NOZZLE SELECTION AND DESIGN CRITERIA

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ABSTRACT

Advances in aircraft performance depend heavily upon improved and properly integrated propulsion systems. Historically, new engines and aircraft are developed concurrently, but the design and test cycle of engine systems is longer than that of the aircraft they power because of demanding flight qualification, reliability, and durability requirements[1]. Consequently, the engine hardware development process starts first, so that the success of the entire program often hinges on engine design decisions made early in the process. Critical to the design of efficient air vehicle systems is the design of the gas turbine exhaust nozzle. Aircraft exhaust nozzles serve two primary functions. First, they must control the engine backpressure to provide the correct, and optimum, engine performance, which is accomplished through jet area variations. Second, they must efficiently convert the potential energy of the exhausting gas to kinetic energy by increasing the exhaust velocity, which is accomplished through efficiently expanding the exhausting gases to the ambient pressure. Since the exhaust nozzle provides the integration between the propulsion and aircraft systems, its design must also consider installed, or thrust-minus-drag, performance. Additional design challenges are introduced by the requirement for features such as thrust vectoring and reversing. This paper provides guidelines and procedures for incorporating these considerations into the design of gas turbine exhaust nozzles.

NOMENCLATURE

W	Flow rate
Pt	Total pressure
P	Static pressure
Tt	Total temperature
T	Static temperature
A	Area
M	Mach number
NPR	Nozzle pressure ratio (Pt_8/P_{amb})
γ	Ratio of specific heats
m	Flow rate
v	Velocity
F	Thrust
C_{Fg}	Gross thrust coefficient
C_{Fn}	Net thrust-minus-drag thrust coefficient
Cd	Flow coefficient (W_{actual}/W_{ideal})
R	Gas constant

subscripts

exit	nozzle exit
amb	ambient (freestream) condition
actual	actual, measured value
ideal	ideal value, based on ideal expansion to P_{amb}
drag	afterbody drag
8	nozzle throat (minimum A)
9	nozzle divergent section exit

superscripts

*	condition where M=1; when used with A_8, $A_8{}^*=A_8Cd$

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BACKGROUND

[2]Since the introduction of jet aircraft on August 27, 1939, when test pilot Erich Warsitz first flew the Heinkel He-178 jet plane (Figure 1), propulsion systems have steadily grown in thrust capability, allowing consistently increasing speeds in both commercial and military aircraft. Coupled with this increase in speed and capability comes a need for increasing nozzle complexity.

Early, subsonic jet aircraft incorporated simple, fixed convergent nozzles. Subsonic aircraft nozzles do not generally require area ratio variations since they operate over low nozzle pressure ratio's (NPR=Pt_8/P_{amb}), ranging between only 2 to 3. A

simple, fixed convergent or very low area ratio convergent-divergent nozzle produces adequate thrust with under-expansion performance losses at cruise less than 1%. Making its initial flight on October 1, 1942, the first jet airplane in the United States, the P-59 (Figure 2), used a fixed convergent area nozzle configuration[2]. As technology progressed, aircraft speeds increased. The Lockheed F-94 (Figure 3) was this nation's first operational jet all-weather interceptor and the first U.S. production jet to have an afterburner, which provided brief periods of additional engine thrust. To accommodate afterburning engine requirements, variable throat area control is needed for good performance. Also making use of afterburning engines, the F-100 (Figure 4) was the USAF's first operational aircraft capable of flying faster than the speed of sound (760 mph) in level flight, making its initial flight on May 25, 1953.[2]

System integration of the nozzle with the engine, bypass, and tertiary flows was a significant complication addressed in the design of the SR-71 "Blackbird" (Figure 5). The SR-71 is a long-range, advanced, strategic reconnaissance aircraft capable of speeds in excess of Mach 3. Studies have shown that less than 20 percent of the total thrust used to fly at Mach 3 is produced by the basic engine. The balance of the total thrust is produced by the unique design of the engine inlet and "moveable spike" system at the front of the engine nacelles, and by the ejector nozzles at the exhaust, which utilize air compressed in the engine bypass system, along with tertiary air provided through the "blow-in" door ejector, to produce thrust. This nozzle employs variable throat area control and a blow-in door ejector system to improve performance at off-design conditions.

