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Section 1

INTRODUCTION

The major objective of this study was to define and evaluate methods by which an optical system could be protected from performance degradation arising from exposure to a beam of heavy metal atoms. The optical system is coupled to a chamber in which the metal atoms are being produced and processed. The coupling aperture is the source of the contaminating metal atom beam, which, if un-attenuated, would degrade the system performance in an unacceptably short period of time.

It was agreed early in the program to concentrate on a gaseous scattering technique, with a stated objective of metal beam flux reduction of about 10^6 . Additional constraints require that the scattering gas must not effuse back into the main process chamber at such a rate that it has significant effect on the vacuum level in the chamber, which is of the order of 10^{-6} torr; finally, the path length between the main chamber and the optical system must not be increased unduly.

This report summarizes the analyses that were performed under the program. Section 2 presents a summary review, while the details of the analyses are described in Section 3. Recommendations leading toward final system design are given in Section 4. Finally, an appendix contains a description and print-out of a program that was developed and used to facilitate the evaluation of system performance parametrically.

Section 2

SUMMARY

Preliminary calculations and experiments¹⁻³ had shown that a simple diffusion tube placed in front of the optical system and fed with low-pressure argon, was not tractable. Therefore, several alternatives and modifications were investigated.

Replacement of the simple diffusion tube with an atomic beam of argon at right angles to the metal atom flux was shown to be feasible, utilizing supersonic nozzle beam techniques. However, a large flux of argon was necessary, requiring large pumping capacity - probably cryogenic pumping. The rate of formation of argon ice would present difficulties in removing it at frequent intervals.

An alternative system, also a supersonic nozzle source beam, using mercury was also feasible. This would, in effect, be a modification of the mercury diffusion pump. A strong advantage of this approach is that the liquid condensate would be much easier to remove than argon, but because of the higher atomic weight, the supersonic nozzle source technique would be somewhat less effective.

It was realized that a combination technique should be much more effective for the following reasons. The optics can be adequately protected by a scattering tube if the argon density is made high enough. However, the argon flux into the system becomes excessive. If a supersonic nozzle source mercury beam is aimed normal to the argon efflux, it is possible to pump most of this efflux away before it can pass out of the buffer chamber and into the main reaction chamber. Although the argon flux is high, it is not necessary to attenuate it to anything approaching the tolerable heavy metal flux in the opposite direction. Thus, the scattering capability required of the molecular beam is much relieved as compared with that needed if it were to function directly as the heavy metal scatterer.

To make a practical evaluation of such a hybrid system, it was necessary to extend the work of Dubrin, McNeeley and others,¹⁻³ to take into account the higher density flows in the scattering tube. The higher order corrections given by Sreekanth⁴ were included in the calculations of the scattering tube flow. These calculations were run for a range of system parameters to outline the configurations that would lead to attenuation of the heavy metal flux of the order of 10^{-6} . The calculations were run for a scattering tube temperature of 100°K (about liquid argon temperature) and 293°K. Scattering tube lengths from 25 cm to 100 cm - and sometimes more - were considered, and pumping speeds in the buffer chamber of 500 to 3000 liters per second (per scattering tube) were allowed.

The result of the calculations has permitted a range of reasonable operating conditions to be delineated. An interesting fact is that, without making the tubes excessively long, it is possible to operate at conditions where the crossed mercury beam essentially provides the diffusion pumping capacity required, suggesting that, in the final concept, the trapping of the beam should follow good diffusion pump practices, with the proper backing pump capacity to remove the argon. Such design details were not within the scope of the present program, but are included in the recommendations outlined in Section 4.

A few calculations were made with a surrogate atom, namely tin, in place of the heavy metal. The results are very similar to those derived for the heavy metal. This case is illustrative of the flexibility of the program written for system performance evaluation. Options on all the relevant parameters are available, making it broadly applicable to address final design issues.

Section 3.

GENERAL DISCUSSION

As noted above, the system finally chosen for analysis consists of an argon-filled scattering tube, whose efflux is deflected away from the entrance to the main chamber by a cross beam of mercury. See Fig. 1. In addition to its function of deflecting the argon beam, this cross beam also deflects a portion of the metal vapor stream into the walls of the scattering tube. This section contains a discussion of the approximate analyses used to estimate the performance of the scattering tube and the cross beam.

3.1 SCATTERING-TUBE ANALYSIS

The argon is admitted to the scattering tube at a pressure p_0 at the end nearest the optics chamber (see Fig. 1), and flows into the buffer chamber, whose average pressure is maintained at the level p_s by a pumping system, which operates at a volumetric flow rate S . Thus, the mass flow rate (from one scattering tube) is

$$\dot{m} = \frac{10^3 S p_s}{RT_s}$$

where S is in liters/sec and all other quantities are in cgs units, and where subscript s denotes conditions at the pump entrance. In order to emit this rate of mass flow from the exit of the scattering tube under free-molecule-flow conditions, it is necessary that

$$\dot{m} = \frac{\pi d^2}{16} c (\rho \bar{v})_{ex}$$

where subscript ex denotes conditions at the exit plane of the scattering tube. The quantity c is a factor dependent on the tube shape (taken as 1.0 here), and the mean thermal speed is given by

$$\bar{v} = \sqrt{\frac{3RT}{\pi}}$$

The solution of Sreekanth (Ref. 4) was used to find the distribution of pressure (and, hence, number density) along the tube. This method assumes isothermal flow, with second-order slip boundary conditions.

