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EVALUATION OF SYSTEMS FOR CONTROL OF EMISSIONS FROM ROCKET MOTORS - PHASE I

U.S. Environmental Protection Agency
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EVALUATION OF SYSTEMS FOR CONTROL OF EMISSIONS FROM ROCKET MOTORS - PHASE I

by

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NOMENCLATURE

Latin

A = area, m^2

A_{exit} = area of nozzle exit, m^2

A_T = area of nozzle throat, m^2

a = number of scoop banks

c = velocity of sound, m/sec

F = rocket thrust, newtons (N)

H = specific enthalpy, kcal/kg

k = velocity reduction factor

k_a = individual 'k' for a scoop bank

k_T = overall velocity reduction factor

Ma = Mach number

MW = molecular weight, g/g mole

m_1 = mass flow rate of water in stream before scoop, kg/sec

m_2 = total mass flow rate of water, sum of incoming mass flow rate and reversed mass flow rate, kg/sec

m_3 = mass flow rate of water after scoop, kg/sec

P = pressure, atm

Q_A = actual volumetric flow rate, m^3/sec

Q_N = normal volumetric flow rate, m^3/sec

R = gas constant = $1.987 \frac{\text{cal}}{\text{g mole °K}}$ (Chapter 4)

$= 0.082 \frac{\ell - \text{atm}}{\text{g mole °K}}$ (Appendix)

T = temperature, °K

v = velocity, m/sec

V_1 = droplet velocity before scoop, m/sec

V_2 = final droplet velocity after mixing with reversed stream, m/sec

w = mass flow rate, kg/sec

Δw_ℓ = rate at which water is evaporated, kg/sec

x = area ratio of scoop inlet to duct cross-section, or mass fraction of water reversed

y = fraction of "m_1" being extracted at steady state

SUBSCRIPTS

0 = rocket chamber

1 = plane 1 on Figure 4-1

2 = plane 2 on Figure 4-1

g = gas

ℓ = liquid

ns = gas other than steam

r = rocket exhaust

st = steam

GREEK

γ = specific heat ratio

θ = angle between scoop inlet and main stream, degrees

ρ = density, g/cm^3

ϕ = angle between scoop outlet and main stream, degrees

ABSTRACT

Design studies related to the control of emissions from solid rocket test firings are presented in this report. Literature in the subject area and contact with those installations treating rocket exhausts are summarized. A pilot scale scrubber currently in operation on a 2.22×10^4 newton (5,000 lb) motor at the Air Force Rocket Propulsion Laboratory in Edwards, California is examined.

If a similar scrubber is used on a large engine (e.g. 2.00×10^6 newton or 450,000 lbs), the amount of liquid required to lower the exhaust velocity is quite high. As a remedy, the installation of scoops is proposed to recycle the liquid. Theoretical performance characteristics for the scoops are derived, and an experiment to test their utility is proposed.

Work is still in progress on designing such an experiment and in devising other methods, involving both wet and dry systems, for reducing the exhaust velocity and temperature.

Section 1
INTRODUCTION

Executive Order 11507 and Air Force Regulation 19-1 direct the Air Force to reduce air pollution resulting from its rocket propulsion research and development activities. In addition, the San Bernardino (California) Air Pollution Control District has ruled that rocket tests of less than five minutes duration will be exempt from emission standards with the exception of the release of halogenated compounds.

In order to comply with these orders, the Air Force Rocket Propulsion Laboratory (A.F.R.P.L.) at Edwards, California has contracted with the Environmental Protection Agency (E.P.A.) to "define the technology required for reducing the gaseous and particulate emissions from rocket motor firings." The primary emissions to be controlled are particulates (Al_2O_3) and the gases CO, HCl and HF, which result from solid rocket motor firings. The E.P.A., in turn, has contracted with A.P.T. (Air Pollution Technology), Inc. to perform Contract No. 68-02-1328, Task No. 8, concerning "Evaluation of Systems for Control of Emissions from Rocket Motors."

This report was prepared by A.P.T., Inc. as required in E.P.A. Contract 68-02-1328, Task No. 8.

The object of the task effort was to conduct an engineering study of existing systems and equipment used to remove gaseous and particulate matter from effluent gas streams to determine what systems might be applicable to cleaning the exhaust from test firing of rocket motors. The primary emissions requiring control are CO, HCl, and HF gases and AL_2O_3 particles. Contact was to be made with the Air Force Rocket Propulsion Laboratory at Edwards, California for additional information on the emissions from rocket motors.

Work on the development of scrubber technology for the control of rocket exhaust is continuing under Task No. 9 of Contract E.P.A. 68-02-1328.

Section 2
SUMMARY AND CONCLUSIONS

The evaluation of systems for control of emissions from rocket motors has been partially completed at this time. The study indicates that the type of scrubber now in operation at A.F.R.P.L. as a pilot system requires an excessive amount of water if scaled up for a rocket of larger thrust. Therefore, if water or some other scrubbing liquid is to be utilized for the purposes of cooling, slowing and scrubbing the exhaust, then some method for reducing the liquid used must be devised.

SURVEY OF EXISTING SYSTEMS

A literature search was carried out to evaluate the present technology of treating exhausts from rockets. Utilization of the resources of the Air Pollution Technical Information Center and the Defense Documentation Center uncovered just one report directly applicable to this study. The system described therein, which served as the design basis for the pilot scrubber at A.F.R.P.L., was discussed and evaluated. Governmental installations and private organizations which have had experience in handling exhausts from rockets were contacted, and information gained from them summarized.

GENERAL MOMENTUM AND ENERGY BALANCES

Momentum and energy balances were performed on a straight-through scrubbing system using liquid injection, similar to the pilot scrubber. Initial conditions were obtained primarily from data supplied by A.F.R.P.L., and calculations were carried out for three thrust levels, 2.22×10^4 N (5,000 lbs), 3.78×10^5 N (85,000 lbs) and 2.00×10^6 N (450,000 lbs).

MOMENTUM EXTRACTION AND REINJECTION

In order to reduce the quantity of liquid needed to lower the exhaust velocity to some specified level, it was proposed that scoops be placed inside the scrubber duct. These devices would remove momentum from the stream in the form of water droplets, which would then be turned around and reinjected at an angle opposing the gas flow. The theoretical effectiveness of the scoops was modeled and found to depend on the outlet angle and the area ratio of scoop inlet to duct cross-section. An experiment is to be carried out on the pilot scrubber to test the theoretical expressions.

CONCLUSIONS

1. A straight-through scrubber requires an excessive amount of water for larger solid motors. Therefore, a method of reducing that quantity must be devised.
2. Scoops provide one simple means of accomplishing this objective.
3. The scoop idea should be tested experimentally on on the pilot system, and a program to achieve this should be planned.

4. The proper placement of scoops or any other obstruction in the flow path depends heavily on the extent of the supersonic core of gas. In this region the exhaust maintains its extreme velocity and temperature conditions, whereas gas outside the core is considerably slower and cooler.
5. Other methods, involving both wet and dry systems, for lowering the extreme velocity and temperature of the exhaust must be studied.

Section 3
SURVEY OF EXISTING SYSTEMS

The resources of the Air Force Rocket Propulsion Laboratory (A.F.R.P.L.), the Air Pollution Technical Information Center (A.P.T.I.C.) and the Defense Documentation Center (D. D. C.) were utilized to survey the literature in this field and to contact those government installations and private companies which have had experience in treating rocket test firing emissions, or in handling high temperature, high velocity gases. The information thus gained is summarized in the remaining material of this section.

The only publication which is directly applicable to the present study is by Garrett (Garrett et. al., 1972). This report served as the design basis for the pilot scrubber presently installed on the 2.22×10^4 N (5,000 lb) test engine at A.F.R.P.L. Thus, it may be considered as the state of the art in the field of rocket exhaust scrubbing.

As can be seen in Figure 3-1, the rocket exhaust is collected by a diffuser which ejects it into the spray chamber. An aqueous solution of potassium hydroxide (KOH) is introduced at this point to cool the exhaust by evaporation and to reduce its velocity by absorption of momentum. These processes continue through the length of the mixing chamber, and the intimate contact between the liquid and exhaust provides the opportunity to scrub out the pollutants. As the gas velocity decreases, more liquid settles to the bottom of the duct. What does not is removed by a massive packing entrainment separator. Wastewater drains from the system to an evaporation pond. The exit gas and wastewater are sampled to determine the effectiveness of the unit. A number of pressure, temperature and flow sensors are used to monitor the fluid mechanics of the system.

