is a slight permanent softening of the material.

V. VARIATION OF MAGNETIC PROPERTIES WITH PERCENTAGE OF TUNGSTEN.

(a) TEMPERATURE OF QUENCHING.

Consideration of the values obtained for the residual magnetism and coercive force after different temperatures of quenching shows that in the case of the 3% alloy, a transformation set in between 700° and 750° and was completed by 800°, while in the cases of the 6, 9 and 12% alloys, the transformation began between 750° and 800° and was not completed until a temperature of at least 800° had been reached. Quenching from lower temperatures than 700°, in the case of the 3% steel, and than 750° in the case of the other steels, softened the material; this was indicated by an increase of residual magnetism and a decrease in coercive force. It is worthy of note, also, that when the transformation has begun, the change is generally indicated first of all by a decrease in residual magnetism, the coercive force beginning to increase at a later temperature of quenching. For excample, in the case of alloy D, containing 11·65% of tungsten, after the quenching from 750° I_r is 810 and H_c is 17·9, giving a value for the product of 14500. When the quenching temperature is increased to 800°, I_r drops to 735, while H_c is 17·4 , i.e., the decrease in I_r has set in, the increase in H_c has not. The value for the permanence is 12800, the lowest for this particular steel. When the specimen is quenched from 850°, I_r drops to 642, while H_c increases to 28·7 The change in I_r has thus begun between 750° and 800°, while the change in the coercive force begins about 50° higher.

(b) RESIDUAL MAGNETISM AND COERCIVE FORCE.

In table 19 have been tabulated the values of the residual magnetism and coercive force for the four steels, quenched from the best temperature in each case:-

TABLE 19. EFFECT OF PERCENTAGE OF TUNGSTEN ON I_r AND H_c

%W	I_r	H_c	I_r x H_c	H_c/I_r
2·88	665	38·9	25900	·058
5·85	654	42·2	27600	·065
8·72	628	44·3	27800	·071
11·65	632	44·1	27900	·070

These figures show a decided improvement in the permanent magnetic properties for the change from 3 to 6% tungsten, but beyond 6% any change is negligible. The similarity of the magnetic properties of steels containing from 6 to 12% tungsten is remarkable.

(C) EFFECT OF STEAMING.

Each steel was subjected to small and large vibrations before and after ten hours' steaming. The changes, for small vibrations, in the apparent residual magnetism are shown by the figures in table 20.

TABLE 20. EFFECT OF SMALL VIBRATIONS ON APPARENT RESIDUAL MAGNETISM.

Percentage of Tungsten	Before steaming		After steaming.	
	Before vibns.	after vibns.	before vibns	after vibns
2·88	421	448	477	453
5·85	524	504	527	513
8·72	502	485	502	489
11·65	494	476	489	475

The changes in I_r' caused by the vibrations before steaming are 43, 20, 17, 18, and after steaming 24,14, 13,14. The final effect of the steaming is therefore inappreciable in the 6,9,12% steels; in the case of the 3% steel, steaming makes it slightly less sensitive to vibrations. For large vibrations, steaming is certainly not an advantage. Table 21 shows the changes in the apparent residual magnetism, caused by heavy vibrations:-

TABLE 21. EFFECT OF LARGE VIBRATIONS ON APPARENT RESIDUAL MAGNETISM.

Percentage of Tungsten	Before steaming		After steaming	
	Before vibns.	after vibns.	Before vibns.	after vibns
2·88	448	399	453	377
5·85	504	433	513	430
8·72	485	433	489	422
11·65	476	425	475	420

The changes in I_r' are thus 49, 71, 52, 51 before steaming, and 76, 83, 67, 55 after steaming. These results show that steaming has a deteriorating effect on the magnetic properties of the first three steels, in that it makes them more susceptible to loss of magnetism by heavy shocks.

SUMMARY.

(a) The residual magnetism and coercive force of low carbon steels containing approximately 3,6,9,12 % of tungsten have been studied.

(b) quenching the 6,9,12% tungsten steels from various temperatures shows a magnetic transformation beginning at about 750° and finishing at 900°; in the case of the 3% steel, the transformation occurs about 50° lower.

(c) The residual magnetism and coercive force of the 6,9,12% tungsten steels are approximately the same; the residual magnetism for the 3% steel is slightly higher, the coercive force considerably lower.

(d) Steaming the 3% alloy for 10 hours makes it less susceptible to small vibrations; the effect on the other alloys is negligible. For large vibrations, steaming has a slight deleterious effect on the 3,6,9% alloys; the effect on the 12% alloy is unappreciable.

(e) In the 3% alloy, about 90% of the increase of intensity of magnetisation when the field is increased from 25 to 50 c.g.s. units, remains as residual magnetism; the increase in residual magnetism for maximum fields beyond 150 c.g.s. units is very small.

THE MAGNETIC EFFECTS

of

MANGANESE IN COPPER ALLOYS,

by

ROBERT C. GRAY M.A., B.Sc., Lecturer in Mathematics

and Physics in the University of Western Australia.

THE MAGNETIC EFFECTS OF MANGANESE IN COPPER ALLOYS, by ROBERT C. GRAY M.A., B.Sc., Lecturer in Mathematics and Physics in the University of Western Australia.

The susceptibility of manganese is known to be very small, yet manganese salts generally show stronger magnetic properties than the corresponding iron salts. In his list of elements in descending order of atomic magnetic susceptibility (i.e. the mean susceptibility of a space containing one gram atom of the substance per litre), Meyer* put manganese before iron, his list being as

(*S. Meyer, Ann.d. Phys., 69, 1889, 239)

follows:- Ho, Er, Gd, Mn, Fe, Sa, Co, Yt, Nd, Ni, Pr.

We have further the well known fact that the addition of 13% manganese to a carbon steel will make it almost completely non-magnetic, just as the addition of 27% nickel will make steel non-magnetic. Manganese, therefore, although possessing itself very weak magnetic properties, has an extraordinarily large influence on the magnetism of iron. Also, Heusler†

(†F. Heusler, Uber die synthese ferromagnetischer Manganlegierungen, Marburg, 1904.)

discovered that strongly magnetic alloys were formed by the addition of aluminium to an alloy of 30% manganese with 70% copper. In this case the manganese helps in the development of magnetic properties, which is exactly the opposite effect to that brought about by manganese in manganese steel. It is also worthy of note that both in manganese steel and in Heusler and similar alloys, the magnetism is very unstable, being very susceptible to heat (or cold) treatment.

