A Study of Mercury Vapour Concentrations at the UBC/Laval 2.7-metre Liquid-Mirror Observatory

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SUMMARY

This report presents results of mercury vapour measurements at the UBC/Laval 2.7-m liquid-mirror observatory. An analysis is made of the physical processes which govern the mercury vapour concentrations during various phases of operation of the telescope. The principal results are the following:

- vapour concentrations inside the observatory depend strongly on the degree of ventilation. Even a small amount of ventilation, is effective at reducing the vapours to acceptable levels.
- during normal operation of the observatory, in which the roof is open, vapour concentrations are below 0.1 mg/m^3 for all but the first hour after implacement of the mercury on the mirror.
- The mercury is stabilized by a thin surface layer of oxide which forms naturally on a time-scale of a few hours. This surface layer reduces evaporation of the mercury by more than five orders of magnitude
- After the oxide layer is established, vapour concentrations within the observatory are inversely proportional to the ventilation fan capacity. For the NASA 3-m observatory, concentrations are expected to fall below 0.05 mg/m^3 within about 3 hrs, when the 1000 cfm fan is operating.
- During startup and the first few hours of operation of the mirror, vapour levels in the observatory can be minimized by *preventing* ventilation. High vapour concentrations are thereby restricted to a thin layer of air above the mirror resulting in a low evaporation rate.

1. INTRODUCTION

Telescopes employing large rotating liquid-metal mirrors (LMTs) have the potential to revolutionize many areas of observational astronomy, and upper atmospheric and space research. Mirrors of up to 3 m aperture, employing a reflecting surface of liquid mercury, have now been successfully operated[1,2,3]. Such mirrors provide large light-collecting areas at a small fraction of the cost of conventional polished-glass mirrors. At present, the largest astronomical telescope employing this technology is the 2.7-m UBC/Laval LMT. This instrument will soon begin regular observations, surveying the sky passing overhead at its Vancouver, British Columbia, location.

The use of liquid mercury on these mirrors poses a possible health hazard unless adequate steps are taken to protect personnel. The most concern centers around mercury vapour which is present in the observatory as a result of evaporation from the mirror surface. In order to reduce the potential hazard, it is essential that mercury-vapour concentrations, both in the observatory and in its immediate surroundings, be controlled and that suitable protection be provided. This requires knowledge of the vapour concentrations under varying conditions and operational phases of the observatory, so that an operational plan can be developed. Also, in the planning and development of new and larger LMTs, it is important to be able to predict and control the mercury vapour levels.

In order to provide further information, a study has been conducted of mercury vapour levels at the UBC/Laval LMT under a variety of conditions. These data have been integrated with a theoretical analysis of the chemical and physical processes relevant to the situation. A model has been developed which is useful for predicting mercury vapour concentrations at this and other observatories over a wide range of conditions.

2. OPERATIONAL PHASES

Liquid-mirror telescopes employ a thin (typically 2 mm thick) layer of mercury covering the parabolic surface of a rotating mirror. The mirror is designed to rigidly support this mercury layer, and to isolate it from vibrations, while rotating about a vertical axis at a constant rate. The vector resultant of gravitational and centrifugal accellerations then produces a parabolic surface on the mirror with an error of less than a fraction of the wavelength of light. In current designs, the rotating mirror is supported by an air bearing, which is both highly accurate and almost frictionless.

In the *startup* phase the mirror is taken from an idle state to uniform rotation, and a stable mercury layer is established which covers the surface. With the mirror stationary mercury pools to the centre. To establish the mercury layer, the mirror is rotated until the mercury begins to extend over the surface. To prevent the flowing mercury from developing irregularities, the angular velocity of the mirror is altered as needed. When the mercury layer reaches the outer rim of the mirror, completely covering the surface, surface-tension stabilizes it. The rotation rate of the mirror is then brought to its equilibrium value, producing a parabolic surface of the desired focal length. The startup phase typically lasts 5 minutes or less for the 2.7-m mirrors.

The *stabilization* phase follows, in which a thin surface layer develops, covering the mercury. The exact composition of this surface layer is not known, but indications are that it consists primarily of mercurous oxide (Hg_2O), the predominant oxide of mercury for the temperature range found in the observatory. The observed effect of this surface layer is twofold: it stabilizes the mercury layer, strongly damping any waves (produced by vibrations that may reach the mirror), and greatly suppresses evaporation of mercury from the surface. The rate at which the oxide layer forms depends on several factors, temperature being the most important. Experience with the operating liquid mirrors indicates that sufficient oxide has formed after one day to stabilize the mirror against waves, and thus provide excellent optical images.

The *operational* phase begins when the oxide layer has formed and stabilized the mirror surface. Optical observations can then commence with the telescope. The mirror continues to rotate, 24 hours per day, at a constant rate and is not disturbed. This phase continues until it becomes necessary to stop or clean the mirror. The operational phase may last many weeks.

In the *shutdown* phase, the mirror rotation is stopped allowing the mercury to pool at the centre of the mirror. If the telescope is to be shutdown for an extended period of time, the mercury may be removed from the mirror by pumping into storage bottles. Small droplets are collected by a vacuum system employing a vacuum pump and a series of air and oil traps. If the the mirror has been stopped for cleaning, the surface of the mercury pool is cleaned by scraping with a flexible hose, the residue being removed using the vacuum system. After cleaning, the mirror may be restarted, in preparation for further observations.

3. MERCURY VAPOUR MEASUREMENTS

The UBC/Laval liquid mirror telescope is housed in a cylindrical building 4.4 m in diameter and 6 m high. The building is equipped with a retractable roof and a ventilation fan. The fan is located on the wall at a height of 1.5 meters. Air is removed from the building at a rate of of 0.024 m^3/s (50 cfm), which is sufficient to provide one air volume exchange each hour. The mirror is centrally located in the building, its surface being 0.8 m above the floor. The focus of the mirror is located 5 m above its surface. A corrector lens and instrumentation package located there is supported by a tripod anchored to the floor. Access to the instruments is provided by a retractable platform extending from a circular catwalk ringing the inside of the building at a height of 3.6 m above the floor.

In order to study mercury vapour levels in the observatory, a series of measurements was made using a Jerome model 431-X mercury vapor analyser. This instrument works by inducting an air sample through a tube into an analysing chamber. The chamber contains a gold foil whose resistivity changes as it absorbs mercury. The instrument displays digitally the mercury vapour concentration in units of mg/m^3, with a resolution of 0.001 mg/m^3 and a maximum range of 1.000 mg/m^3. Vapour levels in excess of 1 mg/m^3 result in a "HL" reading. The instrument was provided by Lockheed Engineering and Sciences Company for the purpose of these measurements, and was factory new. The analyser was calibrated by the factory by exposure to a sample of air saturated with mercury vapor. As the saturation vapour pressure of mercury is a known function of temperature only, the concentration of this reference source is well determined. As a check on the factory calibration, readings from the Jerome analyser were compared with those taken, at the same time and location, using a Bacharach model MV-2 mercury vapour analyser. These readings typically agreed to within 20%.