Using this distribution of number density, the scattering of the metal-atom stream was calculated, in essentially the same manner as that used earlier by Dubrin ¹ and McNeeley ². The approximations made in these papers are:

1. the density is sufficiently low that only single-scattering events occur,
2. the net effect of the distribution of scattering over the tube cross section can be represented by a single scattering center on the tube centerline,
3. the argon velocity is sufficiently small compared to that of the metal-atom vapor that the argon can be considered to be stationary,
4. all metal atoms which strike the tube wall are assumed to condense there.

In addition, the collision dynamics in this report are taken from a hard-sphere model, as was done by McNeeley.

Under these approximations, the fractional decrease in the metal-atom number density N is given by (see Fig. 2)

$$\frac{dN}{N} = n \pi (b_{\max}^2 - b_{\min}^2) dz$$

where $b_{\max}$ and $b_{\min}$ denote the range of impact parameters which are effective in scattering metal atoms to the wall, * and where n is the argon number density. Figure 3 shows this range of impact parameters, for a typical value of u/a .

* McNeeley (Ref. 2) takes $b_{\min} = 0$

For

$$a \equiv \frac{m_{\text{METAL}}}{m_{\text{ARGON}}} = \frac{238.04}{39.95} = 5.958, \quad \theta_{\text{LAB}})_{\text{max}} = 9.66^\circ$$

The expression above for N can be written as an integral:

$$\frac{N_{\text{OUT}}}{N_{\text{IN}}} \equiv 1 - f = \exp \left\{ -n_0 \beta \pi \sigma^2 l_0 \mathcal{J} \right\}$$

where f is called the fractional attenuation, β is a constant (taken here, as in Refs. 1 and 2 to be 1.4), σ is the collision diameter, and $\mathcal{J}$ is the integral:

$$\mathcal{J} \equiv \int_0^1 \frac{n}{n_0} \left[\left(\frac{b}{\sigma} \right)_{\text{max}}^2 - \left(\frac{b}{\sigma} \right)_{\text{min}}^2 \right] d \left(\frac{z}{l_0} \right)$$

For the hard-sphere model, the impact parameter b can be expressed in terms of χ , the deflection angle in center-of-mass coordinates, by

$$b = \sigma \cos \frac{\chi}{2}$$

The deflection angle χ is related to the laboratory scattering angle θ by

$$\tan \theta = a \sin \chi / (\cos \chi + a)$$

whose inverse is

$$\cos \chi^\pm = -a \sin^2 \theta \pm \cos \theta \sqrt{1 - a^2 \sin^2 \theta}$$

Using the half-angle formula for the cosine and expressing the integrand as a function of θ allows $\mathcal{J}$ to be evaluated in closed form for the case where

$n/n_0 = \text{const}$, as:

$$\mathcal{J} = \text{const} \cdot \frac{a d}{2 l_0} \left\{ \frac{\sqrt{1 - a^2 \sin^2 \theta_0}}{a \sin \theta_0} + \sin^{-1} (a \sin \theta_0) - \frac{\pi}{2} \right\}$$

where $\tan \theta_0 = d/2l_0$. The same procedure can be used to recover McNeeley's result (Eqn. 4 of Ref. 2), which corresponds to a mean value of n , called n_m , given by

$$n_m = \frac{1}{2} n_0$$

For the present work, the integral $\int$ was evaluated numerically (by the trapezoidal rule), using the distributions of n/n_0 given by Sreekanth's solution. These distributions tend to be approximately linear, with ratios of n_0/n_{ex} that range from just above 1.0 up to around 50, for large length-to-diameter ratios. Figure 4 shows this ratio, which can be correlated as a function of Reynolds number and temperature.

The equations above were programmed for evaluation on an HP-9825 desk-top calculator, and a series of runs was made, for various values of the pumping rate, the pump inlet pressure, and the tube temperature. A tube diameter of 5 cm was used for all runs. Figure 5 shows a typical set of results, suggesting that attenuation factors of 10^{-6} can be achieved with tube lengths under 100 cm, pumping rates on the order of 10^3 liters/sec, and buffer-chamber pressures of 10^{-4} torr. For this range of values, the number density n_0 at the inlet of the tube is typically 3 to $4 \times 10^{14} \text{ cm}^{-3}$, p_0/p_{ex} is around 10, the Reynolds number is between 10^{-1} and 10^0 , and p_0 is on the order of 3×10^{-3} torr.

3.2 ARGON EFFLUX DEFLECTION BY MERCURY CROSS BEAM

The argon being emitted from the exit of the scattering tube cannot be allowed to enter the chamber. Accordingly, the system under study here uses a mercury-vapor beam oriented perpendicular to the argon flow, so as to deflect it away from the entrance to the main chamber (see Fig. 6). The effectiveness of this beam was analyzed under the same set of assumptions as used above for the scattering tube. This leads to the following equation for the argon number density distribution:

$$u_{Ar} \frac{dn_{Ar}}{dx} =$$

$$-n_{Hg} n_{Ar} \pi \sigma^2 V_{rel} + g \cdot n_{Hg} n_{Ar} \pi \sigma^2 V_{rel}$$

where V_{rel} is the relative velocity of impact. The first term on the right-hand side is the number of argon atoms that would be removed, if every collision were effective; the second term reinstates the argon atoms from the fraction g of the collisions which scatter argon into the opening in the main chamber. This equation can be integrated as:

$$\frac{n_{Ar}|_{x=w}}{n_{Ar}|_{x=0}} = \exp \left\{ - \frac{n_{Hg} V_{rel} \pi \sigma^2}{u_{Ar}} \int_0^w (1-g) dx \right\}$$