In 1909 a joint paper by A.D. Ross and the author[*]

([*]Ross and Gray, Proc. Roy. Soc. Edin., 29, 1909, 274)

gave results obtained by them of magnetometric tests made on alloys containing 62% Cu, 25% Mn, 13% Al; 76% Cu, 16% Mn, 8% Al; and 55% Cu, 30% Mn, 15% Al, respectively, the atomic proportions of manganese and aluminium being approximately equal in the three alloys, while the atomic proportions of copper were 2, 4 and 1½ times those of manganese and aluminium. The intensities of magnetisation for a field of 100 c.g.s. units were approximately 300, 19 and 8 respectively. Heusler and Richarz[†] believed that these alloys were composed of

([†]Heusler and Richarz. Zeit. f. Anorg. Chem. 61, 1909, 265)

compounds of the type M_3Al, where M represents an isomorphous mixture of copper and manganese. Ross and the author, however, suggested, in the light of certain tests made by the author and detailed below, that the magnetism of these alloys was due to the solid solution of manganese with the compound Cu_3Al, the manganese when in solution in this way having a critical temperature above ordinary temperatures. This theory has been since confirmed by Rosenhain and Lantsberry[‡] in a report

†Rosenhain and Lantsberry, Proc. Inst. Mech. Eng. 1910)

of the Alloys Research Committee on the constitution of the ternary system copper - manganese - aluminium. These experimenters state that no evidence was found of the formation of any ternary compound and that if the view is accepted that Cu_3 Al is present in copper aluminium, alloys containing more than 8% aluminium, then this compound is also present in the corresponding ternary alloys, but in that case it holds manganese in solid solution. As the percentage of manganese is increased, the Cu_3 Al will finally become saturated with manganese, and the compounds Mn_3 Al will probably be formed, in solution with other constituents. This compound is known to be magnetic, and possibly any magnetic effects shown in the ternary alloys which are rich in manganese are due to the presence of Mn_3 Al. No records are obtainable, however, of tests made on a series of alloys containing more than 30% of manganese; the difficulty of obtaining satisfactory castings is great.

When working with Ross, the author found that an aluminium bronze containing about 10% aluminium, could be given an appreciable residual magnetism*, the value obtained for the intensity being

*(Ross and Gray: Proc. Roy. Soc. Edin., 29, 1909, 283)

about 0·2 c.g.s. unit. It was decided to examine, if possible the whole copper aluminium binary system. The author prepared and cast about forty alloys, most of them having less than 35% aluminium. The material used was the purest obtainable commercially, but probably contained a small fraction of one percent of impurity.

The alloys were normalised to remove any strain due to the casting, were magnetised between the poles of a large electromagnet, in a field of 4400 c.g.s. units, and the residual magnetism measured. A copper casting had an intensity of·002, and the addition of aluminium increased this intensity to a maximum*

*(R.C. Gray, Proc. Roy. Phil. Soc. Glas., 1910 and 1912-)

of ·03 for 12·5% aluminium, corresponding to the compound Cu_3Al. Beyond this percentage of aluminium the magnetism fell rapidly; and above 17% Al, when Cu_3Al no longer exists, no magnetic effects could be detected. When manganese is added to Cu_3Al it forms a solid solution with it, in which the manganese tends to be in a magnetic state. The intensity of the residual magnetism obtained by Ross and Gray† for a copper-manganese - aluminium alloy containing 62% Cu, 25% Mn, 13% Al was about

†(Ross and Gray, Proc. Roy. Soc. Edin., 29, 1909, 276)

7, while, as stated above the residual magnetism obtained for Cu_3Al for a very much larger magnetising field was·03. It is possible that part of the magnetism is supplied by the Cu_3 Al becoming more magnetic when in solution with manganese, but it seems likely that the hypothesis given above is correct, that the manganese when in solution with Cu_3Al becomes magnetic.

With a view to obtaining further information on the magnetic effect of manganese in ternary alloys, Ross and the author‡ decided to examine a few chosen alloys of the ternary copper-manganese-tin system,

‡(Ross and Gray: Proc. Roy. Soc. Edin., 31, 1910, 85)

An alloy containing 70% copper and 30% manganese was made up, and to this were added quantities of tin, which gave finally the following alloys:-

TABLE 1. ANALYSIS OF Cu - Mn - Sn ALLOYS TESTED.

Designation of Alloy.	Cu	Mn	Sn
14% tin	60·2	25·1	14·1
16% tin	58·7	24·5	16·1
18% tin	57·6	23·9	18·0
30% tin	49·2	20·4	29·8
38% tin	43·4	18·1	38·0
48% tin	36·4	15·0	48·1

Thorough tests were made on these alloys after various standard heat treatments, but it will be sufficient here to consider the magnetism of the castings when normalised, that is, exposed for a brief time to a moderately low heat and slowly cooled to ordinary temperature. The values obtained for the intensity of magnetisation for a field of 100 c.g.s. units are given below in table 2:-

TABLE 2. INTENSITY OF MAGNETISATION FOR A FIELD OF 100 c.g.s UNITS.

Alloy	Intensity of Magnetisation at	
	15°	- 190°
14% tin	55	67
16% tin	77	96
18% tin	82	102
30% tin	0	0
38% tin	96	96
48% tin	1	1

It will be seen that the alloys tested fall into two distinct groups, those containing less than 30% Sn, and those containing between 30 and 50% Sn, and that the two groups are different in that cooling to-190° increases the magnetism in the first group but not in the second. Now copper and manganese form no compounds; copper and tin form one compound*

*(Heycock & Neville, Phil. Trans., 202A, 1903, 1; Giolitti and Tavanti, Gazetta, 38, 1908, 209)

Cu_3 Sn, and perhaps Cu_4 Sn and CuSn; while manganese and tin form Mn_4 Sn and Mn_2Sn,† both of which are

†(R.S. Williams, Zeit. für Anorg. Chem., 55, 1907, 1)

magnetic, the former being the more strongly magnetic.‡

If we assume that

‡(K. Honda, Berlin Ann. Physik, 32, 1906, 1003)

the magnetic properties are due to manganese in solution in copper tin alloys, we find maxima of magnetisation for about 53% Cu, 47% Sn, and 75% Cu, 25% Sn. These do not correspond to any of the known or suspected compounds of copper and tin. It may be of note here, however, that whereas in the copper aluminium series the author found distinct magnetic effects for Cu_3 Al, no such effects were obtained in tests on copper-tin alloys.

If on the other hand we assume that the percentage of manganese is so large that manganese - tin constituents form the basis of these ternary alloys, and that the copper is present merely in solid solution with these constituents, we find maxima of magnetisation when the manganese - tin constituents have compositions about 33% Mn, 67% Sn, and 57% Mn, 43% Sn. The first of these corresponds to MnSn, a compound of doubtful existence, the second to Mn_3Sn, which does not exist. The 14% tin alloy is nearest to Mn_4Sn, which is the most magnetic alloy of the manganese - tin series, but the 16, 18 and 38% tin alloys are all more magnetic than the 14% tin alloy; while the 30% tin alloy, which was non-magnetic, is nearest to Mn_2Sn, found by Williams to be magnetic.

Neither of these hypotheses leads to an explanation of the magnetic results obtained by us. So far as the author is aware, no investigation has been published of the structure of the ternary system Cu-Mn-Sn. It seems probable that much light may be thrown on the effect of manganese in alloys by a study of the magnetism of a binary system, say Cu - Sn or Cu - Al to each alloy of which has been added the same amount, say 5% or 10%, of manganese; and by a study of the Mn - Sn and Mn - Al systems, to each alloy of which 5% or 10% of copper has been added.

THE MAGNETISM OF A SERIES OF MANGANESE STEELS,

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SCOPE OF THE RESEARCH.

This paper gives the most striking results obtained in a research on manganese steel, carried out by the author in the Natural Philosophy Institute at Glasgow University, Each specimen of a graded series of Steels with increasing manganese content was tested when (a) annealed from 900° (b) quenched from 450° (c) quenched from 900°. The specimen was put through magnetisation cycles (i) at room temperature (ii) at liquid air temperature (iii) again at room temperature.

PREVIOUS WORK.

