AN ELECTRIC FURNACE FOR SPECTROSCOPIC INVESTIGATIONS, WITH RESULTS FOR THE SPECTRA OF TITANIUM AND VANADIUM [1]

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In designing an electric furnace for spectroscopic work in the laboratory of the Mount Wilson Solar Observatory, several requirements were kept in mind.

1. An apparatus which should give a long, uniformly heated column of vapor which might be brought to a temperature not very much below that of the electric arc. This need was shown by preliminary experiments which demonstrated the difficulty of producing by furnace methods the spectra of refractory substances such as titanium and vanadium, highly important in solar investigations.

2. Regulation of the furnace temperature, so that the direct effect of varying temperature might be observed, when other conditions remained unchanged.

3. The control of the conditions surrounding the luminous vapor, to observe the effect of changes in pressure and surrounding atmosphere. If spectra can be produced giving almost as many lines as the arc, the superiority of the furnace is manifest in that the effect of external influences such as pressure may be observed without an accompanying change in the action of the light-source itself, such as must take place in the arc or spark under pressure.

4. The possibility to observe absorption effects given when white light is passed through the highly heated vapor in the furnace.

The development of electric furnace work has shown that the type known as the "tube resistance furnace" is the one best adapted to all of these requirements. The temperature in such a furnace is regulated by the strength of the current passing through a tube, usually of carbon or graphite, supported horizontally and containing the substance to be vaporized. Such a tube must of course be pro-

[1] *Contributions from the Mount Wilson Solar Observatory*, No. 28.

