Air Ejector Filter Sampler: A Balloon-Borne Collector of Radioactive Stratospheric Debris[1]

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ABSTRACT

The air ejector filter sampler is a balloon-borne device designed to collect particulate matter from very large volumes (10^6 ft^3) of stratospheric air at altitudes between 50,000 and 130,000 ft. This equipment utilizes an ejector pump to pull air through 2 ft^2 of Institute of Paper Chemistry (IPC) #1478 filter paper at rates on the order of 1000 cfm. Use of this unit has permitted an extension of the U.S. Atomic Energy Commission operational sampling program to higher altitudes than previously allowed by battery powered electro-mechanical systems. Performance of the sampler during a successful operational series conducted in 1965 by the U.S. Air Force at San Angelo, Texas, and Eielson AFB, Alaska, has confirmed pre-program estimates of system reliability.

1. Introduction

Stratospheric sampling programs conducted by the U. S. Atomic Energy Commission, the Air Force and others, have made extensive use of balloon-borne dust collectors. These sampling probes commonly employ battery powered pumps and blowers to pull air through a variety of particle collectors such as impactors, filters and electrostatic precipitators. From the beginning, the electro-mechanical air movers have been a principal source of unreliability in all systems. Carbon dust, oil and battery vapors introduce unwanted contamination; motors overheat easily in the thin atmosphere and burn out; blowers do not operate efficiently.

Because of these problems the Atomic Energy Commission has supported the exploration of concepts to improve sampler performance and extend the operating range to altitudes well above 100,000 feet. This work has led to the development of a promising class of high performance samplers powered by an air ejector pump. The dual air ejector filter sampler shown in Fig. 1 is a type that has been tested successfully at altitudes from 80,000 to 120,000 ft. It has been used operationally by the U. S. Air Force since early 1965 at launch sites in Alaska, Texas and Panama.

2. The air ejector pump

The most significant feature of this new class of sampler is the air ejector pump. This relatively uncomplicated device utilizes no moving parts. Power is derived from a tank of compressed gas and batteries are needed only to actuate valves. There is nothing to wear out or burn out.

Design data for the high-altitude ejector pump have been obtained by McFarland in a feasibility study supported by the U. S. Atomic Energy Commission.[2] This work, involving the theoretical development of continuity and momentum equations, supported by appropriate altitude chamber verification tests, is the subject of an article being prepared for publication. Although a comprehensive discussion of ejector pump principles is not within the intended scope of this paper, for the sake of completeness some important relationships are presented here without proof.

Basically, an ejector pump is a simple device. As illustrated in Fig. 2, a jet of high-velocity primary gas injected into a mixing tube will expand to entrain the surrounding secondary air. The resulting turbulent exchange of momentum between the driving (primary) gas and the driven (secondary) air produces a region of reduced pressure and a net flow through the system.

Two types of air ejectors have been described extensively in the literature [e.g., Alves (1951)]. In the first, primary and secondary streams mix in a tube of constant area, while in the second, mixing occurs under constant pressure conditions in a diffuser. The constant-area ejector was chosen for this application because a large fraction of the pressure rise can be developed in the mixing section itself, whereas constant-pressure ejectors are entirely dependent upon the performance of a diffuser. This is felt to be an important consideration because low air densities encountered at high altitudes tend to be detrimental to the performance of a diffuser.

In McFarland's analysis, which is patterned after that used by Chisholm (1960), the flow is considered to be one-dimensional, steady, frictionless and adiabatic. For the case in which the driving and driven gases are both air at the same total temperature, with sonic

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[1] This work was supported by the U.S. Atomic Energy Commission, Division of Biology and Medicine, under Contract AT(11-1)-401.

[2] McFarland, A. R., 1962: Investigation of an air ejector pump for high altitude sampling systems. Report No. 2277, Contract AT(11-1)-401, Litton Systems, Inc., 2003E Hennepin Ave., Minneapolis, Minn.

flow at the primary nozzle (M = 1.0), the continuity and momentum equations can be written in familiar thermodynamic notation:

Continuity

$$\frac{P_{01}}{P_a}\frac{A_1}{A_9}\left(\frac{2}{\gamma+1}\right)^{(\gamma+1)/2(\gamma-1)}+\frac{P_{02}}{P_a}\frac{A_2}{A_9}\mathrm{M}_2\times\left(1+\frac{\gamma-1}{2}\mathrm{M}_2^2\right)^{-(\gamma+1)/2(\gamma-1)}=\mathrm{M}_9\frac{\left(1+\frac{\gamma-1}{2}\mathrm{M}_9^2\right)^{\frac{1}{2}}}{\left(1+\frac{\gamma}{2}\eta_d\mathrm{M}_9^2\right)};\tag{1}$$