A very large amount of work on manganese steels has been carried out, mostly by Hadfield and Hopkinson.* The steel used was generally commercial Hadfield manganese steel, containing about 12% manganese and about 1¼% of carbon. This steel when heated to 1000° and quenched in water is practically nonmagnetic, while slow annealing from a high temperature makes it magnetic and brittle, the maximum value of the magnetisation being about 46% of that in pure iron.

*(Hadfield and Hopkinson, Journ. Iron & Steel Inst. 89 (i), 1914, 106)

Variation in the annealing gives variation in magnetic properties. Further, it was noticed by Hadfield* in 1905 that a partially annealed (*Hadfield, Jour. Iron & Steel Inst. 67,1905, 198) specimen became more magnetic after being cooled to the temperature of liquid air.

A similar transformation of much larger degree has been known to take place† in nickel steels containing about 19% of nickel (†Hopkinson, Proc. Roy. Soc. 1890, 47, 138). As the percentage of nickel in carbon steel increased from zero, the temperature at which the steel becomes nonmagnetic decreases from 760°for 0% Ni to 0° for about 27% Ni. Above this transformation the steel consists mainly of austenite, so that quenching from a high temperature results in the steel being in the non-magnetic austenitic condition; cooling below zero tends to recrystallise the steel in a magnetic form. It will be seen below that the author has found this effect in steels containing from 3 to 10% manganese, the results in the case of a steel containing 6·5% of manganese being particularly striking.

SPECIMENS USED.

Steels, used had the following percentage, Compositions:-

Table 1. Analysis of manganese steels used.

Specimen	Mn	C	Si	S	P
A	0·20	0·80	0·10	0·020	0·012
B	1·32	0·58	0·19	0·019	0·017
C	2·57	0·70	0·21	0·020	0·022
D	6·50	0·71	0·36	0·020	0·036
E	9·87	0·75	0·44	0·021	0·051
F	12·51	0·60	0·51	0·020	0·060

The results given below for specimen A, containing 0·20% Mn were obtained by Drs. J.G. Gray & A.D. Ross, and are added in this paper for comparison with the results obtained from the other alloys.

The steels were forged into the form of cylinders, about 20·5 cms. long, and about one cm. in diameter.

A STEEL CONTAINING 0·20% MANGANESE.

The values obtained by Gray and Ross for the intensity of magnetisation of this steel under different fields are given below:-

TABLE 2. 0·20% MANGANESE STEEL.

H	Annealed from 900°		Quenched from 450°		Quenched from 900°	
	15°	-190°	15°	- 190°	15°	- 190°
0	0	0	0	0	0	0
10	160	105	135	95	42	30
20	460	350	450	350	92	72
50	830	760	830	750	335	264
100	1050	996	1040	1000	740	660
150	1150	1115	1150	1115	900	850

It will be seen that quenching from 450° puts the steel into a state almost exactly the same as that after annealing from 900°. Also, at low temperatures the steel is less magnetic than at ordinary temperatures, the decrease in I ~~to 4~~ for H = 100 being about 5% for the annealed state and about 10% for the state of the steel when quenched from 900°. In all cases, Gray and Ross found that the magnetic properties of the steel at room temperature were unchanged by the immersion in liquid air.

B. STEEL CONTAINING 1·32% MANGANESE.

This steel was annealed from 900° put through a hysteresis cycle at room temperature, cooled to liquid air temperature and tested, and tested finally at room temperature after the cooling. In all cases, before the test cycle was taken the specimen was thoroughly demagnetised to remove any sensitive state. Also, the specimen remained in the same position in the magnetometer throughout the tests.

The results obtained for the intensity of magnetisation of the annealed specimen are given below:-

Table 3. 1·32% Manganese steel annealed from 900°

H	Tested at 15°	Tested at - 190°	Tested at 15°
0	0	0	0
10	140	135	95
20	460	425	380
50	890	840	845
100	1090	1080	1050
150	1180	1210	1160

The intensity of magnetisation is less at - 190° for fields up to 100 cgs. units, than at 15°, and for stronger fields is greater. Retesting at 15° shows that the specimen has been slightly affected by the cooling, the magnetisation being now slightly less than before for fields up to 150 cgs. units. Compared with the corresponding 0·20% alloy, this alloy is slightly more magnetic.

Quenching at 450° ~~gave~~ but the specimen in a slightly different state to that after annealing from 900°. The following are the readings:-

Table 4. 1·32% manganese steel quenched from 450°

H	Tested at 15°	Tested at - 190°	Retested at 15°
0	0	0	0
10	160	80	90
20	435	330	380
50	860	780	840
100	1100	1050	1070
150	1210	1160	1160

The intensity of magnetisation at - 190° is always less than that at 15°, for the same field; on reheating the specimen recovers part of the loss, but there is a permanent loss due to the immersion in liquid air, as in the case of the specimen annealed from 900°.

Quenching from 900° alters the magnetic properties of this 1·32% Mn alloy. The table

Table 5. 1·32% manganese steel quenched from 900°.

H	Tested at 15°.	Tested at - 190°.	Retested at 15°.
0	0	0	0
10	35	35	50
20	85	85	110
50	410	325	465
100	870	810	930
150	980	960	1020

gives the intensities of magnetisation for various fields. The values are less than in the case of the annealed specimen.

In this case, as before, cooling to - 190° reduces the intensity of magnetisation for moderate fields, though there are indications that for higher fields the intensity at -190° is greater than at 15°. When the specimen was retested at 15°, there was found a considerable permanent effect, the specimen being now <u>more magnetic</u> than formerly, the greatest increase, about 40% being for low fields. This is the transformation noticed by Hadfield. The steel is still, less magnetic than the annealed specimen.

Compared with the 0·20% Mn alloy, the 1·32% Mn alloy is slightly more magnetic.

<u>C. STEEL CONTAINING 2·57% MANGANESE.</u>

The corresponding values of I and H for this steel in the annealed state are given in the table below:-

Table 6. 2·57% manganese steel annealed from 900°.

H	Tested at 15°	Tested at - 190°	Retested at 15°
0	0	0	0
10	35	40	40
20	90	125	140
50	460	570	590
100	770	890	910
150	910	1020	1020

The steel is more magnetic at low temperatures than at ordinary temperatures; retesting at room temperatures shows a <u>permanent increase</u> in the magnetisation due to cooling to - 190°. The percentage increase is greatest, as in the 1·32% Mn alloy, for low fields, the maximum increase being about 55% for H = 20.

Ordinary steel is generally less magnetic at low temperatures than at room temperatures; in the case of the 2·57% manganese steel the increase on cooling is due, as will be seen later, to a permanent transformation having already set in.

When the 2·57% Mn steel is quenched from 450° we get the following results:-

Table 7. 2·57% manganese steel quenched from 450°

H	Tested at 15°	Tested at - 190°	Retested at 15°
0	0	0	0
10	35	55	40
20	100	160	105
50	480	605	485
100	750	910	760
150	885	1030	890

Cooling to - 190° increases the magnetisation, this cooling has only a very slight permanent effect.

When this alloy is quenched from 900°, however, the liquid air transformation is very marked. This will be apparent from table 8 ; —

Table 8. 2·57% manganese steel quenched from 900°.

H	Tested at 15°	Tested at - 190°	Retested at 15°
0	0	0	0
10	30	35	35
20	75	75	85
50	245	260	355
100	510	595	720
150	690	780	880

The magnetisation is increased by cooling to - 190°, and increases still more when the specimen is warmed again to room temperature. It should be noted that the percentage increase is greatest for about a field of 50 cgs. units; and this percentage increase gradually decreases as the field increases. It seems probable that the steel has the same saturation value in the two states, approaching it more rapidly for moderate fields after cooling to - 190°.

