" Alloy Steel and Articles Made Therefrom "

Thesis for Degree of Metallurgical Engineer

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1927

Title

"ALLOY STEEL AND ARTICLES MADE THEREFROM"

A

Thesis

Presented to the Michigan State College

In

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Degree of Metallurgical Engineer

(Met. E)

By

Richard Elwood Bissell

1927.

Approved 5/19/27
H B Dirks
Prof. Mech. Eng.

THESIS

"ALLOY STEEL AND ARTICLES MADE THEREFROM"

1. The Need of New Material of Different Than Normal Characteristic for Aircooled Aircraft Engine Poppet Valves.

2. A Search of the Automotive Poppet Valve Material Field.

3. Test of Materials or Compositions Intermediate in Composition to Previous Known Compositions but with the Addition of Silicon.

4. Discovery of Something Valuable in the New Chrome Nickel Silicon Steel.

5. Characteristics of the New Material.

"ALLOY STEELS AND ARTICLES MADE THEREFROM"

Demands for greater efficiencies, together with less weight, in automotive engines and in particular aircooled aircraft engines, have caused engineers and metallurgists to carefully check over the requirements of each individual part. The materials available and the treatments which make them the more suitable to fill the requirements as listed, are carefully studied.

In the case of the exhaust valve for the aircooled aircraft engine, the requirements are many and the materials heretofore available for other valve service in any condition of treatment, do not thoroughly satisfy the designing engineer or metallurgist.

Dr. Aitchison* lists the <u>types of valve failures</u> as follows:

1. Elongation of the stem of the valve.
2. Distortion of the head of the valve.
3. The presence of cracks in the valve face.
4. Excessive wear of the valve stem.
5. Excessive wear of the valve foot.
6. Burning out of the head.
7. Scaling of the valve.
8. Breaking of the head or neck due to self hardening.

The writer has added, modified and extended this list as follows:

1. Tensile stretching of the valve.
2. Warping or curling of the valve.
3. The presence of cracks due to defects in the original steel - due to expansion or contraction stress fatigue or - due to direct service load stress fatigue.
4. Excessive wear of valve stem.
5. Excessive wear or riveting of the valve foot.
6. Oxidation, scaling or burning due to a combination of temperature and mixture, including added or deposited chemical compounds, from doped fuels.
7. Scaling of the valve.
8. Breaking of the head or neck due to self hardening.
9. Grooving, battering or excess wear of the valve seat.
10. Peaning, riveting, or burring of spring retainer supporting surface edge.
11. Pitting, corrosion or erosion of valve head.
12. Pitting or corrosion of valve stem.
13. Breakage due to brittleness.
14. Foreign matter adhesions to original valve surface, commonly called "pick up".

* Paper read before the Institute of Automobile Engineers, Nov.5, 1909.

Dr. Aitchison has described the properties a valve steel should possess:

1. The greatest possible strength at high temperatures.
2. The highest possible notched bar value.
3. The capacity of being forged easily.
4. The capacity of being manufactured free from cracks, whether these arise in the manufacture of the steel bar or are produced during the forging of the steel.
5. The capacity of being heat-treated easily, regularly, and reliably.
6. The least possible tendency to scale, and if scaling does occur, the scale should be as adherent as possible.
7. The ability to retain its original physical properties after frequent heating to high temperatures, followed by cooling to normal temperature, also after being heated to an elevated temperature for a considerable length of time.
8. No liability to harden when cooled in air from the temperature which it will attain when used normally as a valve in an engine.
9. The capacity of being heat-treated after forging so that it is free from strains liable to produce distortions.
10. Sufficient hardness to withstand excessive wear in the stem.
11. The capacity of being hardened at the foot of the stem with considerable ease if necessary.
12. The capacity of being machined easily and satisfactorily by ordinary methods.

Although this article was prepared about eight years ago, it can be seen that at that time the steel was supposed to possess much. The eight years have not decreased the list, and we are now quite content to eliminate "easy" "normal" operations in the attempt to create a satisfactory valve.

The writer has added:

13. The capacity of operating at high temperatures without adhering to foreign matter.

On the first examination of the list it will be noted that the steel with the greatest possible strength at high temperatures (1) will not have the capacity of being forged easily (3) in strict sense of the word, and also it will be noted that with all the properties from #1 to #11 perhaps even grinding must be resorted to in place of #12.

Such materials as are available for solid one piece exhaust valves up to date might be listed as follows:

	C	Cr	Co	Mo	Ni
Straight Chrome Steels					
Type A.	.45 .55	7.0 8.0			
Type B.	.20 .40	11.5 14.0			
Chrome Cobalt Steels					
Type A.	1.5 1.7	12.0 14.0	2.5 3.5	.60 .80	.50 Max
Type B.	1.3 1.5	12.0 14.0	1.0 1.35	1.0 1.35	.45 .75

Chrome Silicon Steels	C	Si	Cr	W	Mo
Type A.	.35 .50	2.75 3.75	7.0 9.0		
Type B.	.35 .50	2.75 3.75	7.0 9.0	1.15 1.85	
Type C.	.45 .60	1.0 2.0	7.0 9.0		.60 .90
Type D.	.20 .30	3.0 3.8	3.0 3.5		
Type E.	.35 .45	3.6 4.2	1.85 2.50		

Chrome Nickel Steels	C	Mn	Si	Cr	Ni
Type A.	.40 .50	.50 .80	1.0 1.5	12.0 14.0	16.0 19.0

Judging from the writer's experience with these different grades of material, together with careful interpretation of extensive laboratory tests and scientific data, a chart is compiled indicating the relative merit of each material for each of the thirteen properties.

The steel possessing the desired property to the greatest degree is marked 1, and the steel possessing it to the least degree is marked 5*.

