DESIGN AND TEST OF A PROTOTYPE SCALE EJECTOR WING

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Abstract

The use of analysis and scale model testing to design a full scale (prototype) ejector wing is described. A two-dimensional momentum-integral analysis was used to examine the effect of changing inlet area ratio, diffuser area ratio, and the ratio of ejector length to width. A relatively wide range of these parameters was considered. It was found that for constant inlet area ratio the augmentation increases with the ejector length, and for constant length: width ratio the augmentation increases with inlet area ratio. Scale model tests were used to verify these trends and to examine the effect of aspect ratio.

On the basis of these results, an ejector configuration was selected for fabrication and testing at a scale representative of an ejector wing aircraft designed to perform the U. S. Navy Type "A" mission. The test ejector was powered by a Pratt-Whitney F401 engine developing approximately 12,000 pounds of thrust. The results of preliminary tests indicate that the ejector is developing a thrust augmentation ratio better than $\phi = 1.65$. This is essentially the same level of augmentation obtained in the model scale tests. It is concluded that the combination of analysis and scale model testing can be used to design full size ejectors, although questions of scale and temperature effects remain.

INTRODUCTION

Since the cost of developing an aircraft at prototype scale is prohibitive, it has been usual to employ analytic methods and scale model testing in the initial stages of development. However, ejector development has been carried out largely by empirical and cut-and-try methods because suitable methods of ejector analysis and modelling had not been devised. Until recently only one-dimensional analyses of ejector performance were available.[1,2,3] These analyses were useful in identifying some of the factors that affect ejector performance and in establishing ideal levels of performance, but such parametric methods cannot be used for actual design purposes. For this it is necessary to predict the rate of entrainment due to the turbulent mixing within the ejector. Recently, Bevilaqua and McCullough[4] developed a two-dimensional, finite different analysis using integral methods for the jet entrainment, while Gilbert and Hill[5] used a mixing length model to calculate entrainment, and DeJoode and Patankar[6] used a two-equation turbulence model.

Various studies of ejector scale effects have given inconclusive results. The earliest study of aircraft ejector scale effect performed at the Pennsylvania State University[7] indicated that thrust augmentation increases with the ejector scale; however, aircraft scale ejectors built by Boeing[8] and DeHavilland[9] produced less augmentation than the laboratory models from which they were developed. Full scale Rockwell ejectors have generally performed as well as smaller models, but a limited study of the effects of size again suggested that augmentation increases with the scale.[10]

The purpose of this paper is to show that recently developed two-dimensional methods of analysis can be used with scale model testing to design prototype ejector wing aircraft. In the next section the use of the integral method to predict performance trends for a wide range of configurations is described. The results of scale model tests of three ejector configurations are compared to the analytic trends in the following section. In the last section test results from a prototype-scale ejector wing are compared to the analytic and scale models predictions.

METHOD OF ANALYSIS

We undertook to design a full scale ejector wing for a transport type aircraft such as that shown in Figure 1. The integral method of analysis[4] was used to make the initial trade-offs between ejector inlet area ratio and length to width ratio. Although the more sophisticated turbulence models[5,6] could be expected to give greater accuracy, such methods are too expensive and time consuming to use for parametric studies, which require many configurations to be analyzed. The integral method is a two-dimensional analysis in which the jet velocity profiles are assumed to have a self-preserving shape. Since there is a primary direction of flow (through the ejector) it is assumed that the thin shear layer approximation is applicable. This reduces the governing