Three series of measurements were made, the first with the roof closed and the ventilation fan off, the second with the roof open and the fan off, and the third with the roof closed and the fan on. The first series was designed to sample the least-optimal condition in which ventilation of the observatory building is severely restricted. The second series more closely resembles the actual operating situation of the observatory in which the roof is open for observations, and to provide natural light and ventilation for the startup and shutdown operations. The final series was designed to provide a controlled environment, with a known ventilation rate, in which the build up and dissipation of mercury vapours in the observatory could be quantitatively studied.

In order to obtain a complete picture of the distribution of mercury vapour in and around the observatory, measurements were made at the following locations:

- ground level (inside the observatory building) (0M)
- 1 m above the mirror surface (1M)
- 3 m above the mirror surface (3M)

- 5 m above the mirror surface (5M)
- at the intake of the ventilation system (VI)
- at the exhaust of the ventilation system (VO)
- 1 m downwind from the exhaust of the ventilation system (1MD)
- 5 m downwind from the exhaust of the ventilation system (5MD)

The measurements were taken over a series of time during all phases of operation of the telescope. The times at which meaurements were made are as follows:

- immediately prior to startup (mercury pooled at centre)
- immediately after establishment of the full mercury surface (EMPD)
- 1 hr after EMPD
- 2 hr after EMPD
- 3 hr after EMPD
- 6 hr after EMPD
- 12 hr after EMPD
- 24 hr after EMPD
- 48 hr after EMPD
- immediately after stopping the mirror (DMPD)
- 1 hr after DMPD

At each time, the temperature and humidity within the observatory and the estimated wind speed were recorded.

For the second series of measurements (roof open), the roof was kept open for the first 6 hours. For subsequent measurements the roof was opened 2 hrs before each measurement, to allow time for natural ventilation. This simulates the procedure followed during astronomical observations when the roof is opened 2 hrs prior to the start of observations.

For the third series of measurements (roof closed, fan on), the operational phase of the mirror was extended to 144 hrs before shutdown. Additional measurements were made, following the 48-hr measurement, at intervals of 24 hrs. This allowed the rate of decline of the vapour concentrations to be accurately determined. After shutdown, additional measurements were made at a range of heights above the stationary mercury pool in order to verify the diffusion rate predicted by theoretical analysis.

The mercury vapour concentrations obtained by these measurements are listed in Tables 1 through 4. The columns of the first three tables are: (1) time of measurement, in hours after EMPD; the time of DMPD is the same as that of the measurement immediately preceding it (2) estimated wind speed in m/s (3) temperature inside the observatory in degrees C (4) relative humidity in the observatory, in percent (5 – 12) mercury vapour concentration, in mg/m^3, at the indicated positions. Mercury vapour concentrations at the 1m and 5m heights above the mirror, for the three series of measurements, are plotted in Figures 1 through 3.

As can be seen from the figures and the tables, the vapour concentrations are stronly dependent on the degree of ventilation. In the first series, with no ventilation, vapour concentrations rise continuously, reach a peak after about 12 hrs, then slowly decline. The concentrations are high enough to require suitable respiratory protection for any person inside the observatory. In the second series, with the roof open, the vapour concentrations rise briefly, then decline after only an hour. The levels are typically quite low, falling below 0.1 mg/m^3 everywhere after three hours. In the third series, with controlled ventilation, the concentrations rise for the first three hours, then steadlily decline. As the rate of ventilation is modest, the vapour levels are relatively high, compared to the case when the roof was opened.

The third series of measurements is particularly useful in that the rate of ventilation is known. Figure 4 shows the logarithm vapour concentration at the fan inlet, vs. time. The data, for times greater than three hours, are resonably well fit by a straight line, indicating an exponential decline. The line in the figure shows the result of a linear regression on the points having $t \geq 3$ hr. The slope of this line corresponds to an e-folding time of 111 hrs.

4. ANALYSIS

TABLE 1

Series 1 mercury vapour concentrations

Time	Wind m/s	T C	RH %	0M	1M	3M	6M	VI	VO	1MD	5MD
Start	0	11	92	0.238	0.219	0.097	0.096	—	—	—	—
EMPD	0	11	92	0.165	0.269	0.143	0.102	—	—	—	—
1	0	11	92	0.348	0.434	0.341	0.362	—	—	—	—
2	0	13	92	0.745	0.791	0.619	0.579	—	—	—	—
3	1	14	90	0.577	0.505	0.775	0.817	—	—	—	—
6	1	14	90	0.728	0.958	0.965	0.932	—	—	—	—
12	5	11	92	> 1.0	> 1.0	> 1.0	> 1.0	—	—	—	—
24	2	10	92	> 1.0	> 1.0	0.750	0.629	—	—	—	—
48	0	9	89	0.418	0.728	0.629	0.739	—	—	—	—
DMPD	0	9	89	0.398	0.691	0.610	0.693	—	—	—	—
49	0	9	89	0.358	0.340	0.319	0.320	—	—	—	—

Concentrations in mg/m^3
Fan off, roof closed
Time of EMPD: 93/10/30/1215

TABLE 2

Series 2 mercury vapour concentrations

Time	Wind m/s	T C	RH %	0M	1M	3M	5M	VI	VO	1MD	5MD
Start	4	12	76	0.026	0.032	0.005	0.004	—	—	—	—
EMPD	4	12	76	0.161	0.108	0.037	0.024	—	—	—	—
1	4	12	76	0.193	0.230	0.043	0.034	—	—	—	—
2	5	12	74	0.088	0.145	0.021	0.018	—	—	—	—
3	4	12	72	0.062	0.063	0.029	0.037	—	—	—	—
6	3	12	72	0.064	0.064	0.026	0.035	—	—	—	—
12	3	10	76	0.064	0.068	0.034	0.009	—	—	—	—
24	1	9	80	0.040	0.015	0.009	0.006	—	—	—	—
48	1	5	81	0.036	0.049	0.020	0.010	—	—	—	—
DMPD	1	5	81	0.028	0.041	0.018	0.005	—	—	—	—
49	1	5	81	0.030	0.035	0.012	0.008	—	—	—	—

Concentrations in mg/m^3
Fan off, roof open
Time of EMPD: 93/11/03/1000

TABLE 3

Series 3 mercury vapour concentrations

Time	Wind m/s	T C	RH %	0M	1M	3M	5M	VI	VO	1MD	5MD
Start	1	11	80	0.030	0.035	0.012	0.008	0.033	0.029	0.002	0.000
EMPD	1	11	80	0.111	0.150	0.059	0.045	0.059	0.045	0.004	0.000
1	1	11	80	0.879	0.813	0.573	0.572	0.679	0.471	0.012	0.005
2	1	11	80	0.987	0.902	0.702	0.683	0.790	0.769	0.003	0.000
3	1	12	78	0.929	> 1.0	0.696	0.625	> 1.0	0.904	0.063	0.007
6	1	11	78	0.975	0.813	0.315	0.294	0.822	0.943	0.076	0.000
12	1	7	80	0.808	0.927	0.987	0.813	> 1.0	0.686	0.012	0.008
24	1	5	80	0.869	0.817	0.743	0.592	0.759	0.711	0.019	0.004
48	2	5	80	0.678	0.618	0.480	0.307	0.583	0.312	0.021	0.004
72	0	5	83	0.611	0.548	0.541	0.458	0.553	0.606	0.007	0.000
96	0	2	82	0.338	0.319	0.311	0.262	0.316	0.314	0.000	0.000
120	1	2	82	0.259	0.242	0.253	0.188	0.273	0.276	0.000	0.000
144	0	2	84	0.240	0.226	0.212	0.145	0.225	0.243	0.000	0.000
DMPD	0	2	84	0.195	0.169	0.124	0.097	0.180	0.182	0.000	0.000
145	0	4	84	0.294	0.284	0.134	0.076	0.281	0.186	0.003	0.000