PLATE XXIII

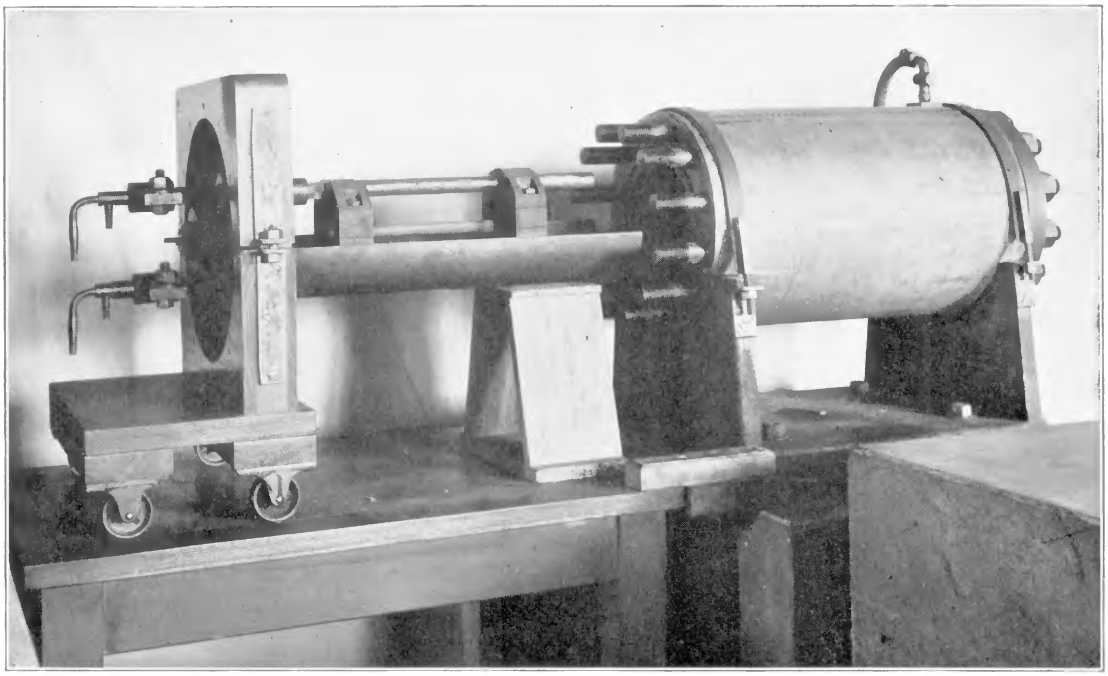

FIG. 1.—ELECTRIC FURNACE OPEN, WITH JACKETING MATERIAL REMOVED

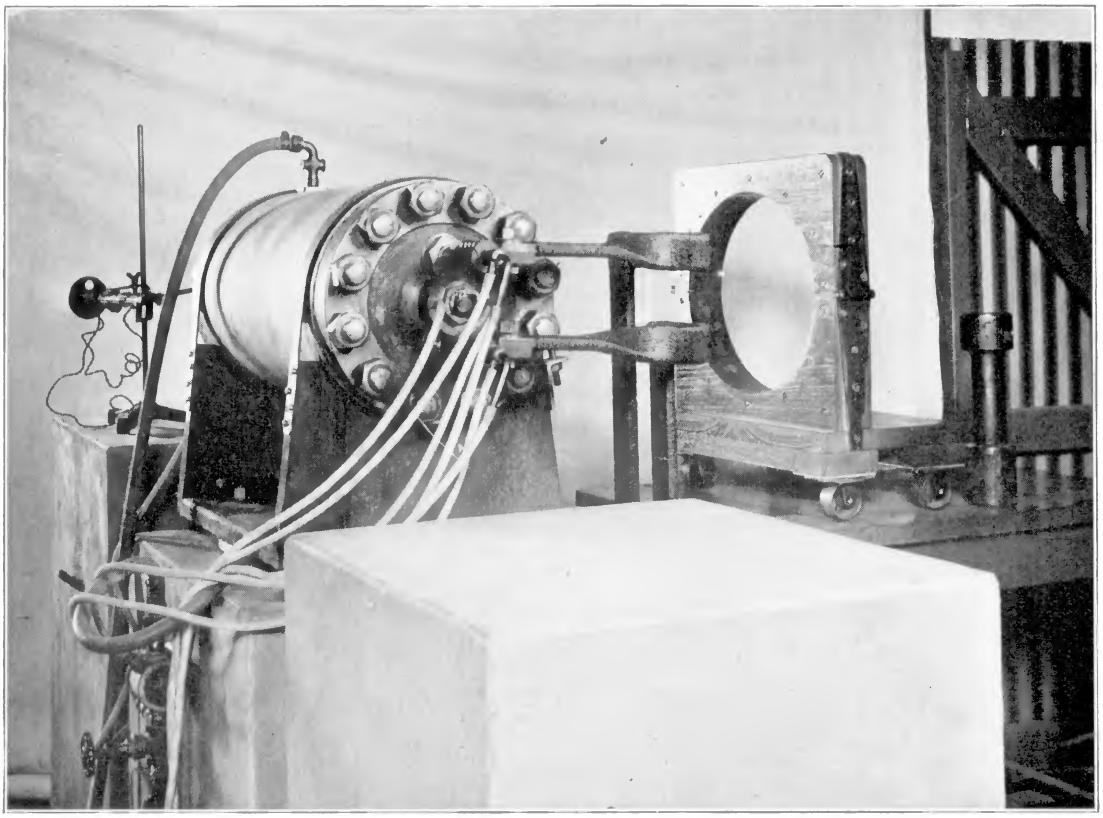

FIG. 2.—ELECTRIC FURNACE CLOSED, IN POSITION

tected from contact with the air, which would cause it to be quickly consumed. The best protection has been found to be a vacuum or a neutral gas around the tube. The inclosure in which the tube is placed for this purpose may be made strong enough to withstand any desired pressure. Such an apparatus, with a regulated current supply to the tube and windows in the walls of the chamber through which the interior of the tube could be observed, would fulfil the several purposes already outlined.

The furnace will be only briefly described in this paper, with a short account of its performance in the first investigation undertaken. The complete description, with detailed drawings, and the full discussion of the results with their bearing on astrophysical problems will be left for a later paper in the *Publications* of the Solar Observatory.

Plan of furnace.—The method adopted for the construction of the furnace was to arrange all of the essential parts in the form of a cartridge attached to one of the heads of a steel chamber, this chamber being built to stand high pressures. The arrangement is clearly shown in the photograph of the open furnace (Plate XXIII, Fig. 1). A half-cylinder of iron, screwed firmly to the head of the pressure chamber, contains two graphite blocks which serve to hold the ends of the horizontal resistance tube and also establish contact between these ends and the copper pipe electrodes which pass through the steel head and carry the electric current. These graphite blocks are each 2 inches thick, about 6 inches wide at the middle, and in three sections. The block for the lower electrode has its top cut low enough to allow the passage of the upper electrode. The blocks are provided with vertical bolts $\frac{3}{8}$ inch in diameter, which hold the sections of the block together and when tightened make firm contact between the copper electrodes and the ends of the resistance tube. Sheets of asbestos or mica under the blocks secure insulation from the iron half-cylinder.

The length of the upper electrode at present employed permits the use of resistance tubes 16 inches long, with 9 inches to be heated between the blocks. Shorter tubes may of course be used by placing the blocks closer together, as contact can be made at any point along the upper electrode. With a longer pipe above, the size of the

inclosing chamber would permit the use of a resistance tube about 22 inches long, with 18 inches heated.

The jacketing about the resistance tube for heat insulation is not shown in the photograph. It was found, as has been noted by other workers in this field, that any jacketing material placed in contact with the resistance tube will fuse to some extent and conduct part of the current. The jacketing now in use works well. A carbon tube was made by boring out a rectangular block (round would serve as well) from end to end with a hole $\frac{1}{4}$ inch larger than the resistance tube to be used. The length was $\frac{1}{2}$ inch less than that of the resistance tube between blocks, the walls no thicker than necessary to secure strength. This tube was split from end to end so that it could be placed around the resistance tube after the latter was in position, giving a free space of about $\frac{1}{8}$ inch all around the resistance tube. The space between this carbon protector and the iron half-cylinder was then filled with carborundum powder, a complete jacketing being obtained by heaping the carborundum entirely over the carbon protector, stiff sheets of mica at the sides of the iron half-cylinder enabling this to be done.