Garrett set up general momentum, energy and material balances which he solved by computer for a number of different propellants, thrust levels, scrubber duct diameters and mass ratios of scrubbing liquid to rocket propellant. The results of these calculations formed the basis for the selection of a 91.5 cm (3 ft) diameter mixing duct for a 2.22×10^4 N thrust solid motor.

Figure 3-2 shows Garrett's predictions for pressure rise through the scrubber, velocity and temperature at the scrubber exit and the concentration of potassium salts in the scrubber effluent, all as functions of the liquid-to-propellant mass ratio. It can be seen that the addition of scrubbing fluid has a marked effect on the exit velocity and on a portion of the potassium salts curve. After about eight grams of water per gram of propellant has been injected, additional water has a much smaller effect on the potassium salts concentration.

In actual practice at A.F.R.P.L., a high velocity core of gas existed throughout the entire 20 meter (65.5 ft) length of the scrubber. This gas was harmful to the entrainment separator and also passed through untreated, because liquid droplets were unable to penetrate to it. The problem was solved by installing a core buster - in this case, a piece of angle iron. This device broke up the core so that it underwent the same treatment as the remainder of the exhaust.

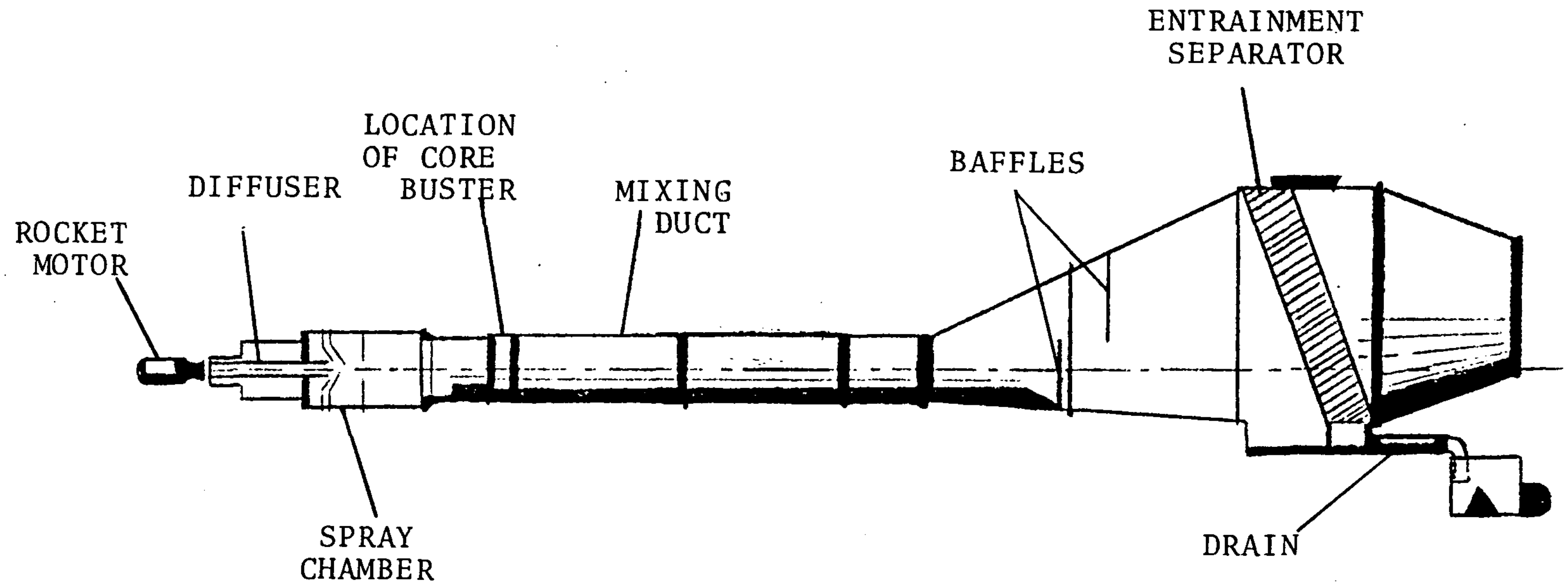

FIGURE 3-1 - Diagram of pilot scrubber at A.F.R.P.L.

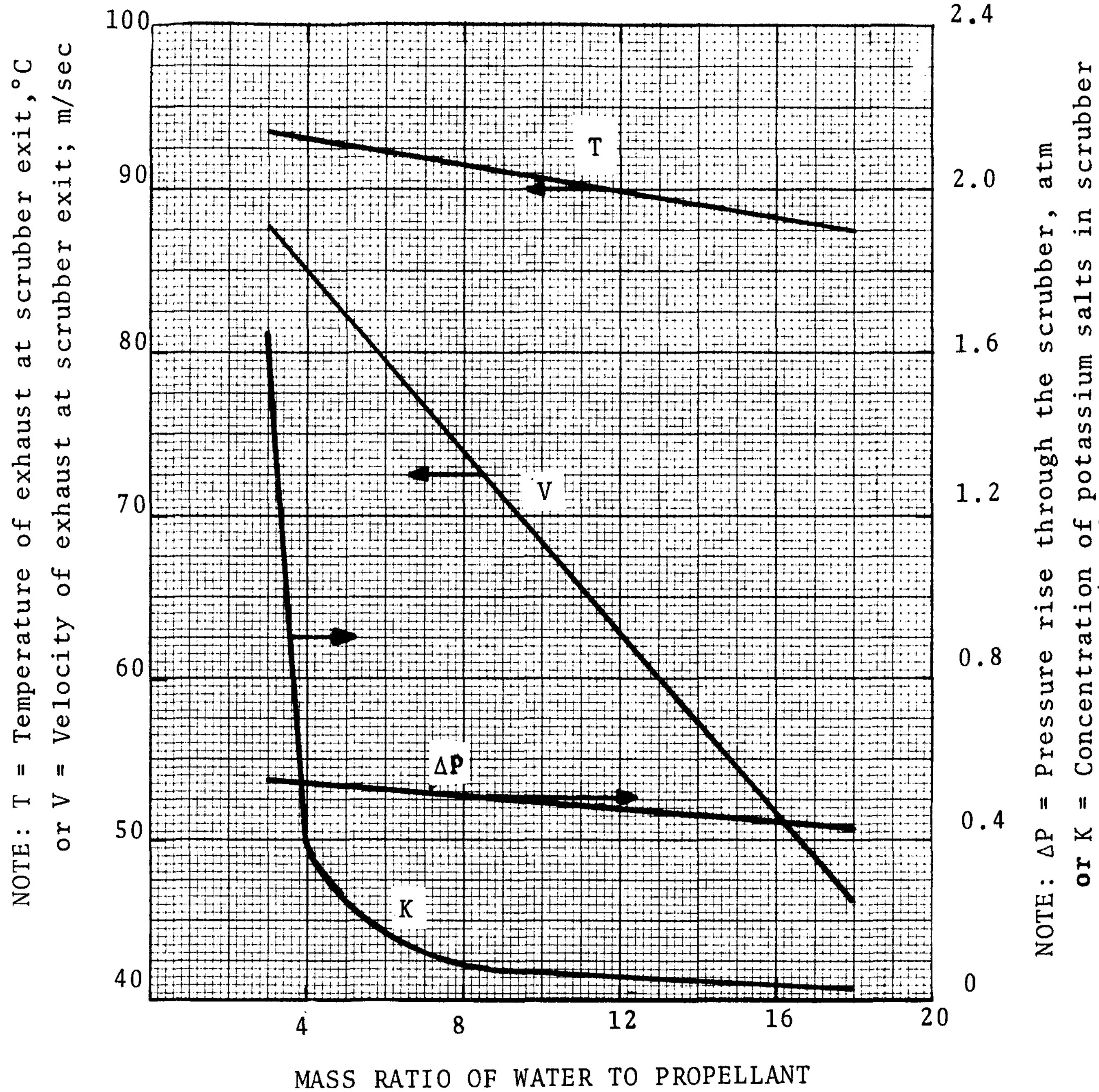

FIGURE 3-2 - Predicted effect of water loading on performance of scrubber for 2.22×10^4 newton (5,000 lb) solid rocket (Garrett). Duct diameter is 0.91 meters (3 feet).

