An Overview of Current Navy Programs to Develop Thrust Augmenting Ejectors

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Abstract

A brief description of current basic research and exploratory development programs related to thrust augmenting ejectors within the Navy is given. The individual pieces of work are related to an overall direction of effort with the objective of developing improved augmenter designs for both lift and control applications.

Introduction

The Navy has been examining the possibilities for a Vertical/Short Take-off and Landing (V/STOL) aircraft since the early 1950's to maintain its sea control capability while enhancing the dispersal of these aircraft within the fleet. Although many propulsion concepts for V/STOL aircraft have been proposed, the particular concept of interest in this paper is the ejector/augmenter. The ejector concept for vertical take-off and landing aircraft has been under consideration for many years. To date, however, a successful aircraft using this concept has not been demonstrated. This fact has been attributed primarily to the low values of augmentation ratio achieved in the aircraft configurations.

During the past 10 to 12 years a significant effort has been applied to developing a thrust augmenting ejector design that produces a high augmentation ratio. The Air Force Aerospace Research Laboratories (ARL) appears to be the primary source of recent basic information on these designs. The work conducted at ARL was summarized by Viets in reference (a).

Based on the ground work set down by ARL and particularly the hypermixing primary nozzle design developed at ARL (references (b) and (c)) the Navy and the Rockwell International Corporation (Columbus Aircraft Division) launched into the development of a high speed aircraft technology demonstrator using thrust augmenting ejectors in the wings to provide lift in the vertical mode. This aircraft, designated the XFV-12A, is now undergoing its initial testing and evaluation.

The purpose of this paper is to briefly outline current on-going basic research and exploratory development programs related to thrust augmenting ejectors being supported by the Navy and to show how these efforts fit into an overall plan or direction of work. The XFV-12A aircraft is not included in this category and its status will not be discussed in this paper.

Background

During the past several years numerous Navy Laboratories and installations have been involved in supporting in-house and/or contractural efforts in many different aspects of ejector/augmenter design (figure 1). Some of these labs are not currently funding ejector work but they remain interested in the technology.

Rather than start by listing and describing the currently funded work, an effort is made to describe the general technology development program goals, how these goals are being approached and how previous, current and planned programs are interrelated. Figure 2 is an attempt to summarize this information and illustrates three main flows or directions of work. The flow of primary interest is the one with direct application to the end goal of developing an improved augmenter for V/STOL applications. This effort starts with the expansion and optimization of those areas that have indicated promise for substantial increases in augmentation ratio, proceeds with a design phase, laboratory model testing, full scale testing and finally aircraft installation and testing. Although the basic research and exploratory development is primarily involved in the data base development, it has become increasingly clear that specific design and installation effects are very important. The design phase and laboratory model testing, therefore, should be broached early in the total plan. Iteration on specific pieces of the data base may be required after the design configuration and requirements are established.

In support of this main program effort there are two additional flows of work. The first is to develop an accurate prediction capability that will not only impact on the main program at a number of points, but will be of value in future years in evaluating a variety of ejector designs. The second area of work that will impact on the main program flow is a general technology development of ejectors and associated effects. This technology development, as it presently exists, is split into the more specific areas of lift and control, since thrust augmenting ejectors may be suitable for both areas.

Figure 2 indicates not only the general goals and the approach being used, but also shows specific areas of interest for which work has been done in the recent past, is currently underway, or is being considered for future studies. This figure is not intended to be all inclusive but hopefully will provide a clear and concise overview of the current ejector technology program within the Navy. The remainder of this paper will briefly discuss the <u>currently</u> funded programs, who is doing the work and which Navy installation is funding the effort.

Advanced Diffuser and End Wall Design

The jet-diffuser ejector was a concept developed by the Flight Dynamics Research Corporation under a Naval Weapons Center contract as part of the STAMP (Small Tactical Aerial Mobility Platform) program (reference (d)). Figure 3 illustrates this ejector design in the STAMP configuration. One of the unique features of this device is the high velocity jet that not only provides boundary layer control for the highly diverging diffuser but also extends the diffuser action beyond the physical walls. High values of augmentation ratio ($\phi \simeq 2.0$) have been obtained with this device in the laboratory at low pressure and temperature ratios. Recent testing of the STAMP configured ejector at the Naval Air Propulsion Center has shown the device to be relatively insensitive to pressure ratio (up to NPR = 2.1) but indicated approximately a 0.15 reduction in ϕ at a nozzle temperature ratio of 2.4.