	1	2	3	4	5	6	7	8	9	10	11	12	13
Chrome Type A	4	1	4	5	3	3	4	4	2	1	1	2	2
Chrome Type B	5	1	3	4	3	2	3	3	2	2	2	2	3
Cobalt Chrome Type A	2	5	4	4	4	2	1	1	1	1	1	4	4
Cobalt Chrome Type B	3	4	4	3	4	2	1	1	1	1	1	4	4
Chrome Silicon Type A	4	2	1	1	1	1	1	1	1	1	1	4	5
Chrome Silicon Type B	3	3	2	2	2	2	1	1	1	1	1	4	3
Chrome Silicon Type C	2	2	2	3	1	3	1	1	1	1	1	2	2
Chrome Silicon Type D	3	2	2	2	3	3	2	2	1	1	2	3	4
Chrome Silicon Type E	4	4	2	3	3	3	3	3	2	1	2	3	4
Chrome Nickel Type A	1	2	2	1	4	1	2	1	1	5	5	4	2

Returning to the writer's list of fourteen types of valve failure and bearing in mind the conditions of operation of an air-cooled aircraft engine exhaust valve, it is seen that failures of type 3, 4, 6, 8, 11, 13 and 14 should be particularly guarded against. This seems to require a merit 1 of steel properties 1, 5, 6 and 10 in particular, and if there be any merits 5 they should be in properties pertaining to ease of manufacture.

Valuable as they are - - the steels listed do not in any instance fulfill exactly the requirement and the indications are that a new material must therefore be sought.

Chrome Nickel Steel A leads the column in property 1 with merit 1. Although this material has great strength at heat, it is always relatively soft cold being austentic. It therefore does

(*Similar to, but not a copy of, Aitchison's Table XVII.)

not resist wear on stem or foot and cyaniding or carbonizing can not be resorted to, to improve the situation.

It appears to the writer that nickel and chromium in combination are necessary for the high strength at heat required and that when sufficient nickel is added for suitable effect here - it is necessary to improve the oxidation resistance and the ability to forge by the addition of some such element as silicon.

In order to harden the material, it will perhaps also be necessary to have the elements in such proportions as will allow the production of martensite for resistance to stem and tip wear at least.

For this purpose the writer proposes to study then the alloys between the straight chrome Type B and the Chromium Nickel Type A, but with added silicon which would appear necessary for the purposes above mentioned.

The test alloys are as follows:

	C	Mn	P	S	Si	Cr	Ni
TEST ALLOY 1	.30	.21	.01	.025	2.00	13.5	3.9
" " 2	.35	.25	.02	.02	2.05	13.4	5.6
" " 3	.33	.22	.02	.015	1.90	11.9	8.2
" " 4	.26	.21	.02	.025	2.60	12.0	10.9

TEST ALLOY #1 Characteristics:

	Br	Sc
Hardness as received ------------------------------------	340	---
" after forging and air cool -------------------	320	55
" " 1650^{o} F 2 hr cool 50^{o}/Hr to 1350^{o}F Packed in Boxes with Mica	436	64-65
" " 1550 Q.O. Following above	400	60-61
" " 1600 Q.O. " "	---	-----
" " 1650 Q.O. " "	436	65
" " 1700 Q.O. " "	436	65
" " 1750 Q.O. " "	476	70
" " 1800 Q.O. " "	476	70
" " 1850 Q.O. " "	456	65-70
" " 1900 Q.O. " "	400	65
" " 1950 Q.O. " "	---	---
" " 2000 Q.O. " "	---	-----
" " 2200 Q.W. " "	228	46-47

Spec. Gr. 7.78

TEST ALLOY # 2 Characteristics:

	Br.	Sc.
Hardness as received -------------------------------	241	44
" after forging and air cool ----------------	200	43
" " 1650° F 2 Hrs cool 50°F/Hr to 1350°F (Packed in Boxes & Mica)	400	55
" " 1550 Q. O. Following above	400	55
" " 1600 Q. O. " "	400	55
" " 1650 Q. O. " "	400	55
" " 1700 Q. O. " "	360	55
" " 1750 Q. O. " "	380	55
" " 1800 Q. O. " "	436	58
" " 1850 Q. O. " "	400	58
" " 1900 Q. O. " "	315	42
" " 1950 Q. O. " "	280	37
" " 2000 Q. O. " "	205	36
" " 2200 Q. W. " "	186	40

Spec. Gr. 7.81.

TEST ALLOY #3 Characteristics.

	Br.	Sc.
Hardness as received ------------------------------	210	---
" after forging and air cool ---------------	180	37
" " 1650°F 4 Hr. 50° F/Hr to 1350° Boxes & Mica	370	58
" " 1550 Q.O.Following above	370	61
" " 1600 Q.O. " "	370	58
" " 1650 Q.O. " "	400	58
" " 1700 Q.O. " "	355	54
" " 1750 Q.O. " "	296	45
" " 1800 Q.O. " "	243	40
" " 1850 Q.O. " "	233	34
" " 1900 Q.O. " "	201	34
" " 1950 Q.O. " "	190	34
" " 2000 Q.O. " "	160	32
" " 2200 Q.W. " "	132	28

Spec. Gr. 7.84

TEST ALLOY #4 Characteristics:

	Br.	Sc.
Hardness as received ----------------------------	163	33
" after forging and air cooled ------------	148	32
" " 1650°F 2 Hr 50°F/Hr to 1350°Boxes & Mica	190	39
" " 1550 Q.O. Following above	158	38
" " 1600 Q.O. Following above	158	37
" " 1650 Q.O. " "	158	36
" " 1700 Q.O. " "	154	37
" " 1750 Q.O. " "	166	39
" " 1800 Q.O. " "	143	35
" " 1850 Q.O. " "	138	35

TEST ALLOY #4 Characteristics: (Continued)

			Br.	Sc.
Hardness after	1900 Q.O.	Following above	132	33
" "	1950 Q.O.	" "	128	32
" "	2000 Q.O.	" "	126	31
" "	2200 Q.W.	" "	114	31

Spec. Gr. 7.84

It is noted that Test Alloy #3 is apparently an austentic steel when forged and the special 1650° - 2 hr. cool 50°/Hr. to 1350° (Packed in boxes with mica) treatment allows it to at least partly revert to martensite which is again changed to and retained as austenite starting on retreatment at 1700 to 1750° F followed by a quench.

It is noted that after a 2200°F heat followed by water quench, the hardness is particularly low. In this condition it is readily turned and milled but drilled or sawn with difficulty.

Since air cooled aircraft motor valves rarely exceed a 1520°F temperature, and since this alloy seems to possess apparent desirable features in that it requires 1700 to 1750°heat following a hardening by slow cooling before it is materially changed, it is desired to study its characteristics further.