The quantity g is that fraction of the surface of the scattering sphere for which the laboratory scattering angle will be inside the cone formed by the scatter and the main-chamber opening:

The laboratory scattering angle of the scatter is given by

$$\tan \theta_2 = -\sin \chi / (1 - \cos \chi) ; \chi = 2\theta_2 + \pi$$

This leads, for the hard-sphere model to

$$g(x) = \frac{1}{2} \frac{\pi [1 - (b/\sigma)_*^2]}{\pi} ; \left(\frac{b}{r}\right)_* = \sin \theta_2 = \frac{w-x}{\sqrt{\frac{d^2}{4} + (w-x)^2}}$$

With this expression, the integral involving q can be expressed in closed form, and the final result is

$$\frac{n_{Ar}|_{x=w}}{n_{Ar}|_{ex}} = \exp \left\{ - \frac{n_{Hg} V_{rel} \pi \sigma^2 w}{u_{Ar}} \left(1 - \frac{d}{4w} \tan^{-1} \frac{2w}{d} \right) \right\}$$

For given w, d, σ, u_{Ar} and V_{rel} , this equation can be used to determine the mercury-atom density required to achieve a specified attenuation of the argon.

3.3 SCATTERING OF METAL ATOMS BY MERCURY CROSS BEAM

The mercury-vapor beam, in addition to deflecting the argon, will also scatter some of the metal-vapor atoms to the wall of the scattering tube. The magnitude of this effect was estimated by considering an extension to the scattering tube, of length w , filled with mercury at a constant density. The mercury was assumed stationary; the notation is given in Fig. 6. At each value of ξ , the range of impact parameters which are effective is that for which

$$\theta_{LAB} > \tan^{-1} \frac{d/2}{l_0 + w - \xi}$$

Thus, the expression for attenuation is formally the same as that derived above for the scattering tube:

$$\frac{N|_{\xi=w}}{N|_{\xi=0}} = \exp \left\{ - n_{Hg} \beta \pi \sigma^2 w \int_0^1 \left[\left(\frac{b}{\sigma} \right)_{\max}^2 - \left(\frac{b}{\sigma} \right)_{\min}^2 \right] d(\xi/w) \right\}$$

However, the limits $\xi=0$ and $\xi=w$ correspond in this case to

$$\xi=0: \theta = \tan^{-1} \frac{d/2}{l_0 + w} \equiv \theta_A$$

$$\xi=w: \theta = \tan^{-1} \frac{d}{2l_0} \equiv \theta_B$$

This integral can be expressed in the same closed form as for the scattering tube, namely:

$$\Delta w = - \frac{ad}{2w} \left[\frac{\sqrt{1-v^2}}{v} + \sin^{-1} v \right]_{a \sin \theta_A}^{a \sin \theta_B}$$

Numerical evaluations show that this integral lies between 0.99 and 1.0, for values of w/d greater than 1.0 and values of l_0/d greater than 5.0. Thus, the attenuation by the mercury is given by

$$\frac{N)_{\xi=w}}{N)_{\xi=0}} = \exp \left\{ -n_{Hg} \beta \pi r^2 w \right\}$$

3.4 COMPOSITE EFFECT OF METAL ATOM SCATTERING BY ARGON AND MERCURY

The formulas derived above can now be used to calculate the scattering of metal-vapor atoms by both the argon-filled tube and the mercury cross beam. There are many parameters that might be varied independently; in order to minimize this number in a logical way, the calculations have been organized in the following way: (all calculations have been done for $d = 5$ cm, $p_s = 10^{-4}$, and a tube-wall temperature of 293°K).

1. A pumping speed is selected; this defines the mass flow, which in turn sets the value of p_{ex} , the argon pressure at the exit of the scattering tube:

$$\dot{m} = p_{ex} d^2 / \sqrt{\frac{2RT}{\pi}} = \frac{10^3 S' p_s}{RT_s}$$

2. Next, a series of mercury number densities are chosen (see Table 1), and for each of these, the distance w is chosen such as to reduce the argon pressure from p_{ex} to 10^{-5} torr

at the entrance to the main chamber:

$$\ln \frac{n_{Ar}(x=w)}{n_{Ar}(x)} = \ln \frac{10^{-5}}{p_{ex}(\text{torr})} = -n_{Hg} \frac{V_{rel}}{u_{Ar}} \pi \sigma^2 \left(w - \frac{d}{4} + \tan^{-1} \frac{2w}{d} \right)$$

This equation was solved by a Newton-Raphson iteration, giving the values shown in Table 1. The values used for the argon and mercury velocities were the limiting velocities corresponding to reservoir temperatures of 300°K and 600°K, respectively, giving

$$\frac{u_{Ar}}{u_{Hg}} = 1.58; \quad \frac{V_{rel}}{u_{Ar}} = \left\{ 1 + \frac{1}{(1.58)^2} \right\}^{1/2} = 1.183$$

The collision diameter used was $\sigma_{Ar, Hg} = 3 \times 10^{-8}$ cm.

- Next, the attenuation of the metal-atom flux by this mercury beam was found, from

$$(1-f)_{Hg} \equiv \ln \frac{N(x=w)}{N(x=0)} = \exp \left\{ -n_{Hg} \beta \pi \sigma^2 w \right\}$$

The values $\beta = 1.4$ and $\sigma = 3 \times 10^{-8}$ cm were used for this calculation, whose results are shown in Table 1.