During the development of the jet-diffuser ejector, it was found that significant differences in augmentation ratio could be obtained with changes in end wall design. Work has been completed by the Flight Dynamics Research Corporation, under contract to the Naval Air Development Center, to shorten and optimize the design of the end walls as well as maximize the augmentation ratio with the new diffuser configuration. Results to date have shown that the end walls can be reduced in length such that they are no longer than the side walls of the original STAMP configuration and are also flaired out to provide additional diffusion. The configuration has been fabricated and tested, showing good flow stability and high values for augmentation ratio ($\phi \simeq 2.0$) at NPR $\simeq$ 1.3 and NTR $\simeq$ 1.0.

A second area of concern with the jet-diffuser ejector is the detached primary nozzles. These present significant installation and packaging difficulties in aircraft applications. The Naval Air Development Center in conjunction with NASA Ames is initiating an effort with the Flight Dynamics Research Corporation to integrate the primary nozzles into the ejector shroud. That is, develop attached nozzles for the ejector while maintaining high augmentation ratio.

Advanced Primary Nozzles

The Rockwell International Corporation supported by the Naval Air Systems Command has studied a wide variety of primary nozzle configurations and designs (figure 4) to enhance the mixing and entrainment process within an ejector (reference (e)). Currently, Rockwell is investigating advanced configurations of hypermixing nozzles both analytically and experimentally.

The development of the advanced hypermixing design is based on a three dimensional mixing code. With this code a wide variety of nozzle configurations can be examined for possible improved mixing characteristics. Having found a computer predicted design that shows promise, it is then planned to fabricate and test this configuration. Current thinking is toward a combination of hypermixing and cross-slot nozzles (figure 5).

A second concept for increasing the primary nozzle entrainment is the use of unsteady flow. Work in this area is presently underway at the Naval Post Graduate School in a joint effort with the University of Queensland (reference (f)). Two basic concepts are being examined in these studies. The first involves a time varying jet deflection with a constant mass flow (fluidic nozzle). The second is a time varying mass flow with no variation in direction (fully pulsed primary and a pulsed core axisymmetric primary nozzle). Figure 6 illustrates the test results for the three different nozzle designs. In this case the entrainment function (Q/Q_E) is plotted against the non-dimensionalized downstream distance. All of these tests, however, were conducted at rather low pressure ratios (NPR $\simeq$ 1.13) and into quiescent air. Although these results appear encouraging, it remains to be determined if similar results can be obtained at the higher pressure ratios necessary for practical application and if high nozzle thrust efficiencies can be obtained.

The previously discussed basic research and exploratory development work is directed to improving the augmentation ratio and stability of ejectors and allowing for the orderly progression to a design phase and eventual aircraft application. Supporting this main effort, as mentioned earlier, are two additional paths of work. One is directed to developing improved predictive capability and the second is a general technology development.

Analytical Studies

There are several programs currently underway to develop an improved predictive capability with the ultimate goal of being able to estimate installed ejector performance. This, of course, will not only impact the main thrust or direction of effort but will also be useful for future evaluations.

Work is currently underway at the Naval Air Development Center to build an in-house predictive capability and understanding of various loss mechanisms and their sensitivity to overall augmenter performance. Several computer codes of varying degrees of sophistication are being exercised and applied to several different ejector configurations of interest. Figure 7 examines the ARL configuration "C" ejector showing the no loss situation, the effects of various losses, and a comparison with experimental data.

Viscous wall jets in a co-flowing field with finite cross flows are being studied analytically by the Rockwell International Corporation (Science Center) under contract to the Naval Air Development Center. Although this particular study is of interest for numerous applications, the application of primary interest is related to secondary stream cross flows within an augmenter having Coanda wall jets. These cross flows are particularly strong for ejectors having a tapered trailing edge as illustrated in figure 8. The spanwise flow is always toward the wide side of the augmenter and is probably due to the lower pressure being maintained for a longer distance at the point when the diffuser flaps are long. Figure 8 also schematically illustrates the mathematical problem being studied for the purpose of examining the evolution of velocity profiles, shear stress, sideslip angles and separation.

As a first step in developing a unified theory to include the effects of external flow on ejector augmentation ratio, the Rockwell International Corporation (Columbus Division), under contract to the Office of Naval Research, has described the ejector in terms of a lifting surface as illustrated in figure 9. The technique makes use of a parabolic, two dimensional analysis utilizing a turbulence kinetic energy model for inner jet mixing. By using a vortex lattice description for the shrouds and wing surfaces an elliptic outer potential solution can be developed that will provide a method of feedback from the ejector exit to the inlet conditions.