D. STEEL CONTAINING 6·50% MANGANESE.

This alloy is extremely unstable. After any considerable heating it is comparatively weakly magnetic; a small amount of cooling below 0° brings about a very considerable increase in the intensity of magnetisation for a given field. The specimen annealed from 900° gave the following readings:-

Table 9. 6·50% manganese steel annealed from 900°.

H	Tested at 15°.	Tested at - 190°.	Retested at 15°
0	0	0	0
10	5	22	28
20	14	59	77
50	67	210	340
100	139	465	580
150	175	590	685

The magnetisation increases very considerably when the specimen is cooled in liquid air; there is a further increase when the specimen is reheated to ordinary temperatures. The transformation caused by the immersion in liquid air has increased the intensity of magnetisation for low fields to 5½ times its previous value, and for higher fields to 4 times its previous value.

This alloy was the most unstable of those tested, as will be seen when the several alloys are compared later.

Similar results were obtained for the steel when quenched from 450°:-

Table 10. 6·50% manganese steel quenched from 450°:

H	Tested at 15°.	Tested at - 190°	Retested at 15°
0	0	0	0
10	8	34	37
20	23	65	85
50	109	220	350
100	185	520	590
150	230	620	700

The steel is more magnetic than in the annealed state but the general results are the same, viz:- a large increase on cooling to - 190° and a further increase on reheating to ordinary temperatures.

When the specimen was quenched from 900°, the steel was in almost the same condition as when quenched from 450°, i.e. the rate of cooling from 900° to 450° has little effect on the microstructure:

Table 11. 6·50% manganese steel quenched from 900°.

H	Tested at 15°	Tested at - 190°	Retested at 15°
0	0	0	0
10	11	24	46
20	26	58	102
50	106	240	378
100	182	495	610
150	215	620	720

It will be noticed that the quenched specimen is more magnetic than the annealed specimen both before and after the transformation. The percentage increase in the magnetic intensity is less for the quenched specimen than for the annealed specimen, being about 320% for low fields and 230% for high fields, the corresponding figures for the annealed specimen being 460 and 300 respectively.

E. STEEL CONTAINING 9·87% MANGANESE.

This specimen when annealed at 900° was almost non magnetic, the intensity of magnetisation being less than unity for a field of 200 cgs. units; immersion in liquid air did not increase the magnetisation to a measurable value.

When quenched from 450°, the specimen became slightly more magnetic, sufficiently for the following results to be obtained:-

Table 12. 9.87% manganese steel quenched from 450°.

H	Tested at 15°	Tested at - 190°	Retested at 15°
0	0	0	0
10	0·6	1·7	3·0
20	1·1	3·5	6·4
50	3·7	11·2	20·0
100	5·5	24·8	39·6
150	6·9	35·1	50·0
200	8·0	41·3	57·5

Here the actual increase in intensity of magnetisation is small, but the percentage increase is larger than for any of the previous alloys; it varies from 400 to 600%. In the case of the alloys of lower manganese content, the percentage increase is a maximum for H about 50 cgs. units, but in this case the maximum occurs for H =200 units, or larger.

The percentage increase is still greater when the specimen is quenched from 900°.

Table 13. 9.87% manganese steel quenched from 900°.

H	Tested at 15°.	Tested at - 190°.	Retested at 15°
0	0	0	0·0
10	0·1	2·5	4·0
20	0·9	5·4	8·5
50	3·7	16·9	27·4
100	7·5	37·2	57·2
150	9·2	51·6	71·8
200	9·9	61·2	82·5

The specimen is more magnetic when quenched from 900° than when quenched from 450°, and the increase after cooling to -190° is now at least seven times the initial magnetisation.

F. STEEL CONTAINING 12·51% MANGANESE.

This steel contains approximately the same percentage of manganese as Hadfield manganese steel, but the amount of carbon present is much smaller. The specimen when annealed at 900° was, like the 9·87% alloy, too feebly magnetic to be tested. When quenched from 450°, it was found to have a measurable intensity of magnetisation.

Table 14. 12·51% manganese Steel quenched from 450°.

H	Tested at 15°	Tested at - 190°	Retested at 15°
0	0	0	0
10	0·1	0·1	0·1
20	0.3	0·3	0·3
50	1·2	1·2	1·7
100	2·3	2·5	2·85
150	2·6	2·9	3·2
200	2·8	3·1	3·4

We have here a feebly magnetic alloy, more magnetic at - 190° than at 15°, and undergoing a transformation by the cooling, the intensity ofmagnetisation being increased about 20%, a small percentage increase compared with previous alloys.

Quenching from 900° increases the magnetisation, which is still, however, very feeble.

Table 15. 12.51% manganese steel quenched from 900°.

H	Tested at 15°	Tested at - 190°	Retested at 15°
0	0	0	0
10	0·15	0·2	0·2
20	0·4	0·4	0·45
50	1·65	1·5	1·8
100	2·6	2·6	2·9
150	2·9	3.0	3·3
200	3·1	3·3	3·6

Cooling to - 190° brings a slight increase, for large fields at least; heating again to ordinary temperatures shows a permanent increase in the magnetisation of the order of 10%. The quantities are all small, being less than a half percent of the corresponding quantities for low carbon steel without manganese.

EFFECT OF VARYING THE PERCENTAGE OF MANGANESE.

For comparison of the results for the different alloys, table below gives the intensity of magnetisation corresponding to a field of 100 cgs. units, for each specimen in the annealed state, and when quenched from 900°.

Table 16. Intensity of magnetisation for a field of 100cgs. units.

% Mn	Annealed at 900°		Quenched from 900°.	
	Before cooling	after cooling	Before cooling	after cooling
0·20	1050	1050	740	740
1·32	1090	1050	870	930
2·57	770	910	510	720
6·50	120	580	182	610
9·87	—	—	7·5	57·2
12·51	—	—	2·6	2·9

The first small percentages of manganese improve the magnetic properties of the steel, probably merely by acting as a flux and removing from the iron any oxide that may be present. The 1·32% manganese steel shows a slight instability, especially in the quenched specimen. The largest change in the intensity of magnetisation is shown by the 6·50% alloys, the largest percentage change by the 9·87% alloys.

TEMPERATURE OF TRANSFORMATION.

The temperature of which the transformation takes place when the steel is cooled was investigated. The above results give merely the transformation due to cooling to liquid air temperature. The 6·50% manganese steel was reannealed at 900° and tested at 15°. This specimen when previously cooled by liquid air, had its intensity of magnetisation increased by about 300%. It was immersed in ice for 18 hours and retested. The magnetisation had increased by 44%, showing that the transformation is not sudden. It is known that other physical properties, besides magnetic, of manganese steels are altered in the transformation, and we have here a steel whose structure is changing as the steel is cooled to 0°C. Such a steel would therefore be untrustworthy in any position requiring constant physical properties. Cooling the alloy further to - 12° increased the intensity by about 12% more.

The 2·57% manganese steel, which had shown a 20% transformation, gave similar indications of the transformation having begun at 0°C, the increase in intensity of magnetisation being about 8%

TRANSFORMATION IN HIGH CARBON STEEL.