Variable exit area became a requirement as aircraft speeds began increasing beyond the transonic region. Fixed-area convergent and very low area ratio convergent-divergent nozzles are normally inadequate for supersonic speeds greater than Mach 2-3. NPR's rapidly increase for Mach numbers greater than 1, and range from 2 to 30. Some short-duration aircraft use fixed, secondary shrouds due to limited supersonic time (or supersonic dashes), such as the B-58, F-4, F-111, B-1, & F-14.[5]

The Boeing F-15 Eagle (Figure 6) was designed from the outset to be the world's most effective air-superiority fighter. First flown on July 17, 1972, it was powered by a pair of Pratt & Whitney F100-PW-100 turbofan engines, which delivered more thrust than the aircraft's weight, allowing the new fighter to accelerate in vertical flight. The most recent version, the F-15E, is a two seat, two engine dual role fighter

capable of speeds up to Mach 2.5 with afterburners. These nozzles employ variable throat area control and dual-mode exit area scheduling. This dual-mode system is passively controlled by the pressure forces acting on the divergent flaps to provide high performance over a wide range of flight conditions. Passive exit area control significantly reduces the nozzle's complexity and weight through elimination of the divergent actuation system. Furthermore, the performance impacts of passive control versus active control are negligible if the pressure balance system is properly designed for the aircraft installation and mission requirements.

Lockheed's F-16 (Figure 7) was designed to be a single-engine, single-seat lightweight day fighter with performance rivaling that of much larger and more expensive aircraft. Highly versatile and exceptionally maneuverable, the F-16 is the world's most popular, most sought-after multi-role fighter. Like the nozzle used in the F-15, the F-16 nozzle employs variable throat area control and dual-mode exit area scheduling

Military aircraft with supersonic *cruise* capability have required more sophisticated nozzle systems than those with supersonic *dash* capability. Independent A_8 and A_9 control is usually required. Throat area variation is needed to match the afterburning requirements, and a separate control of the exit area provides the proper expansion ratio at each flight speed and altitude.

The newest aircraft being developed provide additional nozzle features for added speed and maneuverability. The Lockheed F-22 (Figure 8) is the first aircraft to *cruise* faster than the speed of sound for an extended period of time without requiring the use of afterburners and their associated high fuel consumption. In addition, the F-22 employs thrust-vectoring nozzles to provide maneuverability unmatched by any other aircraft, further complicating the design of the nozzle. The nozzle's exterior shaping is also highly integrated into that of the aircraft to reduce external flowfield drag and provide low radar detection.

Similar nozzle development has occurred for missiles as well. Generally, high-speed missiles have been powered by solid propellant rocket motors. Such is the case with the HAWK missile system, which has been the Marine Corp's primary air defense since the early 1960's. Officially, this missile is capable of speeds in excess of Mach 2.4. Other, lower speed missiles have used turbojet propulsion for cruise operation. Both the Harpoon (Figure 9) and

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Tomahawk (Figure 10) missiles utilize turbojet propulsion for cruise operation. Since these missiles operate subsonically, without afterburners, they obtain high efficiency from fixed convergent nozzles. Missile programs currently underway in the US, such as RATTLRS, are investigating the use of turbojet-powered missiles at significantly higher Mach numbers, thus requiring the use of increasingly advanced nozzle technology.

With the increased requirements for highly efficient nozzles, it is important that the propulsion community provide lightweight, cost-effective nozzles for high-speed flight. These nozzles must integrate with the aircraft to achieve high installed performance (low drag), enhanced vehicle maneuverability, low radar signature, and be easily maintained.

DISCUSSION

Selecting a Nozzle Concept

There are multiple varieties of nozzles to choose from, such as two-dimensional (2D), axi-symmetric, plug, ejector, or single expansion ramp nozzle (SERN). Final nozzle concept selection should be based on the functional requirements of a particular program or vehicle. Each concept should be evaluated based on its merits as compared to the important program parameters. Trade studies should be used to achieve a compromise between weight, performance, stealth, reliability/maintainability, and cost. Additionally, critical flight points must be achieved. The best selection should yield the simplest nozzle to meet the requirements.

The need for variable convergent throat area will be primarily determined by the maximum flight Mach number and whether or not the engine has an afterburner. Non-afterburning, subsonic aircraft can use a fixed convergent nozzle without a divergent section. Afterburning, subsonic aircraft will need a variable convergent section without a divergent section. Supersonic vehicles will not only need variable convergent throat area, but will also need a variable area divergent section.

Fixed Convergent Nozzles

Fixed convergent nozzles provide the primary function of backpressure control for the gas turbine propulsion system. For subsonic applications, variation in throat area is not required for optimum engine performance. Also, the nozzle pressure ratio is generally less than 2 so that expansion ratio

variation provides insignificant benefit. For these reasons, fixed convergent nozzles are well suited to subsonic applications. Thrust is calculated according to the relationship:

$$F = mv_{exit} + \left(P_{exit} - P_{amb}\right)A_{exit} \qquad (1)$$

where the exit conditions are defined at the nozzle throat.