With this idea in mind, these test results are presented.

(1) Forge
(2) Reheat to 1650° F - 2 hrs. cool 50°/Hr. to 1350°F. (Packed in boxes with mica.)
(3) Reheat to 2200° F, quench in water.
(4) Reheat to temperatures shown below, followed by test.

	BRINELL	SCLEROSCOPE	BEND*	FRACTURE
400° F Cool in Air	130	30	8 bends 7 Reversals	Fine Jagged
800° F Quench in Oil	130	30	5 bends 4 Reversals	Silky
1000°F Quench in Oil	124	30	4 Bends	Silky
1200°F " " "	134	30	4 "	"
1250°F " " "	132	30	4 "	"
1300°F Cool in Air	136	30	3 "	"
1350°F " " "	140	31	1 "	"
1450°F " " "	128	30	3 "	"
1550°F " " "	136	31	1 "	"
1650°F " " "	154	34	1 "	"
1750°F " " "	152	34	1 "	"
1850°F " " "	160	34	1 "	Coarsening up
1950°F " " "	132	30	?	Fine

* (Piece held in vise and bent back and forth with hammer blows.)

It is assumed by the writer that the number of reversals of an austenetic steel before fracture are a measure of the proximity of stable martensite.

At 1850°F some tendency appeared to be hardening the material and changing the fracture slightly.

It now seems desirable to put the material through a variety of treatments to determine how it changes from one condition to another, as, from the two tables presented, it is clear that after the same temperature and type of quench, it can be in different conditions, depending upon the preceding treatments it has received.

GROUP TESTS A TEST ALLOY #3
ANALYSIS OF STEEL USED

C	Mn	Si	Ni	Cr.
.38	.33	2.16	7.33	11.50

	BRINELL	SCLEROSCOPE	ROCKWELL
Hardness of stock as received	241		
1. After 2200°F Quench in Water	169	29	11
2. As above, followed by 1650° - 4 hr 50°/Hr. 1350	421	61	47
3. As above 1 & 2, followed by 1250°F 8 min. in Molten Salt Bath, Q.O.	364	56	42
4. As above, 1, 2 & 3, followed by 1450° F 8 min.in Molten Salt Bath, Q.O.	395	60	46
5. As above, 1,2,3 & 4, followed by 1200°F, 8 Min. in Molten Salt Bath, Q.O.	358	55	40

GROUP TESTS B TEST ALLOY #3
ANALYSIS OF STEEL USED (Same as A)

Preliminary Treatment:

(1) Heat to 2200°F, Quench in Water,
(2) Reheat to 1650° F - 4 Hrs, Cool 50°/Hr to 1350° F.
(3) Reheat to temperature shown below, quench and test.

	BRINELL	SCLEROSCOPE	ROCKWELL.
Reheat in Molten Salt 8 min.at 900 F QO	427	62	47
" " " " 8 " " 950 F "	410	61	47
" " " " 8 " " 1000 F "	381	59	44
" " " " 8 " " 1050 F "	369	56	43

	BRINELL	SCLEROSCOPE	ROCKWELL
Reheat in Molten Salt 8 min at 1100 F QO	364	55	43
" " " " " " " 1150 "	366	55	44
" " " " " " " 1200 "	354	55	42
" " " " " " " 1250 "	364	55	42
" " " " " " " 1300 "	372	57	43
" " " " " " " 1350 "	398	61	45
" " " " " " " 1400 "	391	61	46
" " " " " " " 1450 "	396	60	46
Reheat in Molten Lead 8 min at 1500 "	402	60	47
" " " " " " " 1550 "	410	61	46
" " " " " " " 1600 "	375	57	43
" " " " " " " 1650 "	343	54	38
" " " " " " " 1700 "	262	42	29

GROUP TESTS C TEST ALLOY #3
ANALYSIS OF STEEL USED (Sams as A)

Preliminary Treatment:

(1) Heat to 2200° F, Q. W.	166	28	11
(2) Reheat in Molten Lead for 8 Min at 1650 F Q.O.	185	30	16
Followed by:			
1650° F, 4 hrs Cool 50° F.Hr to 1350°F	387	59	43
Then 1650°F, 8/m in Lead, Quench in Oil	302	47	35
" 1280 F, 8/m in Salt, " " "	348	54	42
" 1650 F, 8/m in Lead, " " "	331	49	39
" 1450 F, 8/m in Salt, " " "	384	59	46

GROUP TESTS D TEST ALLOY #3

Pieces treated consecutively (Last piece receiving all previous heats)

	1000 Kg. BRINELL	SCLEROSCOPE	ROCKWELL C
(1) 2200°F, Quench in Water	140	31	10.25
(2) 1700 F, " " Oil -	172	32	15.0
(3) 1450 F, " " Oil	172	32	16.0
(4) 1450 F, " " "	182	36	----
(5) 1450 F, " " "	189	38	----
(6) 1450 F, " " "	210	42	----
(7) 1450 F, " " "	205	42	----
(8) 1450 F, " " "	205	43	----
(9) 1450 F, " " "	238	44	----
(10) 1450 F, " " "	260	47	----
(11) 1450 F, " " "	279	56	----
(12) 1450 F, " " "	316	57	----
(13) 1450 F, " " "	328	57	----
(14) 1450 F, " " "	356	58	----
(15) 1450 F, " " "	372	58	----

From the characteristics as determined above, the writer concludes the method of manufacture of a valve of this material should be as follows:

(a) Forge
(b) Heate to 2100° F, Quench in Water
(c) Machine (except drilling, sawing or threading)
(d) Heat to 1600° F, 6 hours, Cool 50°F/Hr to 1350, then cool in air.
(e) Heat to 1250° F, Cool in Air
(f) Drill, saw, or thread.
(g) Heat to 1450° F, Quench in Oil.

The valve will then be 55 minimum Scleroscope or martensitic head, stem and tip.

Another method perhaps equally as good, would be as above for a, b, c, d, e, f and g, followed by heating of head only to top of guide section to 2100° F, and cool in air. This would give an austenitic head on a martensitic stem.

TENSILE TESTS
HEAT TREATMENT

(1) Heat to 2200°F, Quench in Water.
(2) Reheat to 1650°F, 8 Hrs. Cool 50°F/Hr to 1350°F, (Packed in boxes with Mica.

