CURVED NOZZLES

V. Ilse
Liquid Rocket Plant
Aerojet-General Corporation
Sacramento, California

Introduction

The conventional supersonic nozzle, invented by Laval at the end of the nineteenth century, presents the only practical device for producing supersonic flow of gases in the rockets.

It is an excellent aerodynamic device, but it has several shortcomings from the practical point of view: (1) It is too sensitive to altitude, (i.e., the thrust of the nozzle changes with altitude), and (2) It is too cumbersome and huge for engines with high thrust.

New ideas about the design of supersonic nozzles are being developed in order to improve the deficiencies. All new types of nozzles use the same basic principle of producing supersonic stream: the subsonic stream in the chamber after contraction at the throat emerges as an accelerating supersonic stream in the divergent channel downstream of the throat.

The differences of the new nozzles from the conventional ones are: (1) The throat area is not circular but annular or of another shape and (2) The flow direction from the throat may not be parallel to the engine axis, but tilted inward or outward.

An annular combustion chamber with an annular throat may have a conical or bell-shaped plug in the center of the divergent nozzle. The flow through the annular throat can be directed in three different ways: parallel to the axis, along the skirt, or along the plug.

The first method is used in all conventional nozzles. The nozzles using the second or third method are properly called nozzles with forced deflection of the gas flow, or forced-deflection nozzles.
Thrust-producing capability of an annular nozzle is divided between the skirt and the plug. One of the main factors influencing the division is the degree of forced deflection. By proper deflection, the skirt or the plug can produce the total thrust.

The various annular nozzles have an important advantage over the straight conventional nozzles. As is known, the length of the nozzle skirt is proportional to the smallest dimension of the throat area. The width of the annular throat is much smaller than the diameter of the equivalent circular throat. Therefore, the length of the new supersonic nozzle is always considerably shorter, but the general surface of the skirt remains approximately the same.

The new nozzles have the following disadvantages: The perimeter of the annular throat is long and the width is narrow. The annular combustion chamber and the throat have much greater surface exposed to the direct action of flame and high pressure than the equivalent cylindrical chamber. This creates considerable design problems.

A compromise between the circular and annular designs can be found, when the annular throat is replaced by a group of discrete round nozzles.

For large thrust boosters it will be very profitable to use this idea simply because the single rocket engine with one million or several million pounds of thrust has very large dimensions. Several discrete chambers of some hundred-thousand-pound-thrust range each can be built together, using one skirt, the length of which is adjusted to the diameter of these small composite chambers. Therefore, the entire structure of such a cluster of combustion chambers with a common skirt will be relatively smaller.

Nozzle Development

As rocket development progresses, the shape and dimensions of the divergent part of the nozzle gradually change.

Several factors must be considered in the design of rocket nozzles. The expansion ratio (i.e. exit-to-throat area ratio) should be large to increase the thrust; however, the rocket engine should have a low moment of inertia for ease in gimbal actuation. The nozzle should be light and consequently short. At the same time it should have the mechanical strength to transfer thrust, which constitutes at least 20% of the total engine thrust. From these requirements the bell-shaped nozzle was created. This shape, however, does not always satisfy the conditions for best performance.

A bell-shaped nozzle with a short length must have a large angle of divergence at the throat. (It is worth remembering that the half angle at the throat of the straight, conical
Laval nozzle as used in turbines is small, while in a rocket engine this angle is from 15 to 35°.) In the portion of the bell-shaped nozzle immediately downstream of the throat the gas rapidly expands because the nozzle wall has a large angle of divergence. Due to this sudden change at the throat from the axial direction to the angle of divergence, flow separation due to the inertia of the high speed stream might be expected, and then an oblique shock will arise at the line of reattachment.

In the remaining portion of the nozzle, the divergent flow is gradually turned to flow parallel to the axis of the nozzle. However, it is practically impossible to turn the flow parallel to the nozzle axis because this requires a significant nozzle length. A large expansion ratio at the exit may result in a low jet exhaust pressure on the wall. Consequently, overexpansion may take place, reducing engine performance at low altitude.

It is obvious that the bell-shaped nozzle cannot satisfy all these contradictory requirements. Thus, it is necessary to find a new type of nozzle where, in spite of the short axial nozzle length, there would not be any flow disturbances near the throat or at the nozzle exit, and the exit pressure would be high enough to prevent overexpansion.

In conventional convergent-divergent nozzles, the gas flow from the throat is directed along the axis of the nozzle. The gas then expands in the divergent part of the nozzle and gradually deflects in all directions toward the nozzle wall. In this type of nozzle the expansion is accompanied by natural deflection toward the nozzle wall. Therefore in the conventional supersonic nozzle, expansion and deflection are natural. Such a nozzle can be called a natural-deflection nozzle (N-D nozzle).

