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NASA TECHNICAL MEMORANDUM

NASA TM-78231

(NASA-TM-78231) SRB-TPS SPRAY NOZZLE
DEVELOPMENT FOR MSA-1 APPLICATION (NASA)
36 p HC A03/MF A01 CSCI 13H

N79-28371

Unclas

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SRB - TPS SPRAY NOZZLE DEVELOPMENT FOR MSA-1 APPLICATION

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June 1979

NASA



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SRB - TPS SPRAY NOZZLE DEVELOPMENT FOR MSA-1 APPLICATION

INTRODUCTION

The Solid Rocket Booster (SRB) of the Space Shuttle is designed for refurbishment and reuse. Adequate protection must be provided for its steel and aluminum parts to protect them from heat damage during reentry and from ocean environment corrosion. A low-cost, thermal/corrosion-protective ablative coating for the SRB (Fig. 1) has been developed at the Marshall Space Flight Center (MSFC). This coating is designated MSA-1 (for Marshall Sprayable Ablator) and consists of 10 ingredients. Four of the materials, phenolic microballoon, glass eccospheres, chopped and milled glass fibers, provide the primary insulative properties. The chopped glass fibers also help to provide material integrity in concert with the six other substances. A significant characteristic of the MSA-1 is that its ingredients have radically different specific gravity. This characteristic and the use of commercially available spray equipment not specifically designed for such a mixture caused the spray jet to disintegrate prior to impacting the workpiece. Heavy particles of MSA-1 concentrated in the inside of the jet while light particles formed clouds of fine mist on the outside of the jet thus causing the undesired overspray. Figure 2 shows a cross section of the overspray. It was agreed that overspray was undesirable from a materials standpoint because ingredients were removed upsetting the previously approved material balance.

To improve MSA-1 application, different overspray suppression schemes were conceived, built, and tested. Generally, they were in the shape of a picture frame on which the viscous overspray impacted. These schemes worked; however, spray buildup on these catch-devices culminated in dripping in a relatively short time and the overspray on the frame had to be continually removed by hand. The very questionable quality of the poorly applied MSA-1 and the costly overspray removal operation dictated the development of a new spray nozzle system.

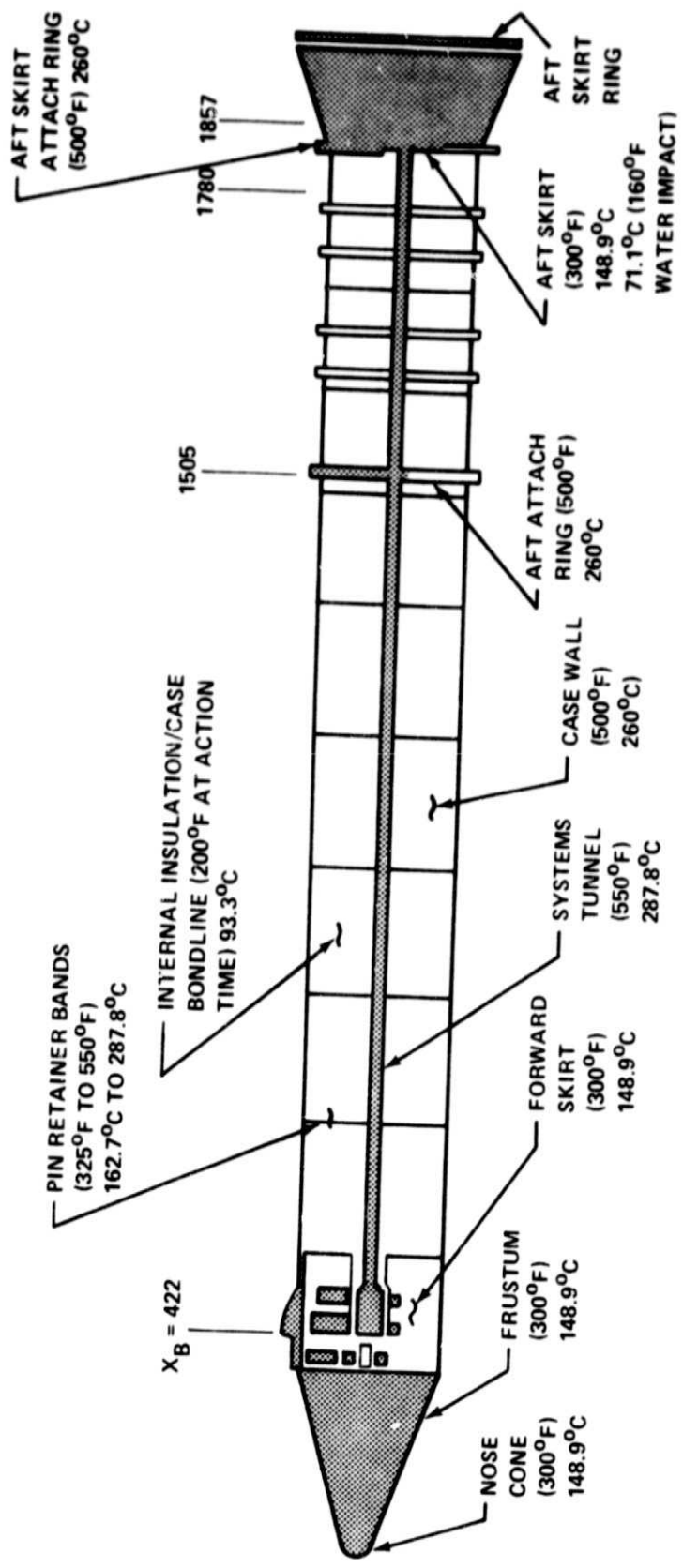


Figure 1. SRB-thermal protected areas.

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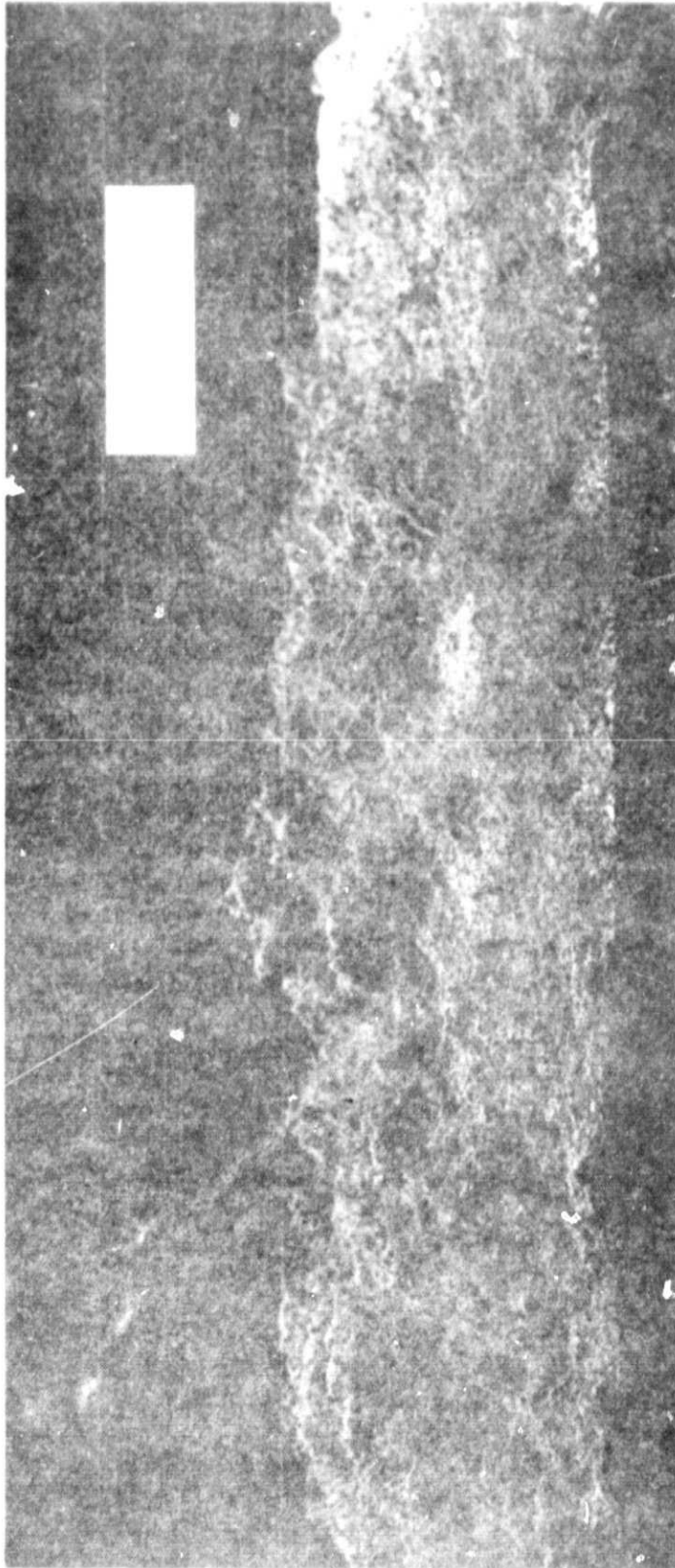


Figure 2. Cross-section of overspray formation.

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PILOT SPRAY SYSTEM

A pilot spray system was conceived and assembled by the Materials and Processes (M&P) Laboratory based on commercially available equipment and components. The system was essentially an automatic spray gun, a material delivery subsystem, mixer/pump, and a turntable (Fig. 3).

