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METAL OXIDATION IN A VACUUM TANK

Andrej Macek

Atlantic Research Corporation

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July 1973

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METAL OXIDATION IN A VACUUM TANK

Dr. Andrej Maček

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This is the Final Report on the Contract No. F30602-72-C-0426, dealing with experimental metal vapor releases in the Atlantic Research Corporation high altitude facility. The Report first summarizes the contents of an earlier report on this contract, covering the period of May 1 through November 30, 1972, and then proceeds to a detailed description of the work done from December 1, 1972 to the end of the contract (April 30, 1973).

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ABSTRACT

This is the Final Report on the Contract No. F30602-72-C-0426, dealing with experimental metal vapor releases in the Atlantic Research Corporation high-altitude facility. The Report first summarizes the contents of an earlier report on this contract, covering the period of May 1 through November 30, 1972, and then proceeds to a detailed description of the work done from December 1, 1972 to the end of the contract (April 30, 1973).

All experiments described herein were done by a technique in which the metal is vaporized from an electrically heated container made of tantalum or tungsten. This technique has now been demonstrated to be efficient for quantitative metal-release studies. Eleven releases of aluminum into air have been made with metal-vapor flow rates of the order of 50 mg/sec at heater temperatures of 2400 $\pm$ 100°K, over the high-altitude chamber pressures from 13.6 to 0.2 Torr (35 to 60km altitude). Release durations were 5 to 8 sec. All these releases generated visible luminosity, ascribed to the $^2B \rightarrow {}^2X$ AlO band spectrum. An approximate analysis of the spectral intensities indicates formation of AlO in the ground vibrational state, probably by the rapid reaction $Al + O_2 \rightarrow AlO + O$. Chemiluminescence caused by active species (O, O_3) is not indicated.

Attempts to demonstrate release of uranium were unsuccessful, because heater temperatures in these experiments remained at about 2600°K; we estimate that 100-200° higher temperatures would be needed. Previous work with a slightly different heater design demonstrated temperature capability of up to 2900°K, indicating that the technique is promising for uranium vapor release experiments.

I. INTRODUCTION

This is the Final Report on the Contract No. F30602-72-C-0426. The contract is a part of the ARPA Ivy-Owl program. The work under this contract deals with experimental releases of aluminum and uranium vapors, and interaction of these vapors with air at pressures ranging from about 20 to 0.2 Torr (30 to 60 km altitude).

All releases were made in the Atlantic Research Corporation high-altitude facility. [redacted] Briefly, two techniques were developed and utilized to release metal vapors: a chemical one in which the heat source is a pyrotechnic mixture of WO_3 and Zr, and an electrical one, powered by storage batteries. In both cases the release metal is placed inside a tungsten or tantalum container provided with an exhaust orifice and heated to temperatures at which the vapor pressure of the release metal exceeds the ambient pressure in the high-altitude facility.

Instrumentation described in Reference 1 included the following: (a) a modified Hilger-Watts spectrograph, covering the range from about 2000 to 6300Å with dispersion of 75Å/mm on film; (b) a dual-channel optical absorption apparatus, utilizing an aluminum hollow-cathode lamp as source, monitoring the 3961Å Al and the near-by 3694-3701Å Ne doublet wavelengths; (c) an optical pyrometer used to calibrate the temperature of the electrical heater prior to release experiments.

All of the work reported in Reference 1 (May 1 through November 30, 1972) was done with aluminum as the release metal at pressures ranging from 0.9 to 20 Torr. The results can be summarized as follows: (a) The chemical release technique generates temperatures in excess of the melting point of tantalum (3250°K according to Reference 2). The stoichiometric WO_3/Zr mixture therefore requires tungsten for the container material. (b) The chemical technique gives erratic release times, ranging from less than 1 sec to about 10 sec. (c) The electric technique gives reproducible vapor release rates, 25-50 mg/sec for 5-10 sec at 2150-2350°K, in approximate agreement with the calculated choked-flow rates through the container orifice. (d) If the metal is placed inside the container in powdered form, it tends to be ejected without vaporization. Wire and plate metal samples give much better results; baffling and use of high purity aluminum are desirable. (e) Release by

both techniques gives luminous jets. At about 20 Torr (air) these are very bright and narrow; at about 1 Torr they are wider and less intense. (f) Emission spectrograms, integrated over the release times, show mostly the blue $B^2\Sigma \rightarrow X^2\Sigma$ AlO band system, with strongest heads at 4842, 4866 and 5079Å, and Al lines at 3961 and 3944Å. Chemical release spectrograms also show some continuum emission, probably caused by ejection of incandescent particles. (g) Attempts at measurement of Al vapor densities by selective absorption of the 3961Å line were largely unsuccessful, because of emission. One release experiment, carried out by the electrical technique at the relatively low pressure of 2.5 Torr, did show selective absorption for a short time (ca. 1 sec) prior to full development of the luminous jet, indicating Al vapor densities exceeding about 10^{12}/cc.