Electrodes.—The current is carried to the ends of the resistance tube by two copper pipes passing through the cylinder head in insulated bushings. Each pipe is made of two tubes, one inside the other, of $\frac{1}{2}$ inch and $\frac{3}{4}$ inch iron pipe size respectively, giving a tube of $\frac{5}{8}$ inch I. D. and $1\frac{1}{16}$ inch O. D. This pipe is plugged at the inner end and the water cooling is given by a thin-walled copper tube, supported coaxial with the electrode pipe, carrying water to one inch from the end of the latter, the water then flowing back and bathing the inner wall of the electrode. A heavy copper lug connects the copper pipe outside the cylinder head to a copper bar $\frac{1}{2}\times 2\frac{1}{2}$ inches which passes to the terminals of the cable from the transformer.

Resistance tubes.—The tubes thus far employed have been of either agglomerated carbon or Acheson graphite, in both cases of $\frac{1}{2}$ inch inside diameter and 12 inches long, $1\frac{1}{2}$ inch at each end being clamped in the graphite contact block. The carbon tubes are molded, of $\frac{15}{16}$ inch O. D. These gave good results only after the furnace had been heated two or three times, being allowed to cool and the

tube cleaned after each heat. The first heating gave off considerable water vapor, also smoke from the constituents of the binding material of the carbon tube. The latter formed a slag at the ends of the tube, almost closing them, so that nothing further could be done until the chamber was opened and the slag cleared away. A strong impurity spectrum was also given, especially of sodium and aluminum. After the second heat there was much less trouble from these sources, and a number of very satisfactory runs were made with these tubes. A further troublesome feature of the carbon tubes is the fact that after a run at a high temperature, the carbon was thoroughly graphitized, making a considerable change in the resistance of the tubes.

Acheson graphite has given better satisfaction in many respects as a material for tubes. There is no appreciable water vapor given off, no slag formed, the material remains apparently unchanged, and the disturbance from impurities in the graphite is very small. The tubes were bored out and turned to $\frac{2}{3}\frac{3}{2}$ inch O. D.

With both the carbon and graphite tubes, the ends of the tubes and also the holes in the graphite blocks for the tube and for the copper electrodes were thoroughly rubbed with powdered Acheson graphite, grade 1310, which filled the pores of the surfaces and greatly improved the contacts.

Pressure chamber.—The steel chamber to contain the cartridge described in the foregoing is shown in each of the photographs, Figs. 1 and 2, Plate XXIII. The length of the chamber without the heads is 24 inches, the internal diameter 8 inches, the walls having a ruling thickness of $1\frac{1}{2}$ inch, thickened at the ends with flanges 3 inches thick and 2 inches wide. In each of these flanges there are twelve steel bolts of $1\frac{1}{4}$ inch diameter to hold the heads. The head to which the cartridge is attached contains, besides the insulated bushings for the passage of the electrode tubes, a bronze window holder which screws into the center of the head and is provided with a high-pressure glass window in the form of a truncated cone with large end inside, the metal around the window being cooled with a special water jacket. For the work thus far, which has been done with the chamber pumped out, a piece of plate glass has been cemented on the outside of the window holder. The second head has a similar window holder and contains in addition two holes into which fit inlet

and outlet pipes for gases and the connections for the high-pressure apparatus. The chamber has been tested to stand a working pressure of 200 atmospheres.

The steel chamber requires efficient water cooling, which is provided for by riveting a cylinder of galvanized sheet iron to the end flanges, allowing the space between them to be filled with water. The water enters below at one end of the jacket and leaves above at the other end.

Current supply.—The current is taken from a 50 K. W. transformer, fed with 2000 volts and giving 5, 10, 20, and 30 volts in the secondary. No regulating resistance is used, the different voltages being used for different temperatures of the furnace, and the voltage is put directly on the furnace tube with as little loss in the connections as possible.

Operation of furnace.—The furnace chamber, whose total weight is over 600 lbs., lies in a rack of cast iron, which rests in turn on the planed ring of an iron plate imbedded in the top of a masonry pier. The rack is centered by a pivot in the bed-plate, and may thus be turned in a horizontal plane to any desired angle. To remove the cartridge from the pressure chamber, the head to which the cartridge is attached is clamped firmly in the carriage shown to the right in the photograph, Plate XXIII, Fig. 2. This is a wooden ring mounted on a base provided with casters. The carriage is then rolled back on a table prepared for it, drawing the head horizontally off the bolts and with it the cartridge. The latter when drawn clear of the chamber is supported by a wooden stand on the table. The graphite blocks, resistance tube, and jacketing material are then placed in position in the open, where all of the parts can easily be put in correct adjustment. The substance to be vaporized is placed in the resistance tube and the cartridge returned to the chamber. The furnace is then turned back into position so that the two windows and the furnace tube in line with them are pointing toward the mirror above the slit of the large Littrow spectrograph,[1] in which position the heavy copper bars from the transformer connections fit into place on the ends of the copper pipe electrodes.

When the furnace is in position, if a run in vacuum is desired, the

[1] See *Contributions from the Mount Wilson Solar Observatory*, No. 27.

air is removed by means of a Geryk pump, the water is turned on through the several jackets, and the closing of a primary switch causes the current to pass.