Momentum

$$\frac{P_{01}}{P_a}\frac{A_1}{A_9}\frac{2^{\gamma/(\gamma-1)}}{(1+\gamma)^{1/(\gamma-1)}}+\frac{P_{02}}{P_a}\frac{A_2}{A_9}\times\frac{(1+\gamma\mathrm{M}_2^2)}{\left(1+\frac{\gamma-1}{2}\mathrm{M}_2^2\right)^{\gamma/(\gamma-1)}}=\frac{1+\gamma\mathrm{M}_9^2}{1+\frac{\gamma}{2}\eta_d\mathrm{M}_9^2};\tag{2}$$

where

A_1 = area, primary nozzle exit,
A_2 = area, secondary nozzle exit,
$A_9 = A_1 + A_2$ = area, diffuser inlet (and mixing tube),
M_2 = Mach number, secondary nozzle exit,
M_9 = Mach number, diffuser inlet,
P_a = pressure, ambient (altitude conditions),
P_{01} = total pressure, primary gas at primary nozzle exit,
P_{02} = total pressure, secondary air at secondary nozzle exit,
γ = isentropic exponent (air = 1.4),
η_d = diffuser efficiency.

A useful measure of the performance of an air ejector pump is the ratio ϕ of the mass flow rate m_2 of air drawn into the air ejector per unit mass flow rate m_1 of primary gas expended. For the same conditions as assumed for the previous equations, this mass ratio can be expressed as

$$\phi=\frac{m_2}{m_1}=\frac{P_{02}}{P_{01}}\frac{A_2}{A_1}\mathrm{M}_2\left[\frac{1+\gamma}{2\left(1+\frac{\gamma-1}{2}\mathrm{M}_2^2\right)}\right]^{(\gamma+1)/2(\gamma-1)}.\tag{3}$$

Eqs. (1), (2) and (3) have been solved numerically on a Control Data Corporation Model G-15D digital computer using the Newton-Raphson iteration process. The ejector parameter values initially selected were those corresponding to an ejector model being evaluated experimentally, where $\gamma = 1.4$ (air), $A_1/A_9 = 0.01$, $A_2/A_9 = 0.99$ and $\eta_d = 0.50$.

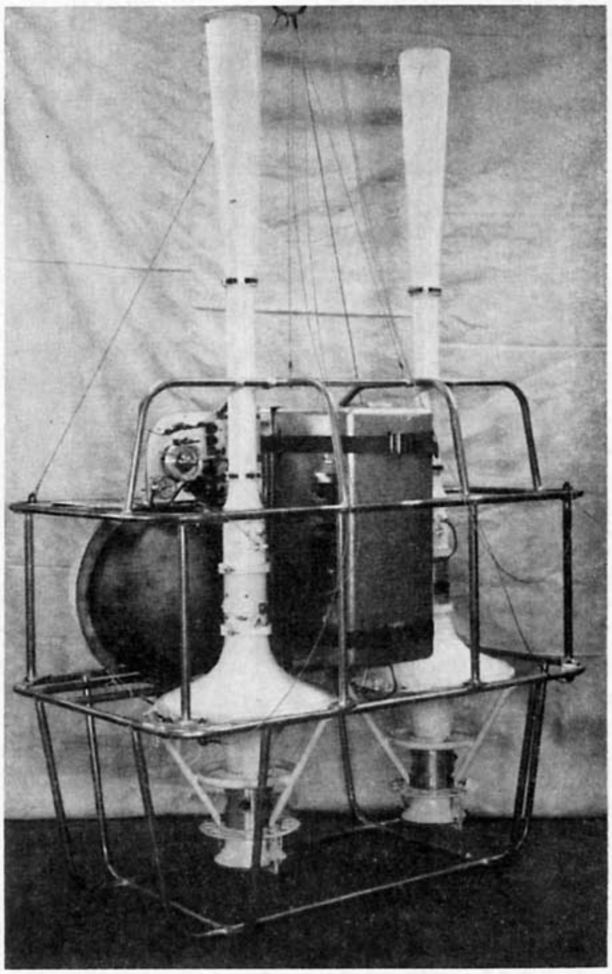

FIG. 1. Air ejector filter samplers in dual configuration for operational flights at 120,000 ft.