Pulled at room temperature:

Elastic Limit	203,750 to 207,500 #/Sq."
Tensile Strength	212,500 to 217,500 #/Sq."
Elongation in 2"	12%.
Reduction of Area	31%

Pulled at 1500° F:

Elastic Limit	29,300 to 30,000 #/Sq."
Tensile Strength	34,525 #/Sq."
Elongation in 2"	12.0 to 14.5%
Reduction of Area	12.0 to 14.8%

OXIDATION RESISTANCE TESTS:

Pieces heated at 1650° F for 8 hours in a relatively tight furnace with pure oxygen inserted continuously from an oxygen cylinder, and with oxygen coming from all minute cracks and crevises, indicate almost entire freedom from scaling. This is considered a very good test.

COEFFICIENTS OF EXPANSION

$32^{o}F - 302^{o}F$	.00001048"/^{o} F
302 - 392	.00001013
392 - 482	.00001019
482 - 572	.00001036
572 - 662	.00001048
662 - 752	.00001053
752 - 842	.00001070
842 - 932	.00001079
932 - 1022	.00001084
1022 - 1112	.00001088

TRANSFORMATION POINTS

Pieces submitted to The Leeds & Northrup Company, 4901 Stanton Avenue, Philadelphia, in the austenitic condition.

Results as follows (Letter of October 20, 1925):*

"These curves were made with the regular transformation point indicator apparatus but we could not discover any critical point. In addition to this, the laboratory made tests taking time temperature readings with a set up much more sensitive than the transformation point apparatus. These time temperature readings have also been taken with" - - - - - etc.

"One of these runs have been plotted so far; blue prints of which are enclosed. These prints have to have the corners matched so that the curve extends across both sheets. No signs of a critical point appear."

"You will note that the thermocouple readings are plotted in mocrovolts. The thermocouple used is one of our standard Rhodium thermocouples which matches up with Table No. 12-A."*

"The variation in heating curves were caused by changing the current through the furnace."

** Curves and tables are found in leather pocket inside of back cover.

MAGNETIC TESTS:

Below is quotation from letter of Dr. John A. Mathews, Vice President of the Crucible Steel Company of America, under date of August 2nd, 1926:

> "Some tests that we made of material taken from one of your shipments showed that after the high quench, the material was fully austenitic and quite soft. The material did not harden until a drawing temperature of 1400 was reached, when it showed a Brinell of 321 and was becoming magnetic. After a 1500 tempering, the Brinell was 375 and the permeability was considerably increased. At a 1600° draw the Brinell was 444 and still higher in induction, indicating the conversion of gamma to alpha iron. The drawing times previously mentioned were one-half hour. On holding for six hours at 1600° the hardness remained the same, but the induction changed from 5500 to 9200. On again drawing at a lower temperature, the material softened to 364 at a 1200° draw and with an induction of 10,500. On bringing up to 1600° again for one-half hour, it once more showed 444 but with an induction of 8000. For all temperings and retemperings from 1000° up, the material showed a high coercive force of from 55 to 67, indicating magnetic hardness, with the single exception of the redraw at 1000 after fully hardening, when the coercive dropped to 28."

IMPACT TESTS:

Treatment:

(1)	After 2100° F Q. W.	116 Foot pounds
(2)	Followed by 1650° F 6 hrs. (Packed in Boxes with Mica) Cooled 50°F/Hr. to 1350°F	3 Foot pounds
(3)	Followed by 1280°F Cool in Air	10.5 Foot pounds
(4)	" " 1450°F Quench in Oil	7.5 Foot pounds.

CONCLUSION.

Let us now see where the new material should be classified on the chart indicating the relative merit of each material for each of the thirteen properties (Page 2):

PROPERTY	1	2	3	4	5	6	7	8	9	10	11	12	13
TEST ALLOY #3	1	2	2	1	1	1	2	1	1	1	2	5	2

This fulfills our original idea that for aircooled aircraft engine valves the steel should have merit 1 of steel properties 1, 5, 6 and 10 in particular, and if there be any merits 5 they should be in properties pertaining to ease of manufacture.

Recent reports from three of the largest builders of aircooled aircraft engines - two in America and one in France - confirm the findings as presented.

B I B L I O G R A P H Y

1. "Valve Failures and Valve Steels in Internal Combustion Engines",

   By Leslie Aitchison,

   Institute of Automobile Engineers, Nov. 5, 1919.

2. "Materials for the Exhaust Valves of Internal Combustion Engines",

   By J. E. Hurst and Harold Moore

   Engineering Vol. 108, pp. 672-74.

3. "Characteristics of Material for Valves Operating at High Temperatures",

   By J. B. Johnson and S. A. Christiansen,

   American Society for Testing Materials, June 1924.