The augmenter wing in transition also provides a fertile area for analytical as well as experimental work. Figure 10 indicates three programs currently underway to study the jet path, vortex distribution, entrainment characteristics as well as pressure distribution on surrounding surfaces caused by a high aspect ratio rectangular nozzle in a cross flow. The first approach indicated in figure 10 is being conducted by the Vought Corporation and is jointly funded by the Naval Air Development Center and NASA Langley. Although this is primarily an experimental study, its ultimate goal is to develop empirical models. In any case, this data will be very useful in verifying and providing a reference point for the other two purely analytical methods.

The second approach to the augmenter wing in transition is being conducted by Neilson Engineering and is jointly supported by the Naval Air Systems Command and NASA Ames. This approach makes use of vortex "rings" and quadralaterals and does require some experimental data as input. The objective is to determine final jet position and pressure distribution on a wing type surface.

The third approach is the most sophisticated and as a result the most risky. This study is being undertaken by Computational Mechanics Consultants, Inc. and is supported by the Naval Air Development Center. The technique being used here is to solve the parabolic form of the Navier-Stokes equations for the viscous jet and match the solution to a potential free stream. The objective is to determine the final jet position and configuration as well as determine the effect on wing loading in and out of ground effect. The advantage of this approach is that it requires no experimental data input.

General Technology Development

As mentioned previously, efforts in this area are directed to both lift and control applications. Although a number of items are listed in figure 2 as areas of interest, not all of them are currently funded. The one area that is presently being funded is that using ejector concepts to augment reaction control systems (RCS). That is, amplify the control thrust for the same engine bleed flow or produce the same thrust for a reduced bleed flow. A near term possibility for this application is the Harrier RCS. Two approaches are presently being examined in this regard.

The first involves a high pressure annular nozzle design with a variable area ratio valve-in-nozzle concept shown schematically in figure 11. This work is being conducted by the David Taylor Naval Ship Research and Development Center (Carderock). The secondary flow for this device enters through a central core as well as around the primary head. The sliding ring valve that moves in and out on the cylindrical core controls the flow. Static tests with this device have indicated a 23% increase in specific thrust over a simple primary nozzle alone at a pressure ratio 9.0 and mixer length to diameter of 2.25. Work is currently underway to examine the system dynamically. Input parameters to be used and output parameters desired for this study are shown in figure 11.

A second concept that is being examined for possible application to reaction control systems is the crypto-steady or rotary augmenter concept shown in figure 12. Both analytical and experimental studies are being conducted with this device as a joint effort of the U.S. Naval Academy and the George Washington University. The device consists of a rotating primary nozzle assembly which is centrally supplied by a high pressure/energy primary fluid. The slot nozzles, having an inclination to the spin axis, discharge the fluid into the primary-to-secondary duct interaction zone as primary jet sheets. Reaction forces cause the primary nozzles to rotate, thus defining helical pseudo blades which accelerate the ambient secondary flow. As can be seen from figure 12, significant augmentation ratios are predicted analytically for this concept.

Summary

Research and exploratory development programs on ejector technology are being conducted in a number of areas by the Navy. Figure 2 attempts to summarize these efforts and show their relationship to an overall direction of work.

Symbols

A_o, A_p'	Primary nozzle area
A_2, A_i	Ejector throat area
A_3	Diffuser exit area
d	Hydraulic diameter of nozzle
F	Lifting force on shroud
L_D	Diffuser length
L_M	Mixer length
NPR	Nozzle pressure ratio
NTR	Nozzle temperature ratio
P^o P_i	Primary nozzle pressure
Q	Volumetric flow rate at position X
Q_E	Volumetric flow rate at nozzle exit
RCS	Reaction control system
T	Thrust from primary nozzle
X	Distance from nozzle exit
U, V, W	Velocities in coordinate directions
U_∞	Free-stream velocity
$\hat{U}_i$	Velocity vector of jet
β_i'	Nozzle inclination angle
ϕ	Augmentation ratio (ejector measured thrust/ideal thrust available from all nozzles due to an isentropic expansion of the same mass flow to ambient conditions)

References

a. Viets, H., "Thrust Augmenting Ejectors," Aerospace Research Laboratories Report ARL75-0224, June 1975.

b. Quinn, B., "Recent Developments in Large Area Ratio Thrust Augmentors," AIAA Paper No. 72-1174, November 1972.

c. Bevilaqua, P. M., "An Analytical Description of Hypermixing and Tests of an Improved Nozzle," AIAA Paper No. 74-1190, October 1974.

d. Alperin, M., Wu, J. J., and Smith, C. A., "The Alperin Jet-Diffuser Ejector (AJDE) Development, Testing, and Performance Verification Report," Flight Dynamics Research Corporation Final Report prepared for the Naval Weapons Center, NWC-TP-5853, 1976.

e. Schum, E., "A Study of Potential Techniques for Increasing Jet Entrainment Rates in Ejector Augmenters," Rockwell International Final Report prepared for the Naval Air Systems Command, October 1975.

f. Platzer, M. F., Simmons, J. M. and Bremhorst, K., "On the Entrainment Characteristics of Unsteady Subsonic Jets". AIAA Journal, March 1978.