Since fixed convergent nozzles lack variability, they cannot be used with afterburning engines. Fixed area convergent nozzles provide high performance for the low pressure ratio, non-afterburning turbojet engines employed in early tactical aircraft and modern subsonic commercial aircraft.

Variable Convergent Nozzles

Tactical aircraft operating at high subsonic or transonic Mach numbers generally use afterburning to achieve the needed thrust to overcome the high drag at these conditions while limiting the size of the engine. Since NPR for these conditions is generally less than 3, limited thrust improvement is achieved by expansion ratio variations, permitting use of a relatively simple, variable throat area convergent nozzle without a divergent section.

Afterburners increase thrust by increasing the gas temperature, and therefore, the exit velocity of the flow. The flow parameter is given by the relationship[3]:

$$\frac{W\sqrt{Tt}}{PtA^*} = \sqrt{\frac{\gamma}{R}}M\left(1 + \frac{\gamma - 1}{2}M^2\right)^{\frac{\gamma+1}{2(1-\gamma)}} \quad (2)$$

Neglecting minor changes in γ, the flow parameter is constant for choked non-afterburning (dry) and afterburning engines. Therefore, the following relationship is used to define the area requirements.

$$\left(\frac{W\sqrt{Tt}}{PtA^*}\right)_{dry} = \left(\frac{W\sqrt{Tt}}{PtA^*}\right)_{afterburning} \qquad (3)$$

Since engine flow and total pressure are nearly the same for dry and afterburning conditions, the required throat area variation is driven by the relative change in temperature, as shown.

$$\frac{A^*_{afterburning}}{A^*_{dry}} = \sqrt{\frac{Tt_{afterburning}}{Tt_{dry}}} \qquad (4)$$

For modern afterburners, this temperature ratio is near 2, therefore requiring a throat area increase of approximately 40 percent relative to the dry area.

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Variable area convergent nozzles are used where transonic flight is an infrequent occurrence and is of secondary importance to mission objectives. For flight Mach numbers in excess of 1.2~1.5 the variable convergent nozzle provides inadequate performance, and a converging/diverging (C-D) nozzle should be used.

Converging/Diverging (C-D) Nozzles

As shown in Figure 11, flight Mach numbers greater than 1.2~1.5 are generally accompanied by NPR's in excess of 3, requiring further expansion of the exhaust flow to increase its velocity and improve the nozzle performance. Equation 1 is used to calculate thrust. However, for a C-D nozzle the exit condition is defined at the exit of the divergent section (station 9, as shown in Figure 12) so that the expansion of the divergent section will accelerate the flow and increase thrust. Ideal nozzle thrust is determined by expanding the flow isentropically to ambient pressure. Dividing the thrust by the product of the total pressure and the effective throat area (PtA_8^*), a non-dimensional ideal thrust parameter may be defined.

$$\frac{F_{ideal}}{PtA_8^*} = \frac{mv_9 + (P_9 - P_{amb})A_9}{PtA_8^*} \qquad (5)$$

This may be rewritten as

$$\frac{F_{ideal}}{PtA_8^*} = \frac{\gamma P_9 A_9 M_9}{PtA_8^*} + \left(\frac{P_9}{Pt} - \frac{P_{amb}}{Pt}\right)\frac{A_9}{A_8^*} \qquad (6)$$

Optimum performance is achieved at the expansion ratio providing $P_9 = P_{amb}$, referred to as the design expansion ratio. Application of the isentropic relationships[4] shown in equations (7) and (8) at the design expansion ratio leads to the ideal thrust parameter shown in equation (9).

$$\frac{A}{A^*} = \frac{1}{M}\left[\frac{1 + \frac{\gamma - 1}{2}M^2}{\frac{\gamma + 1}{2}}\right]^{\frac{\gamma + 1}{2(\gamma - 1)}} \qquad (7)$$

$$\frac{Pt}{P} = \left(1 + \frac{\gamma - 1}{2}M^2\right)^{\frac{\gamma}{\gamma - 1}} \qquad (8)$$

$$\left(\frac{F_{ideal}}{PtA_8^*}\right) = \sqrt{\left(\frac{2\gamma^2}{\gamma - 1}\right)\left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma + 1}{\gamma - 1}}\left[1 - \left(\frac{P_{amb}}{Pt}\right)^{\frac{\gamma - 1}{\gamma}}\right]} \qquad (9)$$