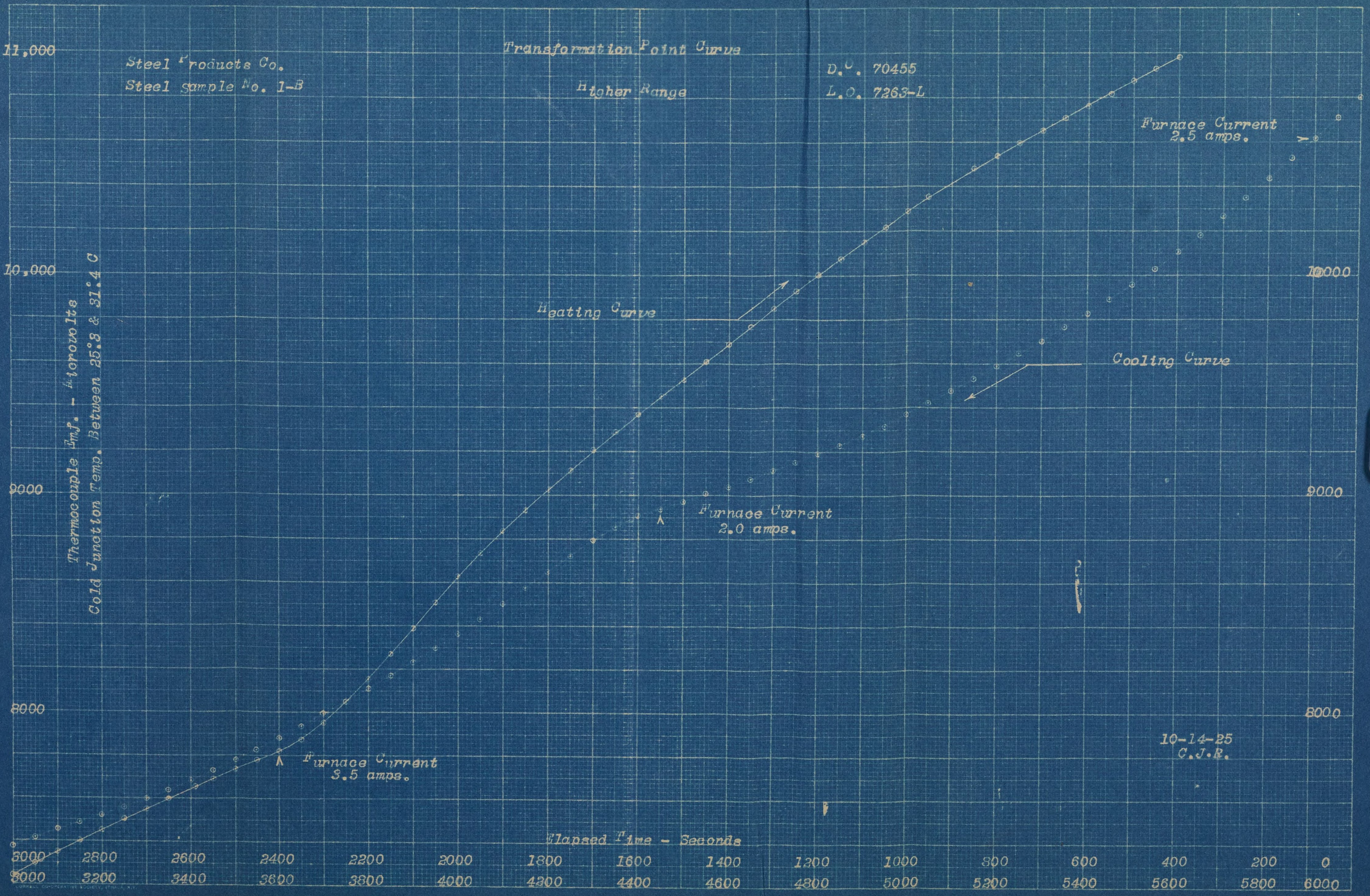
4. "Valve Steels",

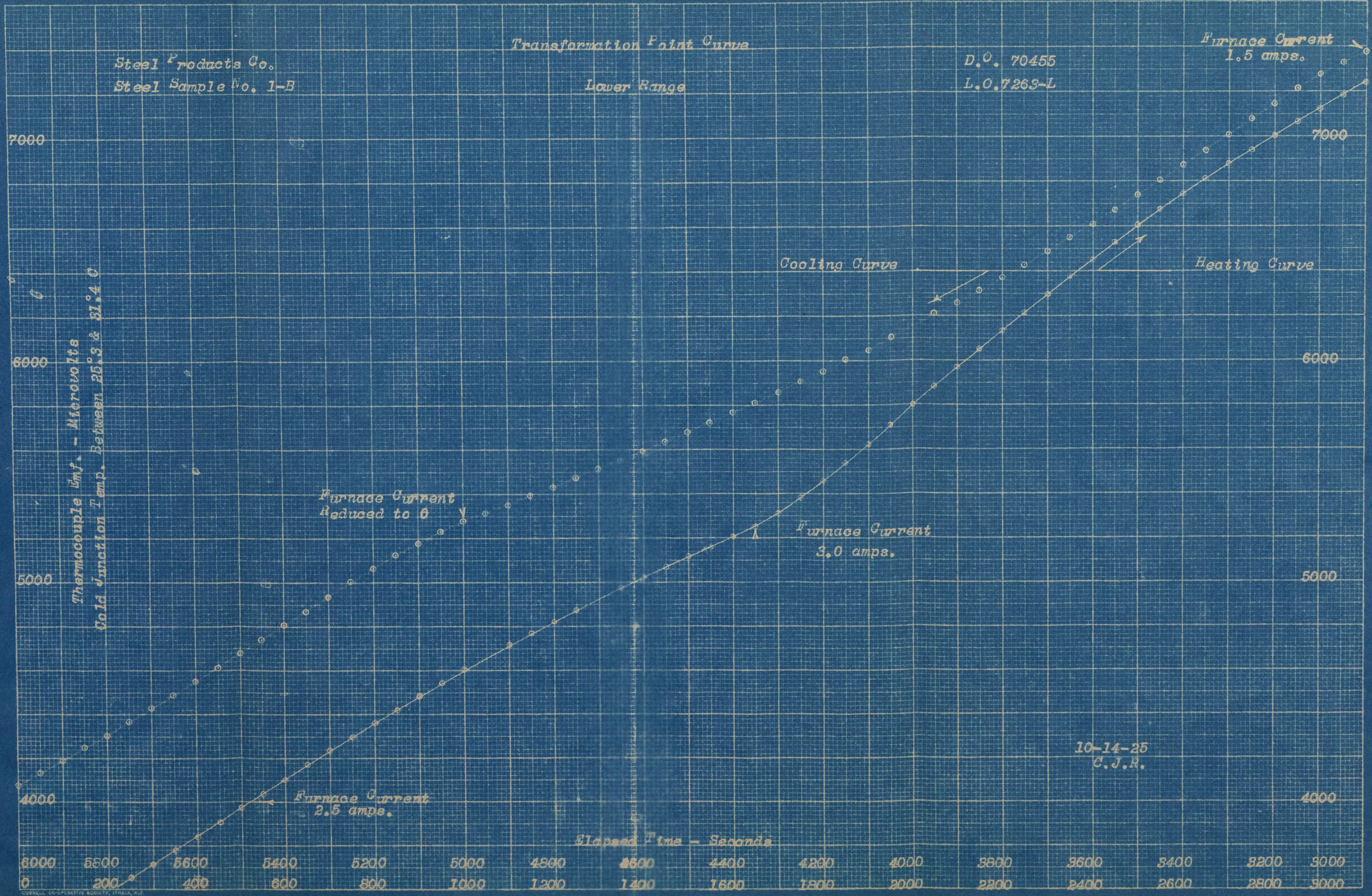
   By P. B. Henshaw,