Although diffuser efficiency η_d is a function of both altitude and Mach no. M_9, it has been treated as a constant in solving the analytical equations. The value of 50 per cent is suggested by Alves (1951) and subsequent comparisons with experimental data indicate that this value was a good choice.

Plots of Eqs. (1) and (2) showing Mach no. M_2 as a function of the secondary pressure ratio P_a/P_{02} for

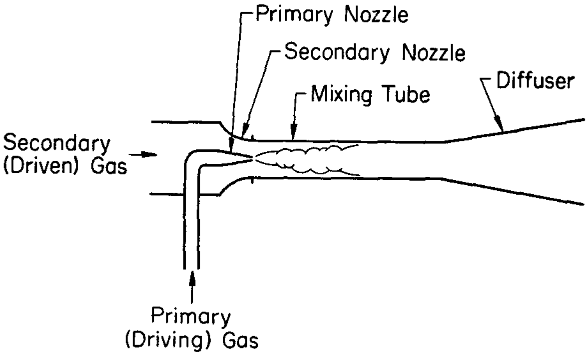

FIG. 2. Constant mixing area ejector pump.

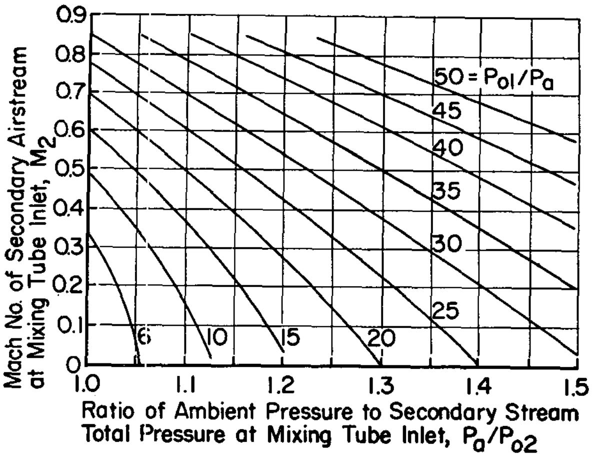

FIG. 3. Theoretical pump performance showing the relationship between Mach number at the mixing tube inlet and secondary pressure ratio for various primary pressure ratios.

constant values of primary pressure ratio P_{01}/P_a are shown in Fig. 3. Similarily, it is possible to solve Eq. (3) and calculate the mass ratio ϕ as a function of P_a/P_{02} for constant values of P_{01}/P_a as displayed in Fig. 4.

It will be noted that the family of curves in Fig. 4 generates an envelope, the upper limit of which is indicated by a dashed line. For a particular pump configuration ($A_1/A_9=0.010$) this line defines the most favorable mass ratios ϕ that can be obtained with optimum combinations of primary pressure ratio[3] P_{01}/P_a and secondary pressure ratio[4] P_a/P_{02}. In order to determine the effect of changes in pump geometry, Eqs. (1), (2) and (3) have also been evaluated with respect to area ratios other than 0.010. In Fig. 5 the dashed curve of Fig. 4 ($A_1/A_9=0.010$) has been redrawn in a comparison with similar curves corresponding to primary nozzle/mixing section area ratios A_1/A_9 of 0.005 and 0.020. This presentation shows that the relationship between mass ratio ϕ and secondary pressure ratio P_a/P_{02} is not a strong function of the area ratio.

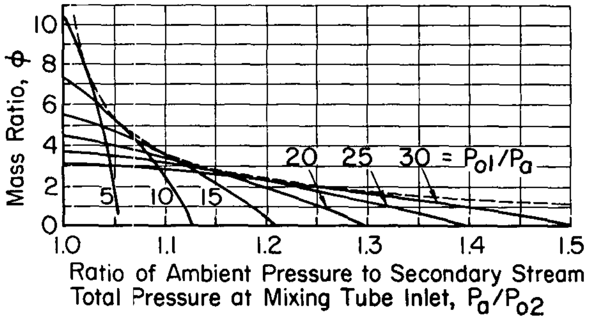

FIG. 4. Theoretical pump performance showing mass ratio as a function of secondary pressure ratio for various primary pressure ratios.