In view of the fact that the electrical vaporization technique allows much better definition of the experiment, the chemical technique was not pursued during the last five months of the program; all the work was done with the electrical technique. The present report contains a description of the progress during the period of Dec. 1, 1972 through April 30, 1973. Section II deals with the instrumentation improvement [redacted]. Section III presents the experimental results. Section IV states major conclusions and recommendations.

II. INSTRUMENTATION

1. The Bausch & Lamb Spectrograph

A large portion of the quantitative data obtained in the work reported here was recorded by a 1.5-meter B & L spectrograph giving spectral dispersion of 10Å/mm from 4430 to about 6200Å. The spectral range thus does not include any of the prominent Al vapor lines, but it includes all the bands of the AlO "blue" spectrum having appreciable Franck-Condon factors (larger than about 0.05--see Reference 3). The spectrograph was used with a 30μm slit and 35mm TRI-X film.

In several runs at pressures of 0.8 Torr and higher the spectrograph was used to record emission from aluminum releases into air. In a few runs at the lowest pressure (ca. 0.2 Torr) it was used in absorption. The background radiator was a tungsten source at 3200-3400°K.

2. Absorption Apparatus

In addition to the Al monitoring source (see Section I), a uranium hollow-cathode source has been installed. Scanning of the U-source spectrum showed that the most convenient wavelengths to monitor by the two-channel system are the 5915Å U line and the adjacent 5944Å Ne line; the 5881Å Ne line is another possibility. This system has not been used in actual release experiments, because the release temperatures were always too low for any substantial vaporization rates of uranium (see Sections II-4 and III).

3. Optical Pyrometer

The optical pyrometer, which was used previously to calibrate the temperature of the electric vaporizer prior to release runs, has been installed inside the high-altitude facility. The pyrometer, viewing the inside of the heater cavity (lined with tantalum or tungsten) through the vaporizer orifice, has now been used during actual releases. Thus we have continuous temperature vs time records of all the runs described in Section III of this report. The pyrometer operates on a narrow wavelength band around 0.9μm, thus avoiding atmospheric absorption (H_2O, CO_2), as well as all active regions of Al and AlO spectra.

4. Electric Heater and Vaporization Temperatures

[redacted] the resistance heater is a graphite sleeve containing a tungsten-lined cavity, heated by a current from batteries. The current is about 1000 amps at about 10 volt. The temperature attained inside the heater cavity, measured by the optical pyrometer, has been varied by addition of external resistance in the form of copper leads (8.11×10^{-5} ohm/ft). The temperature, and the rate of temperature rise (dT/dt), depends also very strongly on the thickness of the graphite wall. The following relationship has been found for the graphite heater design used in the experiments detailed in Section III:

Length of added resistance (ft)	0	8	10	20
Maximum temperature (°K)	2620	2360	2300	2110

The maximum temperature in any given run may vary somewhat depending on details of electrical contact with graphite (see Section III-2).

Theoretical vapor pressure and choked-flow rate out of the heater cavity for aluminum are shown in Figure 1, and the vapor pressure of uranium in Figure 2. Comparison of these vapor pressure data with the temperature data listed in the preceding paragraph shows that the particular heater design used in our experiments is more than adequate for rapid vaporization of aluminum at all pressures of interest. On the other hand, as described in Section III-3, this design failed to give temperatures required for substantial vaporization of uranium. The difficulty is not a fundamental one: we had demonstrated previously, with a slightly different heater design, that temperatures up to 2900°K can be attained by this method. Time limitation during this project did not allow construction of another heater unit for uranium release. Subsequently, under internal Atlantic Research Corporation sponsorship, uranium was vaporized by this technique and the released vapor density measured by optical absorption (Reference 4).

III. EXPERIMENTAL ARRANGEMENT AND RESULTS

1. The Experiment

Although the diagnostic instrumentation was varied somewhat from run to run, the basic experimental arrangement remained the same for all the tests reported here: The resistance heater was placed at a location along the main axis of the cylindrical high-altitude tunnel, the vaporizer orifice facing downstream (toward the vacuum pumping system). Since the tunnel is 180cm in diameter, the nearest wall was 90cm from the vaporizer orifice. The orifice, 0.6cm in diameter, thus was essentially a point source. The graphite heater was surrounded by one or more radiation shields made of tantalum foil. Visual observation and photographic and spectrographic coverage were made from the outside of the tunnel through viewing ports at the right angle to the main axis of the experiment. The sensor of the optical pyrometer, viewing the release orifice, was placed inside the tunnel, along the axis, 90cm downstream of the orifice.