Optical arrangement.—As has been noted, the furnace allows the spectrum of the substance vaporized in the resistance tube to be observed to equal advantage from either end. The Littrow grating spectrograph is usually used with the lens at the 13-foot focus. The light passes through a lens to a mirror which reflects it vertically to the slit. An image of the interior of the tube is thus formed on the slit, the middle portion of the length of the tube being in the sharpest focus. The image is made about the same size as the object and the slit is chosen of such length that only the light from the center of the image passes through, the image of the white-hot walls and of any solid matter in the tube being entirely cut out.

The comparison arc for the identification of lines is placed directly back of the furnace so that its light passes through the furnace tube and gives an image slightly out of focus on the slit if the same condensing lens is used. The proper position of the lens for the furnace tube being known, the adjustment of the image of the tube on the slit may be made by means of the light from the arc, so that all is in readiness for an exposure when the furnace is turned on.

The window at the other end of the furnace may be used to photograph with a prism spectrograph on a movable table, enabling a series of short exposures to be made simultaneously with the longer exposures required by the Littrow; or it may be used to watch the condition of the spectrum by means of a direct-vision spectroscope, enabling the exposures to be begun and ended at the proper time. A third use is for temperature measurements with the Wanner pyrometer during the progress of an exposure with the Littrow spectrograph.

Temperature measurements.—A Wanner pyrometer was used to measure the temperature of the hottest part of the furnace tube. This instrument has a Reichsanstalt calibration, and judging by the good agreement of its readings with and without the dark glass, is highly reliable. The measurements so far taken have been for the purpose of showing the temperatures corresponding to a certain voltage used on the furnace when a given tube was employed. Tem-

perature measurements have not been made when a spectrum was being photographed, as the small window in the furnace head does not allow satisfactory temperature measurements to be made without a bright background such as a graphite plug placed in the central part of the tube. For this reason, special runs of the furnace were made for the pyrometer measurements, reproducing as nearly as possible the conditions under which a certain spectrum was observed. These observations have given results sufficiently concordant among themselves to give a reliable value for the approximate temperature corresponding to each voltage on the furnace. Thus with graphite tubes the following measurements were obtained:

Volts	Degrees C.	Number of Observations
5	1700–1800	4
10	2400–2500	4
20	2850–2950	2
30	3015	1

For the carbon tubes a lower series of temperatures was obtained, 1650°, 2570°, and 2770° being found from one set of readings for 10, 20, and 30 volts respectively.

These temperatures were measured for a certain length and size of tube and would of course vary if any of the dimensions were changed. They are given here merely to show the range of temperatures available in the work already done. Each set of observations was made for a different run of the furnace with a different tube, mounted in as nearly the same way as possible. The temperature was taken in each case after the current had passed long enough to bring the tube to a fairly steady condition, attained only after the jacketing material had become highly heated; and at the lower voltages some increase over the above temperatures could be obtained by prolonging the run.

It will be noted that the use of 30 volts does not give a proportional increase in temperature over 20 volts and that the highest temperature obtained with the graphite tube (which would probably have been increased only slightly, if at all, by the use of a still higher voltage) is considerably below the temperature of the positive pole of the carbon arc, measured by Waidner and Burgess[1] with the

[1] *Bulletin, Bureau of Standards*, Vol. I, pp. 109–124.

Wanner pyrometer as about 3400° C. With the carbon tubes, the graphitizing of the material, which occurred after a short run at 20 volts and thereby lowered the resistance of the tube, was doubtless in some measure responsible for this; but in the case of the graphite tubes the material appears to remain unchanged. In the light of the data thus far obtained, it seems fair to ascribe this condition to the lively vaporization of the carbon (or graphite) which begins at about 2500° C. and becomes so vigorous at 2800° C. that the life of the thin graphite tube is very short when used at 20 and 30 volts. The carbon spectrum was regularly obtained with the graphite tubes at the 10-volt temperature and became very intense at the higher voltages. We have thus conclusive evidence that the vaporizing point of carbon is much below the temperature of the hottest part of the carbon arc, making it probable that the high temperature of the positive terminal is due to a superheating caused by a bombardment of this pole by particles impelled by the electric forces present in the arc.

It has been noted that a graphite plug in the middle of the tube was used when making a pyrometer measurement, in order to provide an incandescent surface at which to direct the instrument. It should give measurements of the same accuracy if the pyrometer were directed at the inner surface of the incandescent tube, and a measurement was made to test this with the bronze window holder removed, giving an opening $1\frac{3}{4}$ inch in diameter in the steel head, which was covered by a piece of plate glass. With this aperture, the pyrometer was directed alternately at the plug and at the adjacent wall of the tube, and the readings were practically the same, showing that the measurements made with the plug in the tube were approximately correct for the wall in the middle portion. When the tube is unobstructed and filled with vapor from any substance placed in it there is of course more or less of a temperature gradient between the wall and the vapor in the center.