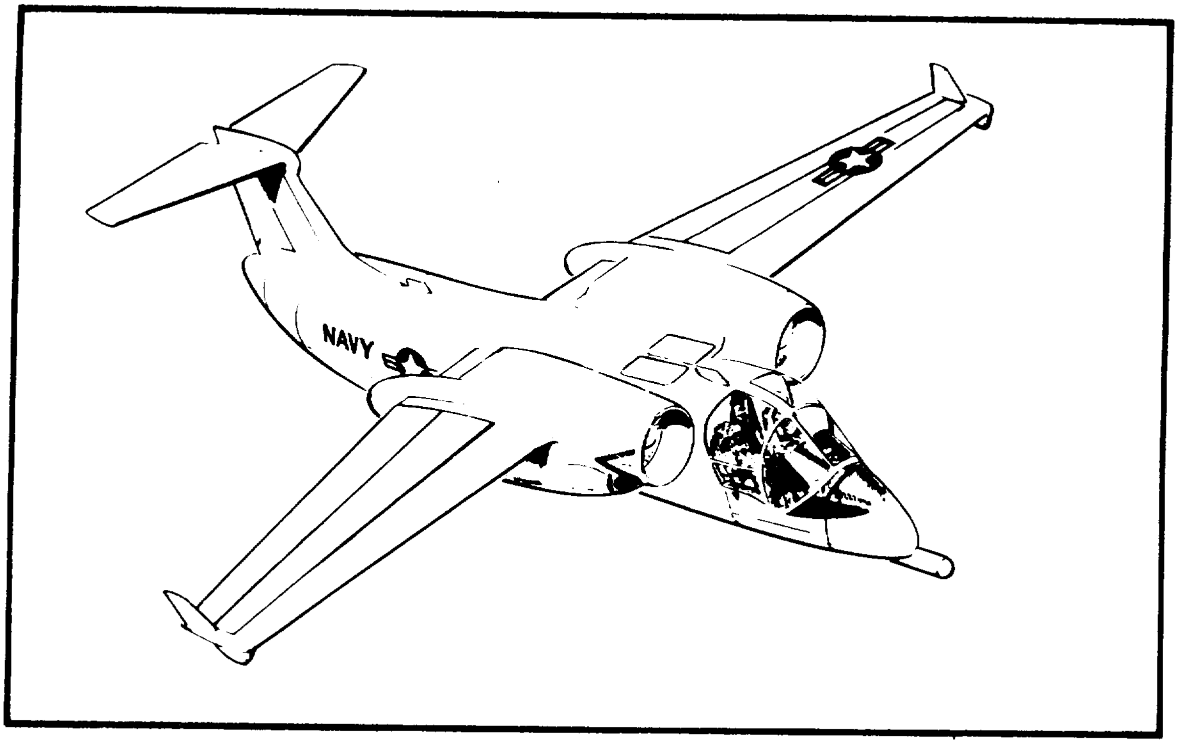

Figure 1. V/STOL aircraft utilizing ejector thrust augmentation in the wing.

elliptic equations to a parabolic set which can be solved by marching in the streamwise direction. A control volume approach was utilized to put the differential equations in finite difference form. The mass and momentum conservation equations are integrated over a control volume coinciding with the walls of the shroud and having length, dx, in the streamwise direction. Pressure and shearing stresses act on the fluid in the control volume at the walls and on the upstream and downstream faces.

The velocity distribution is represented by the superposition of a self-preserving jet velocity profile on a uniform stream. An explicit closure assumption relating the turbulent stresses to the mean flow was not made; however, the use of self-preserving mean velocity profiles is equivalent to an assumption that the stresses are proportional to the rate of strain. In this case the rate of entrainment can be specified by one empirical constant. These equations are solved simultaneously at each dx step through the ejector by straightforward algebraic procedures.

Although solution of the ejector equations has thus been transformed to an initial value problem that can be solved by a streamwise marching procedure, the basic elliptic character of the flow remains unchanged. This means that the velocities at the ejector inlet cannot be arbitrarily specified, but must be compatible with an outer flow that satisfies boundary conditions on the shroud and at infinity. Compatibility of the inner and outer flows is obtained by iterating on the inlet velocity until the exhaust pressure matches the static pressure outside the ejector exit.

This entrainment method provides a relatively simple procedure for calculating the turbulent mixing and entrainment within the ejector. It requires very short computing time, considerably less than one second on an IBM 370. Limitations of the program include the inability to compute compressibility effects and the influence of curvature on the turbulence in the Coanda jets.