Later a nozzle will be described with expansion and forced deflection (F-D nozzle).

In the conventional nozzle the walls are directed at a rather small angle with the thrust direction. Here the usual angle is about 30° at the throat and much less at the exit, thus only a part of the wall pressure develops thrust, another part tends to disrupt the nozzle skirt.

Each ring of the nozzle skirt with the radius \( r \) and the width \( dr \) produces the thrust:

\[
dF = 2 \pi r p \, dr
\]

Thus the element of the thrust depends on the radius of the elementary ring and the wall pressure. Near the throat the radius is small and therefore the thrust of a ring having the width \( dr \) is small. Toward the exit the radius increases but the wall pressure decreases and the thrust produced by
the ring of the same width \( dr \) will diminish. The function

\[
dF/dr = 2\pi pr
\]

is presented in Figure 1. Here the nozzle contour is shown by dotted line. The wall pressure inside the nozzle falls from 375 psia at the throat to approximately 9 psia at the exit of the nozzle. Using this information \( dF/dr \) can be calculated for every nozzle radius.

On the left side of the diagram an integral curve is presented:

\[
F = \int_{r_t}^{r_e} pr \, dr
\]

where the integral should be taken from the throat radius \( r_t \) to the exit radius \( r_e \). In this case \( F \) will be the full thrust produced by the nozzle skirt. For a particular radius of the nozzle 1-3, the local wall pressure is 1-2. It can be shown, that at the ring with radius 1-3, the value of function \( 2\pi pr \) is equal to the length 4-5. The thrust of the nozzle length 3-5 is equal to the integral of the whole surface under the curve \( 2\pi pr \) from the throat to the point 5. This surface is presented by the line 5-6, which is one of the abscissae of the integral curve. In this case, the thrust of the part of the nozzle (length 3-5) is equal to 26,000 lb. The thrust produced by the whole nozzle length is 29,000 lb. The integral curve on the left side of the diagram shows the increase of thrust with the growth of nozzle radius.

Figure 1 presents the basic idea of the graph-analytical method of nozzle thrust calculations, developed by the author.

Curved Nozzles

In the conventional convergent-divergent nozzle, the throat area is perpendicular to the center line of the nozzle. The gas flow expands very rapidly while accelerating in the divergent portion of the nozzle. The expanding gas flow produces a certain pressure on the nozzle wall; however, the elements of the wall surface are unfavorably placed at rather small angles with the direction of the thrust vector. Thus a certain length of the nozzle is required to catch the thrust. An improvement in the nozzle performance can be obtained by using a curved nozzle instead of a nozzle with the straight center line (Figure 2). In the curved nozzle (Figure 2, left) the gas jet, after passing through the throat (a-c), will be deflected by the side wall (c-d). The opposite side of the nozzle (a-e) will experience a reduced pressure. This side (a-e) of the nozzle can eventually be eliminated when the shape of (c-d) is properly selected. The divergent part of the nozzle is then transformed into a curved channel, open on one side (Figure 2, right). This trough-shaped nozzle is
Figure 1. Grapho-Analytical Method of Thrust Determination.

Figure 2. Curved Nozzles--Closed and Open.
a prototype of a building block which can be used for producing various types of new rocket engines. These building blocks can be placed in circles or in straight lines, as will be shown later.

Each element of the nozzle length $dx$ produces the thrust

$$dF = \rho 2\pi rtg\alpha \cdot da$$

where: 
- $p$ = local pressure on the wall.
- $r$ = local radius of the nozzle.
- $\alpha$ = local angle of the skirt contour (between the tangent and thrust direction).

The thrust per unit length of the nozzle is maximum when its derivative with respect to a change in $\alpha$ is zero, i.e., if

$$\frac{d^2F}{d\alpha \cdot dx} = 0$$

It is possible to show that the thrust per unit length near the throat can be made considerably higher in the curved nozzle. The thrust-producing elements of the nozzle wall surface near the throat can be placed almost perpendicular to the thrust direction. Therefore, such a nozzle will be much shorter while producing the equivalent thrust. There are also other circumstances, allowing further reduction of length.

In the curved nozzle, the gas flowing in the divergent part of the nozzle is directed along the wall by turning the throat in that direction. This is a nozzle with forced deflection. Such a nozzle will be called a forced-deflection nozzle (F-D nozzle). The intensity of deflection of the gas jet is variable, depending upon the camber of the deflection surface, plug, or skirt. When the deflection is gradual, the shape overturn $da/dx$ is low. Here, $a$ is the slope of the nozzle outline and $x$ is the nozzle length.