   The Royal Aeronautical Society,

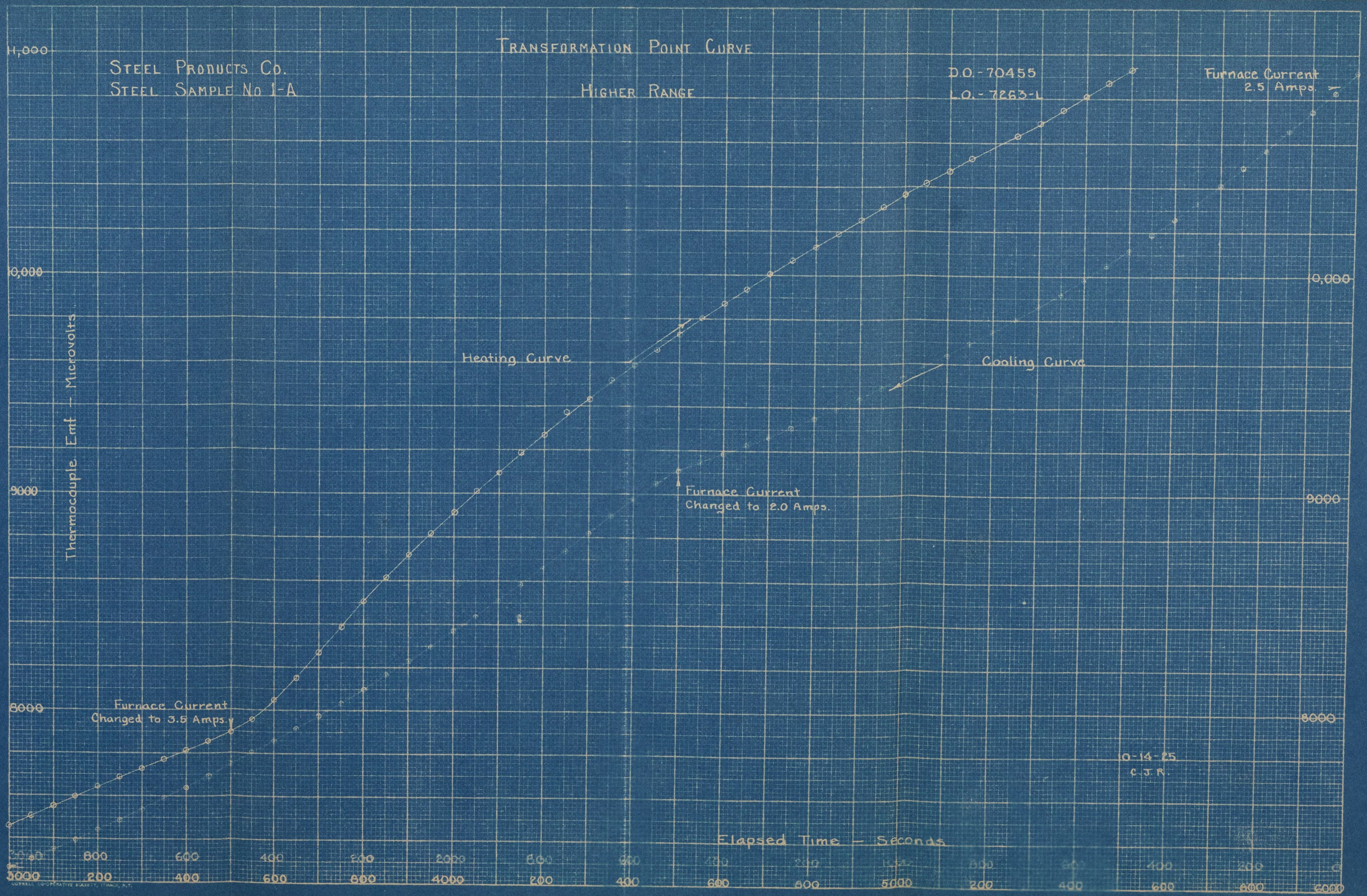
   7 Albemerle Stre. W. I., Dec. 2, 1926.