Parametric trades between ejector throat width, W, and shroud length, L, were made by varying W at constant L/W, and by varying L/W at constant W. Results indicate that the larger inlet area ratios, A_2/A_0, at constant L/W consistently demonstrated higher levels of performance for the entire range of diffuser area ratios. A_2/A_0 was varied by changing the throat width, keeping A_0 constant. This was done for each of several different L/W's. A_2/A_0 is plotted against the maximum Ø (thrust augmentation ratio) attainable at that L/W, Figure 2. Thrust augmentation ratio

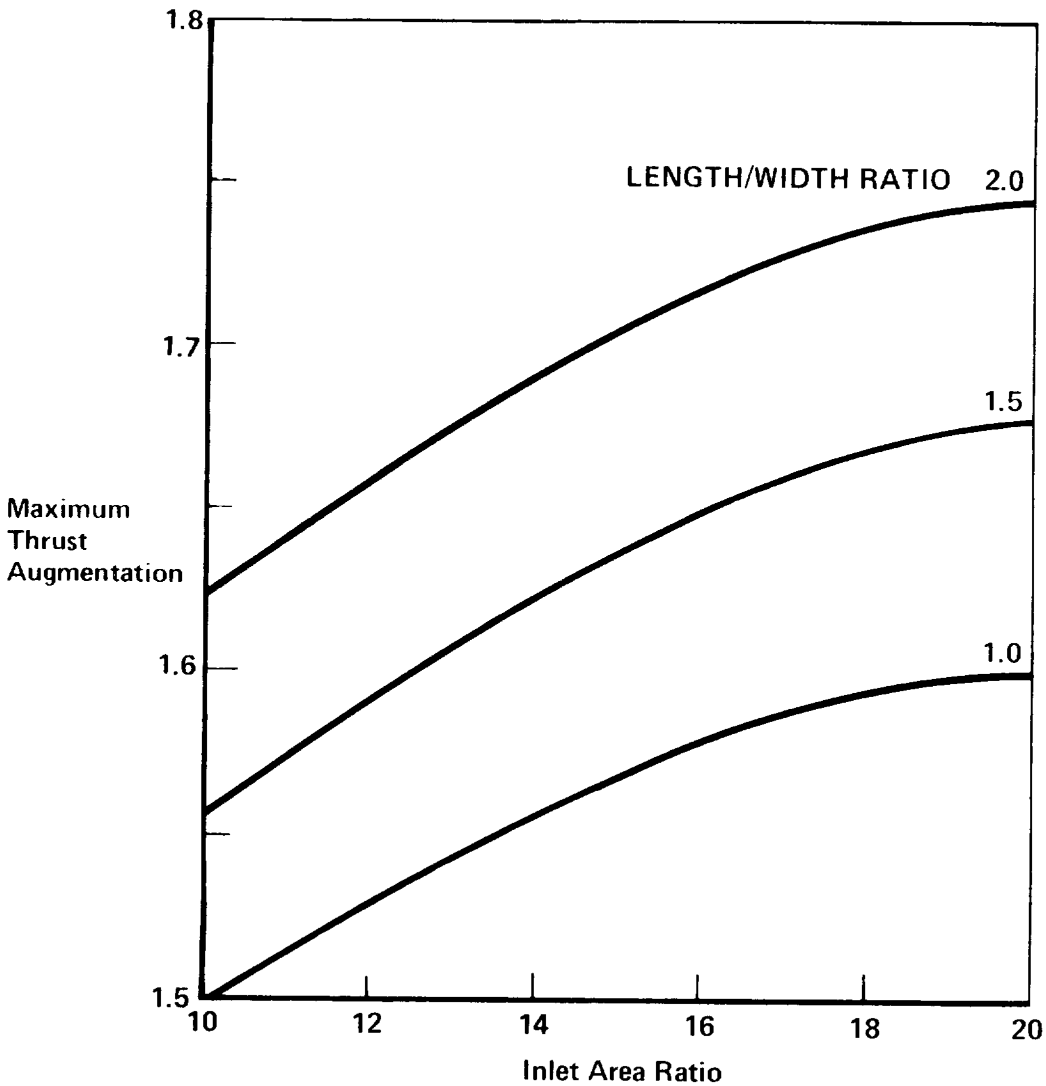

Figure 2. Predicted thrust augmentation ratio as a function of ejector geometry.