Concentrations in mg/m^3

Fan on, roof closed

Time of EMPD: 93/11/05/1100

TABLE 4

Vapour concentrations above a fresh mercury surface after 1 hour exposure to still air

Height (m)	Concentration (mg/m^3)
0.01	> 1.0
0.05	0.541
0.10	0.392
0.20	0.223

Temperature: 4 C

The results of these the measurements may be understood by considering the relevant physical processes of evaporation, diffusion, ventilation, and the formation of the mercury oxide layer. Details of this analysis are presented in Appendix A. In this section, we discuss the principal results.

4.1 Startup

In the absense of any ventilation, air in contact with liquid mercury will become saturated with mercury vapour. The vapour concentration in saturated air depends on temperature, the saturation vapour pressure P_v (in Pascals) being well approximated, for the temperature range of our measurements, by the formula

$$P_{vs} = 1.36 \times 10^{10} \ \exp\{-7345/T\} \tag{1}$$

where the T is the absolute temperature in degrees Kelvin. The corresponding vapour concentration ρ_v (in mg/m^3) is obtained from this using the ideal gas law. The result is

$$\rho_{vs} = 21.74\left(\frac{298}{T}\right) \exp\{24.65(1 - 298/T)\} \ \mathrm{mg/m^3}. \tag{2}$$

The rate of evaporation F_v of mercury can be estimated from the saturation vapour pressure (Appendix A). The number of mg of vapour evaporating each second per square meter of surface area is given by

$$\begin{aligned} F_e &= P_{vs}\sqrt{m/2\pi kT} \\ &= 964 \left(\frac{298}{T}\right)^{1/2} \exp\{24.65(1 - 298/T)\} \ \mathrm{mg/m^2 s}. \end{aligned} \tag{3}$$

This is offset by condensation from the vapour to the liquid mercury. The condensation rate F_c is proportional to the partial pressure of mercury vapour in the air above the mirror surface:

$$F_c = P_v\sqrt{m/2\pi kT}\ . \tag{4}$$

Values of these quantities, for a range of temperatures, are listed in Table 5. From an inspection of the tables, it is clear that (1) the typical vapour concentrations measured in the observatory are much lower than the saturation levels, and (2) the evaporation rates are high enough to rapidly saturate the air in contact with the liquid. These results may be understood as follows:

When the mercury is first exposed to air evaporation occurs rapidly, raising the partial pressure of vapour in a layer of air adjacent to it. For brevity, we shall refer to this layer as the *boundary layer.* As the boundary layer approaches saturation, P_v approaches $P - vs$, and the net evaporation rate

$$F_{en} = F_e - F_c = (P_{vs} - P_v)\sqrt{m/2\pi kT} \ . \tag{5}$$

approaches zero. Further evaporation can only occur if vapour is removed from the boundary layer and transported elsewhere. In the absence of ventilation, the primary transport mechanism for the vapour is diffusion. The flux F_d of mercury diffusing away from the mirror is proportional to the gradient of the vapour concentration,

$$F_d = D\nabla\rho_v \ , \tag{6}$$

where the proportionality constant D is the diffusion coefficient, which for mercury atoms diffusing in air has the value

$$D = 6.17 \times 10^{-5} \left(\frac{T}{298}\right)^{3/2} \mathrm{m}^2/\mathrm{s} \ . \tag{7}$$

The extent of the mercury vapour increases with time as it diffuses outward and is replaced by evaporation into the boundary layer, which remains saturated. After a time t seconds, the distance in metres at which the concentration is half that of the boundary layer is

$$x_{1/2} = 0.0053\left(\frac{T}{298}\right)^{3/4} \sqrt{t} \ \mathrm{m}. \tag{8}$$

This can be compared with the measurements, reported in Table 4, taken one hour after the emplacement of fresh liquid mercury. Eq. (8 predicts that the vapour concentration will be half the saturation value at a height of 0.3 m. In fact, the concentrations are lower than this, suggesting that much of the mercury vapour has been removed by convection or passive ventilation within the building.

The concentration gradient near the surface of the mercury is predicted to be

$$\nabla\rho_v(0,t) = 2.21 \times 10^3 \ t^{-1/2}\left(\frac{298}{T}\right)^{7/4} \exp\{24.65(1 - 298/T)\} \ \mathrm{mg/m^4}, \tag{9}$$

which, for $t = 3600$ s and $T = 277$ (4°C) gives a gradient of 6.46 $\mathrm{mg/m^4}$, which is about half the gradient estimated from the data of Table 4. This is consistent with some degree of convection or ventilation which would steepen the gradient.

The diffusive flux of mercury vapour out of the boundary layer is given by

$$F_d = 0.136 \ t^{-1/2}\left(\frac{298}{T}\right)^{1/4} \exp\{24.65(1 - 298/T)\} \ \mathrm{mg/m^2s}. \tag{10}$$

Because evaporation maintains saturation in the boundary layer, the net rate of evaporation is equal to the rate at which mercury vapour is removed from this layer by diffusion. The net evaporation rate is therefore F_d.

4.2 Stabilization

As mercurous oxide forms on the surface of the mercury, it reduces the rate of evaporation. The formation of this surface layer is likely to be a complex process, dependent on temperature and other factors, and is not easily modeled. General considerations (Appendix A) suggest that the evaporation rate should have the form

$$F_e(t) = F_e(0)\exp\{-t/t_0\} \tag{11}$$

where t_0 is a characteristic time for the formation of the oxide. This time is expected to be a function of temperature, being shorter at higher temperatures. The value of t_0, at $T = 11°\mathrm{C}$, is estimated below to be about 0.5 hrs.

The competition between the declining evaporation rate, and the rate of diffusion out of the boundary layer is illustrated in Figure 5. This figure shows that the evaporation rate is limited by diffusion for about the first 5 hours. By that time, the evaporation rate has dropped to a level that can no longer maintain the diffusion losses from the boundary layer. The vapour concentration in the boundary layer then falls, decreasing the gradient, and the diffusive flux falls to a level equal to the evaporation rate. The evaporation rate is now limited not by diffusion, but by the oxide layer. After a time of order

$$t_h = V^{2/3}/2D \ , \tag{12}$$

where V is the volume of the building, mercury vapour has spread throuout the observatory and the concentrations are nearly homogeneous.

4.3 Operation

Equilibrium will be achieved when the rate of evaporation equals the rate at which mercury vapour is removed from the building by ventilation. If the fan removes C m^3 of air per second, the number of mg of vapour removed per second is

$$Q = \rho_v C \tag{13}$$

where ρ_v is the concentration measured at the intake of the ventilation system. The equilibrium concentration within the building is then given by

$$\rho_v = \frac{F_e(0)A}{C}\exp\{-t/t_0\} \tag{14}$$

where A is the area of the liquid mercury surface.