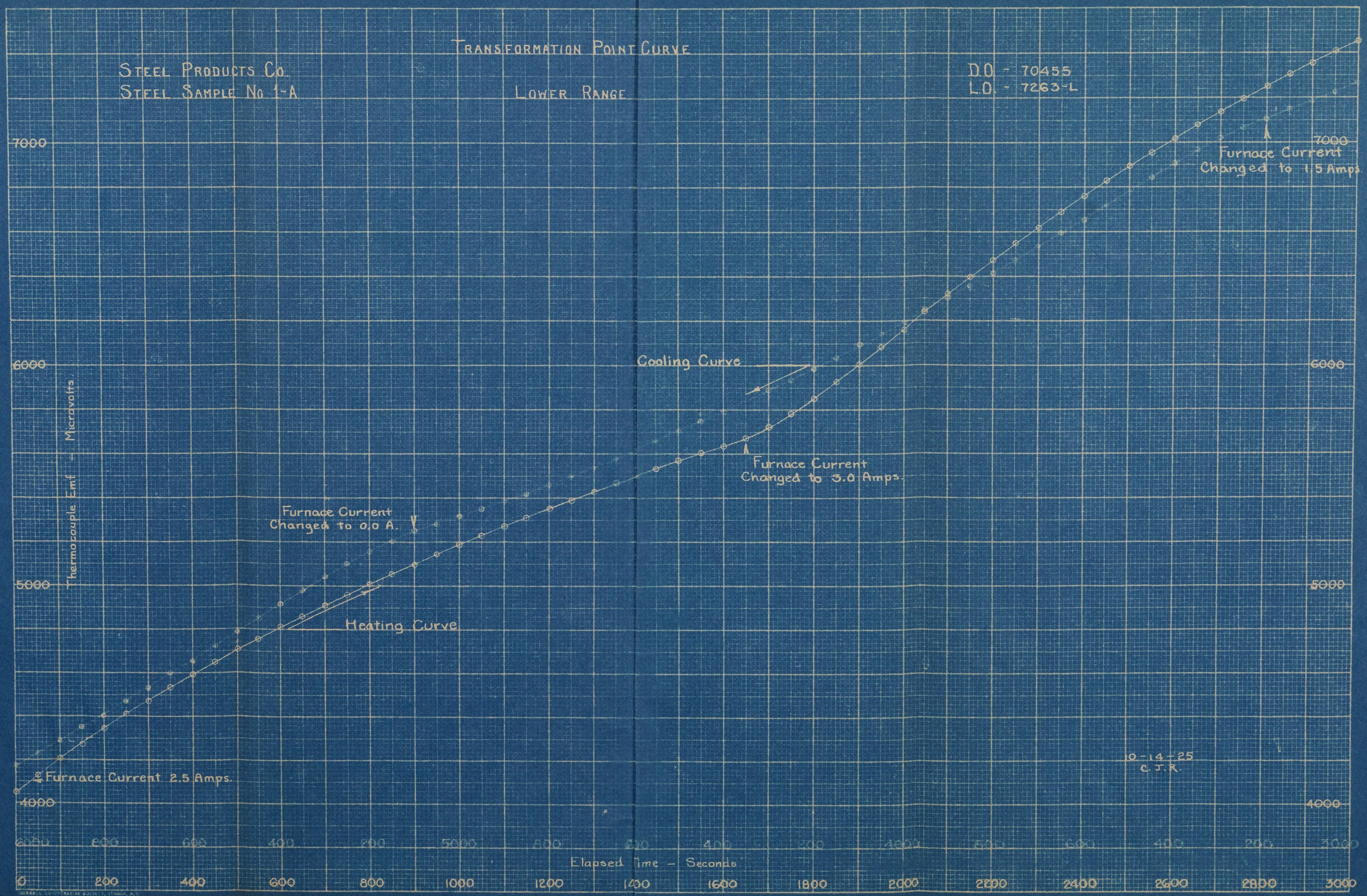
Pocket has: 5 Supples.


Transformation Point Curve
Higher Range
Steel Products Co.
Steel sample No. 1-B
D.C. 70455
L.O. 7263-L
Furnace Current
2.5 amps.
Heating Curve
Cooling Curve
Furnace Current
2.0 amps.
Furnace Current
3.5 amps.
10-14-25
C.J.R.
Thermocouple Emf. - Microvolts
Cold Junction Temp. Between 25.3 & 31.4 C
Elapsed Time - Seconds
11,000
10,000
9000
8000
10000
9000
8000
3000 2800 2600 2400 2200 2000 1800 1600 1400 1200 1000 800 600 400 200 0
3000 3200 3400 3600 3800 4000 4200 4400 4600 4800 5000 5200 5400 5600 5800 6000



Transformation Point Curve
Lower Range
Steel Products Co.
Steel Sample No. 1-B
D.O. 70455
L.O.7263-L
Furnace Current
1.5 amps.
7000
6000
5000
4000
Cooling Curve
Heating Curve
Thermocouple Emf. - Microvolts
Cold Junction Temp. Between 25°.3 & 31°.4 C
Furnace Current
Reduced to 0
Furnace Current
3.0 amps.
Furnace Current
2.5 amps.
10-14-25
C.J.R.
Elapsed Time - Seconds
6000 5800 5600 5400 5200 5000 4800 4600 4400 4200 4000 3800 3600 3400 3200 3000
0 200 400 600 800 1000 1200 1400 1600 1800 2000 2200 2400 2600 2800 3000
CORNELL CO-OPERATIVE SOCIETY, ITHACA, N.Y.


Transformation Point Curve
Higher Range
Steel Products Co.
Steel Sample No 1-A
D.O.-70455
L.O.-7263-L
Furnace Current
2.5 Amps.
Thermocouple Emf - Microvolts
11,000
10,000
9000
8000
Heating Curve
Cooling Curve
Furnace Current
Changed to 2.0 Amps.
Furnace Current
Changed to 3.5 Amps.
10-14-25
C.J.R.
Elapsed Time - Seconds



Transformation Point Curve
Steel Products Co.
Steel Sample No 1-A
Lower Range
D.O. - 70455
L.D. - 7263-L
7000
6000
5000
4000
Thermocouple Emf - Microvolts.
Furnace Current Changed to 1.5 Amps.
Cooling Curve
Furnace Current Changed to 3.0 Amps.
Furnace Current Changed to 0.0 A.
Heating Curve
Furnace Current 2.5 Amps.
10-14-25
C. J. R.
Elapsed Time - Seconds
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
3000

Table No. 12-A. July 10, 1923

THE LEEDS & NORTHRUP COMPANY

PLAT. VS. PLAT + 10% RHODIUM THERMOCOUPLE

Degrees Fahrenheit Cold Junction O°F.