Nozzle performance, or C_{Fg}, is defined as the ratio of actual thrust to the ideal thrust (equation 10). Typical nozzle performance characteristics based on this definition are illustrated in Figure 13 for a range of expansion ratios.

$$C_{Fg} = \frac{F_{actual}}{F_{ideal}} \qquad (10)$$

For a *fixed-area-ratio* nozzle, ideal thrust may be attained only at the design point. As NPR is varied off design, the thrust decreases. A nozzle is said to be over-expanded when operating at a pressure ratio below its design point. At these conditions, the pressure along the divergent flaps expands to sub-ambient pressures. For optimum thrust, the nozzle should be terminated at the point along the flap where the local pressure is equal to ambient pressure, as illustrated in Figure 14. Otherwise, the sub-ambient pressures apply drag on the nozzle surfaces. Normally, a nozzle will over-expand and flow without separation until the ratio of the exit to the ambient static pressure falls below some critical value. When this occurs, the exhaust gases will separate from the nozzle wall and form a shock wave that increases the nozzle pressure aft of the separation. The nozzle exit pressure for this case is near ambient pressure. A nozzle is said to be under-expanded when operating at nozzle pressure ratios above the design point. In this case, the area ratio is too low and the flow expands to a pressure greater than the ambient pressure[5]. As shown in Figure 15, an extension to the divergent flaps would be required to attain ideal thrust. As illustrated in Figure 16, nozzle performance losses are generally much larger for over-expanded nozzles than they are for under-expanded nozzles.

For optimum nozzle performance, the variable convergent-divergent nozzle is used for tactical aircraft with flight Mach numbers greater than 1.5, providing the means to expand the flow to near ambient pressures. Typical examples include the F-14, F-15, F-16, F-18, and F-22.

The required area ratio increases with increasing nozzle pressure ratio as a function of flight altitude and Mach number. Ideally, the internal expansion should be varied continuously as a function of NPR to provide optimum thrust. However, weight, cost,

and performance goals must be balanced to provide the best nozzle to meet aircraft requirements. Depending on these goals, various techniques may be employed to vary the nozzle expansion ratio. These include 1) geometrically scheduled area ratio, 2) passively controlled area ratio, and 3) fully-variable (controlled) area ratio. Additionally, aerodynamic control of the expansion ratio may be provided with an ejector nozzle. Ejector nozzles are able to change the effective nozzle exit area without repositioning the divergent flap by allowing ambient (external) air to fill the over-expanded portion of the divergent nozzle, reducing its *effective* expansion ratio. Blow-in doors are generally actuated or aerodynamically controlled to allow the ambient flow only during over-expanded conditions.

Geometrically scheduled (or fixed-schedule) area ratios are typical of the F-14 and F-18 nozzles. For these nozzles, A_9 is kinematically tied to A_8 so that a distinct relationship exists between A_8 and A_9, as shown in Figure 17. The advantage of this configuration is its light weight and simplicity. However, off-design performance is reduced.

Passively controlled area ratios are typical of the F-15 and F-16 P&W nozzles. For these nozzles, A_9 is kinematically tied to A_8 through a slotted mode strut to allow a range of possible A_9 to exist for a given A_8, as shown in Figure 18. The internal pressures acting on the divergent flaps provide the force necessary to passively move the divergent flaps through their range of possible area ratios. By correctly balancing the flaps, the nozzle is designed so that the area ratio "floats" to its design expansion ratio for optimum performance. This configuration offers multiple advantages, including light weight, design simplicity, and good performance over a wide range of flight conditions. Although performance trades must still be considered over the flight envelope, this configuration significantly reduces the region of the flight envelope where the nozzle must operate off design.

Fully variable (controlled) area ratios are used in the F-22 nozzle. Fully controlling each of the divergent flaps in this nozzle provides both A_9 variation and thrust vector control. As shown in Figure 19, fully variable A_9 provides peak nozzle performance, C_{Fg}, by enabling the nozzle to operate at its peak performance area ratio at all nozzle pressure ratios throughout the flight envelope. Obviously, the advantage of this nozzle configuration is its excellent performance at all flight conditions. However, this nozzle suffers in weight and design complexity.