Different Applications for the Curved Nozzle Principle

Suppose the curved nozzle shape is rotated around the axis I shown in Figure 3, upper right. The resulting device consists of a toroidal combustion chamber of a large radius, and an axial spike. This device is now known under the name "Plug Nozzle" (Figure 3, upper half). The plug nozzle can be considered a cluster of nozzles with forced deflection. In this cluster each elementary curved nozzle has a very small width. The jets from these nozzles are directed toward the center line of the rocket engine. From another point of view, the cross section of this nozzle is seen as a
FORCED DEFLECTION NOZZLE  
(With Plug)

FORCED DEFLECTION NOZZLE  
(With Skirt)

Figure 3. Different Shapes of Curved Nozzles: Above--with Plug; Below--with Skirt.
back-to-back arrangement of the basic nozzle shape. A radial-convergent nozzle would also be a proper name for this device.

When the basic curved shape is rotated around axis II shown in Figure 3, lower right, it will generate a new type of nozzle with a full skirt. In this nozzle, the right and left halves of the cross-section are arranged in the face-to-face position. The jet from the annular throat is directed away from the center line. This engine has a nozzle with a full skirt and utilizes the principle of forced deflection of the jet. The thrust chamber will again have the shape of a toroid, but now with a much smaller radius (Figure 3, lower left). This nozzle is called a skirt nozzle.

Both cases, the plug nozzle and the skirt nozzle (back-to-back and face-to-face positions) utilize forced deflection of the jet toward the hard surface of the central plug or the outside skirt.

A new class of nozzles can be created when an access to ambient air is provided into the central area inside the skirt nozzle with forced deflection.

The nozzle shown in Figure 3, lower left, has a central duct through which the ambient air can penetrate, creating a central core of air. If there were proper pressure in the core it should affect the internal boundary of the jet. A nozzle in which the ambient atmosphere influences one side of the supersonic, expanding jet may be called an aspirating nozzle. Aspiration can be external or internal.

The skirt nozzle with a central duct has internal aspiration. In the case of a plug nozzle, the ambient air has access to all sides of the jet and aspiration is external. Therefore, the plug nozzle is a nozzle using forced deflection and external aspiration.

Various Types of Rocket Engines with the Skirt Nozzle

Four possible types of the rocket engines with the skirts are presented in Figure 4. All of them have annular combustion chambers and annular throats. Two of them, shown on the left, have their throat areas lying in a plane perpendicular to the axis of the engine; thus, the gas jet at the throat flows parallel to the axis of the rocket engines and there exists natural deflection of the gas flow toward the skirt surface and toward the axis. In the engines on the right the throat area is turned in an outward direction; the exhaust jet is then directed tangentially to the skirt. All the nozzles of Figure 4 have skirts. Three of them (except first one) belong to types unlike the conventional nozzle, because the two new methods of influencing the expanding supersonic jet are used. (Forced deflection and aspiration).
Figure 4. Four Types of Annular Nozzles with Skirt.

Figure 5. Comparison of Conventional and Annular Nozzle with the Same Area Ratio, $\epsilon = 25$. 
Type A. Rocket Engine with Conventional Expansion
(upper left)

The supersonic stream from the annular throat flows parallel to the axis of the engine. The gas jet gradually expands laterally, i.e., towards the skirt and the center line of the nozzle. This is the conventional method for expanding the gas jet as used in the Laval nozzle. Notice that forced deflection of the gas jet is not used in this nozzle.

This nozzle might be called a natural-deflection nozzle; the deflection here is produced naturally.

Type B. Aspirating Rocket Engine with Conventional Expansion (lower left)

This is the simple aspirating nozzle. In this design a duct is made in the top of the nozzle. A stream of ambient atmosphere enters the nozzle through this hole. This stream, once inside the nozzle, produces changes in the flow field; however, it does not produce a noticeable effect on the pressure profile along the nozzle wall. Therefore, this type of nozzle does not have practical significance.

Type C. Rocket Engine with Forced Deflection (upper right)

Forced deflection without aspiration is used in this engine. The throat area is inclined toward the skirt, directing the gas jet along the inside surface of the skirt. The pressure profile of the skirt can be changed by using deflectors and skirts of different shapes. The overexpansion of the jet can be prevented.

Type D. Forced Deflection and Aspirating Rocket Engine (lower right)

This rocket engine has a hole for aspiration and simultaneously uses forced deflection of the jet against the wall of the skirt. Experiments show that the influence of the air core on the wall pressure profile is considerably less than the effect of the wall shape overturn.