From the data of Table 3, the characteristic time t_0 may be estimated. For this series, measurements were continued for 144 hours, to allow sufficient time to follow the changes in vapour concentration in the observatory. For the first six hours, the temperature in the observatory was nearly constant at 11°C. The concentration measured at the fan intake peaks after about three hours, indicating that the rate of exhaustion of vapour by the fan is now roughly equal to the rate of evaporation. By this time, diffusion and ventilation have had time to produce a nearly homogeneous distribution of vapour throughout the observatory. At six hours, the concentration is 0.822 $\mathrm{mg/m^3}$ By inserting this value in Eq. (14), the evaporation rate, t_0 can be obtained. This gives an evaporation rate $F_e = 3.55 \times 10^{-3}$ $\mathrm{mg/m^2s}$, which is almost five orders of magnitude smaller than the evaporation rate of fresh mercury at this temperature, 293 $\mathrm{mg/m^2s}$, from Eq. (3). From this we estimate $t_0 = 0.5$ hr, at $T = 11°\mathrm{C}$. This is a very rough estimate, but indicates that the oxide layer forms rapidly and is very effective at reducing the rate of evaporation.

A glance at Figure 4, however suggests that the situation is more complex. after six hours, the vapour concentration, and hence the evaporation rate, continues to decline, but at a much slower rate. Evidently the rate of formation of oxide has declined, either because of the lower temperature, or because of some other factor not included in the analysis. Further carefully controlled studies would be required for a better understanding of this effect.

4.4 Shutdown

At shutdown, the mercury pools to the centre of the mirror, and the oxide layer breaks. Rapid evaporation then produces a saturated boundary layer above the surface of the liquid. If the mercury is not removed or covered this saturate layer evolves as described above, until the oxide layer reforms. The vapour concentrations evolve in the same manner as after mirror startup, but at lower levels due to the reduced surface area of the liquid mercury.

5. DISCUSSION

Let us now examine the three series of measurements obtained at the 2.7-m observatory, in the light of this analysis. In the first series of measurements (fan off, roof closed: Table 1, Figure 1), vapour levels rise continuously throughout the observatory, reaching a peak after about 12 hrs. They then slowly decline. In a perfectly sealed environment,

TABLE 5
Mercury Vapour Parameters vs Temperature

T (C)	P_{vs} (Pa)	ρ_{vs} (mg/m^3)	F_e (mg/m^{2}s)	D (cm^2/s)
-20	0.003	0.319	13.0	0.483
-15	0.006	0.550	22.7	0.497
-10	0.010	0.927	38.6	0.512
-5	0.017	1.531	64.4	0.526
0	0.028	2.483	105	0.541
5	0.046	3.956	169	0.556
10	0.073	6.198	268	0.511
15	0.114	9.558	417	0.586
20	0.176	14.52	638	0.602
25	0.269	21.74	964	0.617
30	0.403	32.11	1436	0.633
35	0.598	46.83	2111	0.648
40	0.875	67.44	3065	0.664

we would expect the vapour concentration to rise continuously until the saturation level is reached. The fact that the vapour levels decline after 12 hrs indicates that (1) The rate of evaporation of the mercury is declining, due to formation of the oxide, and (2) there is some degree of passive ventilation in the building even with the roof closed and the fan off. This is likely to result from air entering through gaps between the fixed and retractable part of the roof, exiting through the fan duct, and through the door which was ocassionally opened to allow access to the building for measurements.

In the second series (fan off, roof open), vapour levels peak after only one hour, then decline. The maximum levels are at most 20% of those in the preceeding series. Clearly, passive ventilation through the roof is very effective at reducing vapour concentrations within the building. The evaporation rate noticibly declines after only one hour.

In the third series (fan on, roof closed), vapour concentrations peak after about 3 hrs and then steadily decline. At the peak, the rate of production of vapour by evaporation has been balanced by the rate of evacuation of vapour by the fan. This equilibrium continues as the evaporation rate, and hence vapour concentrations, decline with the formation of the oxide layer. In this phase, vapour levels could be lowered by simply increasing the fan capacity. The fan of the 2.7-m LMT has a very low capacity (50 cfm) and was not intended to control mercury vapours, but to minimize temperature variations between air in the observatory and the air outside.

We have seen that the concentrations of mercury vapour in the observatory are determined by competing effects of evaporation, condensation, diffusion, ventilation, and the formation of a surface oxide layer. Figure 5 illustrates how these factors govern the evaporation rate. This in turn determines the equilibrium concentration of vapour in the building, through Eq, (14).

Let us now consider the implications of these results, with a view toward predicting (and minimizing) vapour levels in other liquid mirror installations. We have seen that after emplacement of liquid mercury on the mirror, the air in contact with the liquid rapidly becomes saturated with vapour. The presence of this saturated air supresses the evaporation of mercury (Figure 1), to a level much lower than the uninhibited evaporation rate. The mercury vapour gradually diffuses into the observatory, but at a slow rate, travelling only about 0.3 m in one hour.

In order to minimize the total quantity of mercury evaporating from the mirror during the startup and stabilization phase, the best strategy is to minimize ventilation: by keeping the vapour level high near the mirror, evaporation is minimized.

On a time scale of about a day an oxide layer slowly forms on the surface of the liquid. (This timescale may be significantly shorter at higher temperatures.) The rate of evaporation of the mercury is then reduced by many orders of magnitude and vapour concentrations within the observatory can readily be controlled by ventilation. Even a modest amount of ventilation will suffice to keep the vapours at a safe level.

As an example, consider the the NASA 3-m mirror, with the roof closed. The NASA observatory is equipped with three fans, the smallest of which has a capacity of 0.47 m^3/s (1000 cfm). We can estimate the concentration of vapour within the observatory with this fan in operation. During the start up and stabilization phase the vapour concentration at the mirror will reach the saturation level. Vapour levels within the observatory will depend upon details of the air flow as the vapour is evacuated by the fan. After the oxide layer forms, there will be a balance between the evaporation rate and the ventilation rate. The most reliable was to estimate the vapour concentrations within the NASA observatory is by scaling the results of the 2.7-m measurements, using the dependancies indicated in Eq. (14). The 3-m mirror has 30% more surface area than the 2.7-m, but even the smallest NASA fan has 20 times the capacity of the fan of the 2.7-m observatory. Therefore, the vapour concentrations in the NASA facility, at the same temperature, are expected to be lower by a factor of about 16, than the levels indicated in Table 3. This indicates that the concentrations will fall below 0.05 mg/m^3 after only a few hours, if the 1000 cfm fan is run continuously. At higher temperatures, it may take longer for the concentrations to drop to this level, due to the higher evaporation rate (Eq. 3), but this will likely be offest by a more rapid formation of the oxide layer. With the higher capacity fans operating, the vapour levels will be correspondingly lower.