During the runs the tunnel was purged with a laminar stream of air from a porous-plug diffuser located at the upstream end of the tunnel, 4.5 m from the point of release. The mass-flow of air was always about 1gm/sec, giving a linear velocity of about 20cm/sec at 1 Torr, and inversely proportional to the pressure in the tunnel. In addition, in all runs above 1 Torr the graphite heater was protected from oxidation by a much more rapid stream of nitrogen (ca. 300cm/sec at 10 Torr), delivered through a 15-cm diameter pipe placed immediately upstream of the heater. Thus, in the runs in which nitrogen was used there were complex

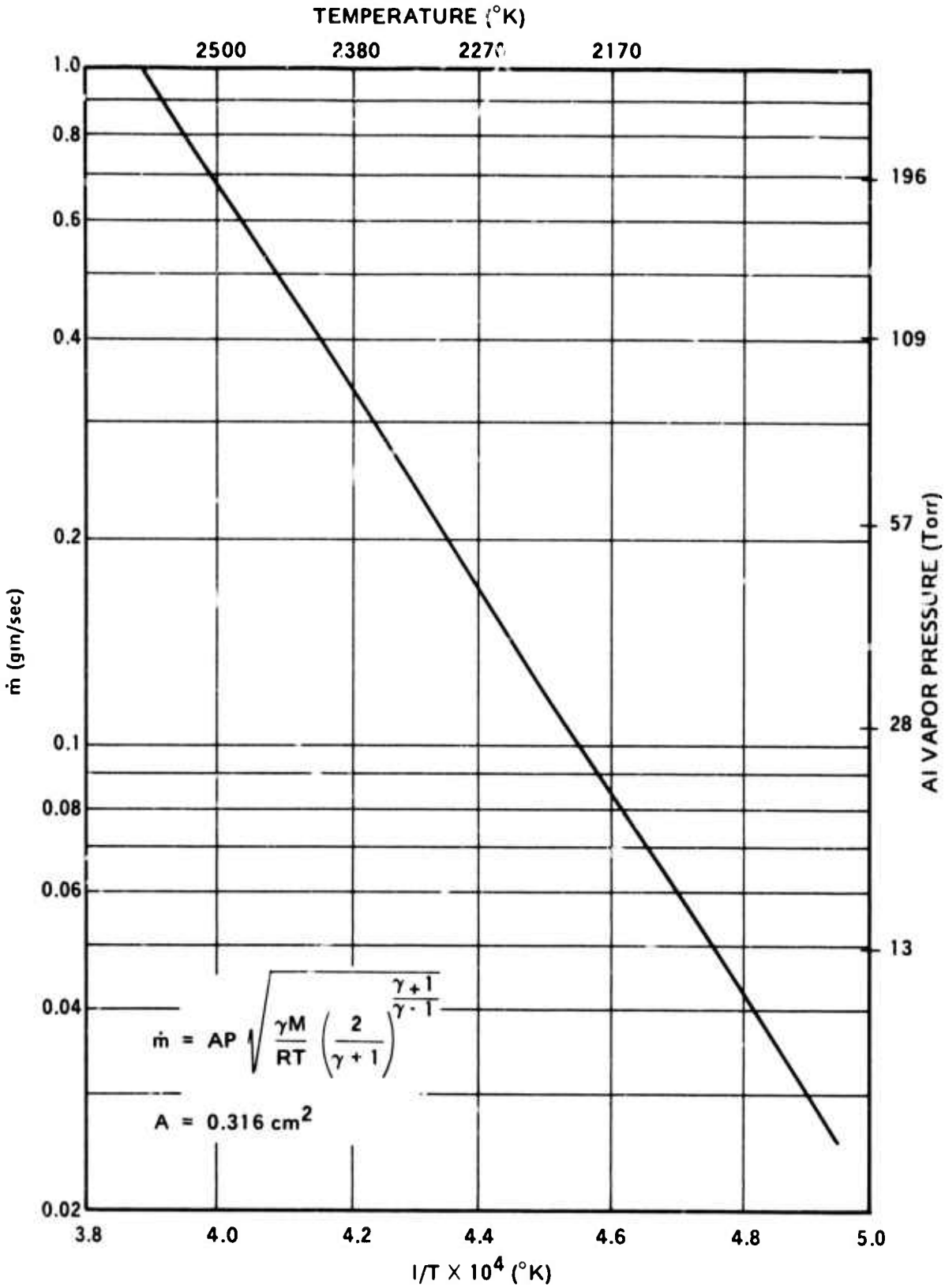

Figure 1. Release Rate and Vapor Pressure of Aluminum.