One method which can be used to reduce the exhaust velocity to subsonic levels is by means of a diffuser. Basically, if the diffuser is long enough (L/D > 8) and the back pressure is high enough, the diffuser should produce the same effect as a normal shock. Most supersonic diffusers are used to produce high altitude conditions at the rocket nozzle exit. The pressure of one atmosphere is then high enough to allow the diffuser to decelerate the exhaust to subsonic values. Roschke et. al (1962) made theoretical and experimental studies of diffusers for simulation of high altitude flight conditions. One of the conclusions reached was that predicted phenomena are not necessarily verified by experiments.

Roschke ran his test on a 2.67×10^4 N (6,000 lb) thrust motor. The diffuser was cooled by a water jacket; yet temperatures in the metal reached as high as 920° K.

Information regarding the experiences of other installations treating rocket exhaust is sketchy because no reports on them have been published. A description of each of these systems follows:

1. The Naval Ordnance Station, Indian Head, Md. tested a rocket whose nozzle pointed upward and which released its exhaust at 2,200-2,300° K. The gas entered a holding tank 7.62 m (25 ft) long and 1.83 m (6 ft) in diameter, with nozzles located along the center. The holding tank volume equaled the exhaust volume produced by one second of burn. A spray type scrubber followed. The design was faulty in that it did not

account for all of the gas coming out of the rocket at once.

On larger motors it was found necessary to place baffles 9-12 m (30-40 ft) from the horizontally fired rockets. An open system was used, with a fan between the pre-cooler and the scrubber because the pressure build-up in a small closed system was too great to handle.

2. Arnold Engineering Developement Center, Arnold AFB, Tn. has worked with closed systems and found there will be back pressure. It has been observed that the AL_2O_3 particles emitted from solid motors are largely in the sub-micron range. A scanning electron microscope reveals that many of the particles are spheres (some are hollow) and some are plates.

   Growth of HCl does not occur by self-nucleation. Instead, the solid particles and water combine, followed by condensation of HCl onto the aggregate.

3. Aerojet Liquid Rocket Company, Sacramento, Ca. has operated a scrubber system for six to seven years, handling thrusts from 4,400 N to 1.58×10^5 N (1,000 to 35,000 lbs). Burn times for the fluorine-hydrazine liquid propellant used lasted anywhere from 20 to 2,000 seconds.

   The exhaust gas enters a supersonic diffuser 10.7-12 meters (35-40 ft) long at Mach number 3-4 and at a temperature of 1,900-3,300°K. The diffuser is surrounded by a water-cooled jacket, but no water is injected into the diffuser.

Ductwork 1.83 meters (6 feet) in diameter follows, with expansions to 2.44 meters (8 ft) and then to 3.66 meters (12 ft). These sections extend for several hundred meters. Water is introduced here to cool, slow and scrub the exhaust. A series of screens is positioned at the end of this section to act as an entrainment separator. Aerojet claimed complete removal of fluorine by means of this system.

4. Atlantic Research Corporation, Alexandria, Va. has studied the use of a magnesium laser to react with toxic chemicals. The products of the reaction are then dissolved in water.

   Experience at Atlantic Research has shown that:

   A. The temperature and pressure changes caused by a diffuser also cause a shift in the equilibrium concentrations of the exhaust components.

   B. Thus far, stainless steel equipment has been used. At high temperatures HF (which is much more toxic than HCl) reacts with the metal at the walls to produce a fluoride coating. However, this coating is removed by the Al_2O_3 particles by abrasion, thus exposing more clean surface. Hence, an erosion problem exists.

Concern was expressed that oxygen added to the system would cause an explosive reaction with carbon monoxide and hydrogen at the elevated temperature. It was also stated that proper diffuser design involves problems with cooling, materials and flow rates which require the aid of a diffuser design expert.

5. Hercules, Inc., Magna, Utah operated an exhaust treatment system eight to ten years ago in connection with a subscale motor, whose mass flow rate was 4,500 g/sec. It ran at a simulated altitude of 21,000 meters, where the ambient pressure is 0.10-0.14 atm. The main interest of the study was in removing beryllium oxide particles of an unknown size distribution. The motor had a 10:1 expansion ratio, the temperature at the nozzle exit was 2,000-2,500°K, and the velocity at that point was about 2,600 m/sec. A straight walled supersonic diffuser 137 cm long and 25.4 cm in diameter followed. A series of water jets impinging on the outside kept the diffuser cooled. However, a number of problems which were never completely satisfied were encountered. The most prominent of these was sizing the diffuser to match the mass flow rate from the motor. During the shutdown transient the diffuser broke down as the mass flow rate decreased. A nitrogen purge was introduced to help counteract this effect. The pressure rise across the diffuser was a maximum of about 0.3 atm; no water was injected into the diffuser.

A long quench duct with spray heads to cool the gas from about 980°K was followed by a vertical cyclone scrubber whose inlet diameter was 35.2 cm. A removal efficiency of beryllium oxides of 99.9% by weight was claimed. The gas then entered a cooling tower through a 38 cm diameter duct at a temperature of 370-420°K. A total of 102 ℓ/sec of water was sprayed in the tower, cooling the exhaust to 322°K and lowering its velocity to 58 m/sec at the tower exit.

Section 4

GENERAL MOMENTUM AND ENERGY BALANCES

The firing of a rocket motor produces an exhaust stream of extremely high velocity and temperature. Momentum and energy must therefore be transferred from the exhaust in order to protect the treatment equipment from severe conditions and to facilitate the scrubbing process.

The gas properties at the nozzle exit plane give the initial state of the exhaust, which then must be altered to some specified final state. Data supplied by A.F.R.P.L. for solid motors of three different thrust levels are sufficient to calculate nozzle exit conditions. The data, for thrusts of 2.22×10^4 N (5,000 lb), 3.78×10^5 N (85,000 lb) and 2.00×10^6 N (450,000 lb) appear in Tables 4-1 and 4-2. Equations used to find the calculated values of Table 4-1 are presented in the Appendix.

Consider a scrubbing system such as the one at A.F.R.P.L. The water or scrubbing liquid which is injected in the spray chamber lowers the gas velocity and temperature. Application of a momentum balance provides information concerning the amount of water needed to absorb the momentum of the gas, while an enthalpy balance tells how much of the injected water must evaporate to bring down the temperature.

A schematic diagram of an A.F.R.P.L.-type system is shown in Figure 4-1. Assumptions are made that:

1. Liquid enters between planes 1 and 2 in a radial direction, thus making no contribution to x-momentum.
2. There are no frictional losses.
3. The gas and liquid velocities are equal at plane 2.
4. There are no radial variations in stream properties.
5. Inbled air at plane 1 is neglected.

The applicable form of the momentum balance can thus be written as:

$$F + P_1 (A_2 - A_1) = P_2A_2 + w_2v_2 \quad (4\text{-}1)$$

where F = rocket thrust, newtons
P = pressure, atm
A = area, m^2
w = mass flow rate, kg/sec
v = velocity, m/sec
subscript 1 = plane 1
subscript 2 = plane 2

If $P_1 = P_2$, Equation (4-1) reduces to:

$$F = P_1A_1 + w_2v_2 \quad (4\text{-}2)$$

If P_1A_1 is negligibly small when compared to w_2v_2, Equation (4-2) can further be reduced to:

$$F = w_2v_2 \quad (4\text{-}3)$$

The term "w_2" consists of flow from both the rocket and the liquid.

$$w_2 = w_r + w_\ell \quad (4\text{-}4)$$

TABLE 4-1: SOLID ROCKET MOTOR CHARACTERISTICS

GIVEN VALUES	2.22×10^4 N (5,000 lbs)	3.78×10^5 N (85,000 lbs)	2.00×10^6 N (450,000 lbs)
Chamber Pressure (atm)	68.0	68.0-204	95.2-163
Atmospheric Pressure(atm)	0.898	0.898	0.898
Burning Duration(sec)	30	75	60
Nozzle Exit Temp.(°K)	2112	1460	1460
Nozzle Throat Dia.(m)	-	0.206	0.381
Nozzle Exit Dia.(m)	-	0.711	1.524
Exhaust Flow Rate(kg/sec)	8.55*	142	748
Specific Impulse (m/sec)	2600	2655*	2674*
Molecular Wt. (g/g mole)	29.08	31.79	31.79
Specific Heat Ratio	1.20	1.18	1.18
CALCULATED VALUES			
Gas Density (g/cm^3)	$1.5.\times 10^{-4}$	2.38×10^{-4}	2.38×10^{-4}
Exit Static Pressure (atm)	0.898	.70-2.10	.67-1.15
Exit Velocity(m/sec)	2493	2372	2245
Sonic Vel. at Exit(m/sec)	850	670	670
Exit Mach Number	2.93	3.54	3.35
Exit Flow Rate (actual m^3/sec)	56.6	597	3140
Exit Flow Rate (normal m^3/sec)	7.32	112	587