The conclusion that that the vapours can be controlled by ventilation is born out by the data obtained at the 2.7-m observatory with the roof open (Table 2). For this series of measurements, passive ventilation from the open roof and light wind was sufficient to keep mercury vapours at very low levels for all but the first few hours after emplacement of the mercury.

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APPENDIX A

In this Appendix we derive formulae that have been used in the body of this report. Unless otherwise indicated, SI units are used throughout.

In the absense of any ventilation, air in contact with liquid mercury will become saturated with mercury vapour. The vapour concentration in saturated air depends on temperature, the saturation vapour pressure P_{vs} (in Pascals) being well approximated, for the temperature range of our measurements, by the formula[4]

$$P_{vs} = 1.36 \times 10^{10} \; \exp\{-7345/T\} \tag{15}$$

where the T is the absolute temperature in degrees Kelvin. The corresponding vapour concentration ρ_v is obtained from this using the ideal gas law,

$$P_{vs} = \rho_{vs} kT/m \; , \tag{16}$$

where $k = 1.3807 \times 10^{-23}$ J/K is Boltzmann's constant, and $m = 3.3308 \times 10^{-25}$ kg is the mass of the mercury atom. These equations give

$$\rho_{vs} = 3.28 \times 10^{8} \; T^{-1} \exp\{-7345/T\} \; . \tag{17}$$

If ρ_{vs} is measured in mg/m^3, and T is referred to the standard temperature of 298 K, this formula becomes

$$\rho_{vs} = 21.74\left(\frac{298}{T}\right) \exp\{24.65(1 - 298/T)\} \; \mathrm{mg/m^3}. \tag{18}$$

To determine the rate of evaporation of mercury, consider first the rate at which mercury vapour condenses. If the density of the mercury vapour in the air immediately above the liquid is ρ_v, the number of mercury atoms striking the surface of the liquid, per unit area per unit time, is given by

$$n = \rho_v \bar{v}/4m \tag{19}$$

where

$$\bar{v} = \sqrt{8kT/\pi m} \tag{20}$$

is the mean speed of the mercury atoms, and the factor of 1/4 results from averaging over the the possible directions of motion of the atoms. The mass of mercury vapour condensing per second, per square metre is the condensation rate F_c:

$$\begin{aligned} F_c &= nm \\ &= \rho_v \bar{v}/4 \end{aligned} \tag{21}$$

From the ideal gas law, this is seen to be proportional to the partial pressure of mercury vapour:

$$\begin{aligned} F_c &= P_v \bar{v} m / 4kT \\ &= P_v \sqrt{m/2\pi kT} \end{aligned} \tag{22}$$

When the air is saturated $P_v = P_{vs}$ and the rate of evaporation F_e must equal the rate of condensation, hence

$$F_e = P_{vs}\sqrt{m/2\pi kT} \tag{23}$$

Combining this with Eq. (15) gives

$$F_e = 964 \left(\frac{298}{T}\right)^{1/2} \exp\{24.65(1 - 298/T)\} \text{ mg/m}^2\text{s}. \tag{24}$$

The net evaporation rate $F_{en} = F_e - F_c$, the difference between the evaporation and condensation rate, decreases as the air approaches saturation:

$$F_{en} = (P_{vs} - P_v)\sqrt{m/2\pi kT} \tag{25}$$

Consider now diffusion of mercury vapour away from the mirror. The flux F_d of mercury diffusing away from the mirror (mg/m^{2}s) is proportional to the gradient of the vapour concentration,

$$F_d = D\nabla\rho_v \ , \tag{26}$$

where the proportionality constant D is the diffusion coefficient[5]. For a small concentration of heavy particles diffusing in a gas of light particles, the diffusion coefficient is given by[5]

$$D = \frac{3(kT)^{3/2}}{\sqrt{8\pi m_1} P(d_1 + d_2)^2} \tag{27}$$

where d_1 and d_2 are the diameters of the light and heavy particles, respectively, m_1 is the mass of a light particle, and P is the pressure. If the light particle is a diatomic molecule, composed of two atoms of diameter d_1, this formula must be modified to take account of the greater cross-sectional area of the molecule. The result is

$$D = \frac{3(kT)^{3/2}}{\sqrt{8\pi m_1} P(5d_1/4 + d_2)(d_1 + d_2)} \tag{28}$$

For mercury atoms diffusing in air, at standard atmospheric pressure, we have $d_1 = 1.38\text{Å}$, $d_2 = 1.85\text{Å}$, and $m_1 = 4.78 \times 10^{-26}$ kg. (The values of d_1 and m_1 correspond to a weighted average of N_2 and O_2 molecules.) This gives

$$D = 6.17 \times 10^{-5} \left(\frac{T}{298}\right)^{3/2} \mathrm{m}^2/\mathrm{s}\ . \tag{29}$$

The vapour density at a distance x above the mercury surface, at time t after emplacement of the liquid, is obtained by solving the diffusion equation

$$\left(D\nabla^2 - \frac{\partial}{\partial t}\right)\rho_v(x,t) = 0 \tag{30}$$

in the one-dimensional region $x \geq 0$, subject to the boundary condition

$$\rho_v(0,t) = \rho_{vs}\ . \tag{31}$$

The solution is

$$\rho_v(x,t) = \rho_{vs}\mathrm{erfc}(x/\sqrt{2Dt})\ . \tag{32}$$

From this we find that the height $x_{1/2}$ at which the concentration has dropped to half the saturation value is given by

$$x_{1/2} = 0.675\sqrt{Dt} \tag{33}$$

Thus, the extent of the mercury vapour increases in proportion to the square root of the time. After a time t sec, this height is

$$x_{1/2} = 0.0053\left(\frac{T}{298}\right)^{3/4}\sqrt{t}\ \mathrm{m}. \tag{34}$$

The concentration gradient is

$$\nabla\rho_v(x,t) = -\rho_{vs}\sqrt{\frac{2}{\pi Dt}}\exp\{-x^2/2Dt\} \tag{35}$$

which when evaluated at the surface of the liquid gives

$$\nabla\rho_v(0,t) = 2.21 \times 10^3 \left(\frac{298}{T}\right)^{7/4} \exp\{24.65(1 - 298/T)\}\ \mathrm{mg/m^4}, \tag{36}$$

which gives a diffusive flux of

$$\begin{aligned} F_d &= \rho_{vs}\sqrt{\frac{2D}{\pi t}} \\ &= 0.136\ t^{-1/2}\left(\frac{298}{T}\right)^{1/4} \exp\{24.65(1 - 298/T)\}\ \mathrm{mg/m^2s}. \end{aligned} \tag{37}$$

The mercury transported away from the surface by diffusion is quickly replaced by evaporation. The net evaporation rate must therefore equal the diffusive flux

$$F_{en} = F_d \ . \tag{38}$$

Lastly, we consider the formation and effect of the oxide layer on the surface of the mercury. Suppose that at time t, a fraction $1 - \epsilon$ of the surface has been covered by the oxide. The rate at which the oxide is produced, will be proportional to the fraction ϵ of surface not yet covered, hence

$$\frac{d\epsilon}{dt} = -K\epsilon \tag{39}$$

where K is a (positive) proportionality constant which is independent of time, but depends on the rate of the reaction which produces the surface layer. In general, K will be a sensitive function of temperature. For a first-order reaction, K has the form[6]

$$K = Z \exp\{E_a/kT\} \tag{40}$$

Where E_a is the activation energy, per molecule, and Z is the rate constant for the reaction.