- The results to this point do not depend on $l_0/2$, because of the negligible variation of ϕ_w with this parameter. Thus, it is possible to combine the results in Table 1 with those of the scattering tube, for various values of $l_0/2$ and n_{Hg} ; Table 2 gives a typical set of results, for several values of the pumping speed.

5. Results of the type described in Step 4 were plotted against the total length $L_0 + w$, and the total lengths required to achieve a combined attenuation of 10^{-6} were read from these plots, for various pumping speeds, and for two values of the mercury-vapor density. These final results are shown in Figure 7, where it can be seen that total lengths on the order of 100 cm are capable of achieving the attenuation level of 10^{-6} , with pumping rates (per tube) on the order of a few hundred liters per minute. It can also be seen that as the pumping speed rises, so does the exit-plane argon pressure; this requires a greater length w to deflect the argon beam, with the result that the majority of the scattering path is in the mercury beam.

It should be pointed out that the pumping rates shown on Fig. 7 are those of a diffusion-pump system; it is possible that a portion of the pumping load could be taken care of by a suitable design of the mercury system.

3.5 RESULTS FOR TIN AS SURROGATE ATOM BEAM

A small number of runs were made using tin as the metal vapor coming from the process chamber. The attenuation of this beam by the argon-filled scattering tube was found, for a pumping speed of 500 liters/sec, a tube diameter of 5 cm, wall temperature of 293°K, and for tube lengths of 50, 60, 70, 80, 90, and 100 cm. The attenuations found for this mass ratio (2.972, compared to 5.958 for uranium) were greater than for uranium. The curve of attenuation versus tube length was essentially identical to that found for uranium, but shifted by 10 cm, i.e., the tube length required to achieve a given attenuation of uranium is approximately 10 cm. longer than that required to achieve the same attenuation of tin.

3.6 MERCURY CROSS BEAM GENERATION

As shown above, the feasibility of this concept depends on the ability to produce the required mercury-vapor densities. Figure 8 shows the number densities and laboratory mean free paths that can be achieved by isentropic expansion of mercury vapor for the indicated reservoir temperatures to various area ratios. It appears that the required ranges are well within reach.

The principal elements of a candidate system for the generation of a mercury beam are sketched in Figure 9.

The Hg beam is formed by expanding heated Hg vapor through a suitable linear, 2-dimensional nozzle, designed to provide maximum beam flux thru a beam-defining skimmer slot. After passage through the collision volume defined by the Hg and M beams, the Hg is condensed in a suitable trap and directed to a collection sump for subsequent recycling to the boiler. Indeed, the entire surface of the system is maintained at temperatures just above the freezing point of mercury. This will provide the lowest vapor pressure, while ensuring that all of the condensate will be returned to the collection sump.

In these initial system design considerations, extensive use was made of data pertaining to the design of large mercury diffusion pumps^{5,6}. In this way, the suggested system and operational parameters are based on established operational design and performance data. These include, for example, boiler temperature, power requirements, boiler pressures, nozzle dimensions, Hg flux throughputs, etc. It appears, so far, that Hg beam flux requirements can be readily met with no extrapolations beyond established practice.

Additionally, some preliminary efforts were directed toward the chemical compatibility of mercury as the M-beam deflecting species. Data on the solubility of M in Hg are available; amalgams in the form of MHg_{2-4} are known to exist, although early references indicate that the chemistry and

physical properties are not well-known. However, it has been reported that amalgams with less than 1% M content are still liquid and stable to air. An estimate of the total amount of M leaving the main chamber during a production cycle is about 40 mg ($\sim 2 \text{ mm}^3$). Considering the total amount of Hg in the system, this contamination by M is very low, and the system performance will not be affected thereby. Decomposition of these amalgams occurs at temperatures below 450°C, so that separation can presumably be achieved if desired.

Section 4

RECOMMENDATIONS

This section briefly outlines the recommended directions for further efforts aimed toward the final design of an operational system for optical system protection.

1. Review by LLNL personnel of the findings to date as presented in this report. Clarifications or further documentation to be submitted as required.
2. Additional test cases run on the program to extend and refine the data base further and to establish overall applicability and acceptance.
3. Upon favorable review of the composite system described herein, structure an approach that leads to concept validation and analysis verification by experiment. The mercury beam generator is a key element in the system and can be addressed as a separate entity for prototype design and testing.
4. On-going interfacing of the prototype design with the MARS facility would be required, as well as supporting calculations and/or further analyses that are more sharply focussed upon final design and coupling of the protective system and the facility. Recognition and compliance with overall system constraints and optimization of cost-effectiveness are considered mandatory. These parameters include size and configuration, pumping, power and cryogenic requirements, downtime assessments and scaling to facility size and other duty cycles.