The MSA-1 was mixed in a Hobart mixer where a density cell monitored the mix during the spraying. From the Hobart mixer, the MSA-1 was gravity-fed into a Moyno pump which forced the MSA-1 through a flexible hose toward the automatic spray gun. Near the gun, the flexible hose branches by means of a T-connector; one branch leads to the spray gun, and the other branch leads to the return-line through which the MSA-1 was pumped back into the Hobart mixer. A low pressure line mounted to the forward end of the spray gun supplied air to the gun's air atomizer system. The gun is connected directly to an oscillator which pivots the gun in a vertical plane at a predetermined angle and frequency. The gun and the oscillator are attached to a mobile bracket which can be adjusted to the angle of the workpiece structure. The spray system also contains a number of valves, restrictors, bleed lines, etc., which are necessary for its operation. Instrumentation, recorder, controller, and visual observation by the operator are used to control the system's operations.

The Binks Automatic Spray Gun, Model 33 (Fig. 4), which was used consisted of the following subsystems:

- a) the restrictor
- b) the compressed air atomizing system
- c) the fluid system.

The restrictor, an orifice mounted between the spray gun head and the MSA-1 return-line, determines the quantity of MSA flowing through the spray gun. Inside the head of the gun, two interchangeable nozzles are installed: one through which the MSA-1 material flows, and the other through which air, which pulverizes the MSA-1 mix to small particles and serves as its carrier, is injected.

The size of the spray gun nozzle orifices is determined by the required amount of the MSA-1 air mixture. A pneumatically operated needle valve regulates the size of the spray gun nozzle orifices.

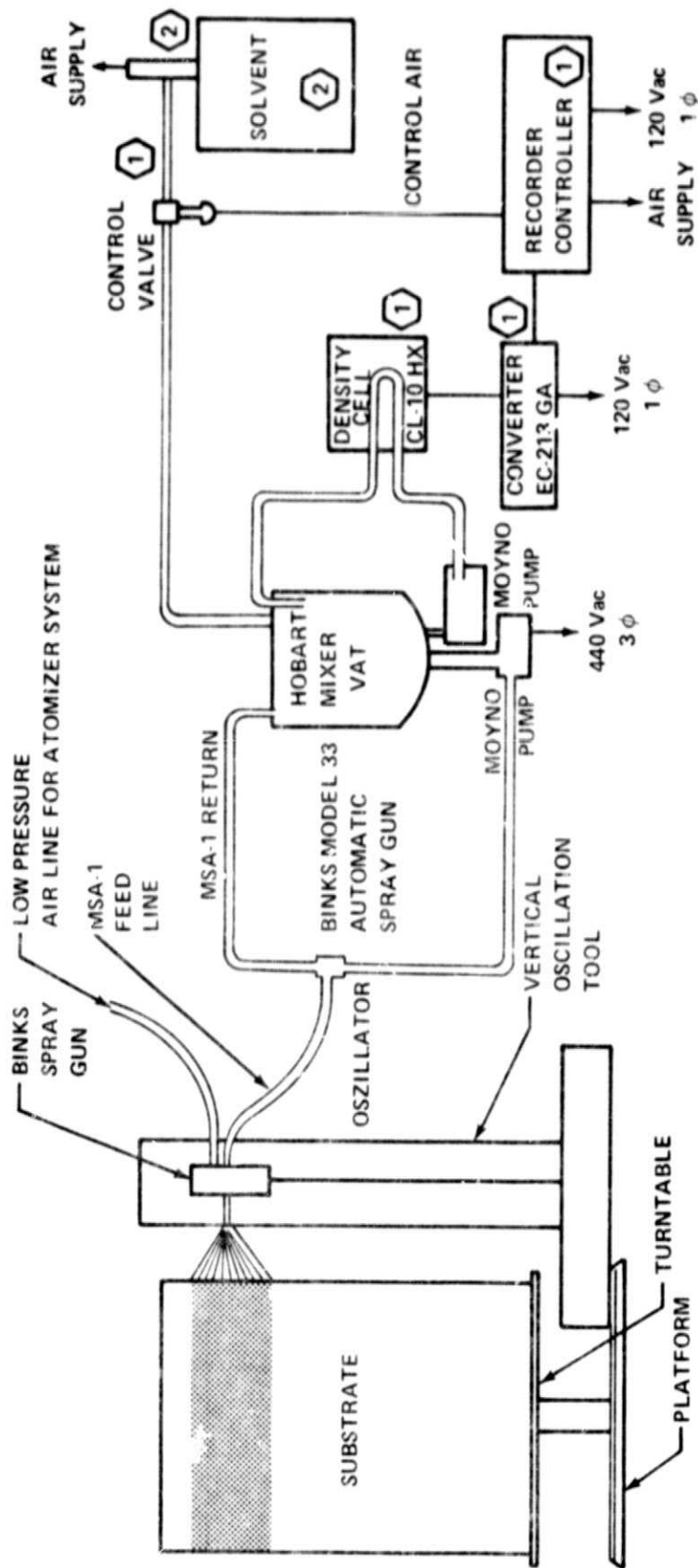


Figure 3. Schematic of the pilot spray system.

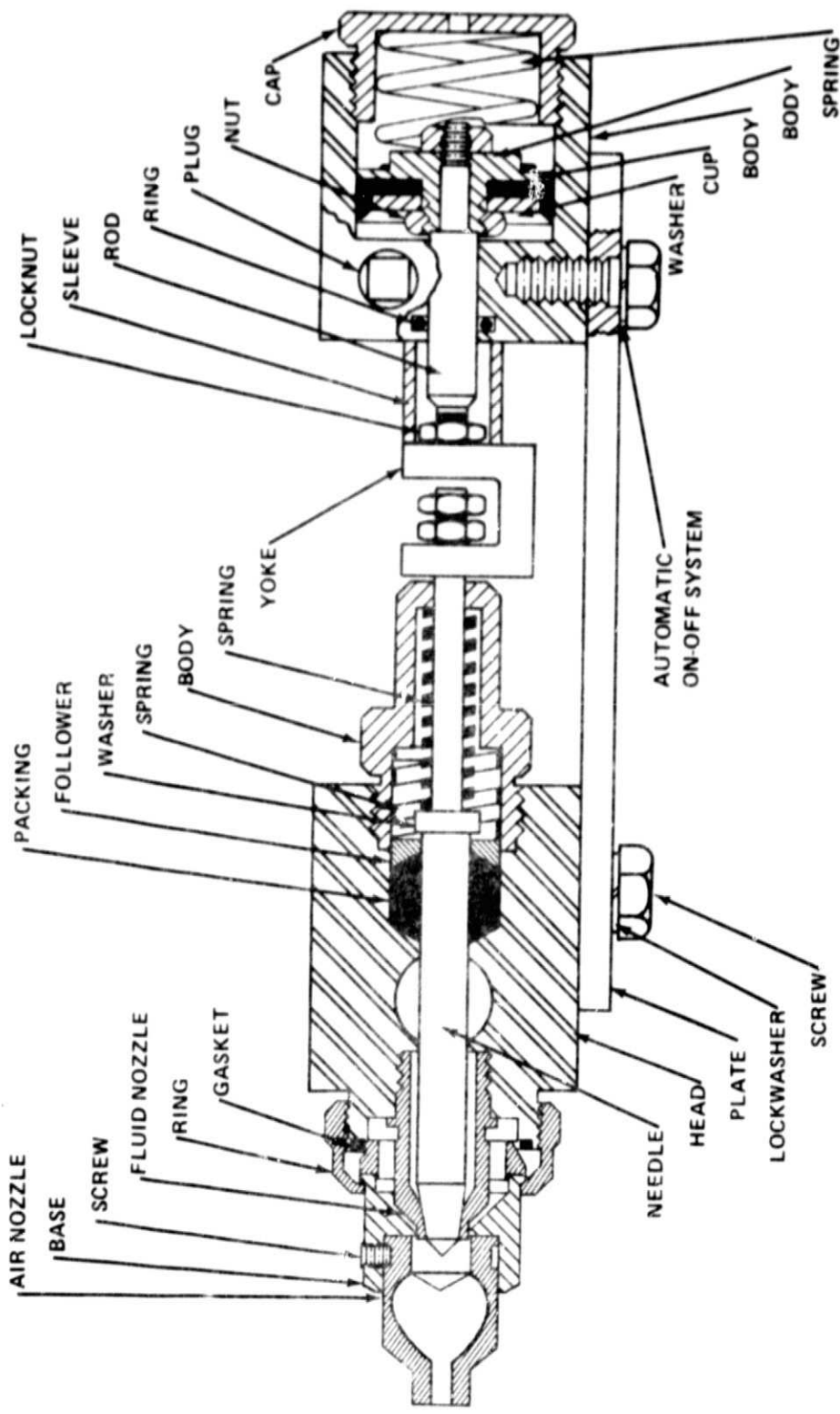


Figure 4. Binks automatic spray gun.

The fluid nozzle of the Binks spray gun has a flange-like shoulder with six holes drilled through it. The axes of these holes are parallel to the fluid nozzle center line. Part of the air flows into the space between the fluid nozzle and the orifice to mix with MSA-1. The rest of the air flows through two holes near the nozzle exit perpendicular to the flow direction to mix with the partially pulverized (atomized) MSA-1.

The front end of the nozzle protrudes beyond the air nozzle to form a chamber in which the rest of the compressed air mixes with the partially aerated MSA-1. The MSA-1 enters the chamber through the central nozzle to be penetrated by the rest of the compressed air entering through two radial holes near the nozzle exit. Interchangeable air chamber nozzles are available in different orifice sizes, in slot, oval or round shapes to produce a desired spray pattern (Fig. 5).