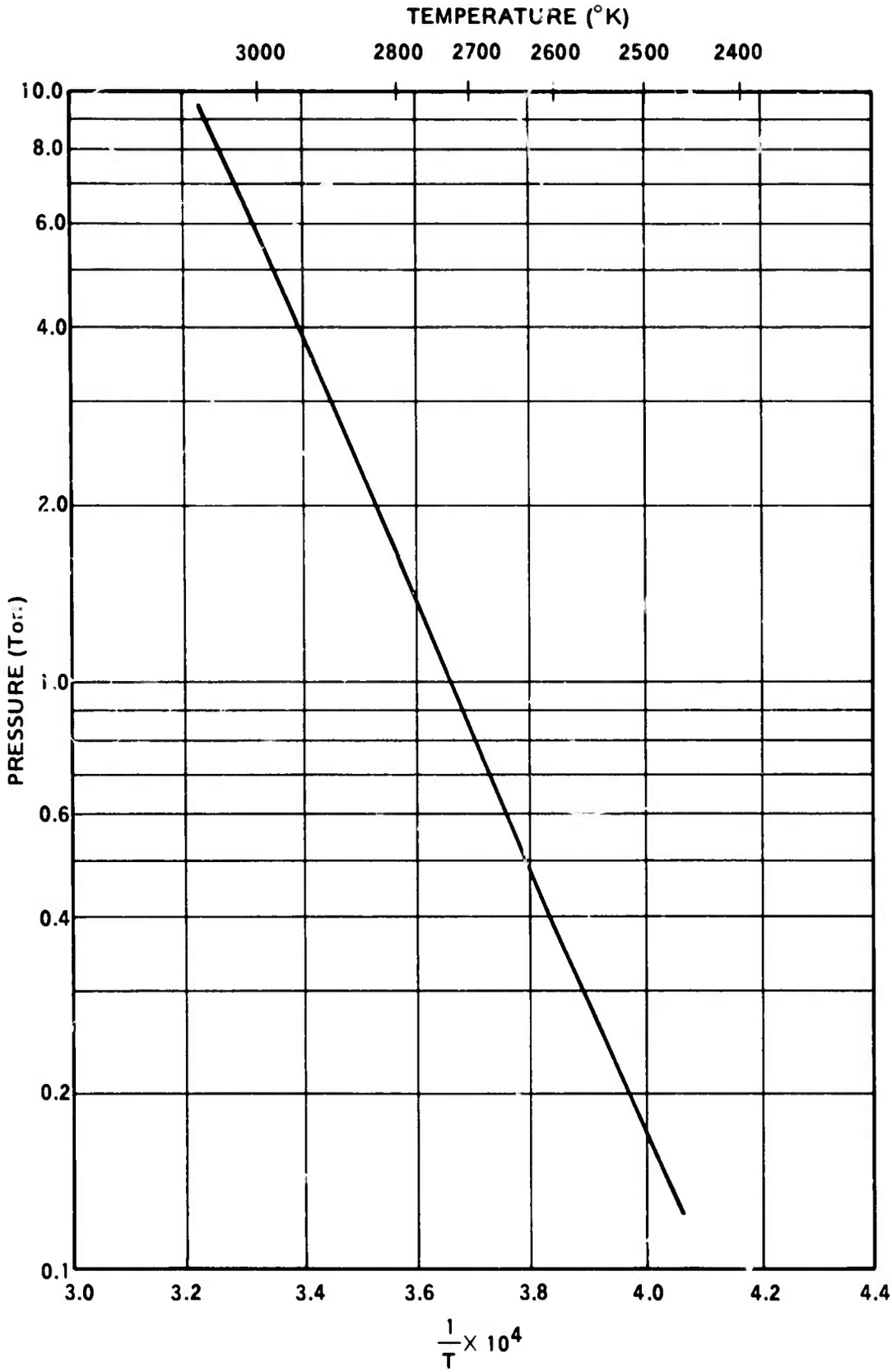

Figure 2. Vapor Pressure of Uranium.

interdiffusion zones of air, nitrogen, and release vapor. However, no effort, either experimental or theoretical, has been made in this program toward detailed spatial resolution of the flowfield parameters.

The key data of the 21 tests are summarized in Table I. The first two columns need no explanation, and the third column (cable length) is discussed in Section II-4. Other experimental parameters and results given in the table will now be discussed under appropriate headings.