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TABLE 1

s	p _{ex}	n _{Hg}	w	(1-f) _{Hg}	log ₁₀ (1-f) _{Hg}
⁻¹ ls	torr	cm ⁻³	cm		
100	5.17E-5	1E+13	50.97	1.33E-1	-0.88
		3E+13	18.15	1.16E-1	-0.94
		1E+14	6.42	7.88E-2	-1.10
		3E+14	2.66	4.25E-2	-1.37
500	2.59E-4	1E+13	99.36	1.96E-2	-1.71
		3E+13	34.35	1.69E-2	-1.77
		1E+14	11.43	1.08E-2	-1.96
		3E+14	4.59	4.29E-3	-2.37
1000	5.17E-4	1E+13	120.07	8.63E-3	-2.06
		3E+13	41.27	7.44E-3	-2.13
		1E+14	13.55	4.68E-3	-2.33
		3E+14	5.35	1.74E-3	-2.76
2000	1.03E-3	1E+13	140.70	3.81E-3	-2.42
		3E+13	48.15	3.29E-3	-2.48
		1E+14	15.64	2.05E-3	-2.69
		3E+14	6.10	7.15E-4	-3.15
3000	1.55E-3	1E+13	152.94	2.35E-3	-2.63
		3E+13	52.23	2.02E-3	-2.69
		1E+14	16.88	1.25E-3	-2.90
		3E+14	6.54	4.24E-4	-3.37

TABLE 2

S	L ₀ cm	Log(1-f) ₀	P ₃ torr	P _{ex} torr	R _e	n ₀ cm ⁻³	n̄ ₀ g s ⁻¹	n _{ex} cm ⁻³	n ₀₄ = 3E+13		n ₀₄ = 1E+14	
									L ₀ +w cm	Log(1-f) ₀	L ₀ +w cm	Log(1-f) ₀
100	100	-4.9	2.35E-4	5.17E-5	.0249	7.74E+12	2.10E-5	1.70E+12	318	-1.43	106	-1.59
	130	-8.6	3.29E-4			1.08E+13			148	-2.30	156	-1.96
	160	-1.36	4.54E-4			1.50E+13			178	-3.30	206	-3.46
	200	-2.36	6.83E-4			2.25E+13			218	-4.16	231	-4.32
	250	-4.32	8.08E-4			3.18E+13			268	-5.23	256	-5.41
	300	-5.40	1.29E-3			4.26E+13			318	-6.34	276	-6.50
500	50	-1.41	3.09E-3	2.59E-4	.125	1.03E+14	1.03E-4	8.51E+12	84	-1.18	61	-3.37
	60	-2.44	4.00E-3			1.37E+14			94	-2.35	71	-3.76
	70	-3.69	4.97E-3			1.64E+14			104	-3.66	81	-5.85
	80	-5.79	5.98E-3			1.97E+14			114	-7.56	91	-7.75
	90	-8.20	6.99E-3			2.30E+14			124	-9.97	101	-10.16
1000	25	-0.37	4.39E-3	5.17E-4	.249	1.44E+14	2.13E-4	1.70E+13	66	-2.50	39	-2.70
	30	-0.78	5.36E-3			1.77E+14			71	-2.91	44	-3.11
	40	-1.38	6.37E-3			2.10E+14			76	-3.51	49	-3.71
	45	-1.60	7.41E-3			2.43E+14			81	-4.35	54	-4.31
	50	-4.58	9.41E-3			3.10E+14			91	-6.71	64	-6.91
	55	-6.14	1.04E-2			3.42E+14			96	-8.27	69	-8.47
3000	60	-8.01	1.13E-2			3.74E+14			101	-10.14	74	-10.34
3000	25	-1.61	1.66E-2	1.55E-3	.748	5.47E+14	6.56E-4	5.11E+13	77	-4.30	42	-4.51
	30	-3.47	1.90E-2			6.26E+14			82	-6.16	47	-6.37
	35	-6.10	2.13E-2			7.02E+14			87	-8.79	52	-9.00

FIGURE 1 SKETCH OF OVERALL SYSTEM

FIGURE 2 SCATTERING TUBE MODEL AND NOTATION

FIGURE 3 RANGE OF IMPACT PARAMETERS

FIGURE 4 CORRELATION OF INLET/EXIT PRESSURE RATIOS

FIGURE 5 ATTENUATION DUE TO ARGON-FILLED SCATTERING TUBE

FIGURE 6 SCAVENGING OF ARGON SCATTERING TUBE FLUX
BY CROSS-BEAM OF MERCURY

$$n_{Hg} = 10^{14} \text{ cm}^{-3}$$

$$n_{Hg} = 3 \times 10^{14} \text{ cm}^{-3}$$

$$d = 5 \text{ cm} ; p_2 = 10^{-4} \text{ torr} ; T = 293^\circ \text{K} ; p_{\text{main}} = 10^{-5} \text{ torr}$$

FIG.7 CONDITIONS REQUIRED TO ACHIEVE $(1-f)_{Hg} \times (1-f)_{Ar} = 10^{-6}$ WITH SUFFICIENT n_{Hg} AND w TO DEFLECT ARGON.

FIGURE 8 ISENTROPIC EXPANSION OF MERCURY VAPOR

FIGURE 9. SECTION THROUGH MERCURY CROSSED-BEAM DEFLECTION SYSTEM

APPENDIX

A printout of the program used to evaluate the scattering-tube performance follows. It uses the Sreekanth second-order theory for the density distribution in the scattering tube. A Newton-Raphson iteration is used to find the inlet pressure for a given tube length with prescribed conditions on tube and buffer-chamber temperatures, and on pumping speed. The program is written for the Hewlett-Packard 9825 in HPL (Hewlett-Packard Language) which is the language for this machine and is also available for the newer 9826 machine. A brief review of the program follows.

The variable list identifies variables, where appropriate, as pertaining to McNeeley's or Sreekanth's notation. Default values are loaded in lines 5 and 6, with options to change any of these in lines 10 through 16. The particular run conditions are entered in lines 17 through 21. Note that pressures (in torr) must always be re-entered when asked for because of the automatic conversion to dynes/cm². (This feature could be removed by checking the flag (13) set when no numerical entry is made).