is defined as: total thrust/isentropic thrust. Since the computer program cannot predict separation, the diffuser area ratio which produced the peak performance was projected from previous emperical correlations between L/W and maximum diffuser area ratio, A_3/A_2, for rectangular augmenters. The analysis indicated:

- A change in A_2/A_0, in the A_2/A_0 = 10 to 16 range, has a sizable effect on augmentation.
- Augmentation is less sensitive to A_2/A_0 in the A_2/A_0 = 16 to 20 region; the percent increase with increasing A_2/A_0 begins to decline.
- An increase in L/W produces an increase in augmentation at each A_2/A_0. L/W testing performed shows that this rate of increase declines with increasing L/W.

MODEL TESTS

Testing to verify the analysis was carried out on the following three basic augmenter configurations. A typical configuration is shown in Figure 3.

Configuration	A_2/A_0	Average L/W	Average L (in)	W (in)	AR
1	13.1	1.53	6.15	4.02	8.488
2	17.3	1.55	8.2	5.32	6.415
3	17.3	1.73	9.22	5.32	6.415

As was done in the analysis, A_2/A_0 was varied by changing the throat width, keeping A_0 constant. In Figure 4 the measured change in augmentation with diffuser area ratio is shown for two inlet area ratios at L/W = 1.53 and for two shroud lengths at A_2/A_0 = 17.6.

The maximum performance from each of the test configurations was slightly below the predicted value; the trends produced compared favorably (Figure 5). The discrepancy in absolute values between the analysis and the test values is at least partly related to the fact that the analysis is for 2-D flow disregarding endwall effects. Local Ø values near the endwalls are considerably lower than midspan values, thus lowering the average value.