Millivolts

Deg. F.	0°	100°	200°	300°	400°	500°	600°	700°	800°	900°	1000°	1100°	Deg. F.
0	0	.321	.694	1.11	1.57	2.05	2.55	3.07	3.60	4.14	4.69	5.25	0
5	.016	.339	.715	1.13	1.59	2.07	2.58	3.10	3.63	4.17	4.72	5.28	5
10	.032	.358	.736	1.16	1.62	2.10	2.60	3.12	3.65	4.19	4.75	5.31	10
15	.048	.377	.757	1.18	1.64	2.12	2.63	3.15	3.68	4.22	4.77	5.34	15
20	.064	.396	.778	1.20	1.67	2.15	2.65	3.18	3.71	4.25	4.80	5.36	20
25	.080	.414	.799	1.22	1.69	2.17	2.68	3.20	3.74	4.28	4.83	5.39	25
30	.096	.433	.820	1.25	1.71	2.20	2.71	3.23	3.76	4.31	4.86	5.42	30
35	.112	.452	.841	1.27	1.74	2.22	2.73	3.26	3.79	4.33	4.89	5.45	35
40	.128	.470	.862	1.29	1.76	2.25	2.76	3.28	3.82	4.36	4.91	5.48	40
45	.144	.489	.883	1.32	1.79	2.27	2.78	3.31	3.84	4.39	4.94	5.51	45
50	.160	.508	.904	1.34	1.81	2.30	2.81	3.34	3.87	4.41	4.97	5.54	50
55	.176	.526	.925	1.36	1.84	2.32	2.84	3.36	3.90	4.44	5.00	5.56	55
60	.192	.545	.946	1.39	1.86	2.35	2.86	3.39	3.92	4.47	5.03	5.59	60
65	.208	.563	.967	1.41	1.88	2.37	2.89	3.41	3.95	4.50	5.05	5.62	65
70	.224	.582	.988	1.43	1.91	2.40	2.91	3.44	3.98	4.52	5.08	5.65	70
75	.240	.600	1.01	1.46	1.93	2.42	2.94	3.47	4.00	4.55	5.11	5.68	75
80	.256	.619	1.03	1.48	1.95	2.45	2.97	3.49	4.03	4.58	5.14	5.71	80
85	.273	.638	1.05	1.50	1.98	2.47	2.99	3.52	4.06	4.61	5.17	5.73	85
90	.289	.657	1.07	1.52	2.00	2.50	3.02	3.55	4.09	4.63	5.19	5.76	90
95	.305	.675	1.09	1.55	2.03	2.52	3.04	3.57	4.11	4.66	5.22	5.79	95
100	.321	.694	1.11	1.57	2.05	2.55	3.07	3.60	4.14	4.69	5.25	5.82	100
M. V. per°	.0032	.0037	.0042	.0046	.0048	.0050	.0052	.0053	.0054	.0055	.0056	.0057	M. V. per°

Millivolts

Deg. F.	1200°	1300°	1400°	1500°	1600°	1700°	1800°	1900°	2000°	2100°	2200°	2300°	Deg. F.
0	5.82	6.41	7.00	7.60	8.21	8.83	9.46	10.10	10.76	11.42	12.08	12.75	0
5	5.85	6.44	7.03	7.63	8.24	8.86	9.49	10.13	10.79	11.45	12.11	12.78	5
10	5.88	6.47	7.06	7.66	8.27	8.89	9.52	10.17	10.83	11.49	12.15	12.82	10
15	5.91	6.50	7.09	7.69	8.30	8.92	9.56	10.20	10.86	11.52	12.18	12.85	15
20	5.94	6.53	7.12	7.72	8.33	8.96	9.59	10.23	10.89	11.55	12.21	12.88	20
25	5.97	6.56	7.15	7.75	8.36	8.99	9.62	10.26	10.92	11.58	12.25	12.91	25
30	6.00	6.59	7.18	7.78	8.40	9.02	9.65	10.30	10.96	11.62	12.28	12.95	30
35	6.03	6.62	7.21	7.81	8.43	9.05	9.68	10.33	10.99	11.65	12.31	12.98	35
40	6.06	6.65	7.24	7.84	8.46	9.07	9.72	10.36	11.02	11.68	12.35	13.01	40
45	6.09	6.68	7.27	7.87	8.49	9.11	9.75	10.40	11.06	11.72	12.38	13.05	45
50	6.12	6.71	7.30	7.90	8.52	9.14	9.78	10.43	11.09	11.75	12.42	13.08	50
55	6.14	6.73	7.33	7.94	8.55	9.18	9.81	10.46	11.12	11.78	12.45	13.11	55
60	6.17	6.76	7.36	7.97	8.58	9.21	9.84	10.50	11.16	11.82	12.48	13.15	60
65	6.20	6.79	7.39	8.00	8.61	9.24	9.88	10.53	11.19	11.85	12.52	13.18	65
70	6.23	6.82	7.42	8.03	8.64	9.27	9.91	10.56	11.22	11.88	12.55	13.21	70
75	6.26	6.85	7.45	8.06	8.67	9.30	9.94	10.60	11.26	11.92	12.58	13.25	75
80	6.29	6.88	7.48	8.09	8.71	9.33	9.97	10.63	11.29	11.95	12.62	13.28	80
85	6.32	6.91	7.51	8.12	8.74	9.37	10.00	10.66	11.32	11.98	12.65	13.31	85
90	6.35	6.94	7.54	8.15	8.77	9.40	10.04	10.69	11.35	12.01	12.68	13.34	90
95	6.38	6.97	7.57	8.18	8.80	9.43	10.07	10.73	11.39	12.05	12.72	13.38	95
100	6.41	7.00	7.60	8.21	8.83	9.46	10.10	10.76	11.42	12.08	12.75	13.41	100
M. V. per°	.0059	.0059	.0060	.0061	.0062	.0063	.0064	.0066	.0066	.0066	.0067	.0066	M. V. per°

Millivolts

Deg. F.	2400°	2500°	2600°	2700°	2800°	2900°	Deg. F.
0	13.41	14.08	14.76	15.43	16.10	16.77	0
5	13.44	14.11	14.79	15.46	16.13	16.80	5
10	13.48	14.15	14.83	15.50	16.17	16.84	10
15	13.51	14.18	14.86	15.53	16.20	16.87	15
20	13.54	14.22	14.89	15.56	16.23	16.90	20
25	13.58	14.25	14.93	15.60	16.27	16.93	25
30	13.61	14.28	14.96	15.63	16.30	16.97	30
35	13.64	14.32	14.99	15.66	16.33	17.00	35
40	13.68	14.36	15.03	15.70	16.37	17.03	40
45	13.71	14.39	15.06	15.73	16.40	17.07	45
50	13.75	14.42	15.10	15.77	16.44	17.10	50
55	13.78	14.45	15.13	15.80	16.47	17.13	55
60	13.81	14.49	15.16	15.83	16.50	17.17	60
65	13.85	14.52	15.20	15.87	16.54	17.20	65
70	13.88	14.56	15.23	15.90	16.57	17.23	70
75	13.91	14.59	15.26	15.93	16.60	17.27	75
80	13.95	14.62	15.30	15.97	16.64	17.30	80
85	13.98	14.66	15.33	16.00	16.67	17.33	85
90	14.01	14.69	15.36	16.03	16.70	17.36	90
95	14.05	14.73	15.40	16.07	16.74	17.40	95
100	14.08	14.76	15.43	16.10	16.77	17.43	100
M. V. per°	.0067	.0068	.0067	.0067	.0067	.0066	M. V. per°