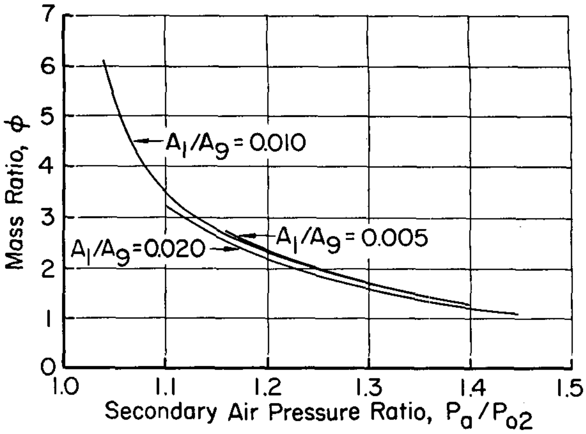

FIG. 5. Optimum mass ratio for different primary nozzle to mixing tube area ratios.

It is interesting to note the absence of scale factors in these relationships. All parameters are given in terms of dimensionless ratios. Performance of the ejector is substantially independent of size, provided geometric and dynamic similarity are observed.

3. Operational filter sampler

Important features of the operational particle sampler (Fig. 1) developed for the U. S. Atomic Energy Commission and flown by the U. S. Air Force during 1965 and 1966, are shown in Fig. 6. Designed for

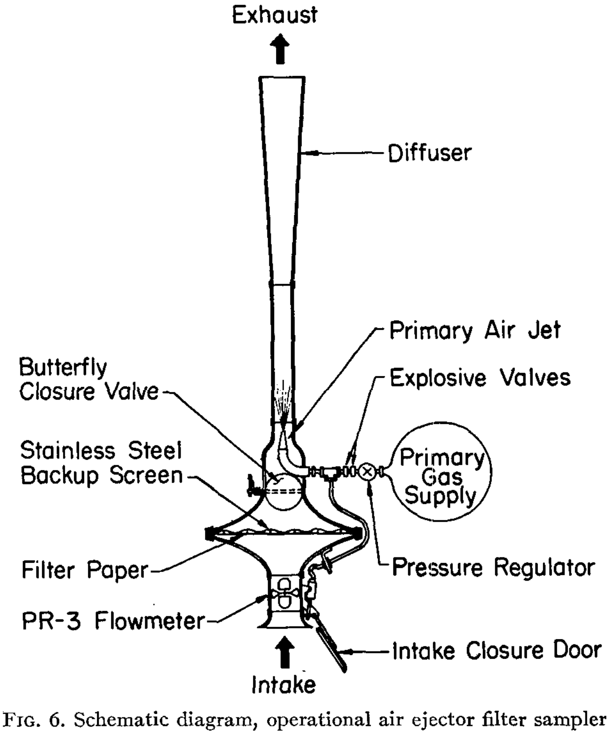

FIG. 6. Schematic diagram, operational air ejector filter sampler.

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[3] Primary pressure ratio P_{01}/P_a is a controllable parameter dependent upon the pressure at which the driving (primary) gas is injected.

[4] Secondary pressure ratio P_a/P_{02} is essentially equal to the pressure ratio P_a/P_b developed across a filter or other resistance upstream of the pump as a consequence of the induced secondary air flow through the collector.

operation at altitudes up to 130,000 ft, each sampler is able to process (at 120,000 ft) approximately 10^5 ft^3 of air at sampling rates on the order of 1000 ft^3 min^{-1}.

In operational use the dual sampler unit is lifted to a predetermined sampling altitude where a timer-programmer or radio-command signal actuates an explosive valve to initiate the flow of primary (driving) gas through the pump. Simultaneously, a pneumatic cylinder opens the inlet door and a uniform flow of air through the sampler is quickly established. At an operating altitude of 120,000 ft the primary gas (40 lb of nitrogen) is expended in approximately 120 min. Upon termination of sampling, the payload is cut loose from the balloon and returned to earth via parachute.

Filter collector characteristics. In order to facilitate direct comparisons with data obtained from other particle collectors such as the Direct Flow Sampler (Wood, 1964), the ejector sampler utilizes IPC #1478 filter paper.[5] This collection medium is widely used in sampling programs, analysis techniques are established, and particle collection efficiency is acceptably high.