Generally, since the propulsion system design must precede that of the aircraft, the nozzle design is optimized for internal performance. Installed performance considers afterbody drag induced by the nozzle external flaps and may actually dictate that the nozzle be over-expanded over a significant portion of the flight envelope. Installed, or thrust-minus-drag, performance is defined as follows:

$$C_{Fn} = \frac{F_{actual} - F_{drag}}{F_{ideal}} \qquad (11)$$

Figure 20 illustrates the typical difference in internal and installed performance, C_{Fg} and C_{Fn}, respectively, at a transonic flight Mach number. For this particular example, the expansion ratio for optimum thrust-minus-drag performance would be achieved at 1.9 rather than the design expansion ratio of 1.55.

Selecting a Divergent Section Type

For nozzles having a divergent section, the best approach to selecting the ideal type of A_9 area control (geometrically scheduled, passively controlled, or variable A_9) is to conduct analytical performance studies that take into account the unique requirements of the vehicle and the performance required throughout the mission. For example, a *geometrically scheduled* nozzle should be seriously considered if a large percentage of the mission time is spent at only several power settings, since it can be designed to match the optimum exit area at these critical flight conditions. A *geometrically scheduled* nozzle will be inherently lighter and less expensive than a *fully variable* nozzle due to the omission of linkages and actuators to drive the divergent flap. However, the *fully variable* nozzle will have better performance characteristics over a larger portion of the flight envelope. Again, the goal is to determine the simplest nozzle arrangement that will meet the mission requirements. Passively scheduled nozzles provide a compromise between geometric and variable scheduling. However, for this type of nozzle, it is important to verify that the pressure-balanced A_9 positions provide acceptable performance at the key flight points. Also, it has been shown that the external flap pressures have a significant impact on the floating A_9 position and must be considered in the design.

Impact of Nozzle Selection on Performance

A study was performed for a supersonic missile-type application to demonstrate the resulting performance for several types of divergent sections. Performance

comparisons of the various A_9 concepts and the considerations for selecting a concept are discussed.

The notional missile trajectory used for this analysis maintained a relation between the Mach number and altitude as shown in Figure 21. A Notional Mission was also defined (Figure 22) to encompass multiple modes of operation; acceleration, cruise, loiter, and acceleration.

Three 2D, variable convergent throat area nozzles, each with a different method of controlling the divergent exit area (A_9), were defined and their performance was evaluated over the mission trajectory. The three A_9 concepts used were:

1.) Fully Variable A_9 – convergent throat area and divergent exit area were varied independently; allowing the area ratio to be fully optimized for thrust-minus-drag (Figure 23).
2.) Two Position A_9 – similar to a passively scheduled divergent nozzle, this concept positions the exit area to a smaller exit area for the subsonic trajectory and a larger exit area once the vehicle passes through the transonic region of the trajectory. Positioning could be selected by a simple two-position actuator, or a one time position type mechanism, such as a pyro actuator, in an actual application. The benefit would be in using a simpler A_9 mechanism than the fully-variable mechanism (Figure 24).
3.) Geometrically Scheduled A_9 – Exit area is a function of the throat area and is scheduled using the flap mechanism (Figure 25).

The three nozzle flowpath geometries were sized to match the required engine modulation requirements. A kinematics arrangement was defined for each of the nozzle concepts to achieve the A_8 vs. A_9 relationships defined above. Using a notional engine cycle, 2D/CD internal nozzle performance characteristics, and external drag characteristic of the defined geometry, the engine was "flown" over the mission and the resulting thrust-minus-drag performance was determined for the three concepts.

The resulting thrust-minus-drag performance (C_{fn}) curves are shown in Figure 26 for the three nozzle types over the notional mission. As shown by the curves, the *fully variable* concept represents the best achievable thrust-minus-drag performance since the exit area is optimally positioned with an A_9 actuator. The *two-position* nozzle performance matches the fully variable over the mission everywhere except for the loiter section. This is due to the exit area being held to a non-optimum position, as the vehicle has

passed through the transonic region and A_9 is being held larger than optimum for the subsonic loiter condition. Note, however, that the loiter performance is still only slightly lower than optimum. The *geometrically scheduled* nozzle has the worst performance of the three. Its performance suffers over the subsonic, acceleration range as well as the loiter range. By design, the kinematics of this nozzle were arranged to provide optimum A_9 at the cruise flight point. Therefore, poor performance is seen at the off-design acceleration and loiter points.

Final selection of one of these configurations will ultimately depend on the vehicle mission. If the mission includes little or no operating time in the loiter mode, then the slightly poorer performance of the *two-position* concept may be acceptable, offering a simpler, lighter weight, and lower cost than the *fully variable* concept. The *geometrically scheduled* concept is significantly simpler and lighter, and would have less seal leakage than the other two concepts. Again, if the unique performance traits were acceptable to the actual mission, then it may provide the best solution. In this case, the poor performance over the acceleration and loiter regions would need to be mitigated before this candidate could be chosen.