SPECTROSCOPIC RESULTS

A series of photographs has been made of the spectra of iron, chromium, titanium, and vanadium with the Littrow spectrograph at its 13-foot focus, using the first order of a plane grating 5 inches

TITANIUM

λ Hasselberg	Intensity Arc	Intensity Furnace	λ Hasselberg	Intensity Arc	Intensity Furnace
4256.18	5	3	4512.88	36	15
4260.91	8	6	4518.18	38	15
4263.28	17	9	4522.97	40	15
4270.30	28	6	4527.48	36	18
4274.73	34	18	4533.42	40	21
4276.55	7	6	4534.97	40	18
4281.49	7	9	4536.25	44	33
4282.85	14	12	4544.83	38	15
4285.15	8	6	4548.93	38	15
4286.15	34	12	4552.62	42	15
4287.55	28	12	4555.64	38	15
4290.07	31	12	4558.28	3	6
4291.32	28	15	4563.60	34	12
4294.28	22	9	4590.11	6	6
4295.91	28	12	4617.41	40	15
4298.82	36	18	4623.24	34	15
4302.08	38	21	4629.47	17	15
4306.07	38	21	4639.83	34	24
4308.64	34	9	4645.36	10	12
4314.95	36	18	4650.16	8	9
4318.83	13	9	4656.60	36	18
4321.82	8	6	4667.76	38	18
4325.30	8	9	4675.27	6	15
4379.40	6	18	4682.08	39	21
4384.85	36	12	4691.50	19	15
4394.04	9	3	4698.94	18	15
4395.17	36	15	4710.34	12	18
4399.92	9	3	4715.46	3	18
4404.42	26	15	4723.32	6	12
4414.29	10	12	4731.33	4	9
4417.88	15	9	4742.94	13	6
4421.92	7	12	4758.30	24	9
4423.00	8	15	4759.44	26	12
4426.24	9	15	4778.44	5	3
4427.28	38	18	4781.91	4	12
4430.19	7	9	4792.65	5	3
4434.15	14	15	4799.95	6	6
4436.75	5	6	4805.25	8	9
4440.49	9	6	4820.56	10	15
4443.97	38	12	4841.00	22	15
4449.32	36	15	4848.62	3	6
4451.07	30	12	4856.18	12	9
4453.48	38	18	4868.44	8	9
4455.48	36	15	4870.28	10	12
4457.59	40	21	4885.25	15	15
4463.70	9	12	4900.08	14	12
4465.96	20	12	4913.76	10	15
4471.40	22	15	4419.99	2	6
4475.00	8	12	4921.90	4	9
4480.72	8	3	4928.50	3	9
4481.41	35	12	4973.25	2	6
4482.84	8	9	4975.52	3	9
4489.24	19	9	4978.39	3	9
4496.33	22	18	4981.91	40	21

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PLATE XXI

South

COMET 1908 *c* (MOREHOUSE) ON SEPTEMBER 30, 1908, AT $14^h\ 22^m$ C. S. T. EXPOSURE $1^h\ 56^m$
10-Inch Lens of Bruce Telescope. Scale: 1 cm = 0°.36

PLATE XXII

South

COMET 1908 *c* (MOREHOUSE) ON OCTOBER 1, 1908, AT $13^h\ 43^m$ C. S. T. EXPOSURE $2^h\ 0^m$
10-Inch Lens of Bruce Telescope. Scale: 1cm=0°.36

TITANIUM—*Continued*

λ Hasselberg	Intensity Arc	Intensity Furnace	λ Hasselberg	Intensity Arc	Intensity Furnace
4989.33	3	9	5210.55	40	30
4991.24	40	21	5219.88	4	21
4997.26	3	15	5224.71	8	18
4999.67	40	21	5238.77	3	18
5001.16	5	12	5246.75	1	9
5007.42	38	18	5251.14	4	18
5009.81	2	15	5266.20	6	18
5013.45	5	9	5283.63	6	9
5014.40	40	21	5295.95	5	15
5016.32	14	18	5297.42	5	9
5020.17	20	18	5298.61	3	12
5023.02	18	18	5369.81	7	18
5025.00	15	15	5397.28	8	24
5036.10 }	20	12	5404.25	5	18
5036.65 }			5409.81	8	24
5038.55	16	12	5426.48	2	24
5040.12	24	15	5429.37	4	21
5043.77	2	15	5436.93	2	12
5045.58	2	18	5438.53	2	9
5053.06	2	12	5446.80	7	27
5064.82	30	21	5449.40	4	6
5087.24	3	15	5453.88	7	24
5113.64	4	15	5460.72	7	24
5120.60	7	12	5471.43	6	12
5145.62	8	15	5474.43	9	18
5147.63	7	21	5477.92	12	15
5152.36	6	21	5481.64	10	21
5173.94	34	27	5488.44	8	12
5193.15	39	27	5490.38	16	21
5194.25	2	6	5504.10	14	9
5206.30	8	21	5512.72	38	27
5208.08	8	18	5514.58	40	42

VANADIUM

λ Hasselberg	Intensity Arc	Intensity Furnace	λ Hasselberg	Intensity Arc	Intensity Furnace
4090.70	38	15	4128.25	44	18
4092.83	42	15	4132.13	43	18
4095.64	32	15	4134.61	42	18
4099.93	33	12	4143.02	9	12
4102.32	26	15	4160.57	11	15
4105.32	42	15	4180.99	26	21
4109.94	42	15	4183.59	11	12
4111.92	44	18	4191.70	14	15
4113.65	9	6	4194.17	12	15
4115.32	42	15	4209.98	15	21
4116.64	40	24	4216.52	21	15
4119.58	15	6	4232.62	16	9
4121.13	9	6	4234.12	14	15
4123.65	44	15	4235.90	8	6