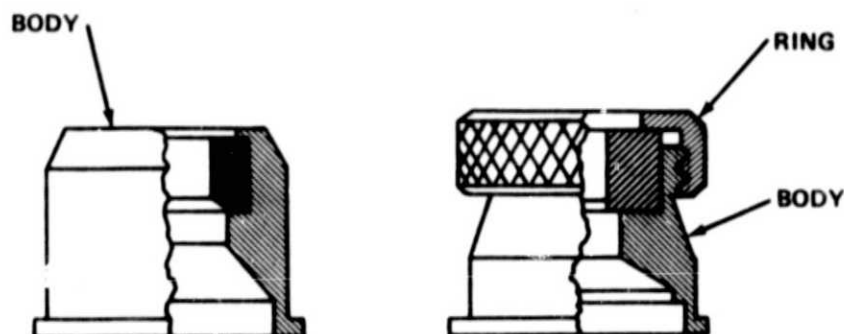


Figure 5. Binks spray gun nozzles.

The air atomizer system disperses the MSA-1 mixture into very small particles giving it the appearance of a fine mist with a density almost like water. To obtain a near perfect spray pattern the choice of nozzle sizes, shapes, feed pressure of MSA-1 and air pressure for the atomizer system are very important.

For purposes of testing the pilot spray system aluminum alloy test panels, $610 \times 610 \times 4$ mm ($24 \times 24 \times 0.150$ in.), were used as workpieces. The panels were either hand-sprayed or sprayed automatically by rotating past the spray gun at controlled rates between 0.00762 and 0.609 m/s. Depending on the MSA-1 coating requirements, the turntable speed, oscillation, and frequency of the spray gun swivel system and the swivel angle were synchronized to assure uniformity and thickness of the MSA-1. Figure 6 shows the pilot spray system during operation.

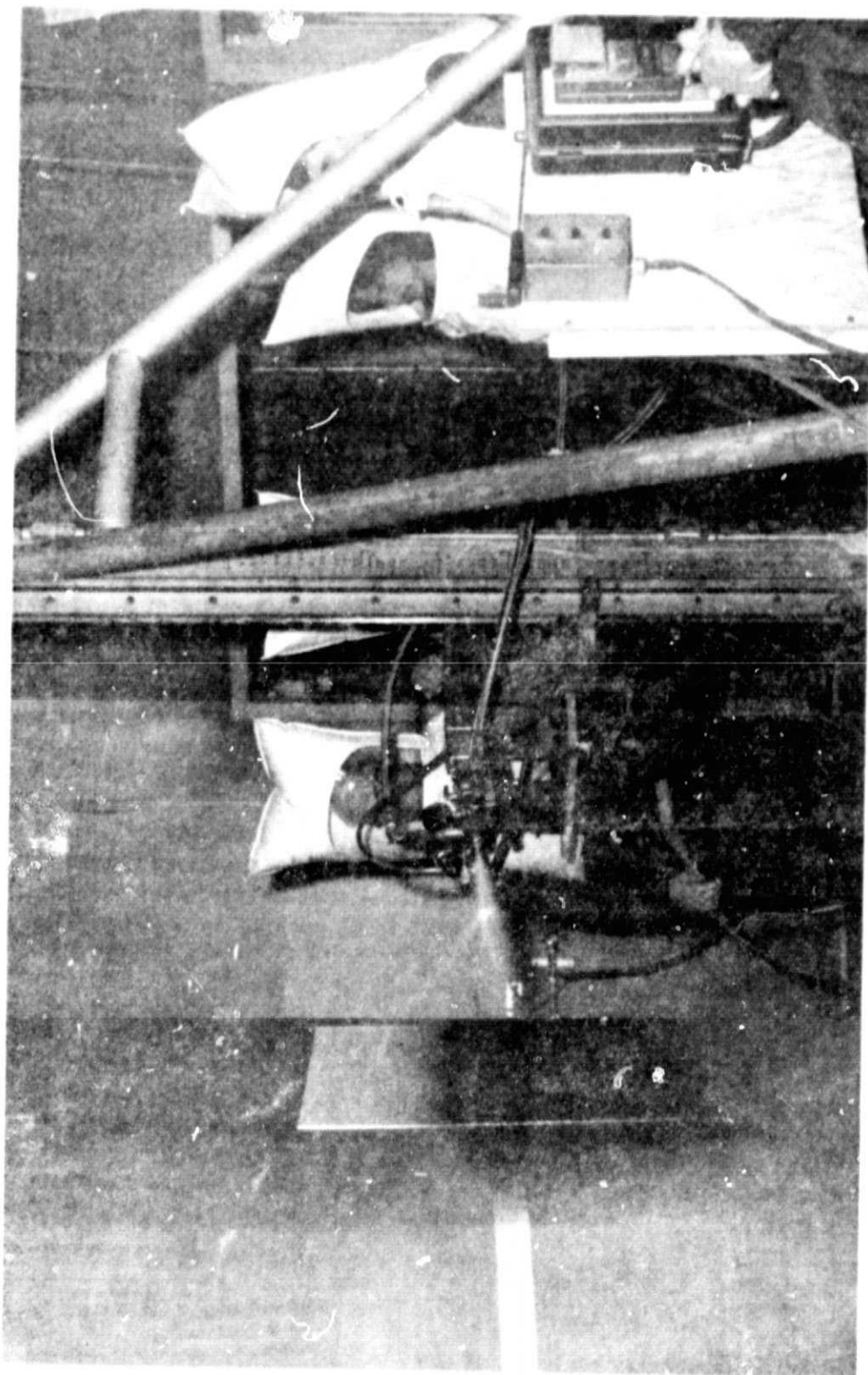


Figure 6. Pilot spray system during spraying.

The spray facility operators are equipped with external air supply respiratory systems and protective clothing. The pilot spray system (Fig. 6), the necessary facility requirements, processing and safety specifications are fully described in the "Solid Rocket Booster Thermal Protection System Materials Processing and Refurbishments Data Transfer Document," MSFC-IN-EH-77-01, February 1977.

The quality of the sprayed-on MSA-1 was evaluated visually during spraying. This evaluation was performed by an experienced operator, estimating the MSA-1 wetness. MSA-1 too wet will drip off the panel, and MSA-1 too dry forms an excessive flocky texture. This wetness can be controlled by adjusting the amount of solvents.

After the degree of wetness was found acceptable by the operator, the smoothness/roughness of the surface was visually evaluated by the operator. This surface condition was attributed to the spray guns air atomizer system. High air pressure caused the surface to be porous, while lowering the air pressure smoothed the surface. A very low air pressure caused the formation of craters on the surface much like a moon scape. Turntable rotation, vertical speed, oscillation and swivel frequency of the spray gun and the output of MSA-1 were synchronized to assure uniformity of thickness and coverage of MSA-1. After curing, the test panels were cut into small segments for nondestructive evaluation.

INVESTIGATION OF OVERSPRAY FORMATION

In an attempt to remove the overspray from the workpiece, several mechanical concepts were developed, tested, and evaluated. The last concept considered was a catch-frame device incorporating a means of automatic overspray removal. This advanced catch-frame system was in a picture frame geometry, but the frame limits were four rotating belts with accompanying scraper blades. The blades were fixed above each belt nearly touching the belt so that overspray was scraped off when the belt moved under the blade. This belt scraper device was an improvement, but still had the disadvantage of positioning and cleaning. Also, the removal of the overspray material from the blades into a container was difficult because the MSA-1 dries very quickly thus plugging up the drain pipes.

Another overspray suppression design was to confine the MSA-1 jet in a "tunnel" framed by four air film panels. This concept would prevent MSA-1 ingredients from escaping the boundaries of a predetermined spraying area but

in actual practice it still would not provide a homogeneous spray jet. Also a major problem was to provide an air film thick enough to deflect ingredients back into the MSA-1 jet stream without the air film causing turbulence at the impact area. Air film thickness and material speed were found difficult to balance therefore the "air tunnel" concept was abandoned.

It became more and more evident that suppression of overspray was more desirable than its removal or deflection. It was understood that a total suppression of overspray would be technically impossible, so the design goal was to suppress overspray to a level which would not influence material properties, nor cause debonding of subsequently sprayed surfaces. To learn more about formation of overspray, a small but thoroughly controlled test program was executed. For this program all test parameters were researched and grouped in categories and the controllable and uncontrollable variables identified. It was believed that there might be some unit-area quantity of overspray that would prove to be a critical threshold, below which overspray would not cause problems. Other contributing variables are:

- 1) Ratio of mix-volume total-volume capacity of the mixer bowl.
- 2) Temperature of the mix in the mixer bowl.
- 3) Pump setting, revolution and pressure.
- 4) Diameter of the restrictor in the feedline.
- 5) Diameter of the gun-nozzles orifice.
- 6) Size and number of holes in the atomizer system.
- 7) Air pressure in the atomizer system.
- 8) Size of the MSA-1 return line.
- 9) Gun-oscillation, angular range and frequency.
- 10) Distance of the gun from the test panel.
- 11) Rotation speed of the workpiece.
- 12) Room temperature and humidity of the air in the spray room.

After all spraying variables were apparently under active control or adequately compensated for during subsequent spray test runs, it was realized the application of MSA-1 was still unacceptable. This situation indicated that there was still another variable (or variables) yet to be identified.