* = Calculated (from: Thrust = Mass Flow Rate X Specific Impulse

Table 4-2: CHEMICAL COMPOSITION OF EXHAUST

	2.22×10^4 N (5,000 lbs)		3.78×10^5 N and 2.00×10^6 N (85,000 and 450,000 lbs)	
	MOLES/100g	MOLE %	WEIGHT %	MOLE %
CO	0.749	20.2	15.12	15.8
CO_2	0.131	3.5	6.75	4.5
Cl	0.003	0.1	0.37	0.3
HCl	0.619	16.7	22.86	18.3
H^+	0.006	0.2	0.01	0.3
HO	0.001	0.1	0.05	0.09
H_2	0.867	23.4	1.15	16.8
H_2O	0.750	20.3	16.27	26.4
N_2	0.313	8.5	9.03	9.4
Al_2O_3(s)	0.260	7.0	28.32	8.1
Others	-	-	0.07	0.01

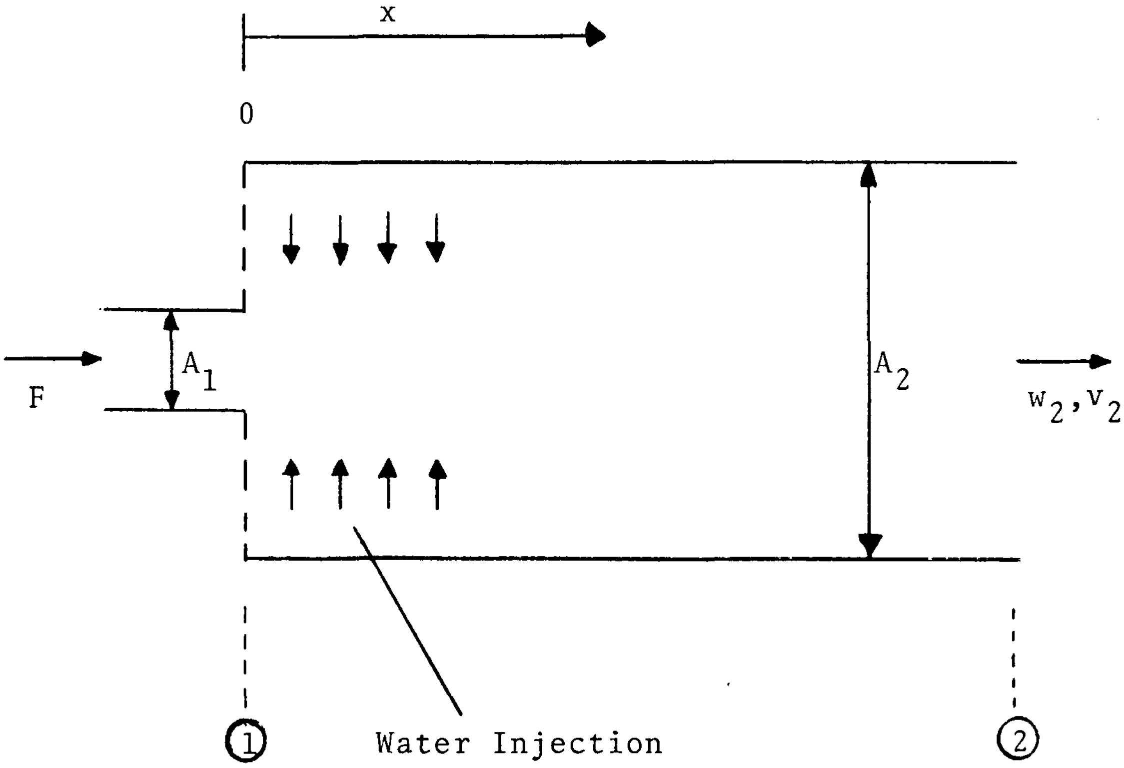

FIGURE 4-1 System for cooling and slowing rocket exhaust.

where subscripts "r" and "ℓ" refer to the rocket and liquid, respectively

Figure 4-2 presents "v_2" as a function of "w_ℓ" for the three thrust levels being examined. Water requirements can be seen to rise sharply as the final velocity reaches 6 m/sec, a fairly high velocity through the entrainment separator (Calvert, et.al., 1974). This velocity is designated in Figure 4-2 by the dashed line.

The scrubbing liquid performs its second function, temperature reduction, primarily by evaporation upon contact with the hot exhaust. For the purposes of this discussion, the liquid is assumed to be water. An enthalpy balance can be written to describe the cooling process as follows:

$$H_r w_r + H_{\ell_1} w_\ell = H_2 w_{g_2} + H_{\ell_2} w_{\ell_2} \quad (4\text{-}5)$$

where H = specific total enthalpy, kcal/kg
subscript g = gas

Equation (4-5) states that the enthalpy entering the system, that of the rocket ($H_r w_r$) plus that of the injected liquid ($H_{\ell_1} w_\ell$), must equal the enthalpy leaving the system, that of the gas phase ($H_2 w_{g_2}$, where "w_g" includes the rocket exhaust and steam) plus that of the unevaporated liquid ($H_{\ell_2} w_{\ell_2}$). If $H_{\ell_1} = H_{\ell_2} = H_\ell$ then Equation (4-5) may be written as:

$$H_r w_r + H_\ell \Delta w_\ell = H_2 w_{g_2} \tag{4-6}$$

where $\Delta w_\ell = w_\ell - w_{\ell_2}$ = rate at which water is evaporated, kg/sec

The gas phase at the exit consists of evaporated water and the rocket exhaust, assumed to undergo no mass transfer with or scrubbing by the injected liquid. Therefore the term "$H_2 w_{g_2}$" may be written as:

$$H_2 w_{g_2} = \frac{T_2 C_{pns_2} w_{ns_2}}{MW_{ns_2}} + H_{st} (w_{st_1} + \Delta w_\ell) \tag{4-7}$$

where T = temperature, °K

C_p = heat capacity, cal/g mole °K

MW = molecular weight, g/ g mole

subscript ns = gas other than steam

subscript st = steam

Equations (4-6) and (4-7) may be combined to yield:

$$H_r w_r + H_\ell \Delta w_\ell = \frac{T_2 C_{pns_2} w_{ns_2}}{MW_{ns_2}} + H_{st}(w_{st_1} + \Delta w_\ell) \tag{4-8}$$

Equation (4-8) may be solved to find the "Δw_ℓ" required to achieve a given temperature "T_2." The velocity contribution to energy at "2" has been neglected. The following values have been assigned in carrying out the calculation:

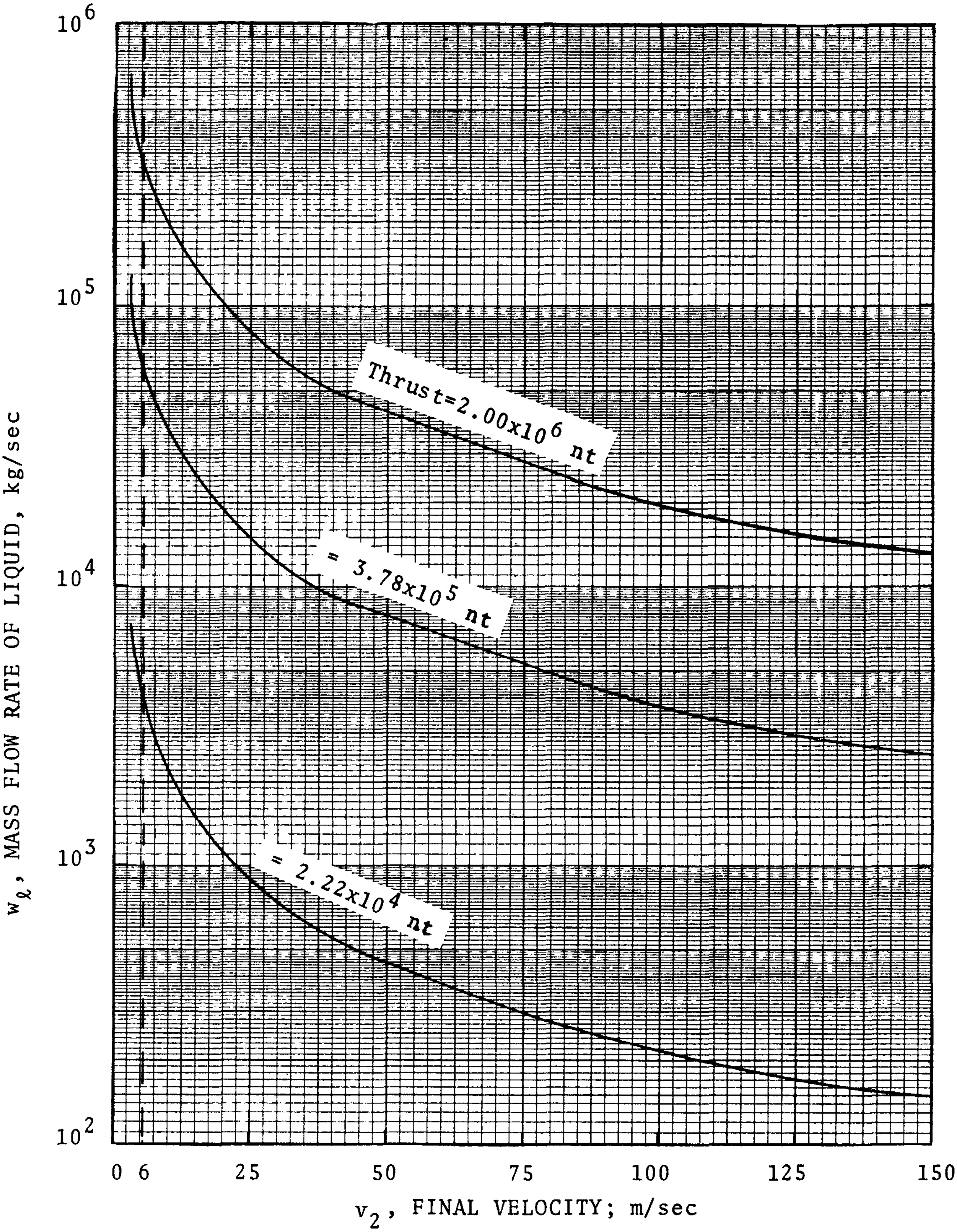

FIGURE 4-2 - Water requirements for reducing exhaust velocity.

$$C_{pns_2} = 4R \tag{4-9}$$

where R = 1.987 cal/g mole °K

$$MW_{ns_2} = \frac{w_r - w_{st_1}}{\frac{w_r}{MW_r} - \frac{w_{st_1}}{MW_{st}}} \tag{4-10}$$

$$H_r = \frac{C_{p1} T_1}{MW_1} + \frac{1}{2(4184)} v_1^2 \tag{4-11}$$

where C_{p_1} = 11.91 cal/g mole °K

Other approximate conditions pertaining to plane 1 are taken from Tables 1 and 2. Values for "H_ℓ" and "H_{st}" may be found in a set of steam tables, eg. Schmidt and List(1962).

The minimum water required to cool the rocket exhaust is that amount of water that would satisfy the enthalpy balance and saturate the gas with steam. All of the water is assumed to be converted to steam. The results for the three rocket sizes are presented in Table 4-3. It can be seen that the mass rate of liquid evaporation is three to four times the mass flow rate form the rocket. However, comparison with Figure 4-2 reveals that both of these rates are over an order of magnitude below the mass flow rate of liquid required for velocity reduction. Hence, water droplets constitute practically the entire mass of the flow stream.

A further examination of the curves in Figure 4-2 indicates that the amount of liquid involved is very large, particularly in the case of the higher-thrust motors. Therefore, it is necessary to provide a different method for removing the momentum from the gas, one which utilizes less water to perform its function.

Table 4-3: MINIMUM WATER EVAPORATION RATES

Rocket Thrust Newtons	Temperature at "2" T_2, °C	Water Vapor Pressure * atm	Min. Water Evap. Rate Δw_ℓ, kg/sec
2.22×10^4	94	0.79	36.4
3.78×10^5	92	0.77	481.
2.00×10^6	92	0.75	2250.

* Water vapor partial pressure is calculated from

$$\frac{P_{st_2}}{P_r} = \frac{MW_r}{18} \frac{\Delta w_\ell}{(w_r - \Delta w_\ell)} \qquad (MW_r = 20)$$

$$P_{st_2} + P_r = 0.94 \text{ atm} \qquad (13.8 \text{ lbf/in}^2)$$

P_{st_2} must then equal the saturation pressure at T_2.

Section 5
MOMENTUM EXTRACTION AND REINJECTION

As stated in the previous section, a problem exists in that the amount of liquid required to reduce the gas velocity in the larger systems is excessive. The configuration under consideration can be characterized as a straight-through system; the liquid is injected and carried through the duct until falling out or encountering the entrainment separator. If this fluid could be recycled in order to work more than once, then the need to introduce more could be eliminated, and the liquid requirements therefore would be reduced.

It is most desirable to accomplish this objective with as little additional expense and equipment as possible. One simple way would be to install scooping mechanisms, as shown in Figure 5-1 into the mixing duct. The injection of the liquid provides an opportunity for momentum to be transferred from the exhaust to the liquid.

This liquid will be collected by a scoop, extracting momentum from the main stream, and then reinjected at an upstream point. Thus a drop of liquid can work a second time by absorbing extra exhaust momentum. Reinjection may be accomplished either radially or at some angle opposite the gas flow direction. In this manner a recycling system is set up within the duct which should lead to an ultimate reduction in the quantity of liquid injected.

The effect which scoops have on the flow and, conversely, the effect of the flow on scoops, must be determined on a theoretical basis. As a result of these calculations, the following scoop characteristics will be determined:

1. Number at each axial location
2. Number of axial locations
3. Inlet angle, "θ"
4. Outlet angle, "ϕ"
5. Width
6. Height, penetration to center
7. Shape
8. Material of construction
9. Thickness

The configuration which is finally selected will be the one which best combines maximum action on the exhaust stream with minimum structural deformation. The desired results are opposed to each other; therefore, compromises in the scoop design parameters will likely be necessary.

Figure 5-1 is a diagram of a scoop and the flow around it. Its effect on gas velocity can be obtained by performing a material and momentum balance around it.

The following assumptions are made in the analysis:

1. The scoop inlet angle "θ" is sufficiently large that all water striking the scoop is reversed.
2. Only water is reversed. No gas is entrained in the extracted flow.
3. The water looses no momentum while being reversed.
4. Water leaving the scoop mixes instantly with the main stream, reducing velocity instantaneously.

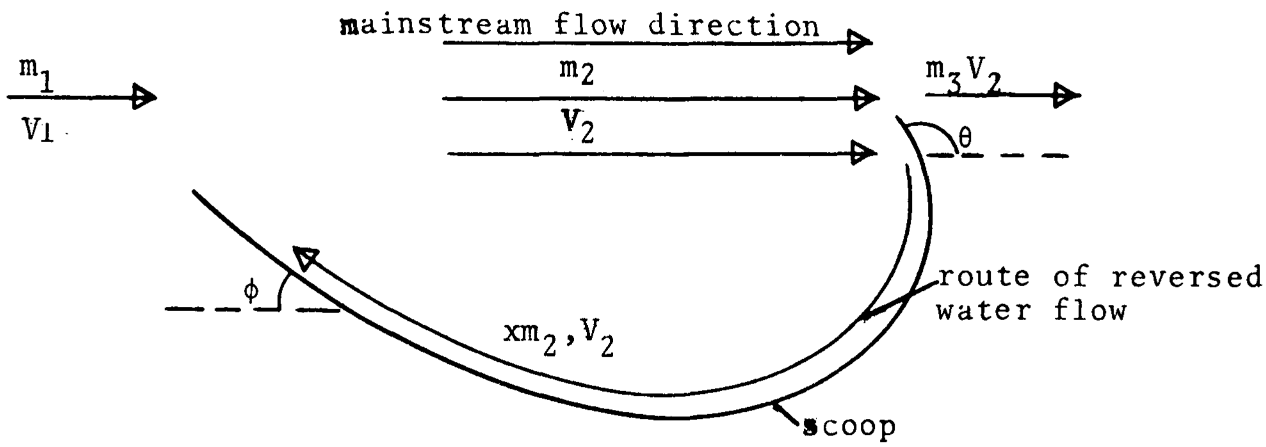

FIGURE 5-1 - Flow around a scoop.