The presence of manganese in steel tends to keep the iron in the non magnetic austenitic state, and the greater the percentage of manganese the more stable is this state. It seems possible that if a steel were heated to a high temperature and quenched sufficiently rapidly, so as to keep the structure mainly austenite, the steel would undergo a similar transformation on cooling to low temperatures. A steel containing 1·64% of carbon was therefore quenched from the temperature of melting copper, about 1100°, thoroughly magnetised and demagnetised to remove the sensitive state (which was considerable), tested at room temperature, tested at liquid air temperature, and retested at room temperature. The following table gives the results:-

TABLE 17. 1·64% carbon steel quenched from 1100°.

H	Tested at 15°	Tested at - 190°	Retested at 15°
0	0	0	0
10	20	20	25
20	50	40	55
50	150	130	195
100	360	340	490
150	480	510	630
200	530	605	690

These figures show that the transformation has taken place, the high carbon steel when quenched from 1100° being in an unstable state corresponding to that of the manganese steels described above.

SUMMARY.

1. Steels containing 0·20, 1·32, 2·57, 6·50, 9·87, and 12·50% manganese have been tested magnetically, before and after immersion in liquid air.

2. The magnetic properties decrease rapidly with increased manganese content beyond 1·32%. Steel containing 9·87% or more of manganese is practically nonmagnetic.

3. The loss of magnetism is due to the manganese causing the retention of the austenitic structure of the iron.

4. Steels containing 2·57, 6·50 and 9·87% manganese, when cooled from 900°, are in an unstable state, cooling to 0° or lower causing a permanent increase in the magnetism of the steel. The increase in the intensity of magnetisation is most marked in the case of the 6·50% manganese steel, being from 140 to 580 for a field of 100 c.g.s. units after the steel has been immersed in liquid air.

5. A similar unstable state has been found in a steel containing 1·64% carbon, when quenched from 1100°, the intensity of magnetism being increased, after cooling to - 190° and re-warming to room temperature, from 360 to 490 for a field of 100 cgs. units.

WIRELESS TELEPHONY TRANSMISSION

by

THERMIONIC VALVE.

by

Robert C. Gray, M.A., B.Sc., Lecturer in Mathematics and Physics in the University of Western Australia.

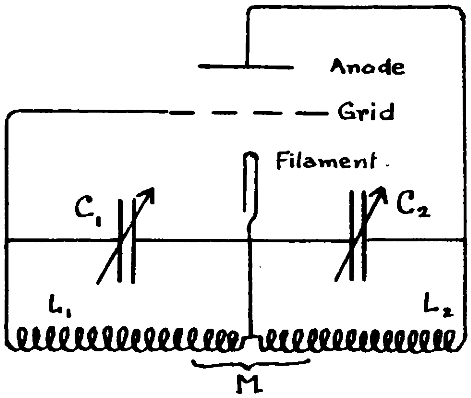
<u>WIRELESS TELEPHONE TRANSMISSION BY THERMIONIC VALVE</u>, by Robert C. Gray, M.A., B.Sc., Lecturer in Mathematics and Physics in University of Western Australia.

While serving as Instructor Lieutenant in the Royal Navy, the writer was employed, during the latter months of the war, on experimental work in connection with wireless telegraphy and telephony at H.M. Signal School, Portsmouth, and in the course of an attempt to design an effective wireless telephone set of low power had occasion to try various circuits, some of them new. A record of some of these results is given below, but owing to the confidential nature of the work only a general indication of the advantages and disadvantages of each circuit can be given.

The essence of wireless telephony is that continuous waves are generated by an arc or by a thermionic valve, and the amplitude or the frequency of the waves is modulated at speech frequency. Reception is carried out by any standard method of rectification without oscillation; if the receiving set were oscillating, the continuous wave carrying the speech would be heterodyned, so that a varying beat note would be heard with the speech.

The fundamental oscillating circuit for a valve is shown below in figure 1:-

FIGURE 1.



The tuned circuit L_1C_1, is placed between the grid and the filament, and a second circuit L_2C_2 tuned to the same frequency is placed between the anode and the filament; these two circuits are coupled together between L_1 and L_2. A slight oscillation in the grid circuit causes a larger oscillation in the anode circuit, and if the coupling between L_1, and L_2 is properly arranged the anode oscillations may be sent back into the grid circuit by this coupling, in phase with the grid oscillations, which are thus sustained. The anode and filament batteries have been omitted from figure 1; they alter the circuit only in detail. The condenser C_1 may be omitted, or the condenser C_2 may be omitted. The presence of both to tune the two circuits tends to make the oscillations more permanent when being modulated. The two condensers C_1 and C_2, in series may be replaced by a single condenser C between grid and anode; the oscillating circuit is now (L_1+L_2) C. These circuits may be further extended and elaborated;* the circuit chosen for (*See L.A. Hazeltine, Proc. Inst. Radio Eng., 6, 1918, 63) wireless telephony depends to some extent on the method of modulation used.

To couple the microphone to the rest of the circuit, an iron - cored transformer was used in several cases; it is well known, however, that an iron-cored transformer distorts speech to some extent, giving the typical metallic sounds heard in most land telephone receivers. The author found that in the reception of wireless telephony, an iron cored transformer amplifier (often called a note magnifier), besides being noisy and sensitive to atmospherics did not give such clean speech as a radio frequency transformer amplifier, or a resistance - capacity - coupled amplifier. Wherever possible, it was found better to couple the microphone to the set by an air cored transformer or by a condenser.

For efficiency it is essential that the amplitude of the continuous wave should be modulated as much as possible by the speech oscillations. This therefore requires adjustment of the circuit so that, among other things, the minimum amplitude produced in the continuous wave by the speech modulation should be the minimum required to sustain the oscillations. If the modulation is too strong the oscillations will stop, and an appreciable interval of time will elapse before the oscillations start up again. The speech transmitted under these conditions will therefore be broken.

The methods of applying the speech oscillations to the continuous waves may be conveniently separated into three groups:-

(a) modulation of the grid voltage.

(b) modulation of the anode voltage.

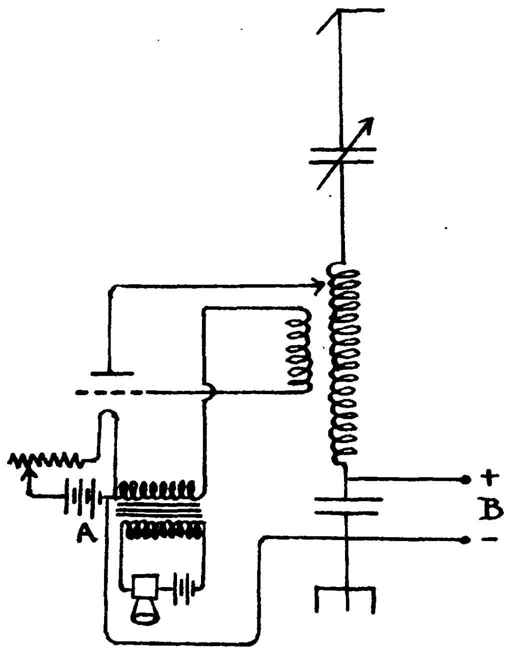
(c) Variation of the resistance of the oscillating circuit.

The three methods will be considered in turn.

MODULATION OF THE GRID VOLTAGE.

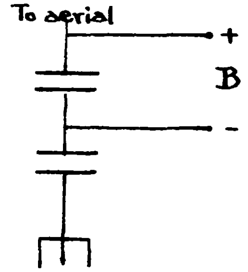
Probably the simplest circuit is that shown in figure 2:-

FIGURE 2.