To further study the spray jet geometry formation, a number of high speed motion pictures (1000 frames/second) were taken during an MSA-1 spray operation. The test spraying of MSA-1 was performed using a standard spray gun where pump settings and atomizer pressures were different for each test. All pictures taken clearly showed a pulsing motion of the spray jet. Four to five pulse formations were visible, indicating a rate of 4000-5000 Hz. Figure 7 shows a typical spray jet formation when spraying MSA-1 and using the atomizer. It can be seen in the figure that the jet geometry changes from a well-formed cone to clouds and later to a mist which is dispersed by the turbulent air surrounding the spray jet. The factors contributing to pulsing were considered to be turbulent flow, the different densities of the constituents of MSA-1 and the flow characteristic of the pumps and atomizer system. To see what happened to the spray jet formation when a homogeneous material was sprayed, water was used in two tests, one with the atomizer and the other without. Because the density of water and the MSA-1 mix are almost identical, the setting of the spray system was the same as for MSA-1 where optimum spray results were obtained. Using the same settings, the water jet formation with the air atomizer turned on was identical to the MSA-1 spray jet (Fig. 8). This was not the case for the test without the atomizer system. This test, with water and without the air atomizer, showed a very distinct pulsing of the jet. Water drops were formed following each other with a spacing approximately the same as their diameters (Fig. 9).

It seemed to be logical to pursue the idea of attaching a divergent nozzle to the gun mouth to change the jet velocity such that the breaking up of the jet stream will be prevented. Three conical divergent nozzles at angles of 8, 9, and 10 degrees were tested. The overall length of these 3 nozzles were empirically determined. The divergent nozzles gave an improvement in the spray pattern; however, overspray was still significant and the cone extension along was not satisfactory.

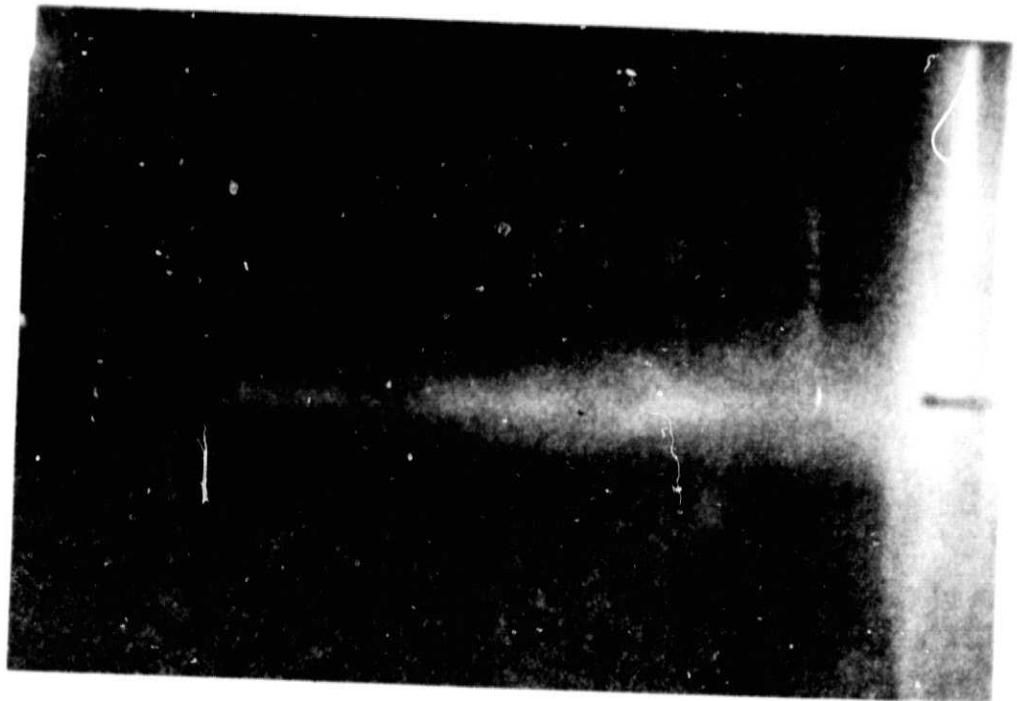
IMPROVED SPRAY NOZZLE SYSTEM (LAVAL-NOZZLE)

Test results from the 8, 9, and 10 degrees straight cone adapter to the commercial spray gun were encouraging, and it was logical to proceed to improved nozzle design. An advancement on a straight cone design is the



Figure 7. Typical MSA-1 spray jet formation with atomizer turned on using a standard Binks gun.

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GUN NOZZLE



TEST PANELS

Figure 8. Water jet formation with atomizer turned on, using a standard Binks gun.

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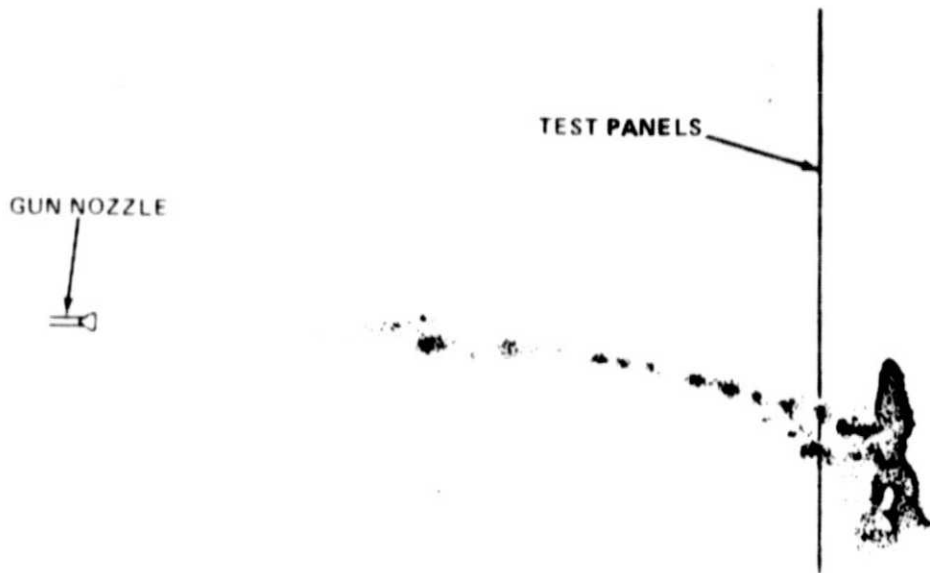


Figure 9. Water jet formation without atomizer turned on using a standard binks gun.

convergent-divergent nozzle first described by Dr. de Laval, who invented this type nozzle for steam turbine systems. It is well understood and is used in the design of rocket engines where additional thrust is gained in the divergent part of the engine nozzle during expansion of the combustion gases. A decision was made to design and test a Laval type nozzle adapter to be mounted on the orifice of the MSA-1 spray gun. (See Appendix for Laval Nozzle theory.)

One of the characteristics of the convergent-divergent nozzle is that, depending on the pressure profile along the nozzle axis, the velocity of the profile flowing through it can be changed from subsonic to supersonic or vice versa. The optimum nozzle exit cone lays between 10 and 12 degrees. With the change in gas pressure the gas flow changes from near laminar to turbulent. The MSA-1 jet is composed of air under pressure from the atomizer system, the evaporating solvents, and fine solid particles. The MSA-1 jet was assumed to be a mixture of air and liquids in which small solid particles are homogeneous dispersed forming a very fine mist.

The designed nozzle (Fig. 10) was built in two separable parts. The first part was a convergent-divergent nozzle where the divergent part (nozzle exit) was 64 mm (2.5 in.). The second part was a 57 mm (2.25 in.) extension of the divergent nozzle and was used to find the optimum performance. It was intended to obtain the optimum exit length by shortening the nozzle exit gradually. Optimum length would be determined when dripping of MSA-1 at the nozzle end ceased and the MSA-1 coating appeared smooth.

The tests performed with the two part nozzle revealed a radical suppression of the overspray and a smooth surface texture. The optimum length of the nozzle exit for the given requirements were determined to be 51 mm (2 in.) measured from the center of the throat to the nozzle end. A second nozzle was designed and simplified by leaving the outside contour cylindrical. To gain more performance data, six different nozzles were built and tested (Fig. 11). They all had a straight exit cone of different angles (8, 9, and 10 degrees) and a 6 mm (0.25 in.) or 9 mm (0.35 in.) throat diameter. The results of these tests were very satisfactory. The best performing nozzle for MSA-1 was the one with a 6 mm (0.25 in.) throat diameter and a 9-degree straight exit angle.