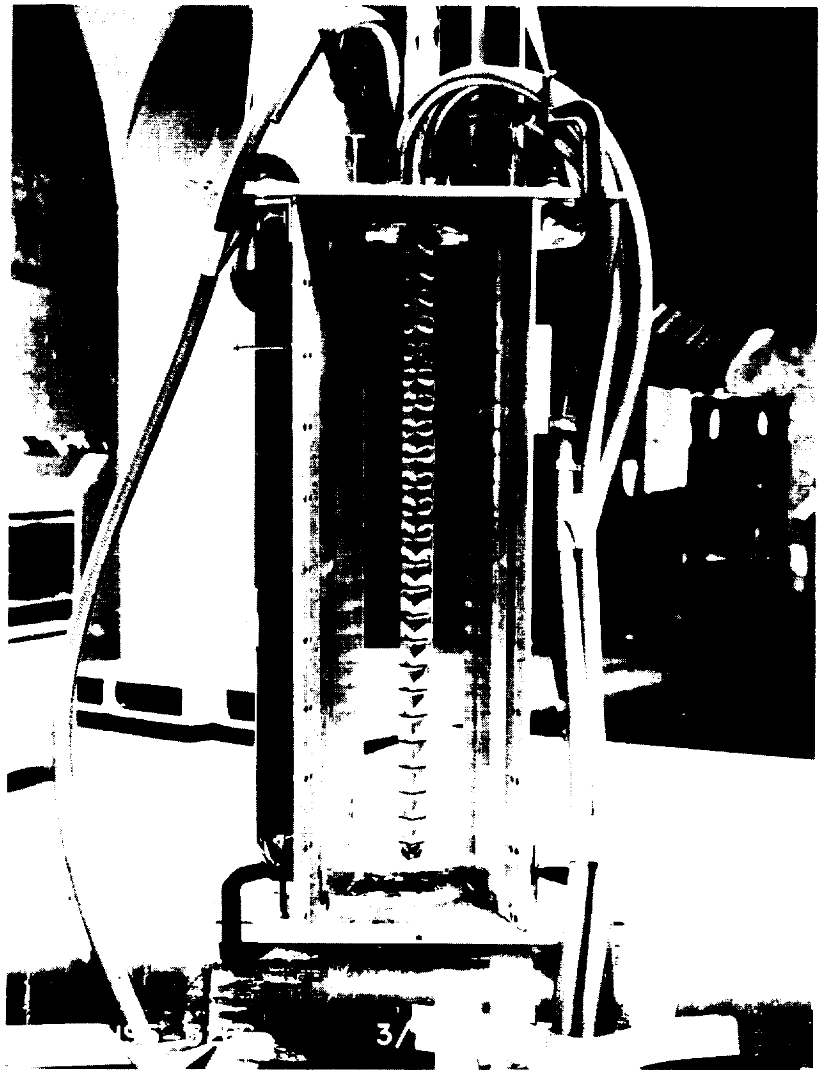

Figure 3. Scale model ejector utilized for all three test configurations.

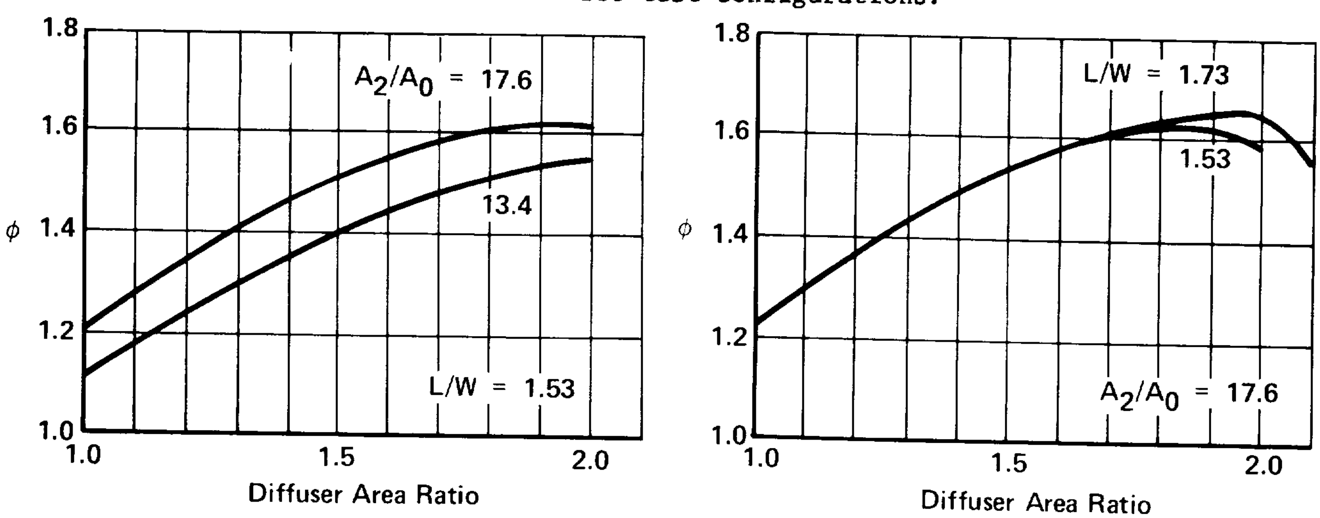

Figure 4. Thrust augmentation ratio measured for the scale model ejectors.