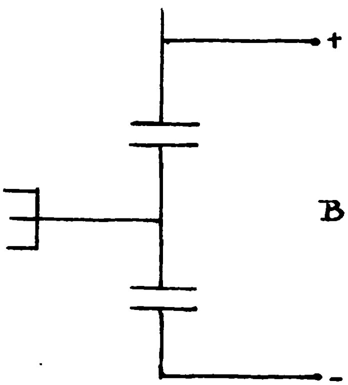
Here we have the tuned aerial forming the anode circuit, while the grid circuit comprises a reaction coil, the secondary of the microphone transformer, and generally a potentiometer (not shown)/ In the microphone circuit a current is flowing from a battery of from 4 to 40 volts, depending on the pattern of microphone, and this current is is modulated by variations in the resistance of the microphone when speech is directed into it. The anode voltage is supplied at the points marked B, the negative being connected to earth and to the negative (or sometimes the positive) of the filament battery A. If it is not advisable to earth this negative lead, an additional micro-farad condenser may be inserted at the foot of the aerial, thus:-

FIGURE 3.



It often happens that the generator supplying the anode potential has the negative terminal considerably negative relative to earth. In that case it is better to connect as shown in figure 4:-

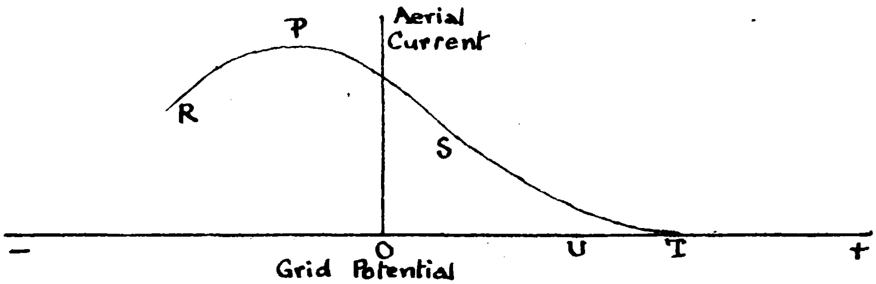
FIGURE 4.



Tuning the grid circuit by putting a variable condenser across the reaction coil stabilises the oscillations, provided the coupling between this circuit and the anode circuit is properly adjusted.

It will be seen that the effect of the microphone is to vary the grid potential, and through it the anode - aerial current. If we plot the aerial current against grid potential, we obtain a curve somewhat of the shape of that shown in figure 5:-

FIGURE 5.



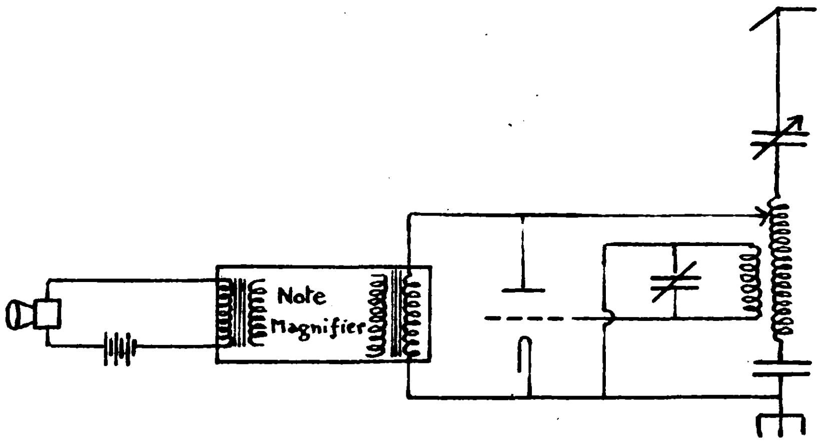
The adjustment we require is that which gives the greatest change in the amplitude of the aerial oscillations, and therefore the greatest change in the aerial current, for a given change of grid potential. It will be seen from the curve that the mean grid potential should be adjusted to correspond to the point S (or R) on the curve. Adjustment for P will give the maximum aerial current, but the possible modulation is negligible. A good indication of the grid potential adjustment is that the aerial current should remain unchanged when the operator speaks into the microphone. The aerial current will drop if the adjustment is too near P; it will rise, with speech, when the adjustment is too near T. Further, the coupling of the microphone should be adjusted so that for a given strength of speech the aerial current will vary just within the limits P and T. If the coupling is too small, only a small variation of aerial current takes place, and the set is working inefficiently. If the coupling is too large, the point P will be passed and the speech distorted, or the point T will be reached when the oscillations will stop and start, and the speech will be broken. The usual microphone transformer does not allow of variation of coupling; a suitable microphone must be chosen and the voltage of the microphone battery varied to give the best effect.

It may be worthy of note here that several endeavours have been made to carry on two - way wireless telephony on the same wave and with one aerial at each station, by working in the neighbourhood of T, known as the "threshold." For reception the aerial must not be oscillating, and the grid potential was adjusted so that the set was on the point of oscillation. The incoming signals were not strong enough to start the oscillations, so that reception was possible, though inefficient; the aerial started oscillating when the operator spoke into the microphone. This method failed, as the speech was broken. When the speech gave an increase in positive potential to the grid, that part of the speech was missed as the set was not oscillating; the parts of the speech that gave negative impulses to the grid were not all transmitted, for oscillations did not set in until a point U of the grid potential was reached.

MODULATION OF THE ANODE VOLTAGE.

In this method the anode voltage is modulated by speech impulses, and this results in variations of the amplitude of the oscillations. The simplest arrangement, if it were practicable, would be to supply all the anode voltage from the microphone circuit. The following circuit was actually tried, a valve being used which oscillated very readily.

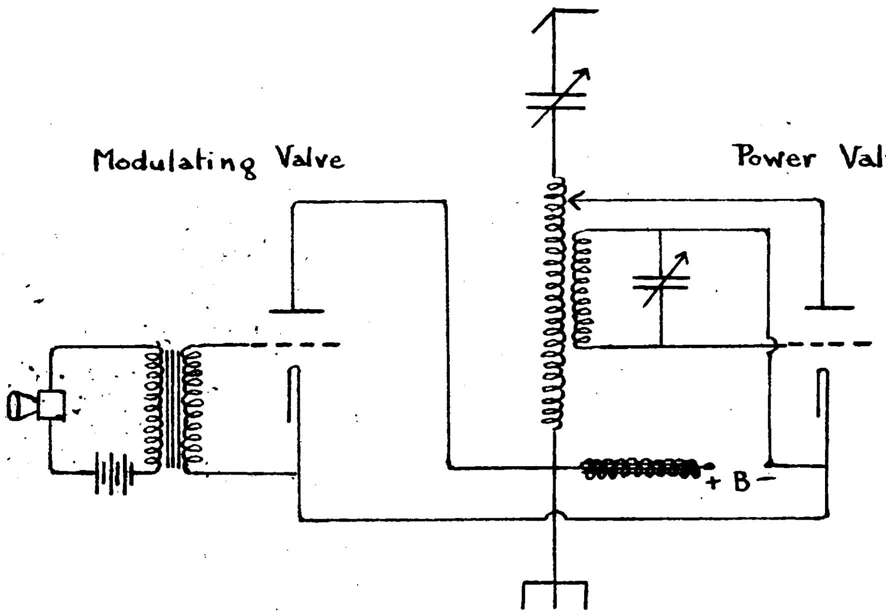
FIGURE 6.