All nozzles, except the type B, may have practical application.

In the nozzles with air ducts, the expanding supersonic flow meets the nozzle wall on one side and on another side meets the air flow penetrating through the air duct inside the core of the annular jet. Thus the gas flow is continuously exposed to ambient condition of air flow in the core, and the jet-free boundary should adjust to this condition.
Experiments with the Annular Throat Nozzle

A group of experiments has been conducted to compare the conventional bell-shaped nozzle with the annular nozzle (type A). Two nozzle models were built for cold flow tests with nitrogen, as shown comparatively in Figure 5. The exit radius of both of them was the same (3.75 in.) as was the throat area. Thus, the area ratio was the same in both cases and equal to $\epsilon = 25$. The length of the annular nozzle was only about one-half that of the bell-shaped nozzle because of a smaller throat gap.

The tests with nitrogen were made in the diffuser and the exit pressure was measured in both cases at different chamber pressures.

<table>
<thead>
<tr>
<th>Chamber Pressure</th>
<th>Exit Pressure Straight Nozzle $P_{el}$</th>
<th>$P_e$</th>
<th>Exit Pressure Annular Nozzle $P_{e2}$</th>
<th>$P_{e2}/P_{el}$</th>
<th>Pressure Ratio $P_c/P_{el}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>800</td>
<td>4.1</td>
<td>6.7</td>
<td>1.63</td>
<td>195</td>
<td></td>
</tr>
<tr>
<td>700</td>
<td>3.6</td>
<td>6.2</td>
<td>1.73</td>
<td>195</td>
<td></td>
</tr>
<tr>
<td>600</td>
<td>2.9</td>
<td>5.2</td>
<td>1.79</td>
<td>205</td>
<td></td>
</tr>
<tr>
<td>500</td>
<td>2.1</td>
<td>4.2</td>
<td>2.00</td>
<td>238</td>
<td></td>
</tr>
<tr>
<td>400</td>
<td>1.5</td>
<td>3.7</td>
<td>2.46</td>
<td>268</td>
<td></td>
</tr>
</tbody>
</table>

The main conclusion from this investigation should be that in the annular nozzle the exit pressure at the wall was always approximately 1.5 to 2.5 times higher than in the straight nozzle of the same geometrical expansion ratio. Therefore, one can expect stronger resistance to flow separation in the annular nozzles.

Another conclusion from these experiments should be that the pressure near the wall is higher than predicted by simple one-dimensional theory. The observed chamber-to-exit pressure ratio was from 195 to 268, i.e., it depended upon the chamber pressure, while the simple theory gives $P_c/P_e = 500$ (for $\gamma = 1.4$). In this case, when the radius of the annular throat is approximately equal to one half of the exit radius, the exit pressure near the center line is slightly higher than at the exit edge.

Two cones (shown by dotted line in Figure 5) were used in connection with the annular chamber. They were put into the center of the nozzle, to prevent turbulence and to guide the flow toward the center of the exit area. However, the presence of these cones did not influence the wall pres-
sure at the exit. It proved that the supersonic stream from the annular throat directed straight downstream divides the internal area of the throat into two volumes which are almost independent.

Experimental Investigations with Different New Nozzles

Many experiments have been conducted by the author with various models of unconventional nozzles in order to investigate their possibilities.

The investigations with forced deflection nozzles were started in the middle of 1959. The nozzles shown here were tested between October 1959 and May 1960. Investigations are continuing with other types of nozzles using the same principle of forced deflection, as well as the combination of forced and natural deflections.

One of the experimental nozzles is shown in Figure 6. It belongs to type D (Figure 4) with forced deflection and aspiration.

This half nozzle was used to investigate the cross-section of the flow field inside the skirt. A piece of cardboard was cut to shape and heavily covered with chalk of a contrasting color. The cardboard was then mounted between the nozzle block and the cover plate. As the compressed gas flowed over the chalk, the supersonic jet removed a part of the chalk, thus presenting the flow line direction along the skirt and around the mushroom deflector. Many fairly well defined shadowgraphs showed the flow field inside the nozzle.

This half nozzle was used for another purpose also as shown in Figure 7, where a plate with a slot covers the side of the nozzle. Several side plates with different shapes of slots were tested. The idea was to investigate the various methods of aspiration of the internal core of the skirt nozzle. The outside air entering the inner area of the half skirt should produce the same effect as in the open plug, thus preventing overexpansion.

On the basis of this idea a rocket engine can be developed that will serve as a building block for the large scale rockets.