- **NAVAL AIR SYSTEMS COMMAND**
- **NAVAL AIR DEVELOPMENT CENTER**
- **NAVAL AIR PROPULSION CENTER**
- **NAVAL WEAPONS CENTER**
- **OFFICE OF NAVAL RESEARCH**
- **NAVAL POST GRADUATE SCHOOL**
- **NAVAL ACADEMY**

FIGURE 1. NAVY LABORATORIES AND INSTALLATIONS WHICH HAVE SUPPORTED OR CONDUCTED WORK WITH THRUST AUGMENTING EJECTORS FOR AIRCRAFT APPLICATIONS IN THE RECENT PAST.

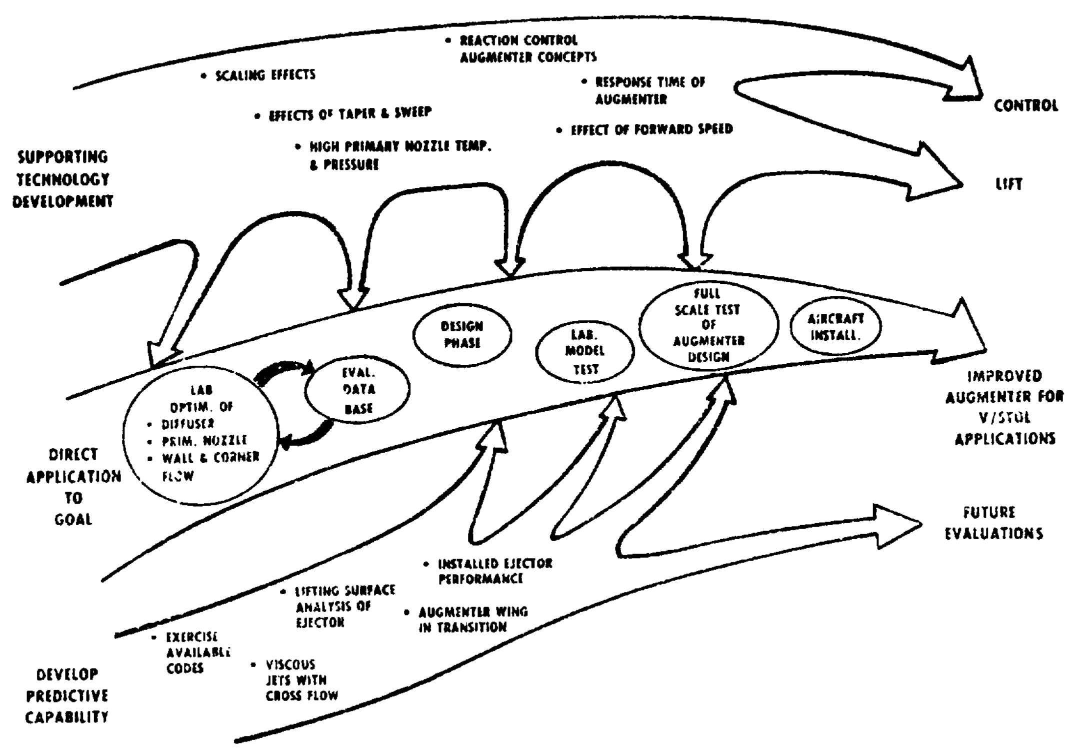


FIGURE 2. EJECTOR TECHNOLOGY DEVELOPMENT.