After the overspray problem was resolved an additional effort was made to improve surface smoothness which would eliminate the need for hand sanding the surface after curing of the MSA-1. It appeared possible to further improve the surface by changing the straight cone of the divergent nozzle to a bell shape (Fig. 12), a configuration not previously investigated. The advantages of a bell shaped nozzle exit in comparison with a straight cone are a greater

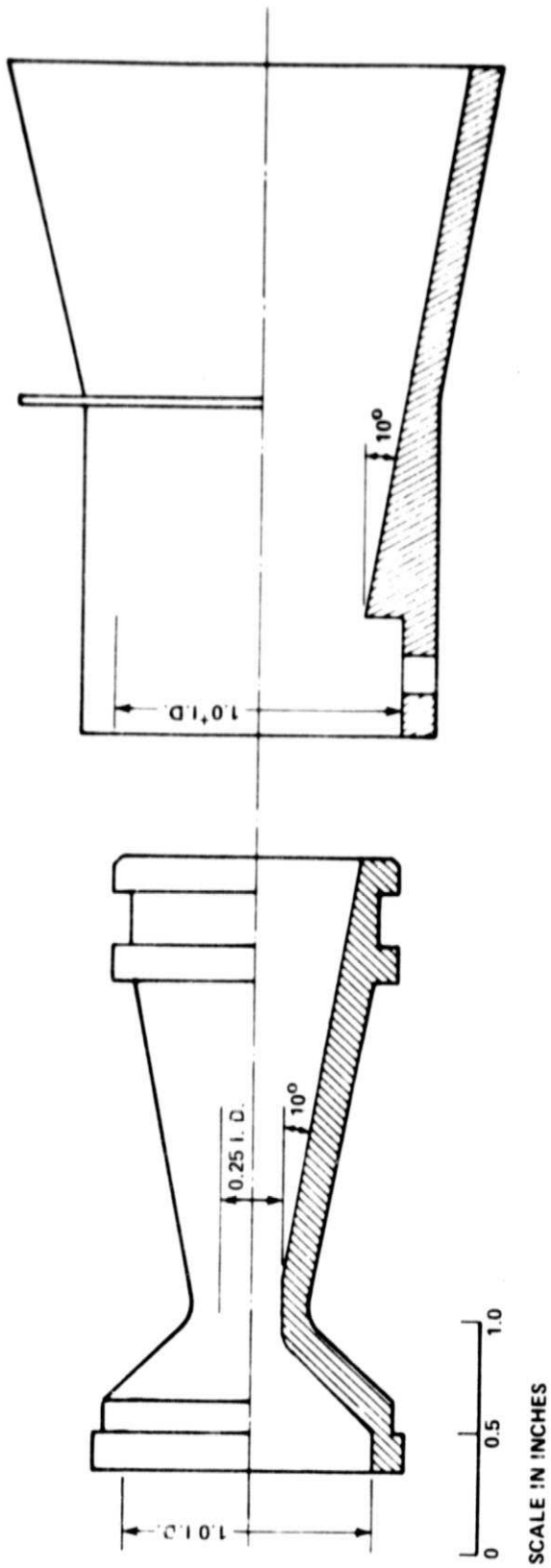


Figure 10. Laval spray nozzle with extension (straight cone).

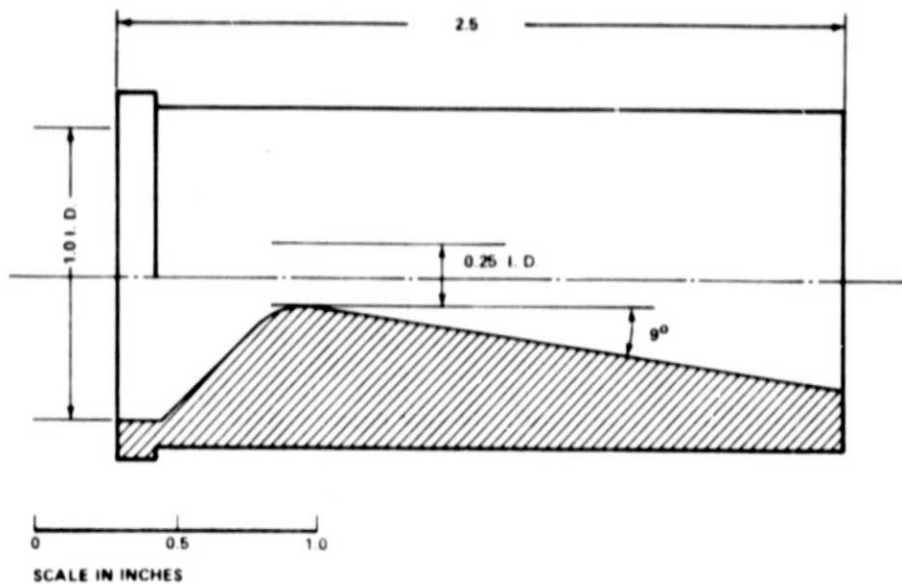


Figure 11. Simplified Laval nozzle (straight cone).

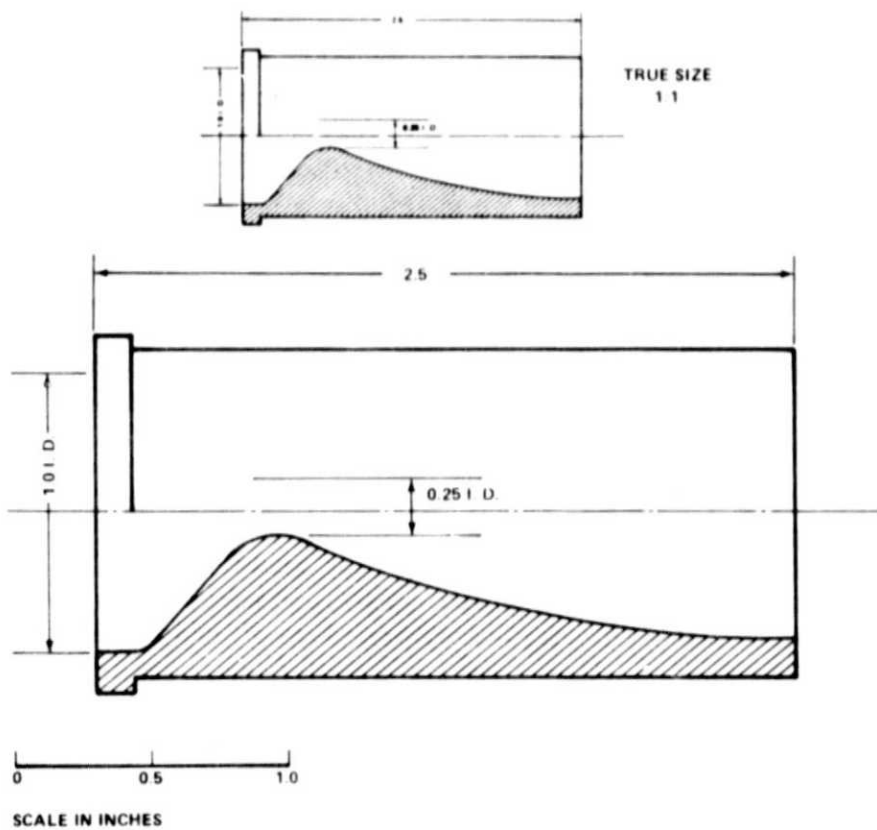


Figure 12. Laval nozzle with bell shaped exit.

surface area and a continuous change of the jet cone to a cylinder, thus narrowing the boundary of bouncing particles on the surface of the MSA-1 jet. After leaving the nozzle exit, the resultant vector of the jet motion is almost parallel to the center of the nozzle. Test results of the bell shaped nozzle proved it to be the best performing; it suppressed the overspray satisfactorily and produced a very smooth surface of the MSA-1 coating.

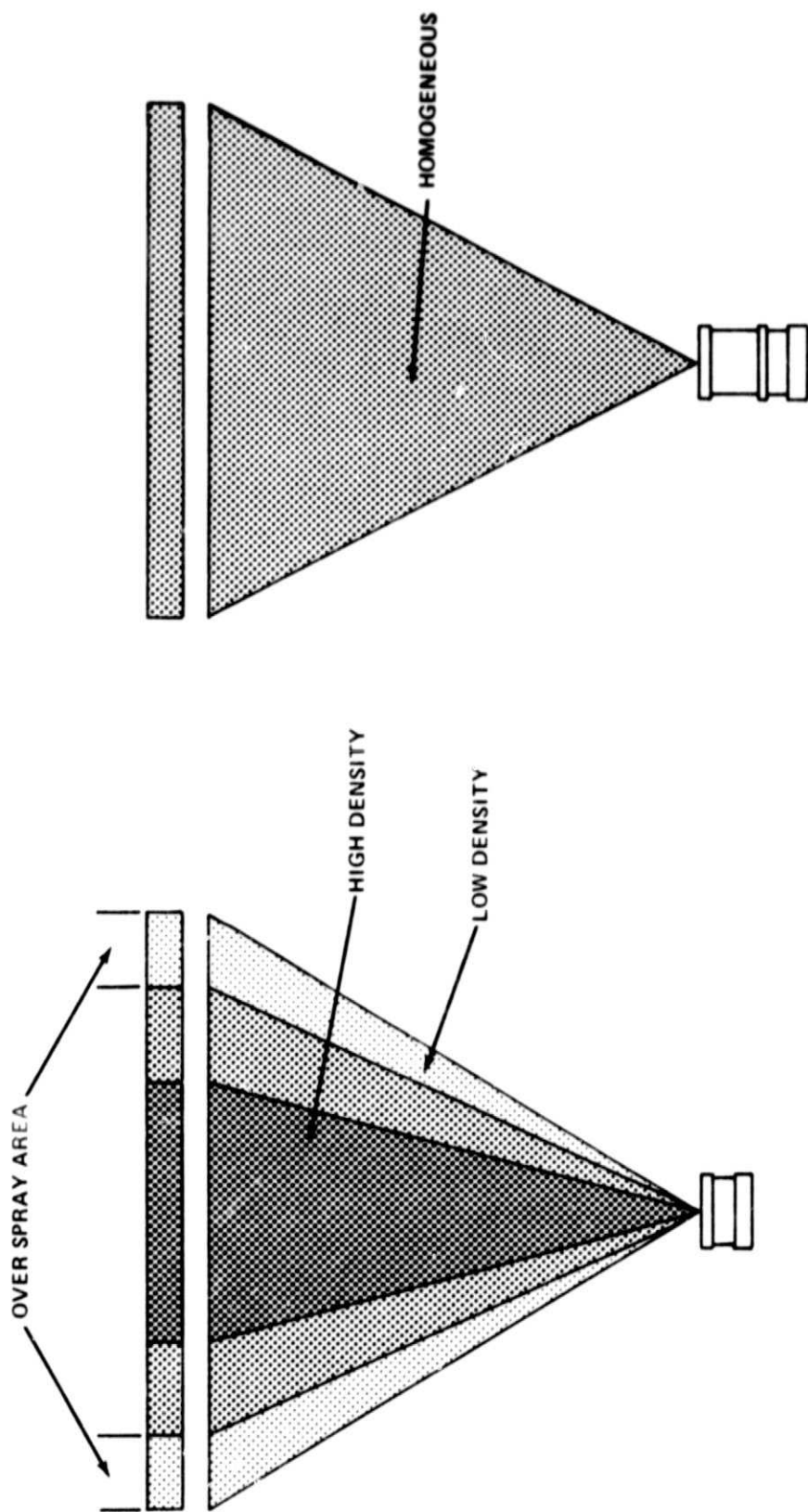
Figure 13 illustrates symbolically the difference of MSA-1 spray jet formation between a jet formed using a standard spray gun and the jet using the bell-shaped Laval type nozzle. The Laval type nozzle is mounted directly to the mouth of the commercial spray gun without any modification to the gun itself (Fig. 14).