VANADIUM—*Continued*

λ Hasselberg	Intensity Arc	Intensity Furnace	λ Hasselberg	Intensity Arc	Intensity Furnace
4251.45	6	9	4469.88	40	15
4257.53	5	6	4474.89	26	15
4259.46	6	15	4480.20	8	18
4265.28	5	6	4489.06	42	24
4268.78	40	15	4491.35	10	3
4271.71	40	15	4496.26	11	27
4277.12	35	9	4502.12	15	15
4283.06	4	9	4506.41	6	6
4284.19	34	12	4514.36	9	3
4286.57	5	15	4517.77	5	27
4287.97	4	15	4524.38	21	6
4291.97	23	18	4529.47	16	6
4293.25	3	9	4530.97	6	6
4296.28	19	18	4537.84	6	3
4306.35	22	27	4540.18	6	9
4307.33	20	15	4545.57	42	12
4309.95	22	27	4552.05	4	24
4330.18	42	24	4554.21	6	24
4332.98	41	21	4560.90	38	12
4341.15	43	24	4570.60	7	6
4353.02	44	27	4571.96	35	12
4356.10	13	21	4577.36	42	33
4363.48	6	15	4579.38	5	9
4368.25	19	18	4580.57	42	30
4379.38	48	39	4586.54	43	45
4384.07	42	6	4591.39	17	6
4384.87	45	33	4594.27	44	48
4390.13	47	30	4600.34	3	3
4392.24	8	18	4606.33	18	27
4395.40	44	30	4607.40	2	6
4400.74	43	24	4611.10	5	9
4405.20	30	15	4619.97	38	27
4406.80	45	24	4624.62	10	18
4407.85	44	21	4626.67	9	15
4408.36	44	33	4635.35	16	36
4412.30	18	24	4640.25	8	21
4416.63	42	27	4640.92	6	12
4420.08	19	21	4646.59	17	21
4421.73	41	27	4666.33	4	24
4423.41	10	15	4670.66	26	21
4426.17	42	39	4684.64	3	6
4428.68	40	24	4687.10	5	15
4429.95	32	33	4710.74	9	24
4434.80	11	6	4717.85	7	9
4436.31	42	27	4721.70	6	9
4438.02	40	30	4723.06	7	9
4441.88	44	30	4742.79	4	6
4444.40	42	27	4766.80	8	6
4449.77	8	15	4776.54	14	9
4452.19	40	21	4784.65	3	15
4457.65	43	42	4786.70	12	6
4459.93 }	48	36	4793.10	2	3
4460.46 }			4797.07	15	6
4462.56	41	18	4799.94	4	15

VANADIUM—*Continued*

λ Hasselberg	Intensity Arc	Intensity Furnace	λ Hasselberg	Intensity Arc	Intensity Furnace
4807.70	18	6	5128.71	5	18
4827.62	28	30	5138.58	4	9
4832.59	26	24	5139.74	3	9
4833.17	26	21	5148.95	3	21
4851.65	40	27	5159.56	3	15
4864.93	39	21	5193.18	6	21
4875.66	41	21	5195.01	7	6
4881.75	42	24	5234.31	7	6
4891.81	3	9	5402.17	12	6
4900.84	4	9	5415.51	17	6
4904.59	7	6	5418.33	3	9
4925.83	5	6	5434.43	6	18
4932.24	2	6	5437.93	2	9
5014.83	3	18	5443.50	1	30
5064.83	2	9	5488.18	17	12
5105.37	6	6	5490.22	5	18

in length with 14,438 lines to the inch. The iron spectrum has been photographed for the region from λ 3700 to λ 6700. The plates thus far taken for the other substances extend only from λ 4000 to λ 5500. Each spectrum was obtained for at least two different temperatures, an exposure being made first with a low voltage on the furnace and then another with a higher voltage, the current being broken for only a few seconds, so that the higher voltage started with the tube and jacketing highly heated from the previous run, and the second exposure was made after a much higher temperature had been established. The exposure times varied with the substance, temperature, and region of spectrum, from one minute at the highest temperatures to 30 minutes for a spectrum barely visible in the direct-vision spectroscope. Ten minutes were usually ample for any spectrum at 2500° C. or higher. The change of temperature during these exposures was not large, and could be kept nearly constant when desired by watching selected parts of the spectrum, especially the carbon flutings, in the visual spectroscope and breaking the current for a few seconds when these became too bright.

It is not the purpose of the present paper to discuss the effects of different temperatures upon spectra; so that in the foregoing tables only a comparison of the arc and furnace spectra of titanium and vanadium is given, with the object of showing the richness of the furnace spectra as compared with the arc and to give a general view

of the relative intensities of lines in the two sources, as these spectra have not heretofore been obtained, to the writer's knowledge, by non-electrical methods. These furnace spectra were among the first photographed and were obtained with carbon tubes at about 2700°–2800° C. The arc spectrum was obtained on the same kind of plate (Cramer Isochromatic) with all optical arrangements the same.