2. Pyrometer Traces

Data in columns 4 and 5 of Table I, pertaining to the temperature history of the vaporizer cavity, were taken directly from experimental pyrometer traces. Two representative samples, from runs 3 and 7, are reproduced in Figure 3. Entries denoted t (sec), listed in the fourth column, are intended to give an idea of the time spent at temperatures where the vapor pressure of aluminum becomes appreciable. The definition of t is entirely arbitrary, and has been chosen for the sake of easy reading of the traces: it is the time from the instant at which the pyrometer output has reached half of its peak value to the instant at which the heating current is turned off (onset of rapid temperature decay). Since temperature is a logarithmic function of the pyrometer output, v(millivolt) = $A\exp(-B/T)$, its value at the beginning of the period t has risen to roughly 90% of the interval between the room temperature and the peak temperature. The temperature vs. time curve usually has a positive, although rapidly decreasing, dT/dt value all the way to the point where the heater is turned off, so the final temperature is usually the peak temperature. Upon occasion, a plateau is reached with temperatures fluctuating slightly ($\pm$ 10°) for a period of time; run 7 is an example. In either case, temperatures were virtually constant during the last 5-10sec of all but a few short runs, the dT/dt values (positive or negative) being only a few degrees per second during that period. Metal vapors were released mostly during this late constant-temperature period.

In view of the fact that in the release runs the pyrometer sensor views the vaporizer cavity through the release cloud, one may question the effect of the released material on the response of the pyrometer. The data in Table I give some pertinent information, because quite a few runs in the table are in effect blank runs without observable metal release: in runs 1, 8, 9, 10 and 11 the

Table I. Summary of Release Experiments.

Run Number	Pressure (Torr)	Cable Length (feet)	Pyrometer Readout		Load	Records[a] Obtained	Comments
			t (sec)	Temperature (°K)			
1	11.5	20	34	1980 - 2110	0.25 gm. Al	MC	Temperature too low for Al release
2	11.9	10	19	2100 - 2300	0.25 gm. Al	MC	Strong luminous jet; spectrum slit 15 cm. downstream of orifice; luminosity at that point too weak to be recorded.
3	13.6	8	21	2110 - 2330	0.25 gm. Al	MC	Strong luminous jet; spectrum slit 15 cm. downstream of orifice. luminosity at that point too weak to be recorded. (See Figure 3 for pyrometer record.)
4	0.82	8	19	2140 - 2350	0.25 gm. Al	MC, SE	Wider, more diffuse luminosity; weak spectrum (15 cm. downstream).
5	12.2	8	19	2140 - 2360	0.25 gm. Al	MC	Strong luminous jet; spectrum slit 15 cm. downstream of orifice; luminosity at that point too weak to be recorded.
6	11.8	0	7	2240 - 2460	0.25 gm. Al	MC, SE	Slit 6.5 cm. downstream; strong spectrum; temperature maintained at 2450 ± 10° for 4 seconds.
7	0.60	0	19.5	2290 - 2520	None	MC	Blank (cleanout) run; see Figure 3 for pyrometer record. Temperature maintained at 2490 ± 10° for 11.5 seconds.
8	0.20	0	14	2250 - 2480	1 gm. U	None	Temperature too low for U release.
9	0.20	0	31	2350 - 2580	1 gm. U	None	Temperature too low for U release.
10	0.20	0	19	2250 - 2480	1 gm. U	None	Temperature too low for U release.
11	0.20	0	10	2250 - 2480	1 gm. U	None	Temperature too low for U release.
12	0.20	0	Instrument failure		0.25 gm. Al	MC	Very diffuse, wide blue glow. Judged too weak to be recorded in emission.
13	0.20	0	10	2090 - 2370	0.25 gm. Al	MC	Very diffuse, wide blue glow. Judged too weak to be recorded in emission.
14	0.20	0	8	2000 - 2290	0.25 gm. Al	MC	Short run. Temperature probably substantially below maximum attainable.
15	0.19	0	10	2170 - 2380	0.4 gm. Al	SA	Slit 5 cm. downstream of orifice. Very weak 4842 Å bandhead in absorption.
16	0.20	0	4.5	2170 - 2380	None	None	Blank run to check out heater. Total heating time: 15 seconds.
17	0.20	0	11	2240 - 2490	None	None	Blank run to check out heater. Total heating time: 25 seconds.
18	0.20	0	20	2330 - 2550	None	None	Blank run to check out heater. Total heating time: 30 seconds.
19	0.20	0	21	2380 - 2620	0.4 gm. Al	SA	Electric contacts adjusted. Note temperature improvement. Same release appearance as in Runs 12 through 15. Spectrum slit 5 cm. downstream.
20	0.19	0	12	2340 - 2560	0.4 gm. Al	None	Release appearance as in Runs 12 through 15 and Run 19.
21	0.19	0	12	2330 - 2550	None	None	Blank run made to observe heater performance. Gradual deterioration since readjustment (Runs 19 to 21).