The speech was passed through a low frequency amplifier, and the resultant potential, about 60 volts, was passed on to the anode by means of an iron cored transformer. The secondary of this transformer is in parallel with the aerial inductance but as its inductance was very large compared with the aerial inductance, the effect on the tuning of the circuit was small. With this circuit, as was to be expected, broken speech was transmitted; only that portion of the speech was sent out which gave sufficient positive anode voltage to start up and sustain the oscillations. Thus less than half of the speech was transmitted. What is required initially is an oscillating set, capable of modulation within the limits of oscillation, and the circuit just described did not fulfil these conditions.

Several circuits are in practical use in which two valves, one a power or transmitting valve, the other a modulating valve, are used. The two anode potentials are generally, though not always, supplied from the same source. The transmitting valve is connected to one of the usual oscillating circuits; the microphone is coupled to the grid of the modulating valve. One such circuit is shown in figure 7:-

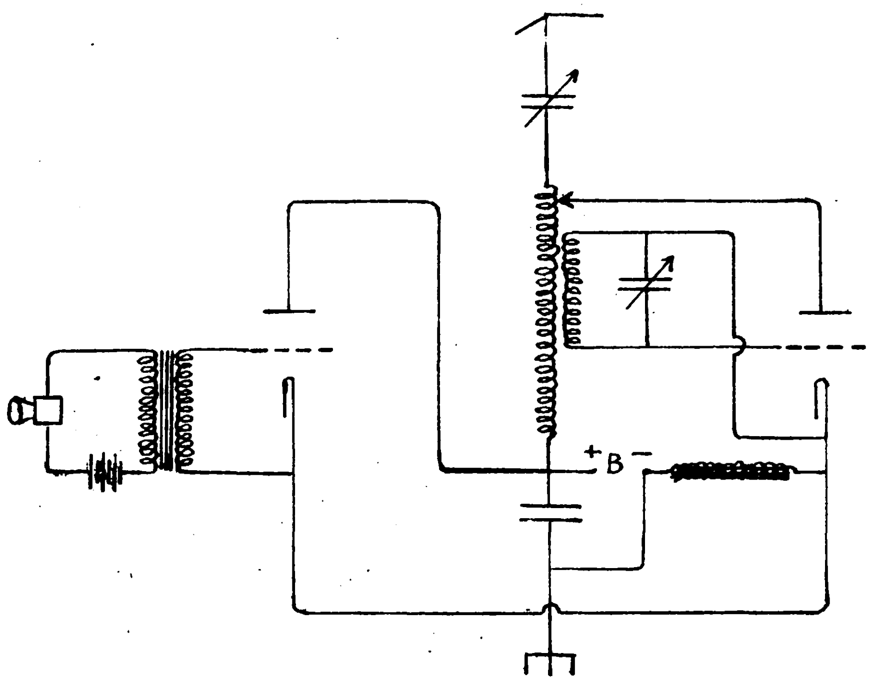
FIGURE 7.



The circuit for the right hand valve is the oscillating circuit shown in figure 2, with a tuned grid circuit. The left hand valve is not oscillating; the grid is modulated by the microphone, the adjustment of the grid potentiometer (not shown) being to the point of maximum slope of the grid potential - anode current characteristic of the valve. The two anode potentials are supplied from the same high potential source B. Modulation of the grid potential of the left hand valve brings about modulation of the anode potential of the same valve, and therefore of the power valve, as a choke coil in the positive lead of the B supply prevents the speech modulations from going that way. The anode potential of the transmitting valve is thus varied, and so the amplitude of the continuous wave oscillations varied. Adjustment of the power of the microphone is necessary as in previous cases, and adjustment of the anode potential to permit of modulation must also be made.

The circuit shown in figure 7 may be modified in many ways. In the diagram the positive terminal of the anode supply is connected through a choke coil to earth. It may be preferable to connect the negative terminal to earth, or it may be already earthed. In such a case the choke coil is removed from the positive to the negative lead of the B supply, and a large condenser inserted at the foot of the aerial. The circuit then becomes that shown in figure 8:-

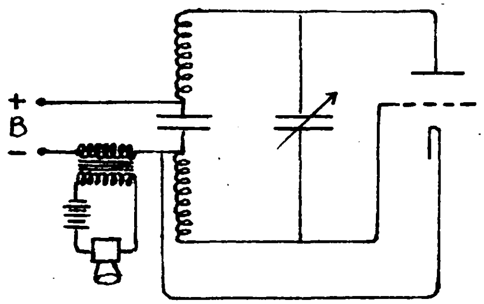
<u>FIGURE 8.</u>



The speech oscillations cause variations in voltage on the first grid relative to the filament, and therefore variations in the voltage of the first anode and hence of the second anode. The choke coil prevents these oscillations from passing through the B supply circuit.

Another circuit that has been suggested is shown in figure 9:-

FIGURE 9.

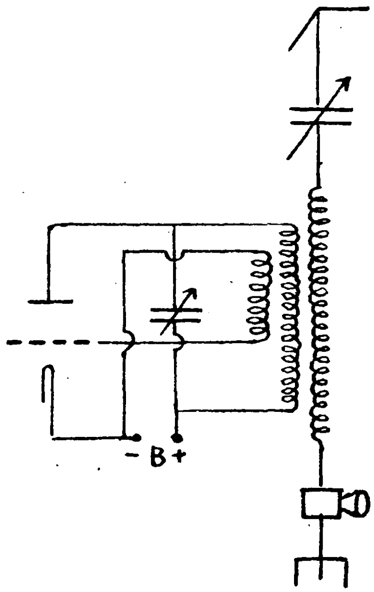


Here use is made of the split inductance circuit, in which the oscillating circuit is placed between the anode and the grid, and the inductance is separated into two parts by a condenser in order to allow anode voltage to be applied. The microphone transformer is connected as shown in the negative lead (or in the positive lead) of the anode supply. This circuit oscillates very readily, and consequently at greater modulation, without danger of stopping the oscillations, seems possible. It will be noticed that the secondary of the microphone transformer is shorted, through the B generator, by a condenser, so that the capacity of this condenser must be kept small. Several attempts by the auther to get efficient results from this circuit have, however, failed.

VARIATION OF THE RESISTANCE OF THE OSCILLATING CIRCUIT.

The simplest method in this case is to put the microphone directly in the aerial, as shown in figure 10:-

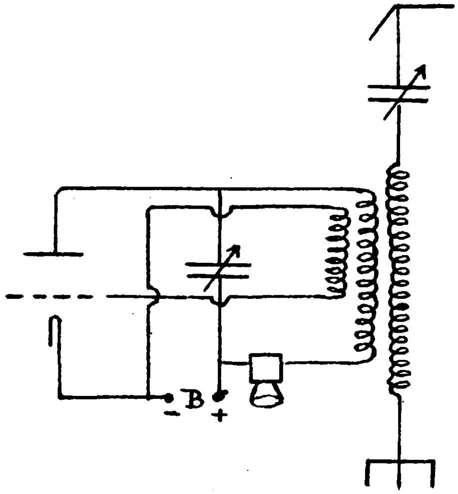
FIGURE 10.-



The microphone must be of fairly low resistance. Many low power sets of this type are in use, and give clean speech. The amplitude of the radiated waves is altered directly by the variations in the resistance of the microphone. The efficiency of such a set depends largely on the choice of a suitable microphone for the aerial in use, and the transmitted power. As all the aerial current passes through the microphone, the microphone must be of low resistance, and special microphones must be used if the power is at all large. Distant control is impossible., i.e. the speaker must be very close to the aerial, as any capacity between the microphone leads will allow the high frequency to pass through it instead of through the microphone.