A filter area of 2 ft^2 has been selected as representing a reasonable compromise between two opposing factors: 1) from the analysis standpoint, minimum filter area is desirable to reduce the amount of interferring background contamination introduced during manufacture and handling; and 2) from the sampler design standpoint, a large filter area is desirable to provide minimum resistance against which the pump must operate. Since sampling rate is a sensitive function of this resistance, it is important to consider filter impedance when adjusting the unit for operation at a particular altitude. The pressure-flow relationships of 2 ft^2 of IPC filter paper are presented in Fig. 7.

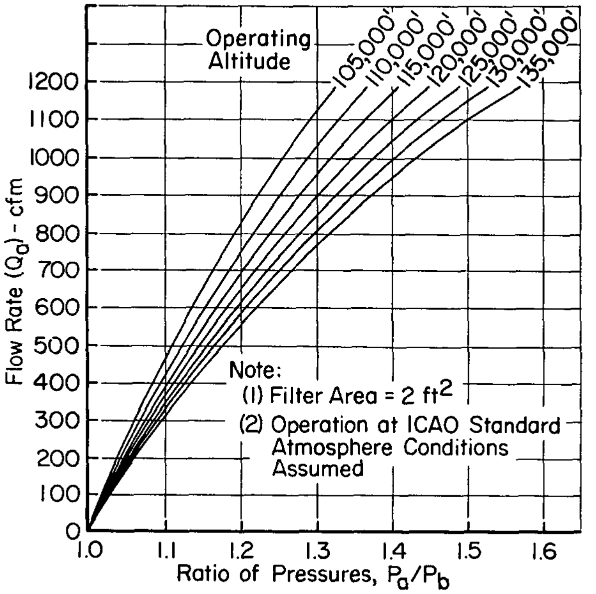

FIG. 7. Pressure drop characteristic of IPC #1478 filter paper. Pressure ratios are developed at various altitudes as a function of volume flow through 2 ft^2 of filter.

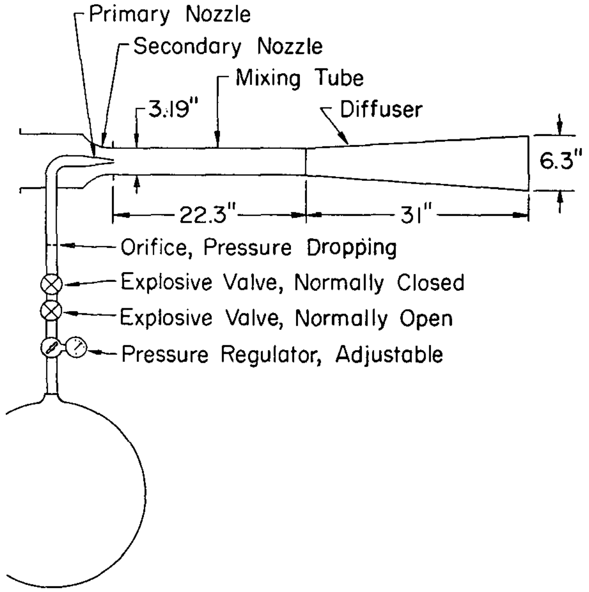

FIG. 8. Schematic diagram of the ejector pump.

Pump characteristics. Important features of the ejector pump are shown in Fig. 8. The primary nozzle has a 0.30-inch throat with an outside contour designed to permit the secondary air flowing over that surface to have a stable boundary layer. Gas from the primary nozzle discharges at the mixing tube entrance plane.

The interior contour of the secondary nozzle is an elliptical section similar to the ASME long-radius nozzles and it has a throat diameter of 3.19 inches.

The mixing tube has a 3.19-inch inside diameter and is 22.3 inches long. This length-to-diameter ratio of 7 is felt to represent the best compromise between a long length required for a complete mixing and a short length minimizing frictional pressure losses. This value is also recommended by Keenan *et al.* (1950).

For pressure recovery the ejector is terminated by a 3-deg half-angle diffusing cone having an exit diameter of 6.3 inches.

A spherical titanium tank with an enclosed volume of 4655 cubic inches contains the primary driving gas. Weighing 50 lb empty, this tank can hold up to 40 lb of nitrogen compressed at 3000 psi.

Titanium is corrosion resistant and able to withstand severe thermal shock. Because of this and its exceptionally low thermal conductivity it is possible to use a convenient filling method in which the required weight of nitrogen is added as a liquid. Subsequent evaporation leaves the tank pressurized at the proper operating level without the use of high pressure pumps and gas-drying systems.