[a]MC — Movie camera record
SE — Emission spectrogram
SA — Absorptinn spectrogram

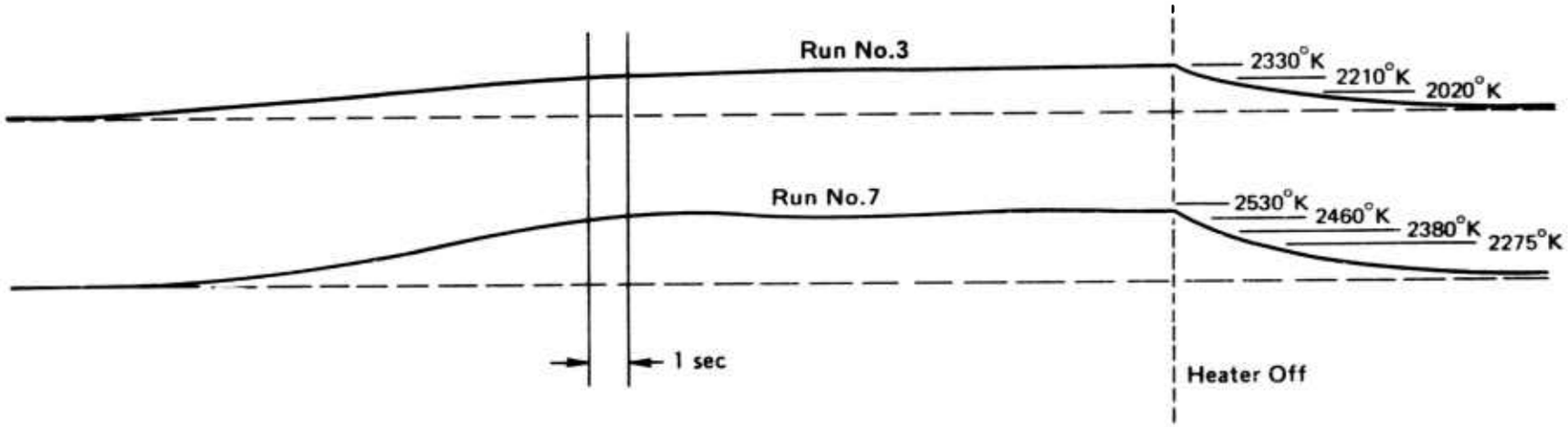

Figure 3. Pyrometer Trace of the Resistance Heater

temperature was too low, and runs 7, 16, 17, 18 and 21 were made with the express purpose of either cleaning out the vaporizer prior to subsequent releases, or checking the heater performance. Only runs with the same resistance-cable length and of the same duration can be used for a comparison of temperatures attained with and without metal vaporization. The few runs which qualify on that basis do indicate a difference: temperatures attained in runs 11 and 17, in which there was no release, are about 100° higher than in comparable runs 13 and 15 with metal release. Two comments may be made here. First, 100°, while easily measurable, is not a large temperature difference. Second, even that difference is not necessarily the result of absorption by the release cloud, because the true temperature of the vaporizer must be expected to be lowered somewhat in the presence of the highly endothermic vaporization process. We conclude that the effect of the release on temperature measurement is not significant. This appears reasonable in view of the fact, mentioned in Section II-3, that the operating wavelength of the pyrometer avoids active regions of the spectrum.

Finally, it must be pointed out that the quality of electrical connections in the heater circuit has more effect on temperature than the process of vaporization. This is illustrated by a comparison of runs 18 and 19.

3. Vaporization Rates

The total amount of aluminum in any one release was either 0.25 or 0.40g (see column 6 of Table I). Typically, this amount was released in 5 to 8 sec, i.e., at an average rate of the order of 50mg/sec at an average temperature of about 2300°K. Theoretically, one would expect release rates of this magnitude at about 2100-2150°K--see Figure 1 and Reference 1. Thus it appears that measured temperatures up to 200° higher than theoretical are needed for release of aluminum. This conclusion is also supported by the result of run 1, Table I. The probable reason for this difference is that the surface temperature of liquid aluminum, which is being rapidly vaporized, is lower than the measured temperature of the cavity walls.

At the present time there is still some uncertainty as to the vapor pressure of uranium. Adopting the recommendation of Reference 5 (see Figure 2), the temperature required for a vapor pressure of 0.2 Torr (high-altitude chamber pressure in runs 8-11) is somewhat in excess of 2500°K. Arguing by analogy with the aluminum-release results, one would expect that temperatures of 2700-2800°K

may be needed for rapid (choked-flow) release of uranium. Thus the netative results in runs 8 through 11 are understandable.