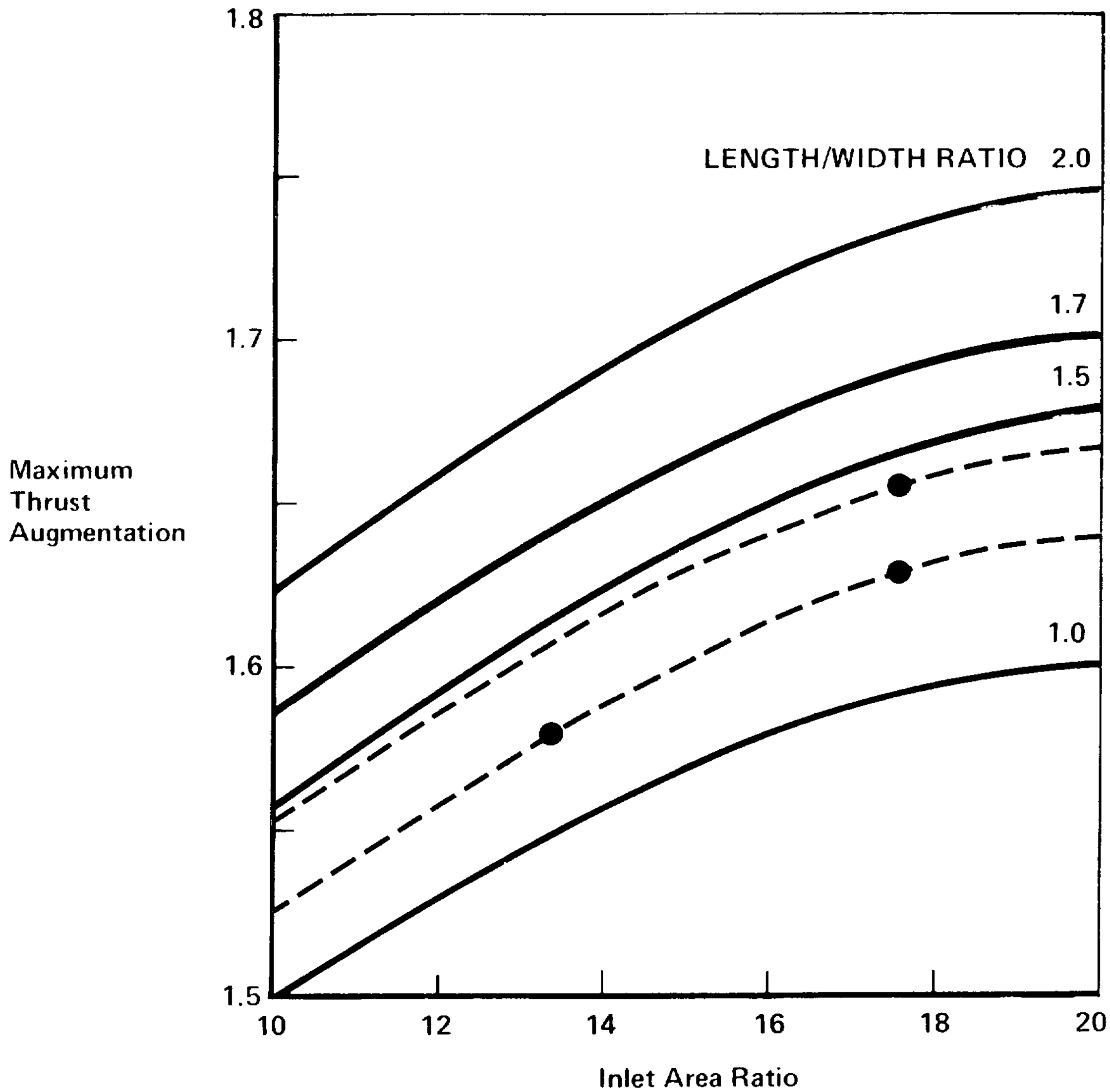

Figure 5. Comparison of predicted (———) and measured (- - -) thrust augmentation ratio.

FULL SCALE PROTOTYPE TESTS

Utilizing results from the analysis and from the small scale model testing, a full scale prototype ejector wing configuration was selected for fabrication and testing. A size was chosen that was representative of an ejector wing aircraft configured to perform the U. S. Navy Type A mission. A section through the full scale prototype augmenter wing is shown superimposed on the airplane ejector wing in Figure 6.