To achieve the desired performance, primary gas

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[5] Developed by the Institute of Paper Chemistry, Appleton, Wisc.

must be expended at a selected constant rate, as dictated by the pumping speed required and the operating altitude. The flow of primary gas is controlled by an adjustable, two-stage pressure regulator and a pressure-dropping orifice as shown in Fig. 8. In normal operation, the regulator maintains a constant downstream pressure on the order of 40-80 psi as the reservoir pressure bleeds down from 3000 psi. The orifice subsequently drops the pressure further, to a value yielding the desired primary pressure ratio P_{01}/P_a at the nozzle exit. Substitution of various-size, calibrated orifices adjusts the primary pressure for operation at different sampling altitudes. Flow is initiated and stopped by two expendable explosive values activated by an adjustable programmer.

Flow measurement. Meaningful interpretation of data from a sampling flight requires a determination of the total volume processed. On the ejector sampler, volume flow is measured by a low-drag turbine anemometer[6] mounted at the sampler inlet. Flow rate is telemetered to a ground receiving station and on-board recorders provide alternate access to information in the event of a telemetry failure. Although some particle loss occurs through impaction on the turbine blades and straightening vanes, this has been determined experimentally to be less than 2 per cent.

4. System operating parameters

An important operating variable is the total pressure P_{01} at which the driving gas is expelled from the primary nozzle of the ejector pump. For a given operating altitude and filter area, this pressure setting will determine the sampling rate Q_a and the volume of ambient air pumped by each pound of primary gas. Fig. 9 presents characteristic performance curves of the ejector pump, showing the relationship of sampling rate Q_a and secondary pressure ratio P_a/P_{02} for different settings of primary gas pressure (expressed as the primary pressure ratio P_{01}/P_a).

Superimposed upon the pump curves are the experimentally determined load characteristics of an IPC filter collector with area of 2 ft². Since the pressure ratio P_a/P_{02} across the pump is approximately P_a/P_b, the pressure ratio across the filter, the intersection of the appropriate filter load curve and a selected pump primary pressure ratio defines an operating point of the pump-filter combination.

The curves shown in Fig. 9 can be used in a number of ways. If for example, we choose to run the pump at a primary pressure ratio of 20, the operating point defined by the intersection of appropriate filter and pump curves yields a sampling rate of 650 cfm at 110,000 ft (solid lines) or 570 cfm at 130,000 ft (dashed lines). If we wish to increase the sampling rate at 110,000 ft to 1000 cfm in order to shorten the sampling time, the curves show that this can be achieved by increasing the primary gas pressure to obtain a ratio, $P_{01}/P_a=49$.

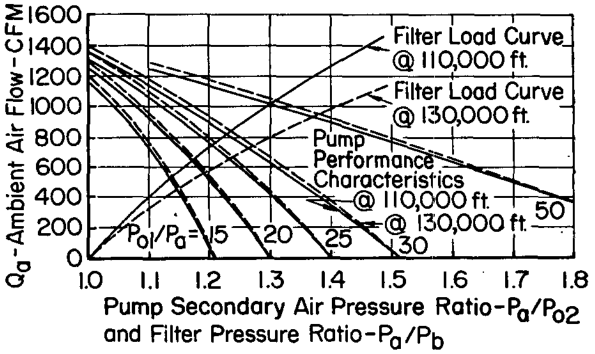

FIG. 9. Operating characteristics of the air ejector filter sampler.

Not immediately evident from this presentation is the fact that an increase in sampling rate obtained by raising the primary gas pressure may incur a penalty in the form of a lower mass ratio, i.e., less air will be pumped by each pound of primary gas. This fact can be expressed in another way by stating that for a given pump-collector configuration, it generally takes more primary "fuel" to sample a given volume of stratospheric air in a short time than would be required over a longer time.

Noting that 650 and 1000 cfm (at 110,000 ft) generate pressure ratios P_a/P_{02} of 1.17 and 1.29 across the pump, respectively, the corresponding mass ratios (pounds of air pumped per pound of compressed nitrogen) may be found by referring back to the appropriate curves of Fig. 4. At 650 cfm, $\phi=2.4$ lb air (lb nitrogen)$^{-1}$; at 1000 cfm, $\phi=1.7$ lb air (lb nitrogen)$^{-1}$.