5. Because of the exhaust's high velocity and turbulence, velocity profiles are taken to be flat, and water droplets are distributed evenly across the duct.

Let "m_1" be the mass flow rate of water in the stream before the scoop and "m_3" be the mass flow rate of water after the scoop. At steady state, these two flow rates should be equal to each other, except for evaporation.

$$m_1 = m_3 \tag{5-1}$$

Define "y" as the fraction of "m_1" being extracted at steady state and "x" as the area ratio of scoop inlet to duct cross-section. Since water droplets are assumed to be evenly distributed, "x" can also be regarded as the mass fraction of water reversed.

A material and momentum balance on the scoop outlet yields:

$$m_1 + xm_2 = m_2 \tag{5-2}$$

$$m_1V_1 - xm_2V_2 \cos\phi = m_2V_2 \tag{5-3}$$

where V_1 = droplet velocity before the scoop

V_2 = final velocity of the droplet after mixing with the reversed stream

m_2 = total mass flow rate, which is equal to the sum of the incoming mass flow rate and the reversed mass flow rate

ϕ = angle between scoop outlet and main stream.

Under steady state conditions, the following equation also holds:

$$ym_1 = xm_2 \tag{5-4}$$

Combine Equation (5-2) and (5-4) to yield

$$y = \frac{x}{1-x} \tag{5-5}$$

From Equation (5-2) one obtains

$$m_1 = m_2(1-x) \tag{5-6}$$

By substituting Equation (5-6) into Equation (5-3), the following equation results:

$$\frac{V_2}{V_1} = \frac{1-x}{1 + x\cos\phi} \tag{5-7}$$

or $$V_2 = kV_1 \tag{5-8}$$

where $$k = \frac{1-x}{1 + x\cos\phi} \tag{5-9}$$

"1-k" has the physical meaning of velocity reduction due to the momentum reversal action of the scoop. "k" is a function of "ϕ" and "x". Once a scoop is installed in the duct "k" becomes a constant. Figure 5-2 presents "k" as a function of "x" for a scoop, with "ϕ" as parameter.

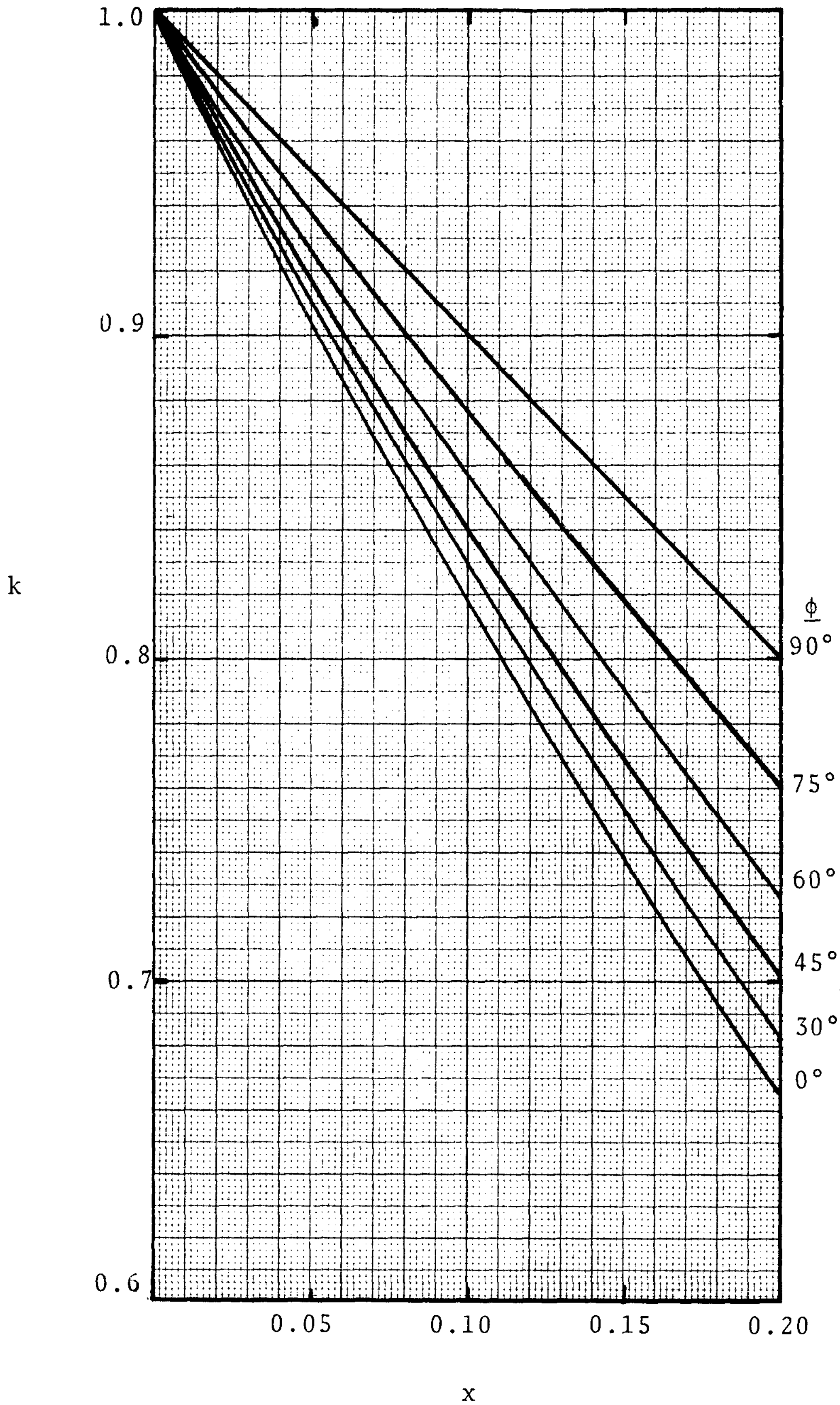

FIGURE 5-2 -"k" vs. "x" for a scoop, with outlet angle ϕ as parameter.

Values of "x" greater than 0.20 are not shown because at any axial position, no more than 20% of the cross-sectional area should be covered by scoops, in order to avoid a great flow restriction. In reality, an "x" value of 0.20 may signify one scoop occupying 20% of the duct area or four scoops at the same axial point, each occupying 5% of the duct area, etc.

Figure 5-2 reveals that the momentum reducing effectiveness of a scoop increases with increasing "x" and with decreasing "ϕ". However, the outlet angle also has a practical lower limit, about 20°.

The next step involves the placement of scoops at more than one location along the duct. The total reduction in velocity, from the final velocity when no scoops are used to that when a certain scoop configuration is employed, is

$$k_t = \prod_{a=1}^{a} k_a \qquad (5\text{-}10)$$

where a = the number of axial points at which scoops are located, or number of scoop banks

k_a = individual k factor for each scoop bank

k_t = overall velocity reduction factor

If each "k_a" is the same, then

$$k_t = k^a \qquad (5\text{-}11)$$

A diagram showing final stream velocity as a function of water loading rate for a 2.22×10^4 N (5,000 lb) was presented in Figure 4-2. This curve is the basis for Figure 5-3, which shows how the water loading required to attain a given velocity decreases as more scoops banks are added. Each scoop bank is identical, with $x = 0.20$ and $\phi = 20°$. Therefore, k_t can be calculated by Equation (5-11). The final velocity we wish to attain is 6 m/sec, the maximum for which reentrainment of droplets from an entrainment separator can be avoided. The water requirement for reaching that velocity is seen in Figure 5-3, to become more modest as scoop banks are added.