A slightly different circuit contains the microphone in the grid or anode oscillating circuit. An example is shown in figure 11:-

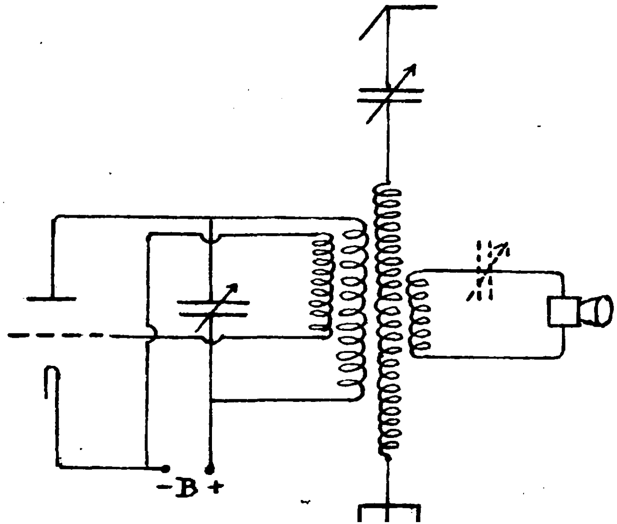
FIGURE 11.



This circuit is not so effective as the last. It has all its objections, viz. no adjustment of the microphone coupling, impossibility of distant control, limitation to low power, and has the further objection that the microphone is in the oscillating circuit of the valve and therefore prevents the valve from oscillating freely, and also alters the wave length.

For low power wireless tolephony transmission the circuit shown in figure 12 is exceedingly useful.

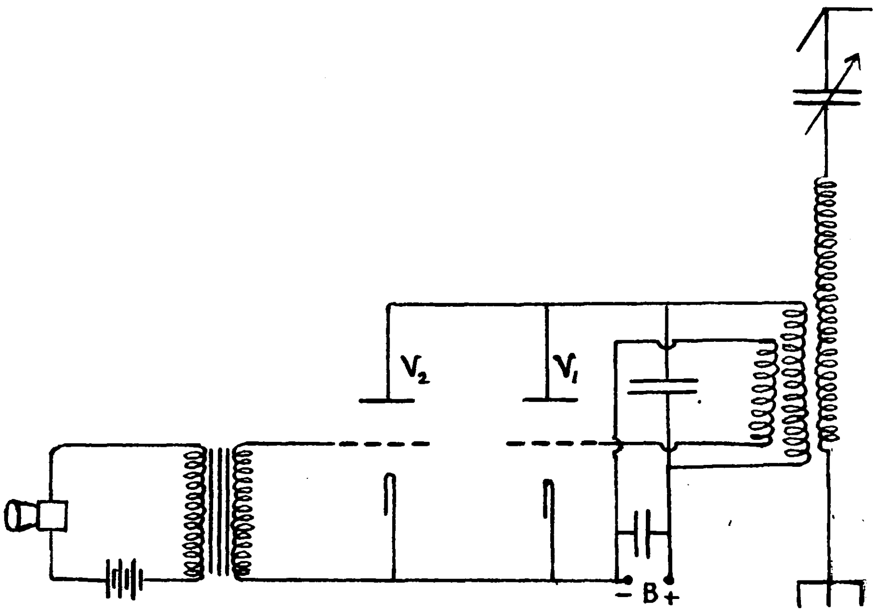
FIGURE 12.



The only difference between this circuit and that shown in figure 10 is that the microphone is now coupled to the aerial instead of being in series with it. This coupling permits of much greater efficiency, as will be indicated below. This method of coupling the microphone was used by Poulsen in the early experiments between Copenhagen and Berlin. The microphone circuit inserts an effective reactance in the aerial, and the author found that best results were obtained by adding a variable condenser to the microphone circuit, and tuning this circuit to the transmitted wave. The impedance in the microphone circuit is then the resistance of the microphone, and the effect of this on the aerial circuit can be contwolled by adjustment of the coupling. In order to adjust the set, the following is the best procedure. The microphone circuit should be left open, and the tuning of the aerial adjusted to give maximum current in the aerial. The microphone circuit should now be closed and coupled loosely to the aerial; the microph-one condenser should be adjusted to give minimum aerial current, that is, to make a maximum the effective resistance introduced into the aerial by the microphone circuit, for a given coupling. The coupling should now be adjusted until the value of the aerial current is a little more than half the value of the aerial current when the microphone circuit was open. Speaking into the microphone should now alter the aerial current between its maximum value and a small value. If the aerial current ceases the coupling is too tight. This circuit was found by the author to give great efficiency when handling small power. It is not adapted for high power transmission,and has the great object-ion that distant control is impossible.

Several circuits have been tried in which the anode - filament resistance of a second valve is connected across the oscillating circuit and this resistance is varied by modulation of the grid potential of this second valve. A typical circuit is shown in figure 13:-

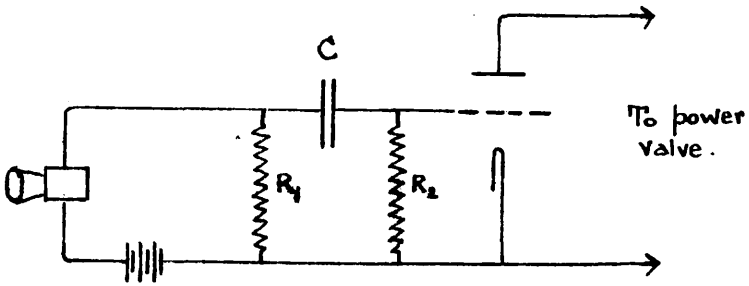
FIGURE 13.



The anode-filament circuit of valve V_2 represents a resistance of the order of 100000 ohms connected across the oscillating circuit of valve V_1. The grid potential of V_2 is modulated by means of a microphone and transformer, and this the anode-filament resistance of V_2 is varied. This method was found to work well with low powers; and it seems likely that high powers could be easily controlled in this way. The circuit permits of distant control.

Various attempts to eliminate iron - cores from the microphone coupling have been made. In the circuits shown above in figure 10,11, 12, no iron-cored transformers are used, but these circuits do not permit of distant control, as high frequency currents pass through the microphone in each case. Capacity coupling has been tried and found very useful. An example of the microphone connections is shown in figure 14:-

FIGURE 14.



The microphone circuit contains a resistance R_1, equal to that of the microphone. Variations in the resistance of the microphone cause variations in the potential drop across R_1; these are passed on to the grid of a modulating valve, which controls the oscillations of a power valve as detailed above. The condenser C should be of large capacity; R_2 is merely a grid leak, to prevent accumulation of negative electricity on the grid. If it is necessary, the speech may be increased to any required amplitude by being passed through a series of valves connected in cascade by resistance - capacity couplings, the last valve being used as a control or modulating valve. The auther found such an arrangement gave clean, clear speech, most of, if not all, the voice tones being transmitted. The strength of signal transmitted was generally lower than that transmitted by similar valves when the microphone transformer was iron-cored.