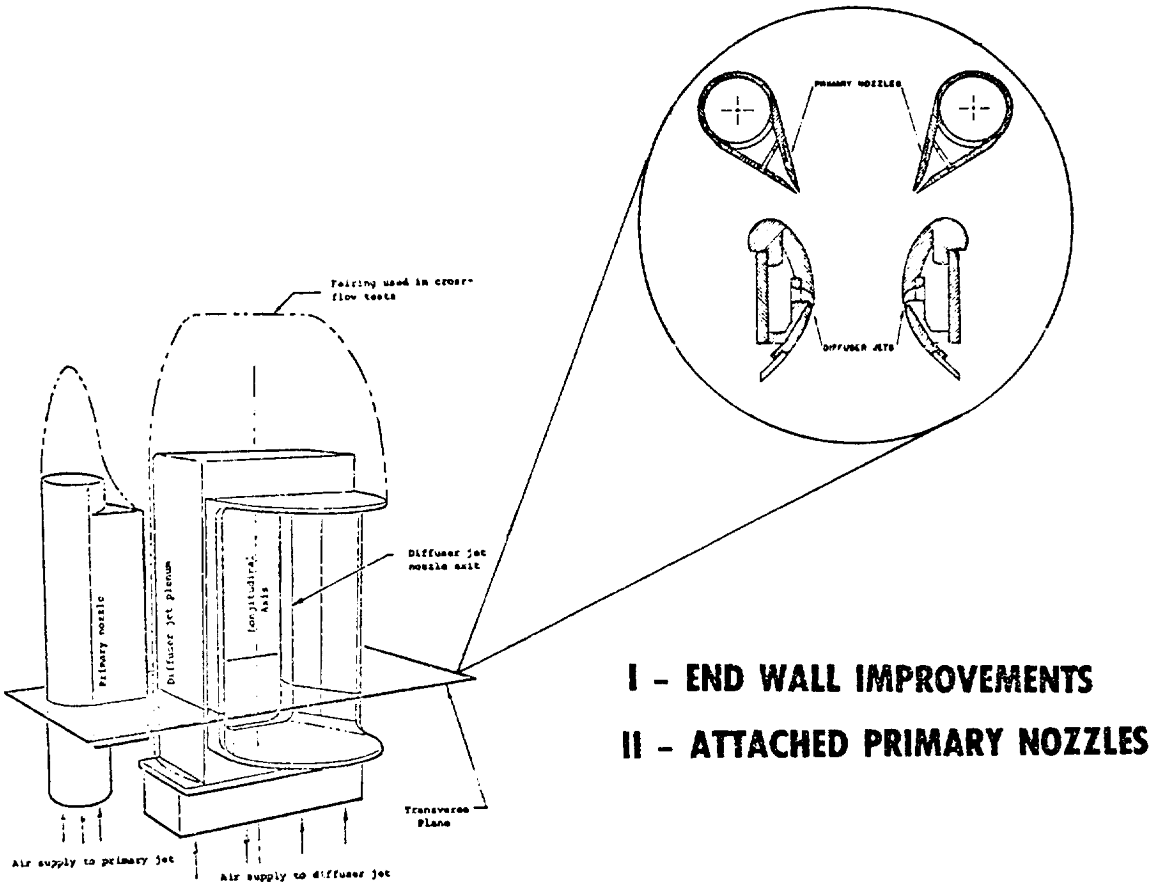


FIGURE 3. IMPROVEMENTS TO ALPERIN JET-DIFFUSER EJECTOR.

- **HYPERMIXING NOZZLE**
- **SWIRL FLOW**
- **JET DISTURBANCES**
- **ACOUSTIC INTERACTION**
- **FORCED PULSATIONS**
- **JET INTERACTION**
- **BASE FLOW TURBULENCE**

FIGURE 4. POTENTIAL PRIMARY NOZZLE DESIGNS FOR INCREASING ENTRAINMENT.