The solution of Eq. (39) is

$$\epsilon = \exp\{-Kt\} \ , \tag{41}$$

from which we conclude that the rate of evaporation of mercury from the liquid will have a time dependence of the form

$$F_e(t) = F_e(0) \exp\{-t/t_0\} \ . \tag{42}$$

where $t_0 = 1/K$ is a characteristic time for the formation of the surface layer.

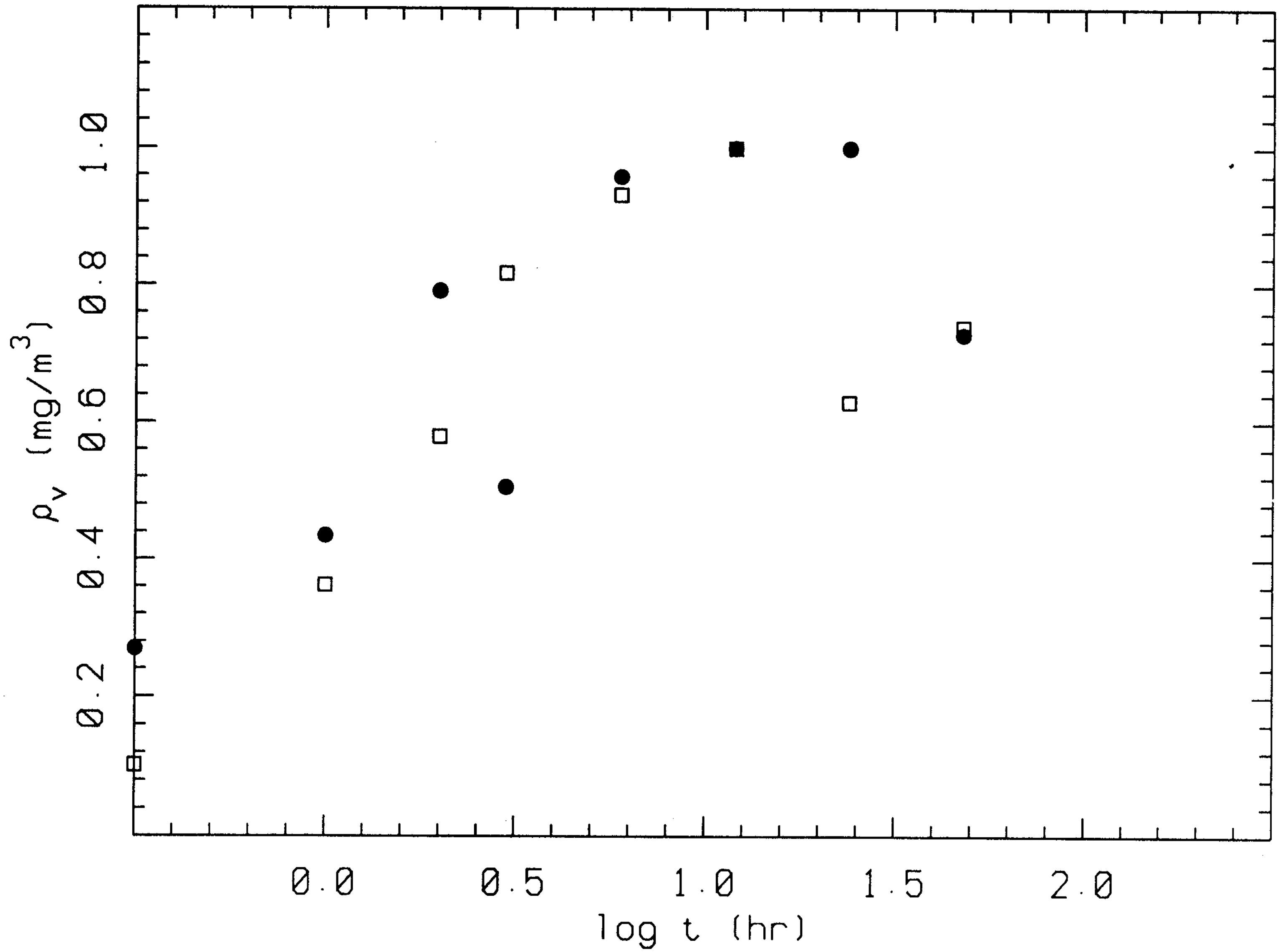
FIGURE CAPTIONS

1. Series 1 mercury vapour concentrations. Filled circles indicate concentrations one metre above the mirror. Open squares indicate concentrations 5 metres above the mirror.
2. Series 2 mercury vapour concentrations. Filled circles indicate concentrations one metre above the mirror. Open squares indicate concentrations 5 metres above the mirror.

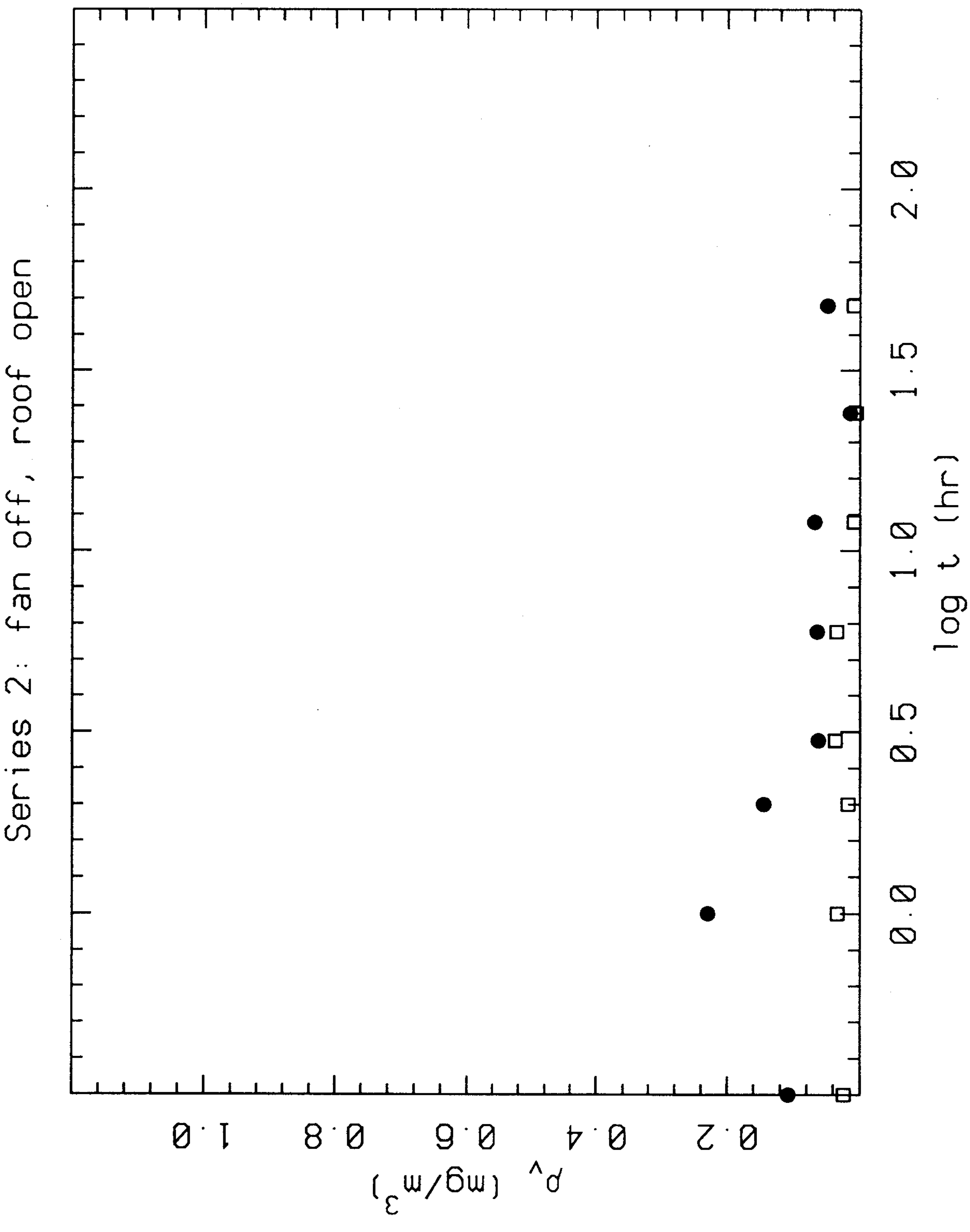
3. Series 3 mercury vapour concentrations. Filled circles indicate concentrations one metre above the mirror. Open squares indicate concentrations 5 metres above the mirror.