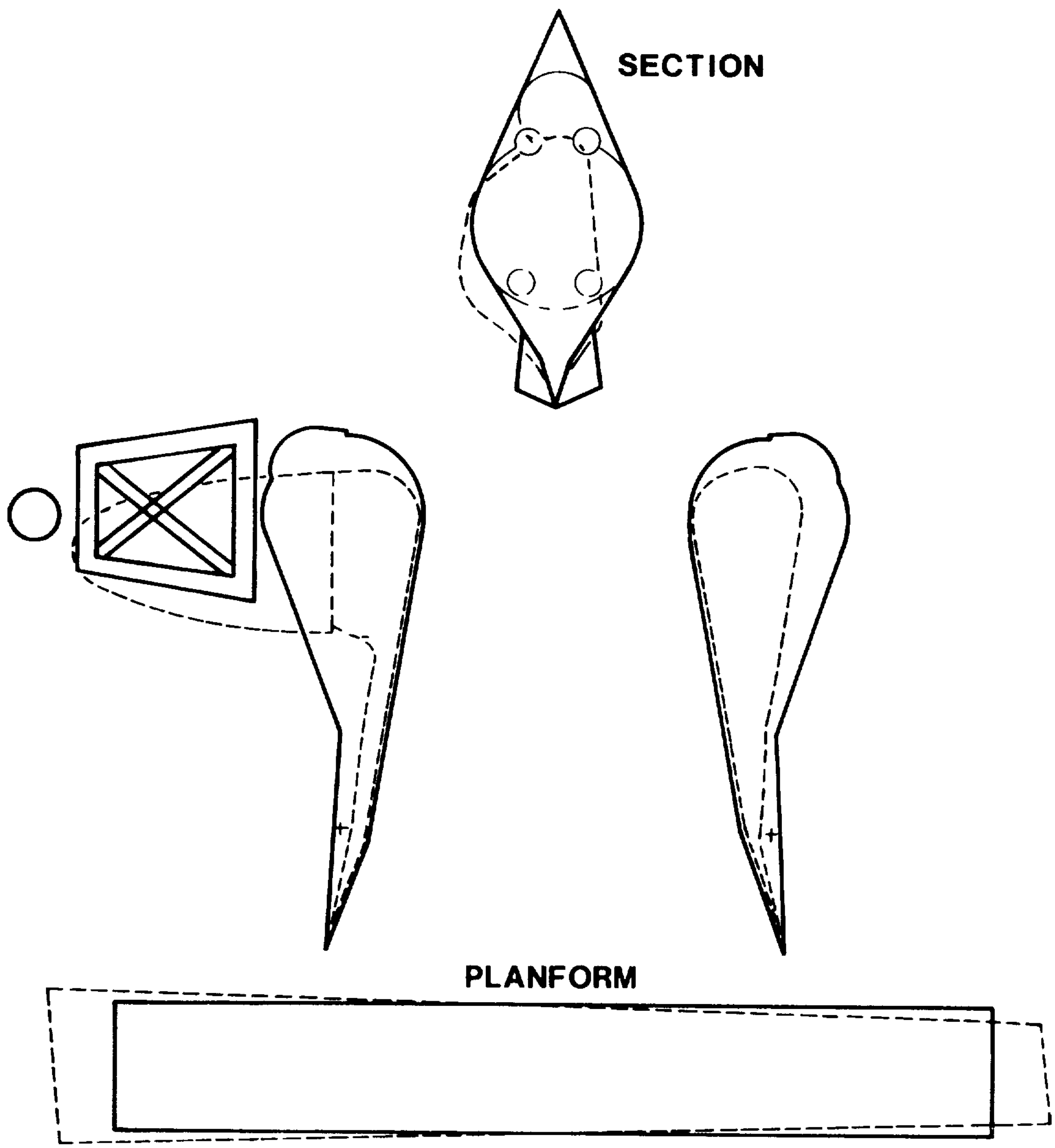

Figure 6. Comparison of aircraft wing design (- - -) and prototype ejector wing tested (———).

Particular attention was given to the design parameters which had been identified by both the analytical and empirical studies as producing significant effects on augmenter performance. This effort resulted in the augmenter wing which is shown in Figure 7.