4. Motion Pictures and Visual Observation

In the aluminum-release runs, both the visual observation and the motion pictures (Kodachrome film, 32 frames/sec) show a blue jet emerging from the heater orifice at all pressures. At pressures of the order of 10 Torr the jets are 10 to 20 cm long and always very bright to the eye. The jet expands very rapidly (within about 1cm of travel) from the orifice diameter (0.6cm) to a width of 2-3 cm; further expansion is very slight. As the pressure is decreased, the expansion angle increases, the brightness decreases, and the length of the plume increases (note that the linear velocity of the free-stream air increases with decreasing pressure). At 0.2 Torr the plume expands so that it almost fills the high-altitude tunnel, and the luminosity is so weak that it can be barely recorded by the movie camera.

5. Emission Spectrograms

The Bausch & Lomb instrument was set up to record emission from runs 2-6. The shutter of the instrument, operated manually, was kept open throughout the duration of the visible jet (5-8 sec). In runs 2, 3, 4 and 5 the slit was focused on a spot 15cm directly downstream of the orifice. These four runs were made at relatively low temperatures (see column 5 of Table I). The strongly luminous portion of the jet in the high-pressure runs 2, 3 and 5 extended only 10-12cm downstream of the orifice, so no readable spectrograms were obtained. In run 4, at 0.82 Torr, the luminosity extended farther downstream; a spectrogram sufficiently strong to show about a dozen of the strongest AlO bands was obtained. In run 6 the heater temperature was increased and the spectrograph slit moved upstream to 6.5cm from the orifice. The run yielded a strong spectrogram, showing a wealth of AlO bands, many of them with resolved rotational lines.

The spectrogram of run 6 is shown in Figure 4. Except for the Na doublet at 5890-5896Å, all the features clearly belong to the $B^2\Sigma \rightarrow X^2\Sigma$ system of AlO bands. Wavelengths and relative peak plate densities of the bandheads are given in Table II, the density being shown below each respective wavelength. These densities were obtained by a calibrated densitometer and are corrected for the

Figure 4. Spectrogram of Run 6. Wavelengths in Angstroms.

Table II. Wavelengths (Å) and Peak Bandhead Plate Densities, Run 6.

V' \ V''	0	1	2	3	4	5	6	7	8
0	4842 100	5079 19	5337 1.5	5615 0					
1	4648 17	4866 24	5102 17	5358 2	5635 0				
2	4471 3	4672 13	4888 5	5123 12	5377 2	5652 0			
3		4494 5	4695 10	4911 2	5143 9	5395 1.5	5666 0		
4			4516 5	4716 4		5161 4	5410 1.5		
5				4537 3	4735 4		5177 2	5424 1	
6					4557 2	4754 2		5192 2	
7						4576 1	4772 1		5206 0.5
8							4594 0.5		
9								4610 0.2	

spectral response of the TRI-X film; however, there is no density vs. intensity calibration, so the actual bandhead intensities correspond only roughly to the density values in the table. Densities of the entire $\Delta v = -3$ sequence are so weak--order of 0.1 or less--that they are entered as zero. Table III gives the analogous wavelength and intensity information for the much weaker run 4 spectrogram.

In both Table II and Table III there are several complete v" progressions. Thus in principle one can determine vibrational temperatures from the relationship

$$\log \sum_{v''} I(v', v'')\, \lambda^4 = -\frac{G'(v')hc}{kT} + \text{const.}$$

where I are band intensities and G' the upper-level term values (Reference 6). Using the Table II and III density values for I(v',v") in the appropriate plots, we get T = 5300°K and 2300°K for runs 6 and 4 respectively. In view of the facts that (a) there is no intensity calibration and (b) the tabulated densities are peak values rather than integrated intensities, one should not take the numerical temperature values very seriously. (One may argue that the 2300°K value is more reliable of the two, because in the weakly exposed run 4 the intensity is apt to be more closely proportional to density). However, the plots clearly suggest normal Boltzmann distributions, with temperatures of the order of magnitude expected in flames. The (0,0) band is the strongest, and other intensities are distributed along a Condon parabola having a normal appearance. The absence of transitions with large v numbers indicates that the observed luminosity is not chemiluminescence generated by energetic species (e.g., O_3 in binary or oxygen atoms in ternary collisions); rather, AlO is formed in the ground vibrational state, most probably by the very nearly isoenergetic reaction,

$$Al + O_2 \rightarrow AlO + O, \qquad (1)$$

which is known to be very rapid --(see Reference 7).
Thus, our results are in sharp contrast to the recently reported AlO spectral data of Gole and Zare (Reference 8), obtained from the reaction

$$Al + O_3 \rightarrow AlO^* + O_2. \qquad (2)$$

Table III. Wavelengths (Å) and Peak Bandhead Plate Densities, Run 4.