5. Operational results

The ejector powered filter sampler was phased into the U. S. Air Force operational schedule on a monthly basis in March 1965. The initial series consisted of eight flights to a nominal sampling altitude of 120,000 ft, six of which were launched at San Angelo, Texas, and two from Eielson AFB, Alaska. Each payload consisted of two samplers and instrumentation in the configuration shown in Fig. 1. In effect, this provided 16 tests. Results are summarized in Table 1.

As shown, there were no instances when a sampler failed to operate. Omitting Flight T-1087-A from consideration as not representative of normal sampler operation due to an error in pre-flight adjustment of the pressure regulators, performance values for the six month test period averaged as follows:

Sampling interval	120 min,
Sampling rate	880 ft³ min^{-1},
Total ambient volume	105,900 ft³,
Equivalent volume @ S.T.P.	550 ft³.

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[6] Wood, R. C., L. R. Graf and L. V. Nelson, 1965: Development and calibration of the PR-3 flowmeter. Report No. 2723, Contract AT(11-1)-401, Litton Systems, Inc., 2003 East Hennepin Ave., Minneapolis, Minn.

Table 1. Performance of the air ejector filter sampler in the first operational series.

Flight no.	Date	Altitude (1000 ft)	Sampler no.	Sampling interval (min)	Sampling rate (ft^3 min^{-1})	Ambient volume (ft^3)	Volume @ S.T.P. (ft^3)	Specific radioactivity*
San Angelo, Texas								
T-1028-A	3/26/65	119.9	1	108	854	92,300	468	43
			2	108	873	94,300	480	60
T-1038-A	4/22/65	119.0	1	114	938	107,000	558	41
			2	111	940	104,300	544	48
T-1046-A	5/20/65	117.4	1	121	806	97,500	534	62
			2	121	835	101,000	553	69
T-1066-A	6/27/65	117.5	1	124	787	97,600	538	59
			2	124	708	87,700	484	50
T-1078-A	7/24/65	120.0	1	126	825	100,600	498	50
			2	122	842	106,000	525	43
T-1087-A	8/24/65	120.5	1	116	578	67,000	324	56
			2	116	392	45,400	216	86
Eielson AFB, Alaska								
A-37-A	7/22/65	118.5	1	128	960	123,300	634	102
			2	124	977	121,000	623	92
A-39-A	8/16/65	119.1	1	128	997	127,000	639	92
			2	126	978	123,200	620	92

* Total gamma, counts per minute per thousand standard cubic feet of air. A more detailed explanation of these data is available in USAEC Health and Safety Laboratory Reports (HASL-161, 164) from which these values were obtained.

The operating altitudes listed for individual ascents (Table 1) are averages derived from telemetered data. Due to the fact that the balloon system gross weight decreases steadily during the sampling period as 70–80 lb of nitrogen are expended, the altitude at termination is nearly always higher than the level at which sampling started. With respect to the flights summarized in Table 1, the average increase in altitude was 1700 ft.

In selecting operating parameters for these flights, we have arbitrarily chosen a 2-hr sampling period as the maximum consistent with reasonable tracking and recovery costs. Accordingly, the pump has been adjusted for a sampling rate that will completely expend all compressed nitrogen "fuel" within that period. It is possible, however, to shorten the sampling period and achieve higher flow rates if a reduction in the total volume processed can be tolerated. Conversly, lower sampling rates would yield a somewhat larger total volume over a longer sampling period.

6. Future work

The simplicity and reliability of ejector-powered sampling probes suggest avenues of approach to other areas of scientific interest. For example, this laboratory has designed and tested an ejector-powered cascade impactor that collects stratospheric dust in three size fractions on two impactor stages and a filter[7]. Another sampler to be flight tested in the summer of 1966 will operate at 140,000 ft to obtain samples of extraterrestial debris for electron microscope, electron mirror microscope and nuclear magnetic resonance analyses.

Also under investigation is a lightweight gas generator that will ultimately replace the high pressure nitrogen system now being used as the power source for the ejector pump. This system will utilize the catalytic decomposition of hydrazine-base mixtures to generate the required primary gas flow. Weight savings will result through more efficient utilization of "fuel" and elimination of the relatively heavy, high-pressure storage vessels.

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[7] Zeller, H. W., 1965: Large volume impactor collector. Report No. 2893, Contract AT(11-1)-401, Litton Systems, Inc., 2003 East Hennepin Ave., Minneapolis, Minn.