To substantiate and document the superior performance of the bell-shaped Laval type nozzle in comparison with all other new nozzle systems, a test program was established and test were performed inhouse. These test results are shown in Table 1.

These data show that the straight divergent and bell-shaped divergent nozzle in comparison with the commercial nozzle exhibits an average decrease of approximately 2 percent in density, which is understandable because the lightweight particles which were previously scraped off the panel as constituents of the overspray are now contained in the MSA-1 coating. The coating tensile bonding strength has been reduced by approximately 2.5 percent for the altered MSA-1 mixture which is in the safe range of the required strength. To better see the spray pattern formation, the spraying operation was stopped midway from one end of the panel to the other. Each test panel was photographed and typical examples are shown in Figures 15 through 20. These figures demonstrate very dramatically the suppression of overspray and the improvement of the surface smoothness.

CONCLUSIONS

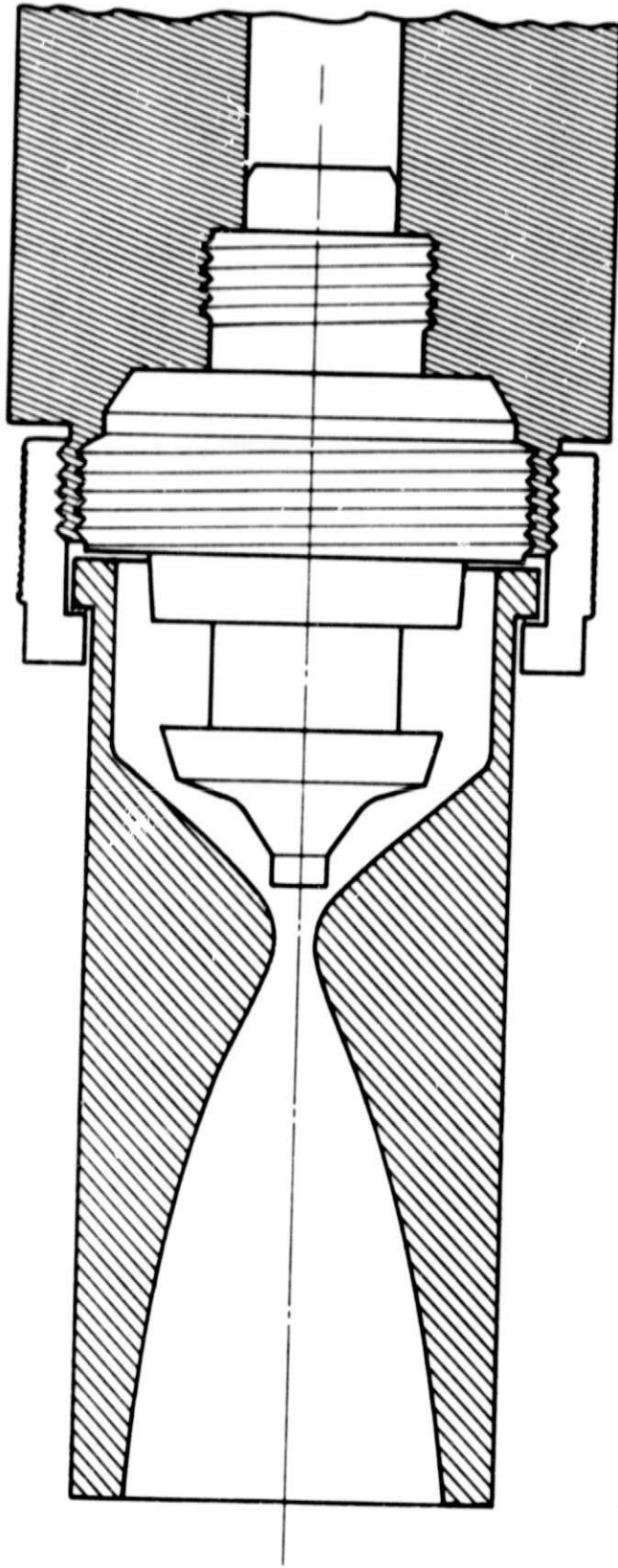
As a result of this study of various nozzle designs for use in the TPS sprayable system, it was determined that one of the most critical conditions that must be controlled is the nozzle shape. This does not mean that other variables such as the MSA-1 constituents mixture ratio, temperature control of the spray material, pump setting, air pressure, etc., are of less importance; however,



STANDARD BINKS GUN
WITH "de L'AVAL" NOZZLE

STANDARD BINKS SPRAY GUN

Figure 13. Schematics of MSA-1 spray jet pattern.



0 0.5 1.0
SCALE IN INCHES

Figure 14. Assembly of Laval nozzle and Binks automatic spray gun.

TABLE 1. TEST EVALUATION DATA

Test Group	Nozzle	Throat Diameter (in.)	Restrictor Diameter (in.)	Pump Setting	Air Atomizer Pressure (psi)	Average Density (lb/ft ³)	Flatwise Tensile Load (lb)
1	Laval Bell Shaped	0.25	0.165	3	30	14.5	131
		0.25	0.165	3	30	13.8	125
		0.25	0.165	4	55	14.2	132
		0.25	0.165	4	30	14.2	132
2	Laval Bell Shaped	0.35	0.165	2	40	13.2	113
		0.35	0.165	2	40	13.5	108
		0.35	0.165	4	30	12.4	110
		0.35	0.165	4	55	13.0	110
3	Laval Straight 9 Degrees	0.25	0.165	2	30	14.1	111
		0.25	0.165	2	30	13.4	115
		0.25	0.165	3	30	13.2	85
		0.25	0.165	3	30	13.2	85
4	Laval Straight 8 Degrees	0.25	0.165	3	30	15.2	133
		0.25	0.165	3	30	15.1	157
		0.25	0.165	5	30	14.1	122
		0.25	0.165	5	30	14.1	122
5	Laval Straight 9 Degrees	0.35	0.165	2.5	55	13.0	105
		0.35	0.165	2.5	55	12.8	119
		0.35	0.165	3	55	14.0	78
		0.35	0.165	3	55	14.0	70
6	Laval Straight 8 Degrees	0.35	0.165	3	55	12.8	102
		0.35	0.165	3	55	13.6	113
		0.35	0.165	4	55	12.8	75
		0.35	0.165	4	55	12.1	68
7	Standard Nozzle	0.25	0.165	4	25	15.2	136
		0.25	0.165	4	25	17.2	135
		0.25	0.165	4	25	15.0	136
		0.25	0.165	4	25	17.2	127

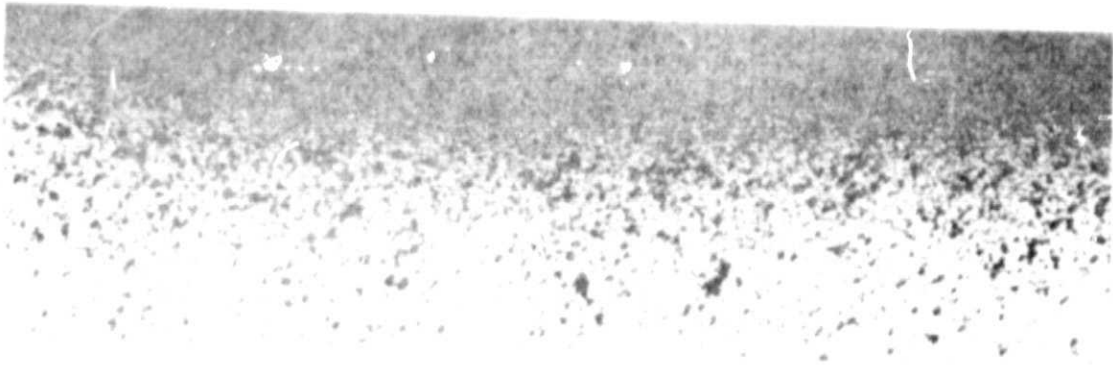


Figure 15. Spray pattern obtained using a standard Binks spray gun.