Two methods of assembly of these blocks are shown in Figure 8. In the upper part are two rows of such nozzles in face-to-face position and in the lower part, a back-to-back arrangement is used. In both cases the ambient air has free access to one side of the expanding jets.

The other shape of a half-circular nozzle is shown in Figure 9. It belongs to type B, without forced deflection, but with aspiration. The central aspirating duct could be plugged, then the nozzle transforms to type A. The circular
Figure 6. Half-Nozzle with Forced Deflection (F-D) and Aspiration, with Side Plate Removed.
Figure 7. Half-Nozzle with Forced Deflection and Side Aspiration: Black Arrow—Compressed Gas; White Arrows—Ambient Air.
Figure 8. Block Assembly of Forced Deflection Nozzle
Position of Deflectors: Top--Face-to-Face; Bottom--Back-to-Back.
Figure 9. Half-Nozzle with Annular Throat and Central Aspirating Duct, no Forced Deflection.

Figure 10. F-D Nozzle with Large Central Duct for Aspiration. Mushroom Shape Deflector is Seen Inside.
nozzles of all four types (A, B, C, and D) were also tested. Several nozzles in these experiments had very wide central ducts to improve the aspiration (Figure 10).

**Typical Pressure Changes in the Nozzle**

The main purpose of all the experiments was to measure the pressure profile at different chamber pressures and to test various deflection methods. The methods used in this investigation are described below.

A typical diagram of chamber pressure changes observed in the experiments is presented in Figure 11. The rate of pressure change was slow, and every experiment continued about 60 sec. The slow change of $P_c$ makes it possible to observe a steady-state condition along the whole length of the nozzle.

Three diagrams of pressure variations in Taps 1, 2, and 3, as well as the position of the taps are shown in Figure 11. Let us investigate the pressure variation diagram at pressure Tap 3. This pressure first increases up to 37 psia (Point b), then decreases to 13 psia (Point c), and then gradually rises to 25 psia (Point d). Curve section c to d is the normal rise of static pressure at a given point on the nozzle wall with the rise of chamber pressure.

Pressure changes, during the transition period when the separation region and the shock wave system travel across the orifices of a pressure tap, are shown as a, b, and c on the diagram.

During the chamber pressure rise, Curve 2 hits a maximum at $b^1$ which is observed 5.5 sec later, after the pressure maximum at pressure Tap 3. The maximum $b^{11}$ is observed still later at 19 sec at Tap 1. Thus the separation region travels downstream along the nozzle surface when the chamber pressure rises. The same phenomenon is observed in reverse order during the shutdown, when the shock system at separation area crawls from the exit edge to the throat, while the chamber pressure falls. It is noted that the maximum static pressure at a given point during the shutdown is the same as at the start and occurs at the same chamber pressure.

**Design Conditions for a Radial Convergent Nozzle**

(Plug Nozzle)

In the radial-convergent nozzle (Figure 3, upper half), exhaust flow passes through an annular throat and then is directed against a conical plug. As the exhaust expands, the plug surface forms one boundary for the flow and the ambient atmosphere the other one.
Figure 11. Diagram of Pressure Changes in Three Pressure Taps During the Changes of the Chamber Pressure $P_c$. 
The design of plug nozzle shape by the method of characteristics usually produces very long spike-shaped plugs, which are unacceptable from the practical point of view. This attempt of nozzle calculation should be recognized as completely unsuccessful. Experiments show that a short plug could be built which would be as good as the long one. The experiments also show that the subsonic wake behind the truncated plug can produce the same thrust as the chopped-off part of the plug and the much shorter plug can be used without loss of performance.

From experiments it is well known that the length of the plug has small influence on the performance. Thus, for example, when the length of the plug changes from full length to 20%, the thrust efficiency changes only 2% (for optimum conditions) to about 5% at conditions very far from optimum. This is the best proof that the performance depends not so much on plug shape and especially not on the length, as upon the fact that in the plug-type thrust devices, the flow is radial-convergent and consequently congests at the end of the plug. The significance of this is explained in Figure 12.

The gas flow from the throat to the end of the plug changes drastically in shape which cannot be properly evaluated by the method of characteristics. Take for example a segment of the plug nozzle flow. At the throat it has a rectangular shape (a-b-c-d.). At the end of the plug the flow will have a triangular, cross section (c'-d'-o'). The side a-b gradually diminishes to zero.

The streams along the generatrices (a-a') and b-b') should collide unless they do not turn toward d' and c'. It is obvious that the stream tubes congest in the wedge-shaped channel and bulge out.