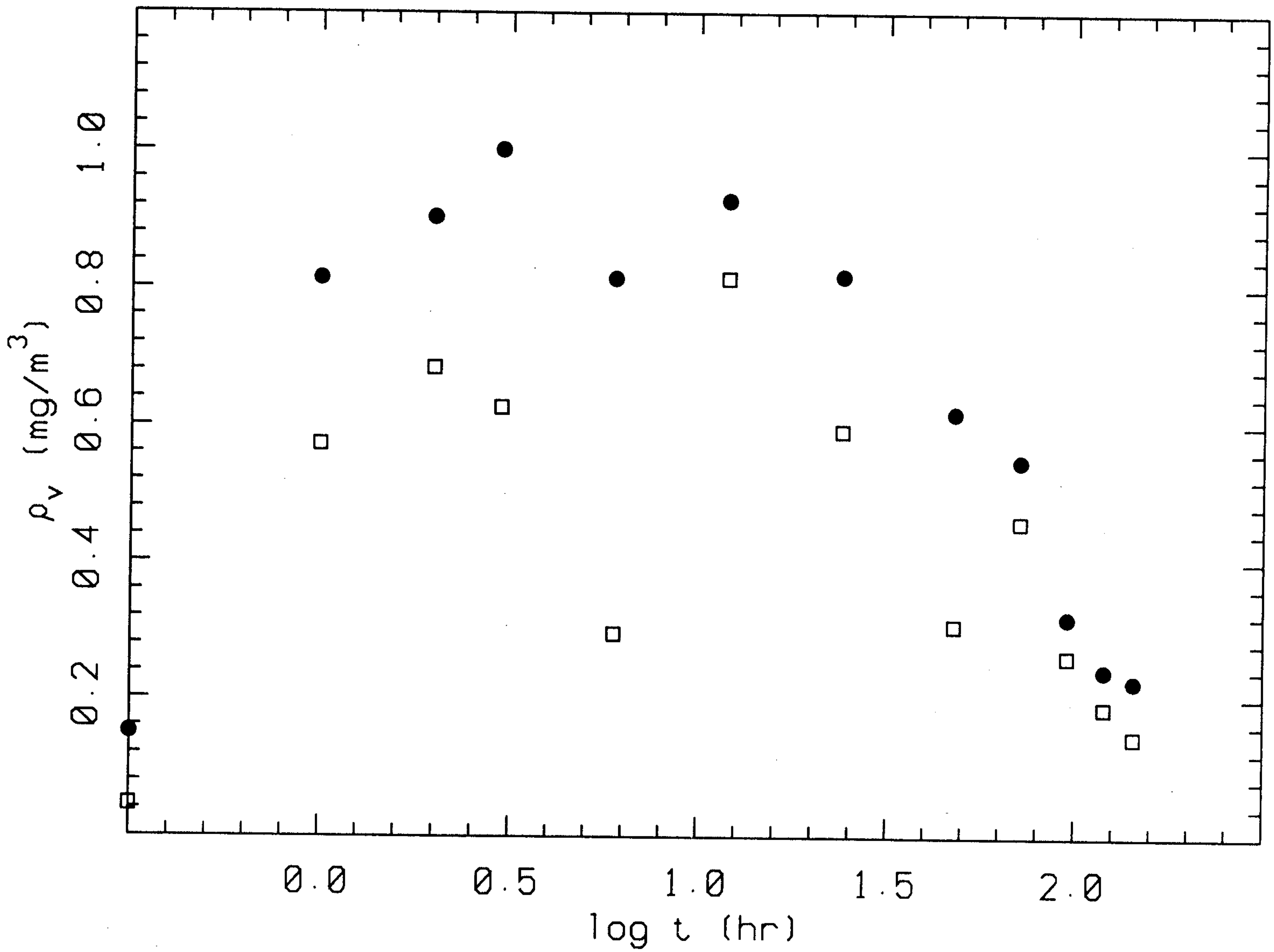
4. mercury vapour concentration at the intake of the ventilation fan, measured with the fan on and the roof closed. The straight line indicates the result of a linear regression using the points having $t \geq 3$ hr.

5. Factors limiting the evaporation rate. The solid line shows the rate of evaporation, ignoring condensation. The exponential decline is due to the formation of an oxide layer on the surface of the mercury. The curved line shows the rate of diffusion of mercury vapour from a saturated boundary layer. The evaporation rate is limited by diffusion until about five hours after emplacement of the mercury on the mirror. After that time, it is limited by the oxide.