In order to examine the validity of these predictions and as a basis for the final design selection, it is proposed that experiments be run on the pilot scrubber at A.F.R.P.L. In the course of these experiments, certain data must be examined and observations made as to how quantities change as the scoop parameters are altered. Velocity, pressure and temperature measurements should be made at various axial locations in the duct. The temperature data can serve as a check that sufficient cooling water is being evaporated. Because of the great amount of liquid present in the flow stream, a conventional pitot tube cannot be utilized to find the velocity. However, that quantity may be arrived at indirectly if the pressure, temperature and mass flow rates of gas and liquid are known. It would also be advantageous to measure the magnitude of the forces acting on each scoop, as an aid in determining the

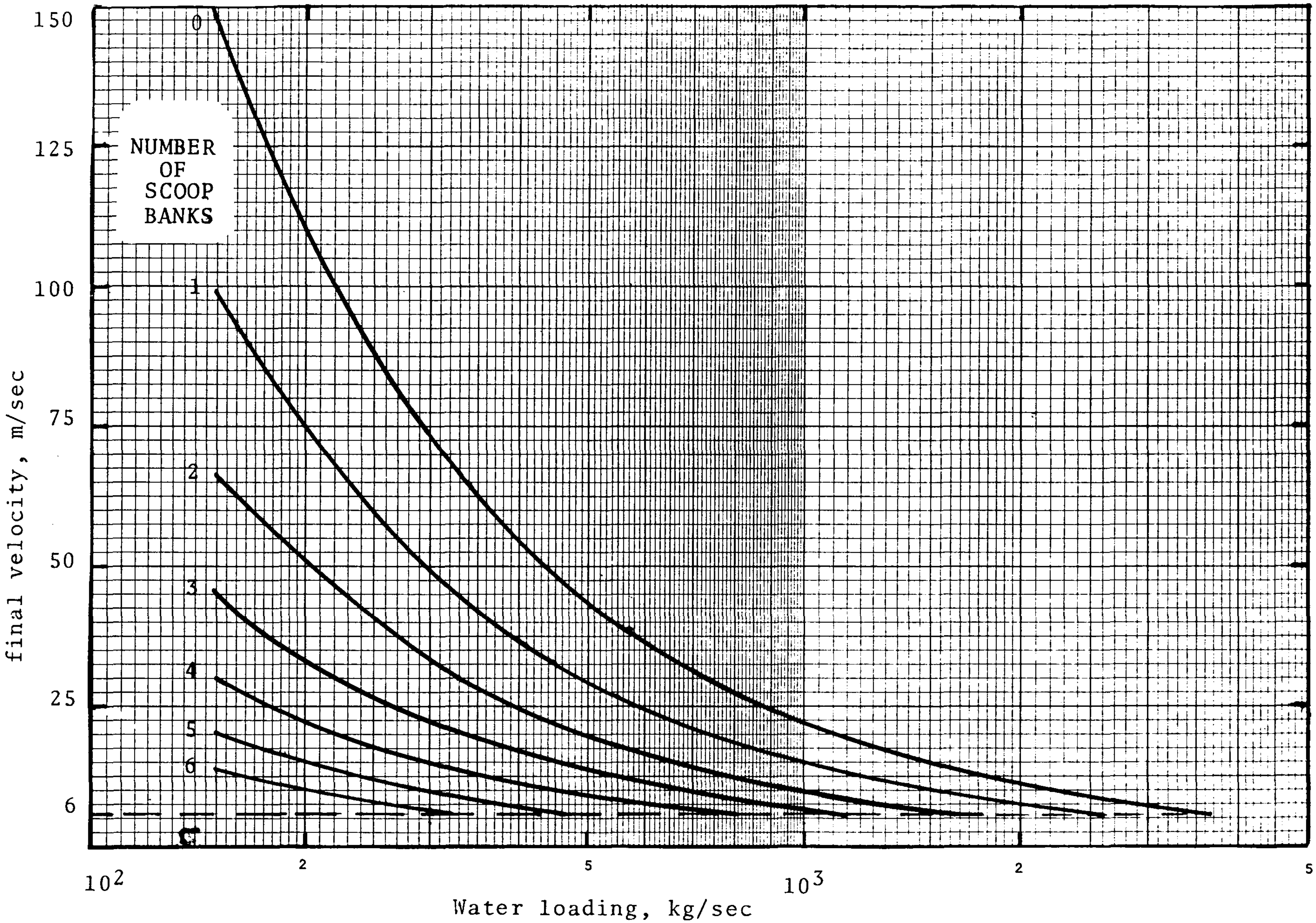

FIGURE 5-3 - Final stream velocity vs. water input, with number of scoop banks as parameter. For each scoop bank, x=0.2 and ϕ=20°. Thrust=2.2×10^4N rate of liquid flow to the scoop and the structural requirements. In this way it can be determined how much of the flow area consists of a supersonic core, unpenetrated by droplets of liquid.

Load cells can be used to make the measurements of force on the scoops. In order to guard against the possibility of the scoops cocking and giving misleading readings, three load cells could be arranged at each scoop to account for that possibility.

At the present time there are a number of pressure and temperature taps installed on the pilot system. In addition, near the duct outlet there are two rakes designed to give a radial pressure distribution. One measures the total pressure, while the other detects static pressure, so that velocities can be determined here. Figure 5-4 gives the location of the pressure sensors in the scrubber system.

Two methods have been proposed for mounting the scoops that would permit the forces acting on them to be ascertained.

1. The scoops could be welded to the duct wall or to a sleeve fitting snugly inside the duct.
2. I-beams could be welded to the wall, forming a rail on which scoops could roll by means of bearings. A short section could be cut and welded for each scoop, or several scoops could be placed on one long beam. Portions of the support can be cut to allow removal of scoops at positions other than the end of the beam.

A diagram of this configuration appears in Figure 5-5

The length of the mixing duct currently on the pilot scrubber, 7.62 m (25 ft), limits the number of scoop banks which may be installed. Five evenly spaced banks seems to be the greatest number wherein one bank does not block flow to the one behind it. Each bank consists of four scoops, each of which intercepts a total of 5% of the cross-sectional area of the duct and is positioned 90° from each other around the duct. The scoops of successive banks are shifted 45° to provide for a more complete coverage of the flow.

The presence of a core of supersonic gas which should dissipate as it flows through the mixing duct also plays a role in scoop design. Near the spray section, where the core is expected to be greatest in extent, the scoops themselves should not extend very high; however, the outlet angle should be large to permit the reinjected water to penetrate and break up the core as much as possible. As the core weakens, scoops can be made taller and their outlet angle decreased in an effort to absorb more momentum. Penetration to the center becomes less important as the distance downstream increases.

Therefore, the scoops must serve a number of purposes, depending on their axial location in the system. In order to do this, each scoop or bank of scoops may have a different value for "x" and "ϕ". Inlet angle "θ" can always be 180°. The end product is thus likely to consist of a variety of scoop designs.

Table 5-1 summarizes the data required in the scoop experiments, which will be used to determine the final velocity in the mixing duct.

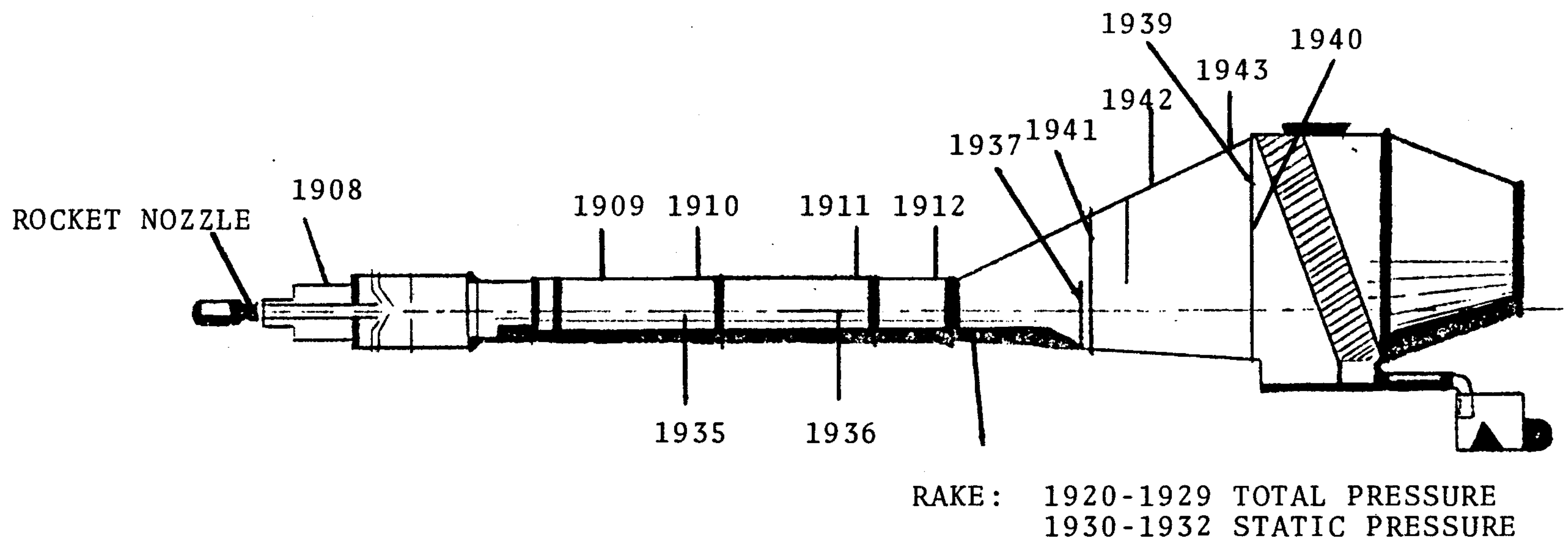

FIGURE 5-4 - Location of pressure taps along scrubber system. Numbers refer to the AFRPL designation for the pressure taps.