The sides (b-a-d'-o') and a-c-c'-c') are supported by the neighboring streams. The gas jet downstream of the throat is open to the influence of the outside atmosphere through the surface (d-c-d'-c'). This influence has been much publicized as the essence of the plug nozzle superiority over the conventional nozzles, where the whole expanding flow is surrounded by the hard walls. However, one important phenomenon was overlooked. The gas jet from the throat is directed along the plug surface, which guides the flow more or less gradually turning it parallel to the engine axis. Inertial forces hold the flow near the plug wall in the upper part of the plug. In the lower part of the plug where the diameter becomes small, the congestion of the high speed streamlines helps support internal pressure high enough to prevent overexpansion of the main mass of flow.

The selection of the conical plug instead of the curved...
Figure 12. A Segment of the Plug Nozzle Flow.

Figure 13. A Segment of the Skirt Nozzle Flow.
ones, shows that the whole process of gradually turning the supersonic flow to the axial direction is now accomplished by the flow itself.

It has been said that if the plug nozzle is covered by a cylindrical shield, it is transformed into a conventional nozzle and is not worth further consideration. This is an extreme expression of the opinion that only outside ambient pressure will influence the flow. Such a complete disregard for the principle of forced deflection might lead only to creation of incorrect nozzle shapes.

In reality, the forced deflection of the jet toward the plug by means of proper turning of the throat area, and later the forced congestion of flow tubes around the plug, are much more important than the influence of outside pressure; therefore, a plug nozzle with a cylindrical shield does not lose its quality, but acquires new ones.

It has been proved by experiments that the ambient pressure produces insignificant effects on the wall pressure through the high-speed stream. The changes in diameter and shape of the boundary surface of the jet observed during the plug nozzle investigation are significant, but it does not mean that the area ratio of every stream tube changes proportionally, especially those located in the vicinity of the plug, where the stream tubes experience more severe action from all sides from the surrounding stream. The changes in the area ratio of the outer stream tubes may be great, while the area ratio of the stream tubes along the plug surface does not change significantly and they remain underexpanded. Therefore, the considerable change in the outer boundary shape and consequently in the observed average area ratio does not mean that there exist significant changes in the cross-section of the tubes near the surface of the plug.

The main phenomena which regulate the performance remain: (1) curvature of the plug, (2) flow congestion. The influence of the ambient atmosphere is the third factor affecting the plug nozzle performance.

During the missile flight, the pressure of the missile base is significantly lower than the pressure in the free stream. This lowered base pressure can cause overexpansion of the outer region of the jets around the plug and result in decreased efficiency. Therefore, it is recommended that a cylindrical shield be placed around the plug (Figure 3, upper left) which would guard the expanding stream from the direct action of the moving ambient air. This guard cylinder will not affect performance which depends greatly upon the curvature of the plug and flow congestion.
Evolution of the Plug Nozzle Concept

A considerable step in the evolution of the plug nozzle concept occurred when it was discovered that the long isentropic plug could be replaced by the conical truncated plug. The long isentropic plug is shown in Figure 14(a). New possibilities in the development of the plug nozzle are presented in (b), (c), (d), and (e) of Figure 14. In plug nozzle (b) the flow from the annular slot is directed radially. This arrangement produces a short deflector, but the diameter of the device should be increased.

In the reversed deflector, shown in (c), the flow from the throat is directed in an upward direction at a small angle and then gradually turned back.

The purpose of designs like (b) and (c) is to produce very short nozzles and transform the plug nozzle into a dish-type nozzle.

This idea was tested by NACA (1) in the form of shape (d). Here the central recirculation zone produces the same effect as a plug.

In the last figure (e) the main jet is surrounded by an annular auxiliary jet. The devices for investigation of these five types of nozzles have been built.

Design Conditions for a Radial-Divergent Nozzle

(Skirt Nozzle)

In the radial-divergent nozzle, exhaust flow from an annular throat is directed along the skirt, as shown in Figure 4-C. Here, as in the radial-convergent nozzle, inertial forces hold the flow along the divergent skirt. The compressive turning of the gas flow on the nozzle wall produces a favorable effect in preventing overexpansion. The combination of the proper direction of the jet at the throat together with the shape of the skirt will prevent overexpansion at the exit end, and, therefore, sustain the performance level above the conventional nozzle.

This capability in this nozzle is less than in the plug nozzle; however, the multitude of internal shocks inside the congested flow around the plug of constantly diminishing size will produce losses that do not exist in the nozzle with smooth expansion along the divergent surface.

In the plug nozzle, the flow congested around the end of the plug cannot be guided properly by a bayonet-shaped plug; it will lose the necessary alignment with the rocket engine axis and will not acquire the proper acceleration. The loss of thrust alignment will be especially noticeable on truncated plugs of large engines and permanent vibration of thrust vector will probably be observed. In the F-D skirt nozzle, the
Figure 14. Evolution of the Plug Nozzle.
flow is well guided due to the large skirt perimeter.