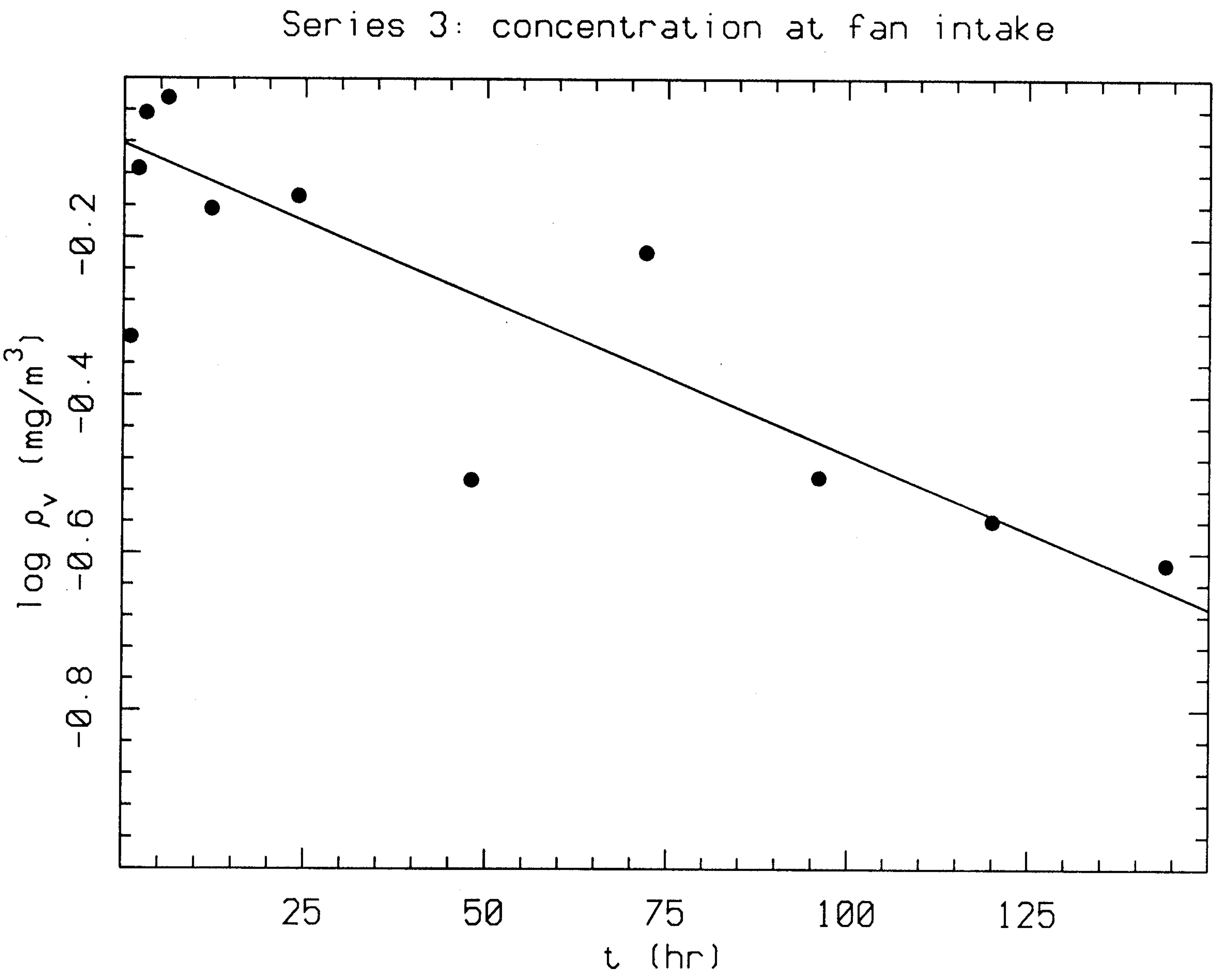


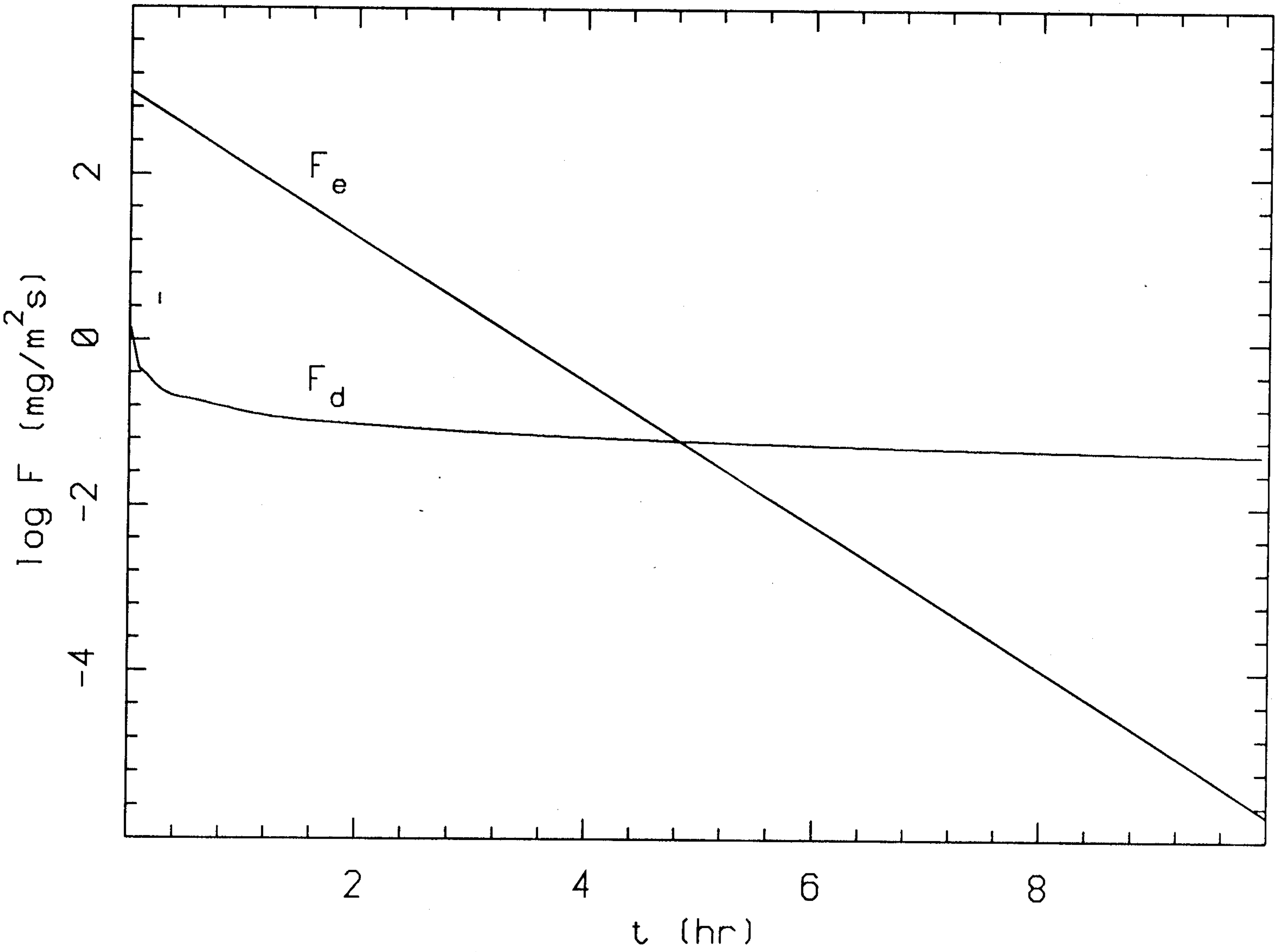
Series 1: fan off, roof closed


Series 2: fan off, roof open
ρ_v (mg/m^3)
0.2
0.4
0.6
0.8
1.0
log t (hr)
0.0
0.5
1.0
1.5
2.0



Series 3: fan on, roof closed


Series 3: concentration at fan intake
log ρ_v (mg/m^3)
-0.2
-0.4
-0.6
-0.8
25
50
75
100
125
t (hr)



Factors limiting the evaporation rate