The intensities of lines for both arc and furnace spectra were measured by means of a photographic scale made with the Littrow spectrograph by illuminating the slit with a constant voltage incandescent lamp and photographing the direct reflection from the grating with exposures ranging from 1 to 40. This gave a fairly satisfactory scale as regards gradation in blackness. The change in width of the lines of the scale with exposure time was also measured and a curve plotted to show this variation. This scale was placed in a special holder on a Zeiss spectrocomparator, so that when a spectrum plate was mounted on the moving carriage any line of the spectrum could be brought into the field of the eyepiece opposite the lines of the scale, giving, except for overexposed and reversed lines, a good measure of the intensity by selecting the line of the scale having the same blackness as the spectrum line. If the spectrum line was widened, this was considered in the final estimate of its intensity. Lines of intensity greater than 40 were estimated as closely as possible by extrapolation.

After the tables for arc and furnace were prepared, all of the intensities of furnace lines were multiplied by 3, which gave the spectrum as a whole about the same strength as that of the arc and rendered the relative differences more distinct. Although this proceeding is open to objection from the photometric point of view, it serves well for the rough comparison aimed at in these tables, where the differences in intensity are usually large.

Photographs of the arc and furnace spectra are reproduced in Plates XXIV and XXV for a part of the region covered by the tables of titanium and vanadium lines. Each furnace spectrum shows the spectrum of the other element as an impurity. These photographs, considered in connection with the tables, offer material which may be discussed under the following heads:

1. The question of temperature radiation. There is nothing to

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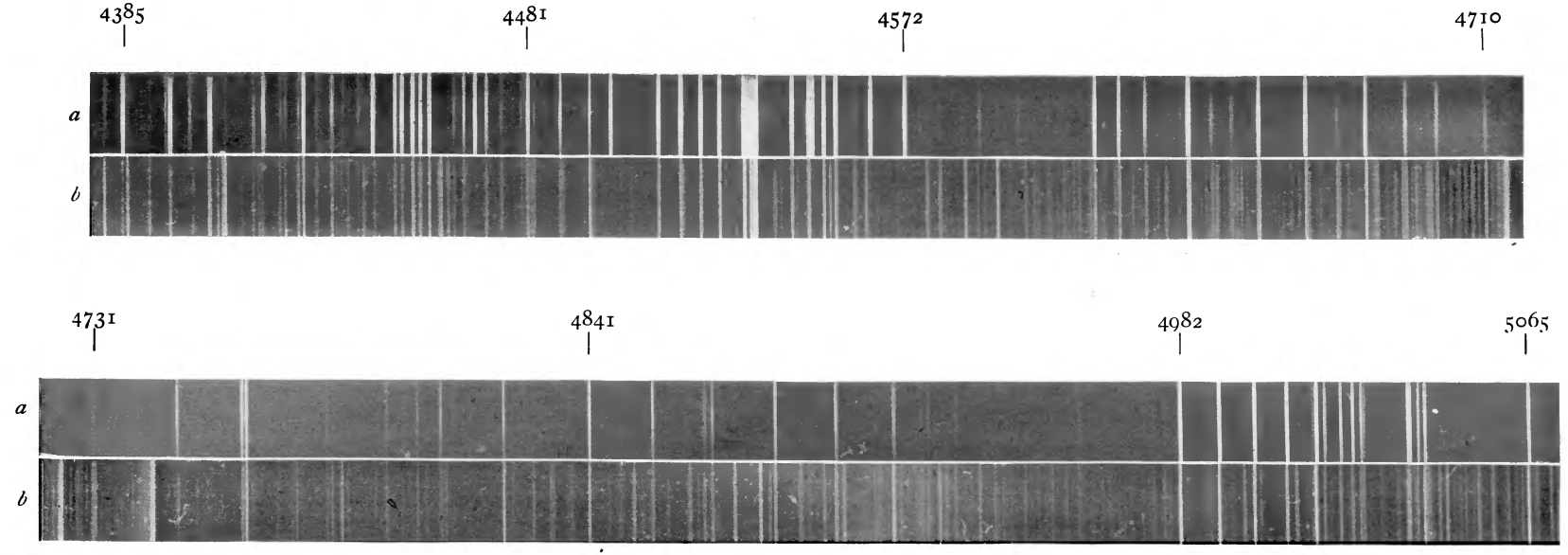
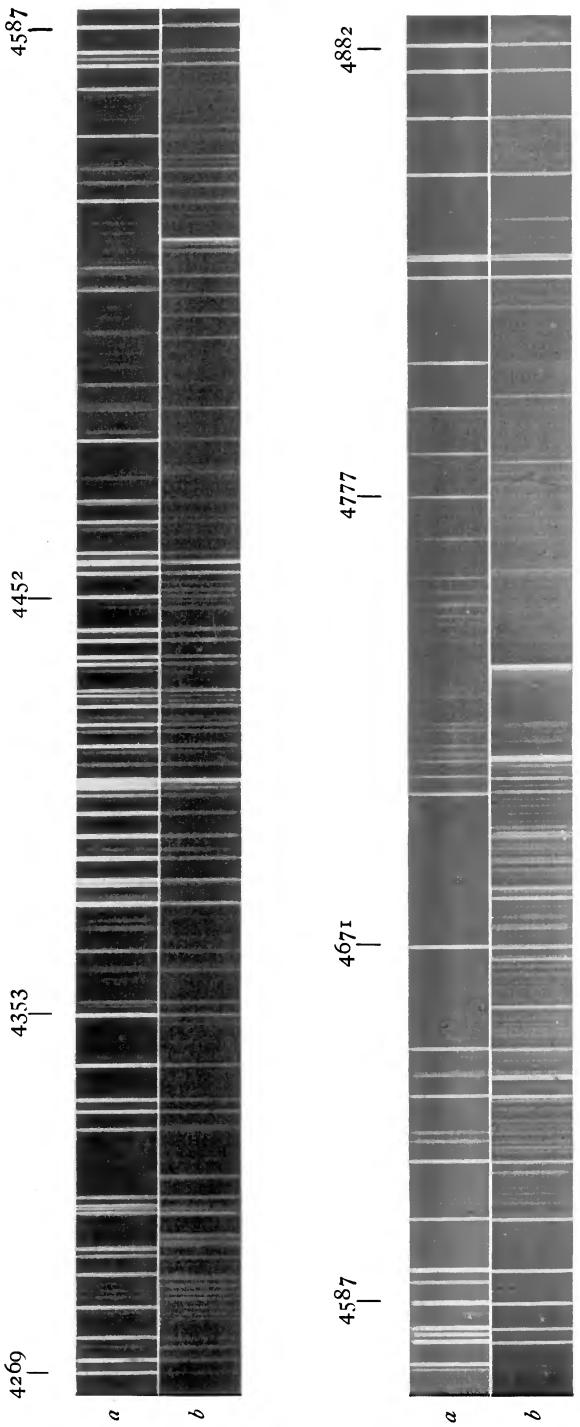
PLATE XXIV