An initial guess for inlet pressure is required, but no great accuracy is necessary. The iteration will usually converge quite quickly, although there were a few cases where the iteration was divergent and the exact inlet pressure had to be determined by single run-through calculations. The iteration was always carried out with 5 segments; that is $N = 5$ in line 12. This would ordinarily determine the inlet pressure with sufficient accuracy to do a 50-segment calculation with no further iterations. The program stops at line 44 for instructions on number of steps (segments) per printed-out value - to keep the print-out table reasonably short. At this point, the special function key, f 6, will print the inlet pressure in torr. The calculation can then be re-run with 50 segments.

An option to plot the number density distribution is offered in line 49. Suitable scales are automatically selected.

The scattering calculation starts at line 81 with default values of the constants being entered, followed by options to change these. The results are printed along with values that would have been obtained without the second order corrections in the density distribution and without the nearly head-on collision contribution.

The automatic file selection in the recording instructions starting at line 127 was used for the initial survey. This section should be modified for general use.

The special function keys are automatically loaded by the program, f 0 through f 6 being useful for operating the program.

COMPLETE LIST OF VARIABLES.

SIMPLE

A mass-ratio (a)
 B β of Srekanth's eqns.
 C ST-Size.
 D Effective Tube Diam. (cm)
 E Probability of Penetrating Tube.
 F Plotting Scale Factor (No. Density)
 G " " " " "
 H Temporary Storage in "chi"
 I Element No.
 J
 K Temporary Storage in "calc"
 L " " " " "chi"
 M Index for printing data on plot.
 N Number of Segments.
 O
 P Pressure at Diffusion Pump, p_s (enter torr)
 Q Mass Flux (gm/sec)
 R $Z[R]$ is start of last interval in f_{dl}
 S Pump Speed (l/sec)
 T Temporary Storage in "Scatter"
 U Av. value of l in each interval.
 V " " " " "
 W $\sum \left(\cos^2 \frac{X^*}{2} - \cos^2 \frac{X}{2} \right) \Delta l$
 X Srekanth's X
 Y Integrand $\cos^2 \frac{X^*}{2} - \cos^2 \frac{X}{2}$
 Z l_m

STRING

A\$[16] Date

ARRAY

A
 B[2] $\beta = B[1]$; $\sigma = B[2]$
 C[0:3] Effusion factor = C[0]; Srekanth's $C_1 = C[1]$
 " " " " " " $C_2 = C[2]$
 D
 E[2] Our Expectation = E[1] McNealey's = E[2]
 F[0:50] $K_n = F[2]$
 G
 H[1:3] Used in Newton-Raphson Iteration.
 I
 J[120] Run No. File
 K[0:3] $K_{n0} = K[0]$; $\bar{K}_n = K[1]$; $k = K[2]$ (Boltzmann)
 L[3] $\tan^2 \theta = L[1]$; $\cos X^* = L[2]$; $\cos X = L[3]$
 M
 N[0:50] Argon Atom No. Density (atoms/cm³) = N_m
 O
 P[0:50] $p_0 = P[0]$; $p = P[1]$; $p_{av} = P[N]$ (enter torr) (dynes/cm²)
 Q
 R[2] Gas Constant = R[1]; $R_g = R[2]$
 S
 T[2] Tube Temp. = T[1]; Chamber Temp. = T[2]
 U[0:3] $\mu = T[0] = U[1] T[1]$ U[2]
 V
 W
 X
 Y
 Z[0:50] Srekanth's $(\gamma - \gamma_0) = Z[1]$; $Z[N] = l_0$

VAR

r1 Plot Indicator

r2 n_m (used for both "Ours" & "McNealey's")

WINDEX MACHINE (DATA)

TAPE LIST.

vrk	0		
#0	6	5722	7000 ← Program
#1	5	102	1000 ← Spec. Fn. Keys
#2	2	960	1000 ← File Record
#3	0	0	1000 ← Spare
#4	0	0	2000 ← J=1 record
#5	0	0	2000 etc.
#6	0	0	2000
#7	0	0	2000

trk	0		
#70	0	0	2000 ← J=67 record
#71	0	0	0

f0: #sto"Output"

f1: #sto"Start"

f2: #sto"Data"

f3: #dsp
"Superimpose";
sfs 1;M+1+M

f5: tnt(-

f6: #flt 4;prtP[
.01/1333;spc3

f10: fnt4f4.0;fo
r J=1to119by 2;
wrt 16;J,J[J],J
+1,J[J+1];next
J;spc3

f11: #sto"N-R"