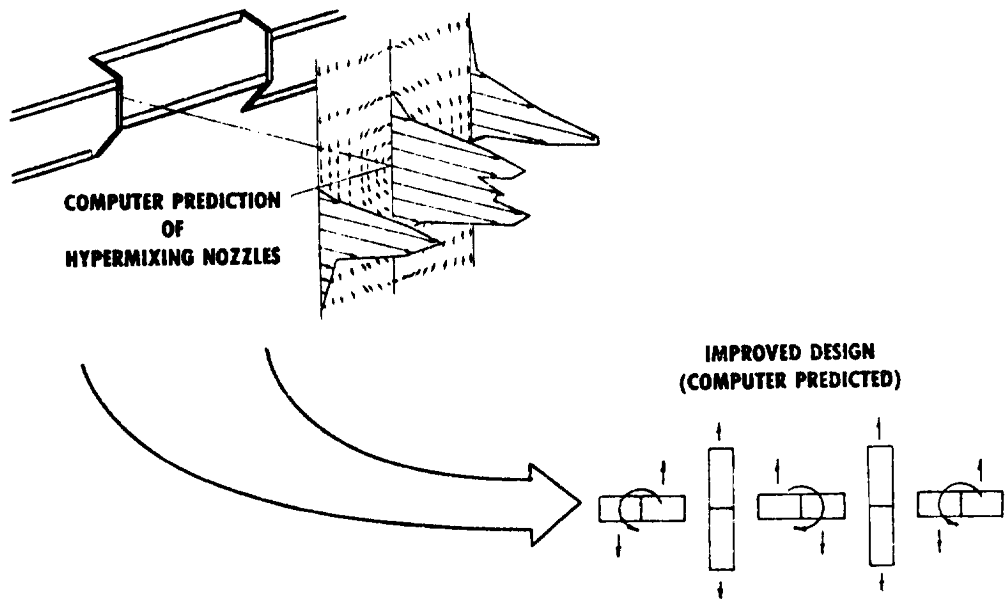


FIGURE 5. DEVELOPMENT OF ADVANCED HYPERMIXING NOZZLES.

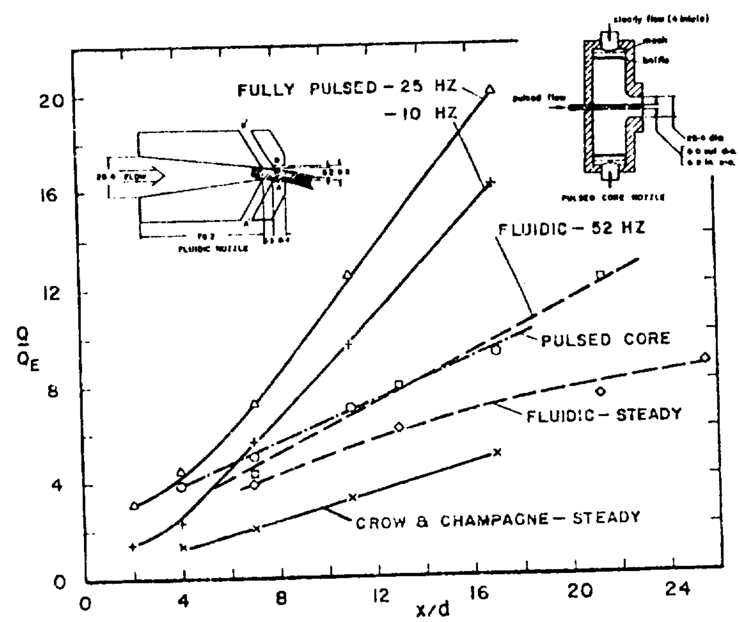


FIGURE 6. INCREASED ENTRAINMENT DUE TO UNSTEADY FLOW.

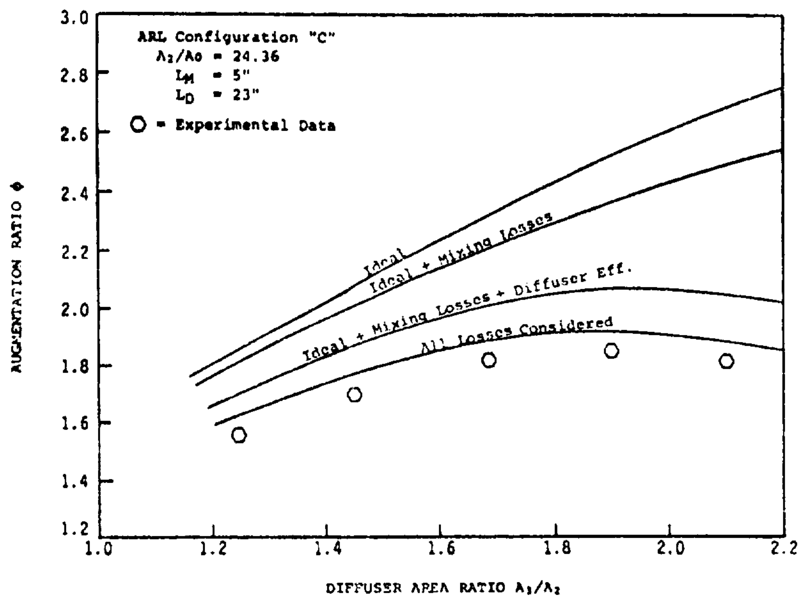


FIGURE 7. EXERCISE SEVERAL EJECTOR COMPUTER CODES AND COMPARE TO AVAILABLE EXPERIMENTAL DATA.