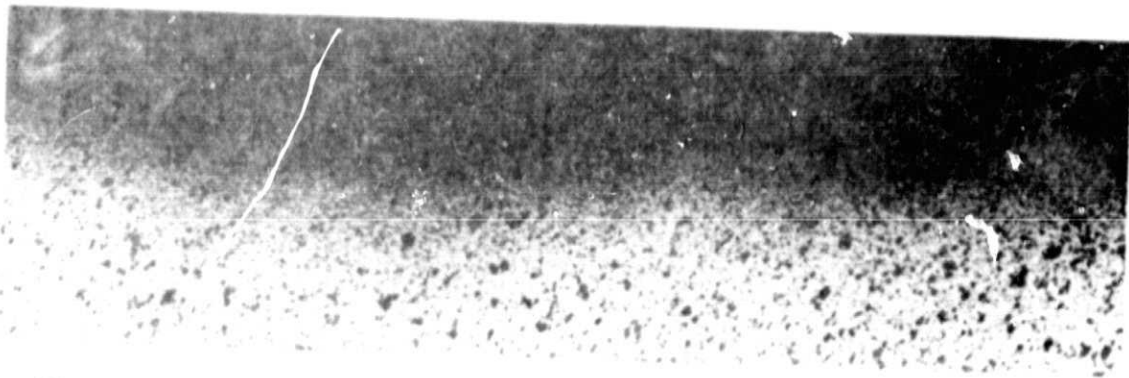


Figure 16. Spray pattern obtained using a 10 degree straight cone Laval nozzle mounted on standard Binks spray gun.

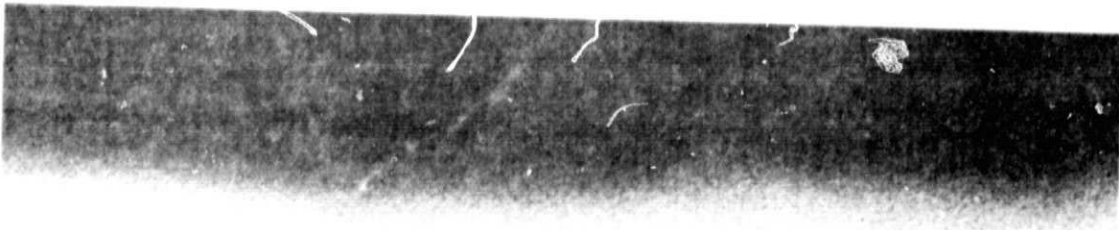


Figure 17. Spray pattern obtained using a bell shaped Laval nozzle exit mounted to a standard Binks spray gun.

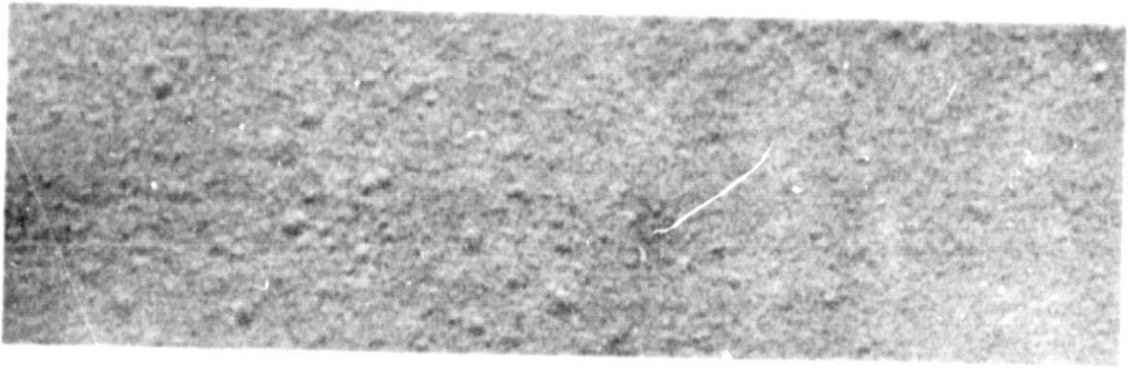


Figure 18. Surface roughness of MSA-1 obtained using a standard Binks spray gun.

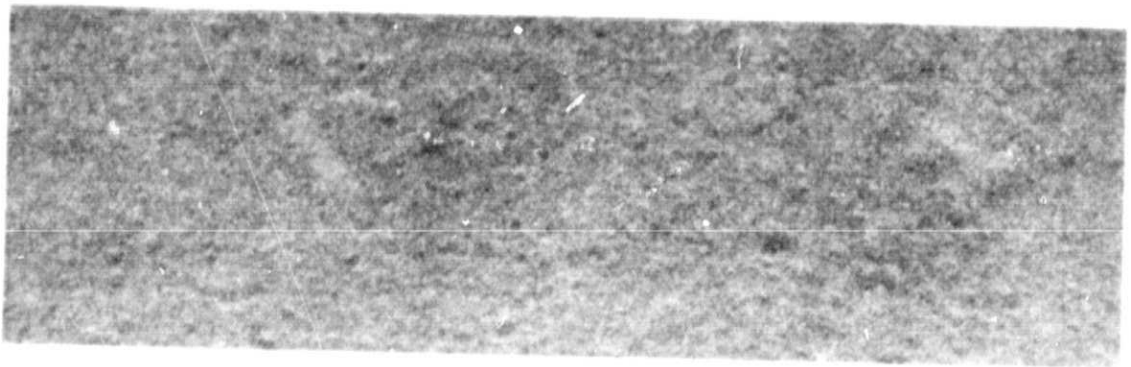


Figure 19. Surface roughness of MSA-1 obtained using a 10 degree straight cone Laval nozzle mounted on a standard Binks spray gun.

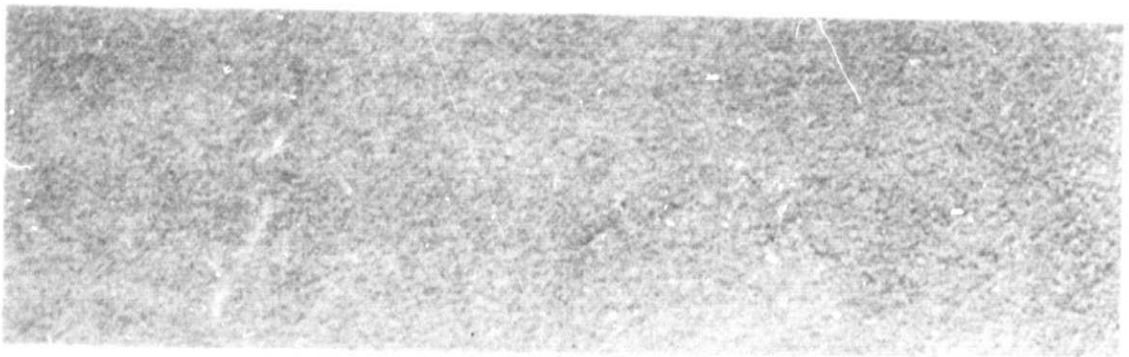


Figure 20. Surface smoothness of MSA-1 obtained using a bell shaped Laval nozzle exit mounted to a standard Binks spray gun.

the nozzle shape is one of the most important factors in the formation of the jet stream. This nozzle development improves the overall efficiency of spraying mixtures of different density constituents, reduces waste and the need for excessive manual labor, and in addition improves reproducibility and the quality of MSA-1 as sprayed. The fact that MSA-1 can be sprayed continuously will greatly contribute to the economical application of a thermal protective coating to the SRB program.

APPENDIX

THEORY OF THE LAVAL NOZZLE

The Laval nozzle theory¹ is based on the assumption that the internal flow under investigation is one-dimensional, i.e., the quantities such as pressure, temperature, velocity, etc., are uniform over any cross section of a channel and that the material behaves as an ideal gas. Internal flows may involve property changes along the inside of a channel resulting from area change, heating, and friction. There is only one spatial coordinate needed to be described and the partial derivatives of the other coordinates are zero.

A very important property of compressible fluid flow is the velocity of propagation of a disturbance in the fluid. The velocity of propagation depends on the magnitude of the disturbance. If the disturbance is very small the velocity of the propagation is called sound or acoustic velocity. The velocity of sound can be determined by investigating a fluid in a long tube where a disturbance has occurred and the wave front is moving at velocity a .

The momentum equation of a control volume of a cross sectional area A is:

$$A[p - (p + dp)] = \rho \cdot A \cdot a[(a + dV) - a] \quad (1)$$

which gives $-dp = \rho \cdot a \cdot dV$ where

ρ = density

c_p = specific heat at constant pressure

c_v = specific heat at constant volume

k = ratio of specific heat

1. W. F. Hughes and J. A. Brighton, Fluid Dynamics, Schaum Publishing Co., 1967.

a = velocity of sound

V = velocity of fluid

R = ideal gas constant

A = area

M = Mach velocity

and the continuity equation for the control volume is

$$\frac{d\rho}{d\rho} = -\frac{dV}{a} \quad (2)$$

Combining both equations,

$$\frac{dp}{d\rho} = a^2 \quad (3)$$

For an ideal gas we may use the equation $a^2 = k \cdot R \cdot T$.

A small disturbance at a point in a stationary fluid will be propagated radially in all directions with the wave fronts forming concentric spheres. If a disturbance force moves at velocity V less than a ($V < a$), we have again wave fronts like spheres but these are no longer concentric.