SPECTRUM OF TITANIUM
(*a*) In Carbon Arc; (*b*) In Electric Furnace

PLATE XXV



SPECTRUM OF VANADIUM
(*a*) In Carbon Arc; (*b*) In Electric Furnace

indicate that temperature was not the sole and sufficient agent in producing these spectra. Electrical action, other than the ionization at a heated surface, was entirely excluded, no arc of any sort being present. As to chemical action, the small residue of air in the pumped-out chamber should have had its oxygen consumed long before the metal in the tube reached its vaporizing point, and if this were not the case, it is scarcely conceivable that enough could have reached the substance at the middle of the white-hot tube to give the vigorous radiation observed as long as a trace of the metal remained. To be sure, some impurities are contained in the material of the carbon tubes; but the tubes of Acheson graphite, containing extremely little foreign matter, were fully as efficient in giving the spectra of the substances placed in them. The spectroscopic evidence on this point is the fact that titanium gives a pure line spectrum, with no trace of the flutings given in the flame of the arc burning in air and generally ascribed to the oxide.

2. The number of lines given by the furnace as compared to the arc. For titanium the rather strong arc photograph gives 31 lines of intensity 3 or higher (1 indicating a line barely visible on the plate) which do not appear on the furnace plate for this region (λ 4250 to λ 5500), the furnace plate thus showing 85 per cent. of the arc lines. For vanadium, the number is relatively smaller, 73 per cent. of the arc lines being given by the furnace from λ 4100 to λ 5500. Longer exposure with the furnace would doubtless have brought out more of the weak lines, as none of the furnace lines attained maximum intensity.

3. The temperatures at which the carbon flutings appear and reach high intensity have been given. The band at λ 4737 may be seen in the reproductions of both the titanium and vanadium furnace spectra. This and the band at λ 5165 are easily obtained of considerable intensity. The cyanogen bands at λ 3883 and λ 4216 also appear, but faintly on account of the small supply of nitrogen.

4. Mention may be made here of the behavior of the "enhanced lines," those given relatively strong in the electric spark as compared to the arc. Eleven of the enhanced lines of titanium given by H. M. Reese[1] appear in the table of titanium furnace lines, and with one exception

[1] *Astrophysical Journal*, 19, 322, 1904.

are relatively much weaker in the furnace that in the arc. Five enhanced lines are among the 31 arc lines not found on the furnace plate, the two strongest in this list, $\lambda 4501.43$ and $\lambda 4572.15$, being given by Reese as enhanced in the ratio 9 to 5. A full consideration of this interesting point, together with a study of the enhanced lines of iron, will be given when tables showing the effects of different furnace temperatures upon the several spectra are published.

5. An examination of the tables for both vanadium and titanium shows that generally the lines of shorter wave-length are much stronger in the arc than in the furnace; while in the green region the furnace lines are as a rule relatively stronger. As these lists of intensities for arc and furnace were made up quite independently, the showing made when they are placed side by side is striking evidence of a shift of maximum in the spectrum due to a temperature difference in the two sources.

MOUNT WILSON SOLAR OBSERVATORY
August 20, 1908