The shape of the expanded flow in a segment of the skirt nozzle with forced deflection is shown in Figure 13. Here (a-b-c-d) is the throat area and the flow slides along the widening skirt (a-b-a'-b'). Part of the flow expands along the surface (c-d-o-i'), toward the center of the plug.

Many investigations of the skirt shape in an F-D nozzle, both theoretical and experimental have been conducted at Aerojet-General Corporation, Liquid Rocket Plant. The distribution of the thrust and $C_F$ were studied. One sample of the constant Mach line distribution, found by the method of characteristics is given in Figure 15. The annular nozzle issues a radial-divergent jet, which gradually turns down. In this case, the central area of the skirt is surrounded by the cylinder. The expansion ratio is $\varepsilon = 31$. The gas flow accelerates along the skirt up to $M = 4.5$ and more considerably along the cylinder where the exit Mach number is more than $8$.

An F-D skirt nozzle may vary in its appearance in connection with general missile design. The combustion chambers can be placed in different positions in relation to the skirt, three of which are shown in Figure 16. Stress and weight analysis, as well as many other considerations, can help to select the best position and the best design for the combustion chamber.

From the gas dynamic point of view, position 2 of the combustion chamber will be the best, however, it requires a large radius of the central hole. For the aspiration purpose it is necessary to have a very large central hole, and the chamber in position 2 will prevent the access of ambient flow.

Position 1 is reasonably good, but it makes the engine longer. With the chamber in position 3 the engine becomes shorter, however, the design is much more complicated in comparison with positions 1 and 2.

The exit edge pressure at the skirt can be as low as it is in conventional nozzles, therefore, the introduction of ambient air into the central area of the skirt may be useful to some extent. However, the problem of introducing the air is great and difficult. One solution--the introduction of the air through the side slot has already been mentioned (Figure 8).

The central aspirating hole of a six-chamber F-D nozzle (Figure 17) has only about 10% of the nozzle exit area and that is not very much. In another case (Figure 18), the proximity of the middle body prevents the penetration of air. To solve this problem, a booster having a cluster of combustion chambers with separate deflectors and common skirt,
Figure 15. Lines of Constant Mach Number in Forced Deflection Nozzle. Mach Number Tolerance $\pm 0.2$ Area Ratio $\epsilon = 31$.

Figure 16. Different Positions of Combustion Chambers in a F-D Skirt Nozzle.
Figure 17. Cluster of Combustion Chambers with a Common Skirt, Central Air Duct for Aspiration.

Figure 18. F-D Skirt Nozzle with Toroidal Combustion Chamber.
(Figure 19) was designed at the end of 1959.

The supersonic stream from each of six combustion chambers flows in curved channels. Deep slots between the channels ensure the access of ambient air in necessary amounts. The lower part of the engine presents the uninterrupted bell-shaped skirt.

The above considerations show how difficult it is to introduce the proper amount of air into the skirt. The scoops around the missile are necessary.

The consequence of all this is that in the circular F-D nozzles it is not possible to accomplish proper aspiration effect because of the many obstacles.

A group of nozzles based on the idea presented in Figure 6, and placed in several parallel rows would be, in our opinion, the best method of the clustered rocket engine with workable aspiration.

**Comparison of Various Annular Nozzles**

In spite of a multitude of new nozzle shapes and even a seemingly basic difference in flow directions of the unconventional nozzles, they all belong to the same class of annular nozzle as is shown in Figure 20.

Shape 1 presents an engine with an annular throat and with straight discharge of the jet in a direction parallel to the axis. Internal cone (c-d) and outside skirt (a-b) are both thrust-generating surfaces. T is the position of the throat plane, which is perpendicular to the thrust direction (to the axis).

In Shape 2 the skirt is cylindrical and does not generate thrust. All the thrust is generated by the internal cone. Cylindrical surface a-b will experience a higher static pressure than the skirt surface (a-b) in Shape 1. This fact and also the direction of the surface parallel to the axis will reduce the possibility of flow separation and loss of thrust due to overexpansion. The length of cylinder a-b may be different and this will influence the performance to some extent.

Shape 3 has an internal cylindrical surface which does not generate thrust. The outside skirt produces the thrust and gives usual performance. This shape has no special advantages, except the possibility of using the central orifices for turbine exhaust.

In all of these shapes the throat plane is perpendicular to the axis, i.e., the throat has a neutral setting.