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0: dsp "          Tik 0:File 0"wait 1000
1: dsp "          LLNL / SCATTERING TUBE"wait 1000
2: dim A,8[2],C[0:3],D,E[2],N,N[0:50],P,PI[0:50],Q,R[2],S,T[2],Z[0:50]
3: dim F[0:50],A[16],B,H[13],K[0:3],L[3],U[0:3],X,J[120];trk 0;ldk 1;list k
4: ldf 2,J[*]
5: ent "Date".A[1]→C[0];5→D[1].38tnf(-16)→K[2];50→N[2].081tnf6→R[1];293→T[2]
6: 1.292tnf(-6)→U[1];.907→U[2];1.1466→C[1];1.356→C[2]
7: "Start":0→r[1]→H
8: ent "To Change Basic Values, Enter 1",r1
9: if r1=0;go "Data"
10: ent "Effusion Shape Parameter =",C[0]
11: ent "Effective Diameter (cm) =",D
12: ent "No. of Segments =",N
13: ent "Gas Const.,R(Cmf2/sec2 deg K) =",R[1]
14: ent "Chamber Temp.(deg K)=",T[2]
15: ent "Viscosity, Enter Multiplier",U[1],"Enter Power",U[2]
16: ent "Sreekanth's C(1)=",C[1],"C(2)=",C[2]
17: "Data":ent "Inlet Pressure (torr)",P[0];P[0].333tnf3→P[0]
18: ent "Tube Temp.(deg K)",T[1],"Desired Length (cm)",H[10]
19: ent "You May Enter Q (gm/sec)",Q
20: cmf 13;if fls13;ent "Pump.Speed(1/s)",S;Q[R[1]T[2]/tnf3S→P;go "Calc"
21: ent "Pumping Speed (1/sec)",S,"At Pressure (torr)",P;P[1.333tnf3→P
22: tnf3→SP/R[1]T[2]→Q
23: "Calc":4Qr(2R[1]T[1])/r1D2C[0]→P[N]
24: U[1]T[1]U[2]→U[0]
25: 4Q/rU[0]D→R[2];sfz 2
26: "Recalc":U[0]2R[1]T[1]/(P[0]D)2→B
27: 3.32tnf(-2)T[1]→K[K/P[0]D→K[0]
28: for I=0 to N
29: P[0]-1(P[0]-P[N])/N→P[1]
30: (K/2D)(1/P[0]+1/P[1])→K[1]→F[1]
31: "Chi":1/3+4C[1]K[1]+16C[1]2K[1]2+8C[2]K[1]2+64C[2]2K[1]24→H
32: H+64C[1]C[2]K[1]23→H;H/(.5+4C[1]K[1]+8C[2]K[1]2)2→X
33: "Zee":(P[1]/P[0])2-1+16C[1]K[0](P[1]/P[0]-1)+32C[2]K[0]2tn(P[1]/P[0])→H
34: 8C[1]K[0](P[0]/P[1]-1)+8C[2]K[0]2tn(P[0]/P[1])2-1)-ln(P[1]/P[0])→L
35: -(H+2R[2]2BXLD)/64R[2]B→Z[1]
36: P[1]/6.64tnf(-23)R[1]T[1]N[1];next I;if abs(Z[N]-H[10])<.05;cfz 2
37: fxd 2;dsp "Tube Length=",Z[N];if fls2;go "M-R"
38: "Output":prt A;if fxd 2;prt "Shape Fact.",C[0];if fxd 0;prt "Segments",N
39: fxd 2;prt "Tube Length",Z[N],"Eff. Diam.",D;if fxd 0;prt "Pump Speed",S
40: fxd 0;prt "Chamb.Temp.",T[2];prt "Tube Temp.",T[1]
*67E7

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41: flt 2:prt "Chamber torr",P/1.333tnf3
42: flt 2:prt "Inlet torr",P[0]/1.333tnf3
43: flt 2:prt "Mass Flux",Q1spc
44: ent "Step Size",C1if C=0;jmp 0
45: prt " Z[I]  N[I] "
46: fnt 1,f6.1,c2,e8.2;for I=0 to N by C1wrt 16.1,Z[I]," ",N[I];next I
47: spc 1:prt " 2      Kn";for I=0 to N by C1wrt 16.1,Z[I]," ",F[I];next I
48: spc 1
49: 0>rlent "To Plot, enter 1",r1
50: if r1=0;sto "Scatter"
51: if fl1;sto "Graph"
52: "Plot":cfs 2;if N[0]/tnfint(log(N[0]))<3;sf 2
53: cfs 3;if Z[N]/tnfint(log(Z[N]))<3;sf 3
54: tnfint(log(N[0]))>F;if fl2;F/10>F
55: tnfint(log(Z[N]))>G;if fl3;G/10>G
56: scl -.2Z[N],1.2Z[N],-.2N[0],1.2N[0];0>rlent "If D62 Plotter,enter 1",r1
57: if r1=1;psc 705;
58: if r1=1;lim -.2Z[N],1.3Z[N],-.2N[0],1.3N[0];xax 0,G,0;yax 0,F,0;sto +2
59: axc 0,0,G,F
60: if fl3;sto +6
61: for I=1 to 5;plt 2IG,0,1;clt -1.3,-1.5;fxd 0
62: if G=1;sto +3
63: if G=10;clt -.5,0;sto +2
64: clt -1,0
65: lbl 2IG;next I;sto +5
66: for I=1 to 6;plt 5IG,0,1;clt -1.8,-1.5;fxd 0
67: if G=1;sto +2
68: clt -.5,0
69: lbl 5IG;next I
70: if fl2;sto +4
71: for I=1 to 10;plt 0,IF,1;clt -3.5,0;if I<10;clt 1,0
72: lbl I;if IF>N[0];I-1;I;plt 0,IF,1;lbl " X10^n",log(F);sto +5
73: next I;sto +4
74: for I=1 to 15;plt 0,2IF,1;clt -3.5,0;if I<5;clt 1,0
75: lbl 2I;if 2IF>N[0];I-1;I;plt 0,2IF,1;lbl " X10^n",log(F);sto +2
76: next I
77: "Graph":plt 0,0,1;clt 1,N;flt 2;lbl "P(0)=",P[0]/1.333tnf3," torr"
78: flt 2;lbl " Q=",Q," gm/sec";fxd 0;lbl " T=",T[I]," deg K"
79: for I=0 to N;plt Z[I],N[I],-2;next I;pen
80: cfs 1;dsp " FINISHED";wait 1000
*20249