Future Directions

The weight and cost of aircraft exhaust systems has increased at an alarming rate in recent years with the advent of thrust-vectoring nozzles, such as that used in the Lockheed F-22. Mechanically operated thrust vectoring nozzles utilize moving divergent flaps to produce thrust vectoring and optimum A_9 control. As aircraft designs are continually improved to increase performance and add features, new technologies must be sought to make them affordable to acquire, deploy, and maintain.

Multi-functional nozzles can accommodate more than engine area control, providing thrust vectoring or thrust reversing. These special application nozzles are typically used to reduce the demands of the aircraft control surfaces, resulting in overall system improvements. Several programs have been initiated recently to take advantage of these unique capabilities. The X-44 MANTA (Multi-Axis No Tail Aircraft) aircraft concept (Figure 27) is a delta-winged F-22 that uses thrust-vectoring nozzles as a flight control feature. It has no rudders, stabilators, or ailerons. The functions of the flight control surface features are replaced by the multi-axis, thrust vectoring nozzles. Other aircraft programs have removed the vertical and horizontal tails and

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incorporate highly integrated exhaust systems. They include NASA's X-36 tailless research aircraft (Figure 28), Boeing's X-45 UCAV Unmanned Combat Air Vehicle, and Northrop-Grumman's X-47 UCAV Operational Systems. These innovative designs promise to reduce weight, drag, and radar signature and increase range, maneuverability, and survivability. The nozzles are very integrated into the vehicle's outer contour.

New technologies, such as fluidic vectoring, may provide lightweight, low cost aircraft systems for achieving high vectoring effectiveness while maintaining high levels of thrust performance. Fluidic vectoring nozzles provide vectoring through use of high pressure air injected in the divergent section of the nozzle, minimizing the number of moving parts and improving durability. The commercial benefits include reductions in aircraft weight, improvements in nozzle reliability through reduced part count, and reductions in signature and life-cycle cost.

Other technologies important to nozzle design include high temperature material development, advanced cooling, and advanced liner fabrication techniques. Carbon Matrix Composites (CMC's) offer lower density and higher operating temperatures than conventional metals. Many development programs have been conducted to resolve the technical issues associated with CMC's. Once resolved, their use will ultimately become more widespread. These technologies result in performance improvements due to reduced

requirements for cooling, typically supplied by the engine fan air.

SUMMARY

Integral with both the aircraft and the propulsion system, exhaust nozzles are unique to each application and must be designed for the appropriate air vehicle mission. As required aircraft speeds increase, so do functional requirements for the nozzle, resulting in increasingly complex nozzles. Mechanical complexities may be reduced, however, by considering mission-weighted performance and life requirements. Mission studies conducted for single use systems (missiles) have provided simple kinematic designs capable of achieving high thrust throughout the flight envelope. Further improvements may be achieved through aerodynamic solutions, such as fluidic injection and ejectors.

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FIGURES

Figure 1 - He-178

Figure 2 – Bell YP-59A

Figure 3 - Lockheed F-94

Figure 4 - North American F-100 "Super Sabre"

Figure 5 - Lockheed SR-71 "Blackbird"

Figure 6 - Boeing F-15 "Eagle"

Figure 7 - Lockheed F-16 "Falcon"

Figure 8 - Lockheed F-22 "Raptor"

Figure 9 – Boeing AGM-84 "Harpoon"
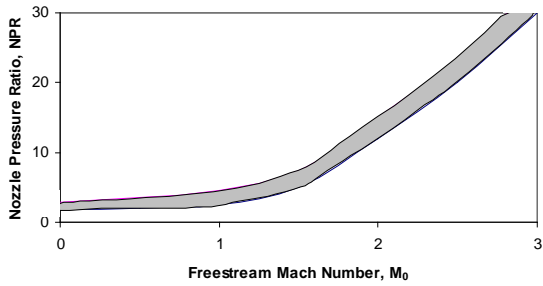

Figure 10 - Raytheon BGM-109 "Tomahawk"

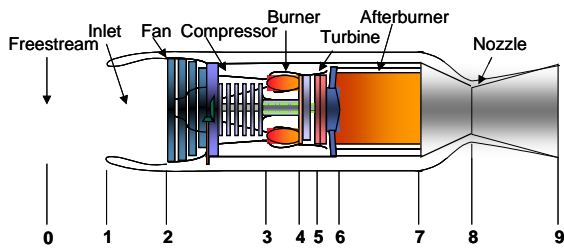*Figure 11 - Typical Nozzle Pressure Ratio Schedule for Supersonic Cruise Aircraft[5]*