V' \ V"	0	1	2	3	4
0	4842 100	5079 9			
1	4648 9	4866 24	5102 8		
2		4672 9		5123 4	
3		4494 4	4695 6		5143 3

Gole and Zare find a whole series of B → X bands to be stronger than the (0,0) band, the strongest among them corresponding to v' = 14 ± 2; indeed, the B state was found to be vibrationally inverted.

Once AlO molecules are formed, the origin of the subsequent electronic excitation in our release experiments is not clear. The most reasonable explanation is that the entire release plume--consisting of nitrogen, aluminum-containing species, and excess oxygen--is heated to flame temperatures by the large amount of energy released in the sequence of chemical reactions leading from AlO to condensed Al_2O_3 (whatever that sequence may be). The luminous plume then would extend to the point in our flow experiments where AlO concentration becomes depleted, and/or where temperature drops due to dissipation processes. It is pertinent to point out here that the rate of formation of AlO by Reaction 1 equals approximately the rate of Al vapor release through the orifice, so the concentrations of AlO in the upstream regions of the plume must be quite large.

Alternative (non-thermal) explanations of the origin of plume luminosity are not appealing. If atomic oxygen formed by Reaction 1 were a key species, it could conceivably act in three ways. First, if it formed substantial amounts of ozone (doubtful), it could generate chemiluminescence by way of Reaction 2. However, as discussed above, the band-intensity distribution then would be drastically different from the observed one. Second, it could act directly by the ternary association reaction

$$Al + O + M \rightarrow AlO^* + M \qquad (3)$$

If so, the large energy release (in excess of 5eV) would no doubt again lead to abnormal band-intensity distribution, with quantum numbers at least as high as in the case of ozone. Third, it could act by the mechanism proposed to explain luminosity in high-altitude releases (Reference 9):

$$AlO + O + (M) \rightarrow AlO_2^* + (M) + h\nu \qquad (4)$$

However, in this case one would expect to see a chemiluminescent continuum peaking around 5000Å -- indeed, Reaction 4 was postulated precisely to account for

observed continua in that range of wavelengths. Our emission spectra show only a weak continuum, increasing in intensity toward the red. This again is consistent with the thermal hypothesis, the condensed Al_2O_3 particles being the most obvious source of emission. Finally, resonance-scattering of the light from the heater as the source of AlO luminosity also does not appear likely, because the orifice leading into the light source is very small (0.6cm in diameter), while the luminous clouds in low-pressure experiments are quite wide.

6. Absorption Spectrograms

In runs 12, 15 and 19 (see Table I) the Bausch & Lomb spectrograph was set up to view a tungsten light source -- 3300 $\pm$ 100°K true temperature, corresponding to 2700 $\pm$ 80°K brightness temperature at the source -- through the aluminum release cloud 5cm downstream of the orifice. A short (1/100 or 1/200 sec) single exposure was made in each run at about the peak of the release experiment. The only feature of the spectrograms, other than the tungsten continuum, are weak (0,0) AlO bands in absorption in runs 15 and 19 (in run 12 the film was overexposed). Assuming LTE and a light intensity degradation between the source and the plume amounting to about 20% (one lens and one window), we place the upper limit of the plume temperature at 2500-2600°K.

IV. CONCLUSIONS

The electric resistance technique has been demonstrated to be an efficient method for quantitative metal-release studies. Reproducible aluminum release rates of the order of 50mg/sec at heater temperatures of 2400 $\pm$ 100°K have been obtained in the high-altitude chamber at pressures of the order of 10 Torr or less. The technique appears applicable to substantially less volatile metals. For example, estimates based on the measured performance of the heater indicate that at the heater temperature of 2900°K the vaporization rate of uranium into an ambient atmosphere of 0.2 Torr or less would be of the order of 5mg/sec. Thus, releases of uranium and of metals having similar volatilities promise to yield important information on interaction of metal vapors with gaseous oxidants.

Release of aluminum vapor into air generated visible luminosity, ascribed to the $^2B \rightarrow {}^2X$ AlO band spectrum, at all pressures from 13.6 to 0.2 Torr. An approximate analysis of the spectral intensities indicates formation of AlO in

the ground vibrational state; it also indicates that the release plume is at a temperature of the order of magnitude encountered in flames. More accurate spectroscopic work should be performed with the purpose of obtaining quantitative rotational and vibrational temperatures.

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