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81: "Scatter":rad;5.958+A;1.4+B[1];2.96tnf(-8)+B[2];ent "Mass Ratio=",A
82: ent "Beta=",B[1];"Sigma=",B[2];Z[N]-Dr(A+2-1)/2+Z
83: for K=1 to N;f Z[N]-Z[K]<Z[K]-R;N+K
84: next K;0+M;sf 14;flt 2
85: for K=0 to N-R;Z[N]-(Z[N-K]+Z[N-K-1])/2+U
86: (N[N-K]+N[N-K-1])/2+V
87: (D/2(Z[N]-U))+2+L[1];0+H;1-(A+2-1)L[1];T;if T>0;T+H
88: (-AL[1]+H)/(1+L[1])+L[2]
89: (-AL[1]-H)/(1+L[1])+L[3]
90: (L[2]-L[3])/2+Y
91: YV(Z[N-K]-Z[N-K-1])+N+M;sto +2
92: if frc(K/D)=0;flt 2;sf 14;prt exp(-#B[1]B[2]+2N);cf 14
93: next K;sto 1
94: sf 14;exp(-#B[1]B[2]+2N)+E[1];cf 14
95: "Print":fnt c10,f6.3;wrt 16,"Mass Ratio",A
96: fnt c10,f6.1;wrt 16,"Beta ",B[1]
97: fnt 1,c8,e8.2;wrt 16.1,"Sigma ",B[2];sec
98: wrt 16.1,"Expect. ",E[1]
99: if r1=0;sto +2
100: plt 0;0,1;M+1;M;plt 1,M;flt 2;lbl "Expect.=",E[1]
101: 0+M;for i=0 to N-1;W+(Z[i+1]-Z[i])(N[i+1]+N[i])/2+M;next i
102: W/Z[N]+r2;wrt 16.1,"Av Nm. ",r2;3.619tnf15(P[0]-P[N])/T[1]+r2;sec
103: .5Z[N](1+r(1+(1-A+2)(D/2Z[N]+2))-.25Dr(A+2-1)+r3
104: atn(r(A+2-1))-atn(2Z[N]/D)+r4
105: atn((2Z[N]/AD)r(1+(1-A+2)(D/2Z[N]+2)))+r5
106: r3+.25AD(r4-r5)+r3
107: sf 14;exp(-#B[1]B[2]+2r2r3)+E[2];cf 14
108: wrt 16.1,"McNeeley",E[2];wrt 16.1,"McNeeley",r2;sec ;sf 14
109: fxd 2;prt "log(1-f)",log(E[1]);prt "Proj.X-sec",N[0]B[1]+B[2]+2Z[N];sec
110: cf 14;sto "Record"
111: "N-R":(.5+4C[1])F[N]+8C[2]F[N]+2+2+H
112: H(4C[1]+(32C[1]+16C[2])F[N]+192C[1]C[2]F[N]+2+256C[2]+2F[N]+3)+H[1]
113: 1/3+4C[1]F[N]+(16C[1]+8C[2])F[N]+2+64C[1]C[2]F[N]+3+64C[2]+2F[N]+4+H
114: 2H(.5+4C[1])F[N]+8C[2]F[N]+2+(4C[1]+16C[2]F[N])H[2]
115: (.5+4C[1])F[N]+8C[2]F[N]+2+4+H[3]
116: (H[1]-H[2])/H[3]+H[4]
117: H[4]*3.32tnf(-2)+T[1]/2DPI[N]+H[5]
118: P[N]/P[0]+H[6];8C[1]K[0]+H[7];8C[2]K[0]+2+H[8];2B/H[6]+H[13]
119: X(-H[7]/H[6]+2-2H[8]/H[6]+3-1/H[6])+H
120: H+H[5](H[7](1/H[6]-1)+H[8](1/H[6]+2-1)-ln(H[6]))+H
*19797

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121: BH+X(H[7])(1/H[6]-1)+H[8](1/H[6]+2-1)-1n(H[6])H[13]→H
122: 2H[6]+2H[7]+4H[8]/H[6]+2R[2]↑2H+128R[2]Z[N]B+H[9]
123: (H[10]-Z[N])64BR[2]/D→H[11]
124: H[6]-H[11]/H[9]→H[12]
125: P[N]/H[12]→P[0]
126: sto "Recalc"
127: "Record":0→J;if T[1]>100;J+60→J
128: J+15(ørnd(H[10]/25,0)-1)→J
129: J+5(ørnd(S/1000,0)-1)→J
130: J+abs(ørnd(log(P/1333),0))-1→J
131: if J[J]#0;beep;ent "Filing Error; Ent.J",J;jmp 0
132: fxd 0;dsp "      Ready To Record; J=",J;sto
133: J→J[J];prt "J=",J;spc 3;if J>67;sto +3
134: trk 0;rcf J+3,A,B[*],C[*],D,E[*],N,N[*],P,P[*],Q,R[*],S,T[*],Z[*],F[*],A#
135: sto +3
136: trk 1
137: rcf J-60,A,B[*],C[*],D,E[*],N,N[*],P,P[*],Q,R[*],S,T[*],Z[*],F[*],A#
138: 0→r1;ent "If Last Case, Enter 1",r1
139: if r1=1;trk 0;rcf 2,J[*]
140: dsp "END"
141: end
*51e8

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