Figure 12 - Engine Station Designations
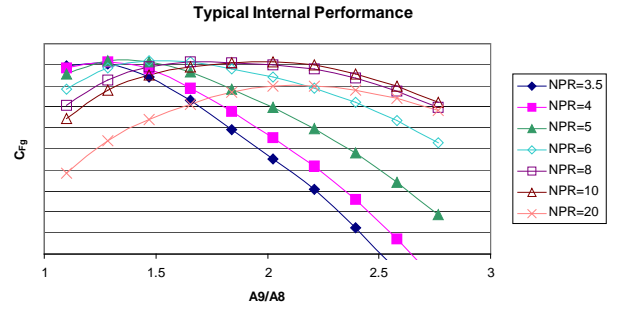
Figure 13 - Typical Nozzle Internal Performance Characteristic
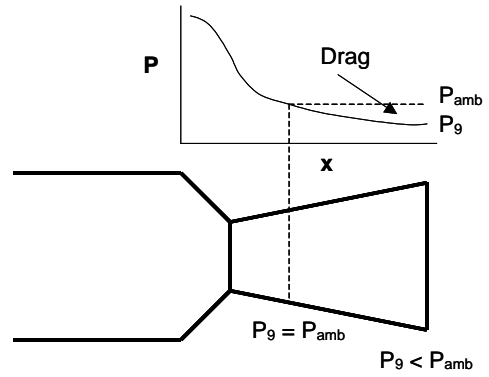
Figure 14 - Over-Expanded Nozzle (A9 too large)
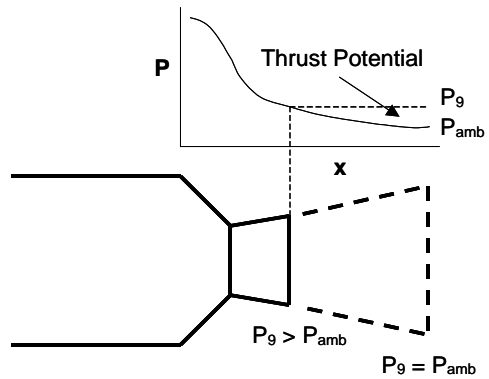
Figure 15 - Under-Expanded Nozzle (A9 too small)
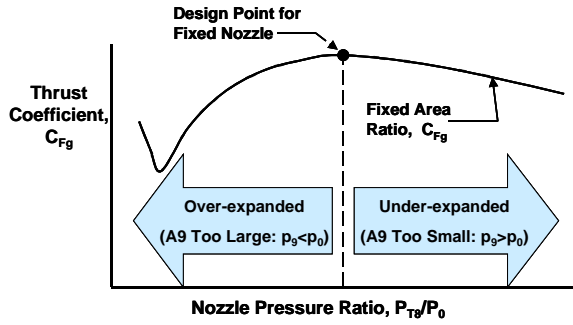
Figure 16 – Typical Nozzle Performance
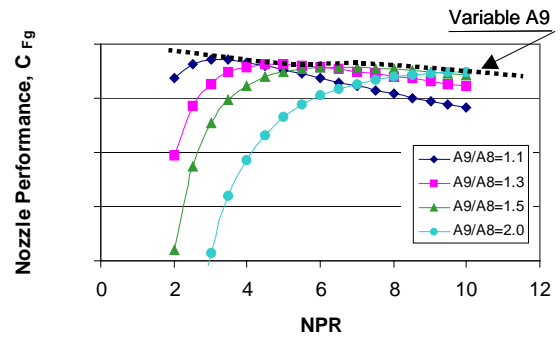
Figure 19 – Fully Variable Nozzle Exit Area
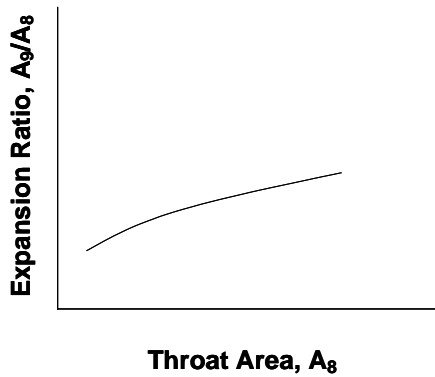
Figure 17 – Geometric Scheduled Nozzle Expansion Ratio
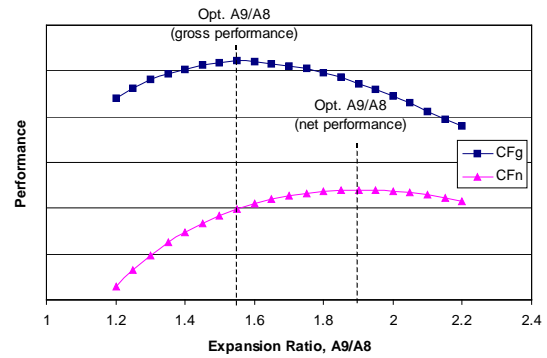
Figure 20 - Expansion Ratio for Optimum C_{Fg} and C_{Fn}
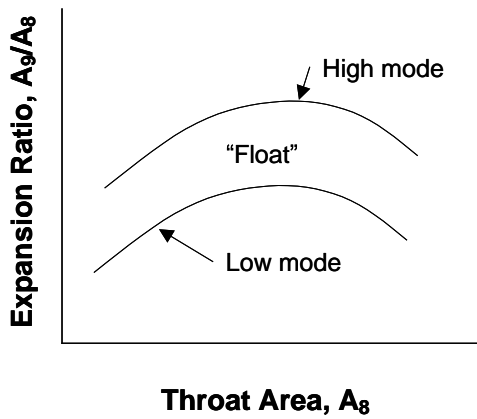
Figure 18 – Passively Scheduled (Floating) Nozzle Expansion Ratio
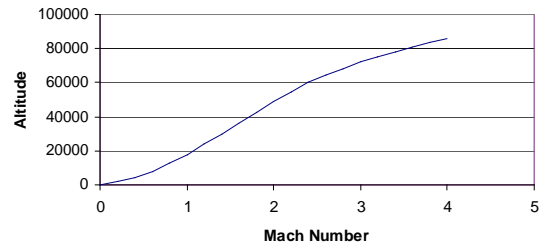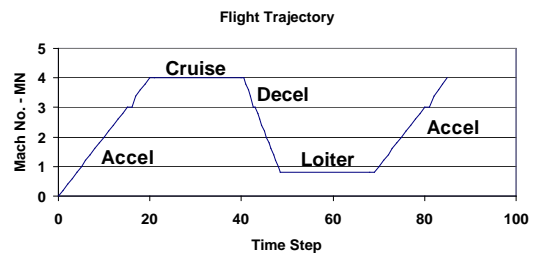