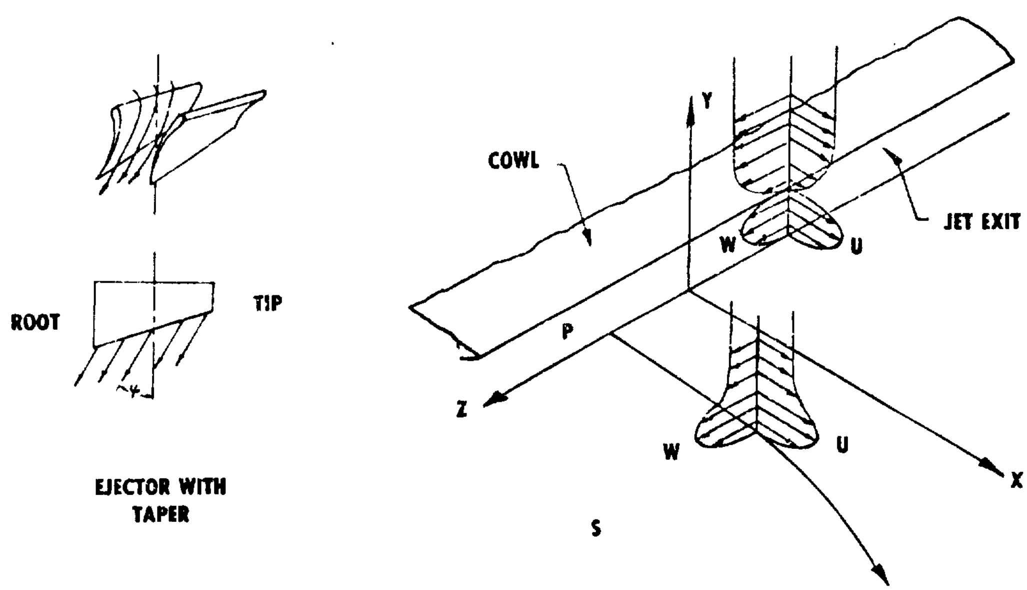


FIGURE 8. THREE-DIMENSIONAL WALL JETS WITH CROSS FLOWS.

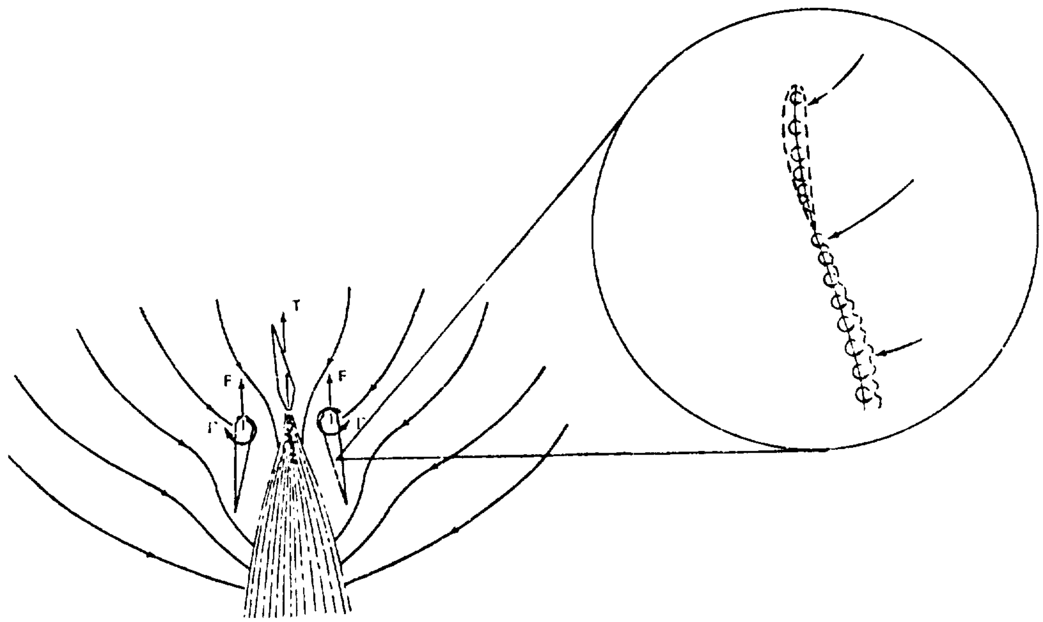


FIGURE 9. LIFTING SURFACE THEORY FOR THRUST AUGMENTING EJECTORS.