In subsonic flows where $M < 1$, an infinitesimal disturbance will be felt throughout the entire flow. In a supersonic flow where $M > 1$, a disturbance is felt only over a portion of the flow which demonstrates an interesting and important difference in the behavior of subsonic and supersonic flows.

Many flows can be considered as isentropic which implies they are frictionless and adiabatic with no discontinuity in the flow properties; an example for such a flow is the internal flow in nozzles and diffusers (a change in area is the predominant cause of change of flow conditions).

The energy equation for steady, one dimensional, adiabatic flow of an ideal gas is given by

$$V^2/2 + c_p T = \text{constant} . \quad (4)$$

For the acoustic velocity, we obtain

$$V^2/2 + \frac{k}{k-1} \cdot \frac{p}{\rho} = \text{constant} . \quad (5)$$

Differentiating this equation, we obtain

$$VdV + a^2 \frac{dp}{d\rho} = 0 . \quad (6)$$

The one-dimensional steady flow continuity equation (1) differentiated gives:

$$\frac{dp}{d\rho} + \frac{dA}{A} + \frac{dV}{V} = 0 . \quad (7)$$

If we combine these equations, we obtain

$$\frac{dA}{A} = \frac{dV}{V} (M^2 - 1) . \quad (8)$$

Assuming an ideal gas, where the flow is one-dimensional, steady, adiabatic, and frictionless, the continuity equation for the flow in a converging nozzle is

$$\dot{m} = A_2 V_2 / v_2 \quad (9)$$

where \dot{m} is the mass rate of flow and v is the specific volume $1/\rho$.

The energy equation expressed in terms of the enthalpy is

$$\frac{1}{2} (V_2^2 - V_1^2) = h_1 - h_2 \quad (10)$$

where

M = Mach number

\dot{m} = mass rate of flow

h = enthalpy

p = pressure

v = specific volume

h_1 and h_2 = enthalpies per unit mass.

Assuming that $V_1 \ll V_2$, equation (10) will read:

$$V_2 = \left\{ \frac{2k}{k-1} p, v, \left[1 - (p_2/p_1)^{(k-1)/k} \right] \right\}^{1/2} \quad (11)$$

The combination of equations (9) and (11) yields

$$\frac{\dot{m}}{A} = \left\{ \frac{2k}{k-1} \frac{p_1}{v_1} \left[(p_2/p_1)^{2/k} - (p_2/p_1)^{(k+1)/k} \right] \right\}^{1/2} \quad (12)$$

In this case we take the inlet condition of a divergent nozzle as fixed; the mass flow change takes place as a result of changes in the pressure p_2 of the nozzle exit.

From equation (12) we see that if there is a receiver at the nozzle exit (throat) of a convergent nozzle and the pressure ratio of receiver pressure p_R over the inlet pressure p_2 equals unity, the mass flow \dot{m} reaches a maximum. A further reduction of the receiver pressure yields no change in the mass flow rate. Experimentally it is also observed that the throat pressure p_2 is never less than the value for maximum mass flow. This minimum throat pressure is called the critical pressure p_c . It can be found by differentiating the energy equation and setting the result equal to zero. Thus we obtain

$$\frac{p_2}{p_1} = \frac{p_c}{p_1} - \left[\frac{2}{k+1} \right]^{k/k-1} \quad (13)$$

where p_c is the critical (minimum) throat pressure. Combining this equation and the velocity equation proves that for a convergent nozzle the Mach number is equal to unity when the pressure is critical.

Therefore, we conclude that an improvement in the jet spray profile can only be achieved by an increase in the velocity, i.e. an increase of the area by means of a divergent extension. The flow must pass through a section of a converging-diverging area which characterizes the laval nozzle. Figure 21 shows such a nozzle configuration with the flow characteristics superimposed. The flow regime of the convergent-divergent nozzle demonstrates the flow characteristics schematically. For example, if the receiver pressure p_R is slightly reduced (condition 1 and 2 on the diagram), there is flow from left to right. The flow is subsonic throughout with the converging portion functioning as a nozzle and the diverging portion as a diffuser. By further reduction of the pressure at the end of the nozzle (condition 3), the pressure reaches a minimum (critical) at the throat and the velocity there will be equal to sonic velocity and the velocity in the divergent section will be subsonic. A further reduction of the receiver pressure p_R (condition 4 and 5) causes the flow to be supersonic following the throat for a short distance. This condition is followed by a discontinuity in pressure (shock), and the flow will be subsonic to the exit of the nozzle. At condition 5 the shock has moved to the exit. If the pressure at the nozzle end is between conditions 5 and 6, the nozzle is overexpanded and shock waves occur outside the nozzle with the pressure going from a higher to a lower value.

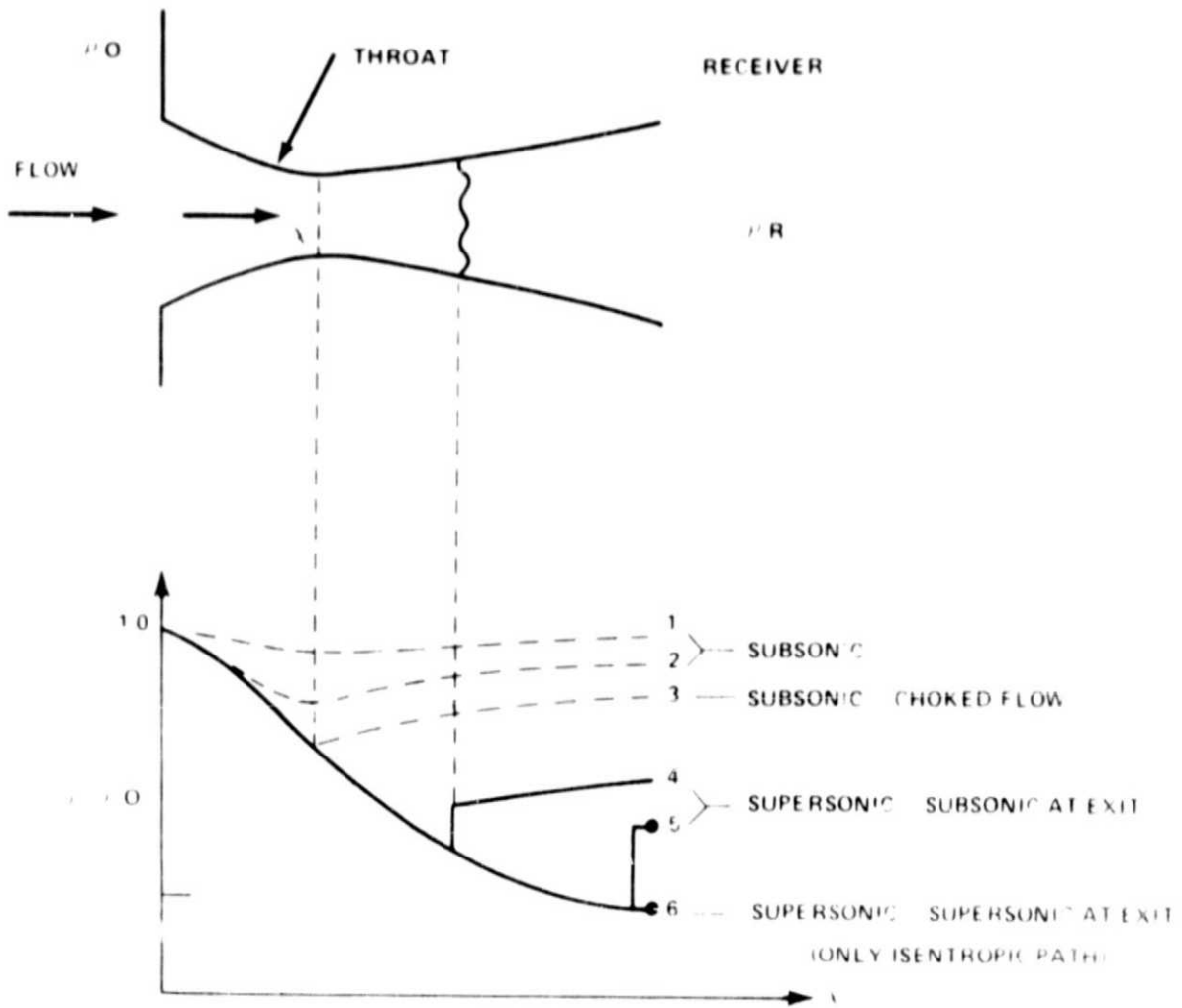


Figure 21. Theoretical flow regimes of a converging diverging Laval nozzle.

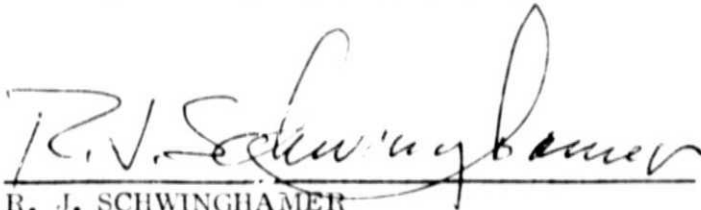
This theory was used as a guide in determining the first convergent-divergent spray nozzle adapter design which resulted in the first spray nozzle adapter (Fig. 10).

APPROVAL

SRB – TPS SPRAY NOZZLE DEVELOPMENT FOR MSA-1 APPLICATION

By Willibald Peter Prasthofer

The information in this report has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

A handwritten signature in black ink, appearing to read "R. J. Schwingamer", written over a horizontal line.

R. J. SCHWINGAMER

Director, Materials and Processes Laboratory