In Shapes 4, 5, and 6, the radial throat line T is turned at an angle (+ α ) i.e., the throat has a positive setting. The annular throat has a conical shape and directs the flow along the skirt.
Figure 19. Cluster of Combustion Chambers with Deep Slots Between the Supersonic Channels, Sidewise Aspiration, Common Skirt in Downstream Part.
Figure 20. Three Types of Rocket Engines.
Shape 4 has two thrust-generating surfaces: plug (c-d) and skirt (a-b). On the sketch, point d of the plug is in the plane of the exit edge b. However, point b can be located above or below the exit area. The truncated plug also can be used. Thus, a group of engines of the same type but with slightly different sensitivity to ambient conditions can be created. By varying the angle $\alpha$ of throat setting, a different distribution of thrust between the plug and the skirt can be achieved.

In Shape 5 the setting of the throat is the same, but the plug is absent; however, the presence of the plug in any shape has relatively small effect if all other conditions remain the same.

Further variations of design are shown in Shape 6. Dotted lines mean that a cylinder can be used instead of the plug.

There is still one way in which the shape of the engine can be changed; it is to take out cylinder c-d and open the central hole. Now we have a forced-deflection nozzle with the central aspirating duct.

In the three following Shapes 7, 8, and 9 throat setting is negative (-$\alpha$); therefore, the jet from the annular throat is directed toward the axis of the engine.

In Shape 7 both the plug and the skirt generate thrust. The larger amount of thrust is produced by the plug. By changing the setting angle it is possible to diminish the thrust produced by the skirt to zero.

Then the skirt can be replaced by a cylinder (Shape 8), which will guard the flow around the plug from outside disturbances.

When the setting angle is large enough, all the thrust can be produced by the plug only and the outer skirt can be eliminated completely. It becomes Shape 9.

The comparison of these shapes shows that all the different nozzle systems present variations of only one basic type: the annular nozzle. By changing the setting angle $\alpha$ at the throat from a positive to a negative value, a number of different types of nozzles (ranging from the plug nozzle to the skirt nozzle) can be produced. Variations of the throat angle also dictate what portion of the thrust will be provided by the plug and what portion by the skirt. Either can be responsible for all or none of the thrust.

Even in the conventional Laval nozzle the velocity of the gas flow is not constant across the cross section. This was shown in Figure 21. At the exit area the velocity is maximum at the center and slightly less at the wall. The direction of the velocity vectors also varies. The local flow rate is not equally distributed and has a tendency to be larger in the center of the stream. All this is presented in two
Figure 21. Velocity (V) and Flow Rate (W) Distribution in Different Types of Rocket Engines.
The right half of the same figure shows the local flow rate in the annular nozzle with a neutral setting of the throat area.

Here the case is more complicated than in the straight nozzle. Now the distribution of v and w can change considerably with changes of the shape of the skirt and the plug and also with changes of the radius and width of the annular throat.

It is understandable that the thrust produced by every element of the exit area of the engine is a function of the radius and may have a shape similar to w, i.e., to have one maximum at the center in the case of the conventional nozzle, and two maximums along the diameter in the case of an annular nozzle.

In two forced-deflection nozzles (with plug or with skirt) the thrust is produced only by one surface. Figure 21-b shows the distribution of v and w in these two cases. In the F-D skirt nozzle, maximum of w is near the skirt and maximum of v is somewhere near the center. In the F-D plug nozzle, on the contrary, maximum w concentrates near the plug.

Conclusion

All various types of unconventional nozzles can be derived from an annular nozzle, where several elements can be changed.

The setting of the throat can be positive, negative, or neutral.

The rocket engine can be built with or without the external boundary (skirt) or the internal boundary (plug), and with or without aspiration, central or sidewise.

The radial-divergent nozzle (skirt nozzle) has some advantages over the radially convergent nozzle (plug nozzle). The very small surface of the plug in relation to the amount of gas which it must influence means the supersonic stream is not well guided in the area where congestion occurs. As a consequence the turning and acceleration of the flow are not as smooth in the plug nozzle as they are in the radial-divergent nozzle. Another advantage of the radially divergent nozzle is that its skirt covers the jet and guards it from unnecessary influences of outside atmospheric perturbations. The jet around the plug nozzle can also be covered by a cylindrical shield to stop the irregular expansion and protect the jet from the wild disturbances incurred during missile flight.

Many attempts have already been made to adjust these new principles to rocket engine designs; however, the shape of the new nozzles is not yet stable or definite. The search for new designs is continuing and will eventually bring many new forms.
This paper is based on the many experiments conducted by the author at Aerojet-General Corporation in 1959 and 1960.

References