APPROACHES

- **EXPERIMENTAL (AR = 4)**
  - **DEVELOP EMPIRICAL MODEL FOR**
    JET PATH
    VORTEX DISTRIBUTION
    ENTRAINMENT
- **ANALYTICAL**
  - **VORTEX "RING" APPROACH**
  - **DETERMINE FINAL JET POSITION**
  - **DETERMINE WING LOADING**
- **ANALYTICAL**
  - **VISCOUS JET**
  - **POTENTIAL FREE STREAM**
  - **DETERMINE FINAL JET POSITION & CONFIGURATION**
  - **DETERMINE WING LOADING IN AND OUT OF GROUND EFFECT**

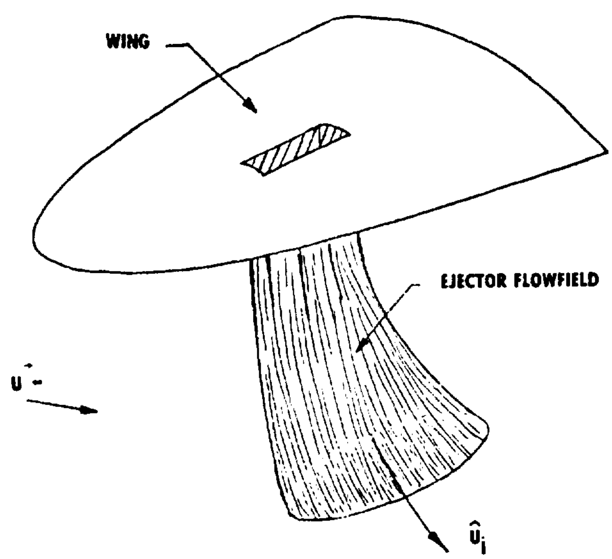
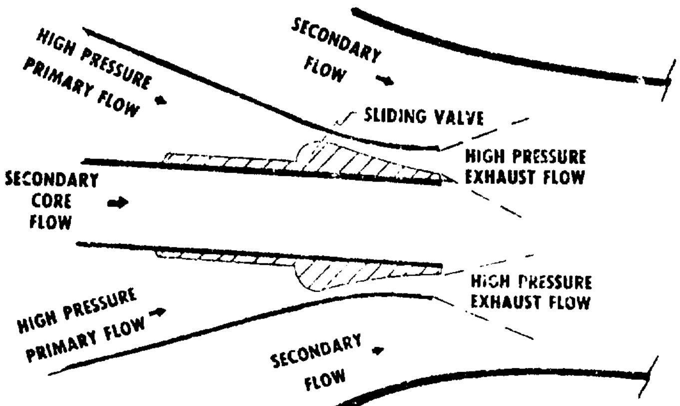


FIGURE 10. AUGMENTER WING IN TRANSITION.

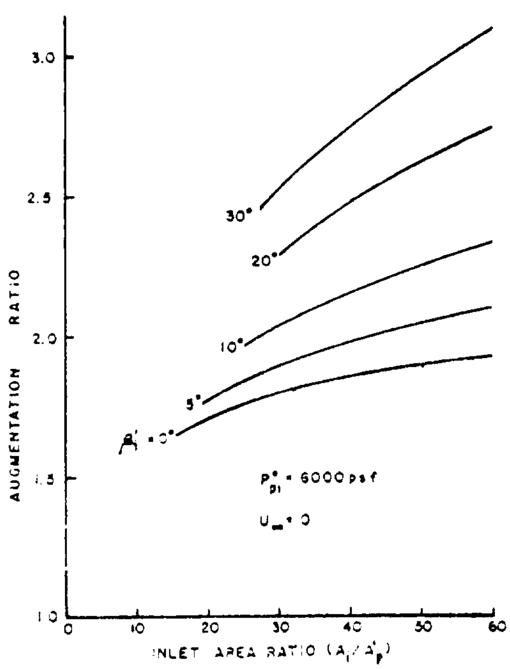


CROSS SECTIONAL SCHEMATIC OF VARIABLE AREA RATIO VALVE IN NOZZLE

DYNAMIC EXPERIMENTATION

- **INPUTS**
  - **STEP & SINUSOIDAL**
  - **AMPLITUDE = 10, 50 & 90% OF MAXIMUM**
  - **FREQUENCY RANGE = 0-20 HZ**
  - **INCREASING & DECREASING THRUST**
- **OUTPUT**
  - **THRUST AMPLITUDE**
  - **RESPONSE RATE**
  - **PHASE LAG**

FIGURE 11. AUGMENTATION OF REACTION CONTROL SYSTEMS.



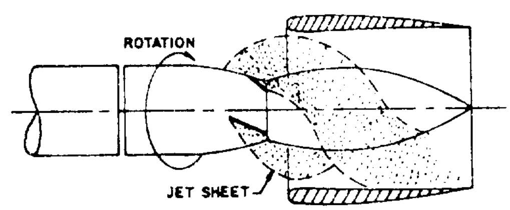


FIGURE 12. CRYPTO STEADY AUGMENTER PERFORMANCE (THEORETICAL).