Figure 21 – Notional Missile Trajectory
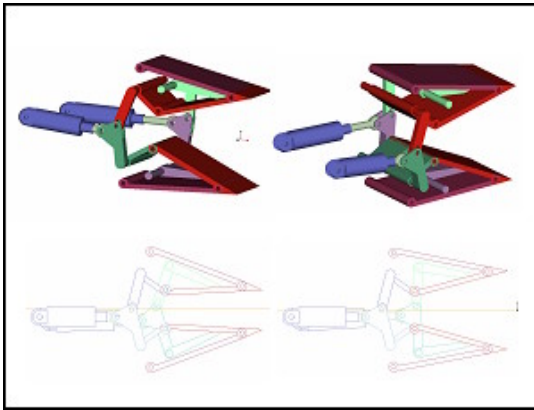

Figure 22 – Notional Missile Mission

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Figure 23 – Fully variable A$_8$ & A9 Nozzle Concept

Figure 24 – Two-Position A$_9$ Nozzle Concept

Figure 25 – Fixed Scheduled A$_9$ Nozzle Concept

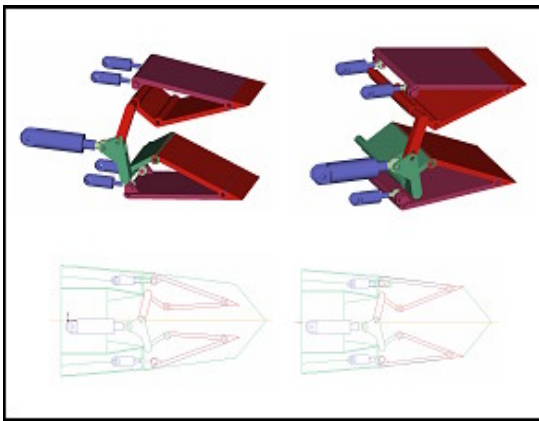*Figure 26 – Thrust-Minus-Drag Performance for Three Nozzle Concepts over a Notional Mission*

Figure 27 - X-44 MANTA (Multi-Axis No Tail Aircraft), lower aircraft; F22, upper aircraft

Figure 28 - X-36 Tailless, Thrust-Vectoring Drone Research Aircraft

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