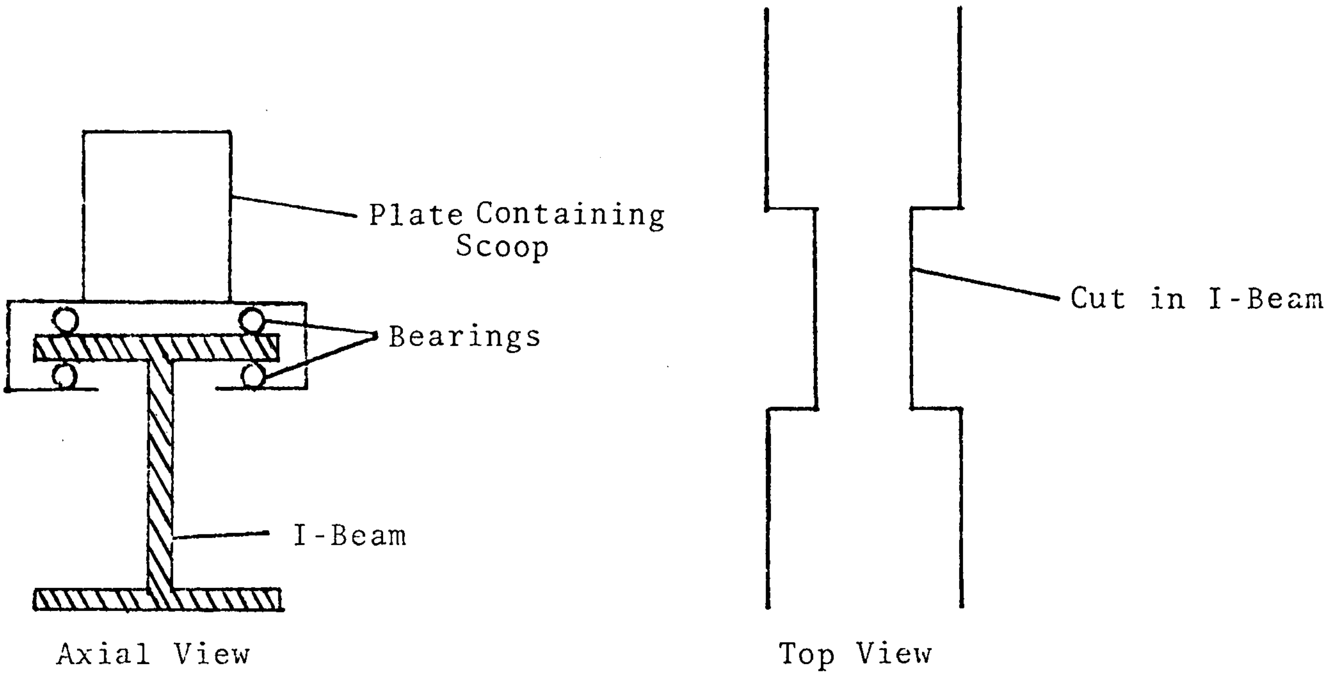

FIGURE 5-5 - Supporting scoops on I-beam.

Table 5-1. SCOOP EXPERIMENT - REQUIRED DATA

(Refer to Figure 5-4 for locations)
PRESSURE: Static wall along mixing duct. Total and dynamic at rake.
TEMPERATURE: Static wall along mixing duct.
MASS FLOW RATE: Measure flow rate of liquids into scrubber.
FORCE: Use load cells to measure axial force on one scoop in each bank.

APPENDIX

The calculated values for exhaust at the nozzle exit, which appear in Table 4-1, are determined according to the equations presented in this section.

Gas density is calculated by assuming the exhaust is ideal and applying the ideal gas law in the form

$$\rho = \frac{P(MW)}{RT} \times 10^{-3} \tag{A-1}$$

where ρ = density, g/cm^3

$R = 0.082$ ℓ-atm/g mole °k

The exit velocity for the 2.22×10^4 N (5,000 lb) motor was figured from the following expression (Bennett and Myers, 1962):

$$v^2 = \frac{202\gamma P_o}{(\gamma-1)\rho_o}\left[1-\left(\frac{P_o}{P_o}\right)^{(\gamma-1)/\gamma}\right] \tag{A-2}$$

where γ = specific heat ratio

P = pressure

subscript $_o$ = rocket chamber

$\rho_o = 6.81 \times 10^{-3}$ g/cm^3

The speed of sound may be calculated as a function of temperature according to

$$c = \sqrt{\frac{(1.01 \times 10^5)\gamma RT}{MW}} \tag{A-3}$$

where c = speed of sound, m/sec

Mach number is defined as the ratio velocity to sonic velocity.

$$Ma = \frac{v}{c} \qquad \text{(A-4)}$$

where Ma = Mach number

In the case of the 3.78×10^5 N (85,000 lb) and 2.00×10^6 N (450,000 lb) motors, chamber density is not given but the nozzle geometry is known. Mach number may therefore be calculated from the following equation (Bennett and Myers, 1962):

$$\left(\frac{A_{exit}}{A_T}\right)^2 = \frac{1}{Ma^2}\left[\frac{2}{\gamma+1}\left(1 + \frac{\gamma-1}{2} Ma^2\right)\right]^{\frac{\gamma+1}{\gamma-1}} \qquad \text{(A-5)}$$

where A_{exit} = area of nozzle exit, m^2

A_T = area of nozzle throat, cm^2.

For these rockets "Ma" is calculated from Equation (A-5) and "c" is calculated from Equation (A-3), leaving "v" to be determined from Equation (A-4).

In all cases, the actual volumetric flow rate of exhaust at the nozzle can be figured by:

$$Q_A = \frac{w}{\rho} \times 10^{-3} \qquad \text{(A-6)}$$

where Q_A = actual volumetric flow rate, m^3/sec w = mass flow rate, kg/sec

"Q_A" can be corrected to normal conditions according to :

$$Q_N = Q_A \times \frac{273}{T} \qquad (A\text{-}7)$$

where Q_N = normal volumetric flow rate, m^3/sec

REFERENCES

Bennett, C.O. and J.E. Myers. Momentum, Heat and Mass Transfer. McGraw-Hill, Inc. New York, 1962.

Calvert, S., I.L. Jashnani, S. Yung and S. Stalberg. Entrainment Separators for Scrubbers - Initial Report. A.P.T., Inc. E.P.A. Contract 68-02-0637, October 1974, E.P.A.-650/2-74-119a.

Garrett, J.W. et. al. A Design Study for Toxic Rocket Exhaust Gas Cleaning. ARO, Inc. AEDC-TR-72-97, August, 1972.

Roschke, E.J., P. F. Massier and H.L. Gier. Experimental Investigation of Exhaust Diffusers for Rocket Engines. Jet Propulsion Laboratory. NASA Contract NAS 7 - 100, March 1962, TR 32-210.

Schmidt, A. and H. List. Material and Energy Balances. Prentice-Hall, Inc. Englewood Cliffs, N.J. 1962.

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16. ABSTRACT

The report gives results of design studies related to the control of emissions from solid rocket test firings. It summarizes literature in the subject area and contact with those installations treating rocket exhausts. It gives results of an examination of a pilot scale scrubber currently in operation on a 22,200 N (5,000 lb) motor at the Air Force Rocket Propulsion Laboratory, Edwards Air Force Base, California. If a similar scrubber is used on a large engine (e.g., 2 million N or 450,000 lb), the amount of liquid required to lower the exhaust velocity is quite high. As a remedy, the installation of scoops is proposed, to recycle the liquid. Theoretical performance characteristics for the scoops are derived, and an experiment to test their utility is proposed.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Air Pollution	Liquid Cooling	Air Pollution Control	13B
Exhaust Gases	Exhaust Velocity		21B
Solid Propellant Rocket Engines			21H
Test Facilities			14B
Scrubbers			13A

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