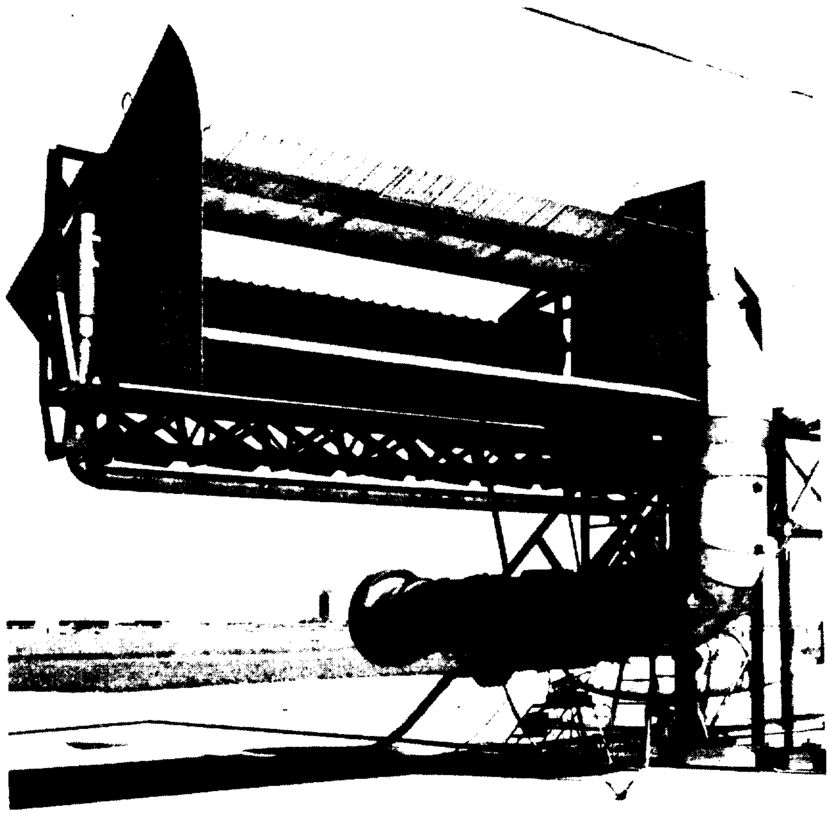

Figure 7. Prototype scale ejector wing shown rotated 90° to minimize ground effects.

The major parameters of the configuration are:

Span	245.8 inches
Throat (W)	38 inches
Flap Length (L)	60 inches
A_0	561 sq inches
Flow Split	(Coanda, 20%; Center Nozzle, 55%; Endwalls, 5%)

The large scale augmenter test facility was intentionally designed to feature a high degree of testing flexibility. This flexibility allows variations in a number of major augmenter geometric parameters such as throat width (W), flap length (L), Coanda nozzle gap (t), and diffuser flap angle (δ_F). The test facility as a whole also allows a great deal of testing flexibility and includes the capability to rotate the entire augmenter panel, vary the static height of the augmenter panel above the ground plane, and provisions for "taxi" and "flight" testing modes. Specific instrumentation and recording capability can be added as required.

The complete test article consists of a ninety (90) foot steel boom, a thirty (30) foot model support frame, engine mount facility for cradling the XF401 U. S. Navy engine (this engine being available on site for use), two twenty (20) foot flaps with both flaperon units and extender surfaces, the twenty (20) foot centerbody, the air distribution systems consisting of the plenum, and various pieces of ducting hardware, and the boom tie-down structure.

Initial testing of the full scale prototype augmenter wing has shown that the configuration is developing a thrust augmentation ratio in the $\phi = 1.65$ range.

Large scale performance measurements (throat velocity, flow quality) indicate that its overall performance level can be increased. Utilizing the flexibility built in the large scale augmenter evaluation will permit: (a) increasing L/W, (b) limited variations in A_2/A_0, and (c) increasing A_3/A_2 delaying flow separation to higher values of diffuser area ratio. Comparison of test results from this configuration with those obtained from its scale model counterpart indicate that the large scale ejector is currently obtaining augmentation ratios similar to the model at comparable A_3/A_2 ratios, all other design parameters being consistent (Figure 8).

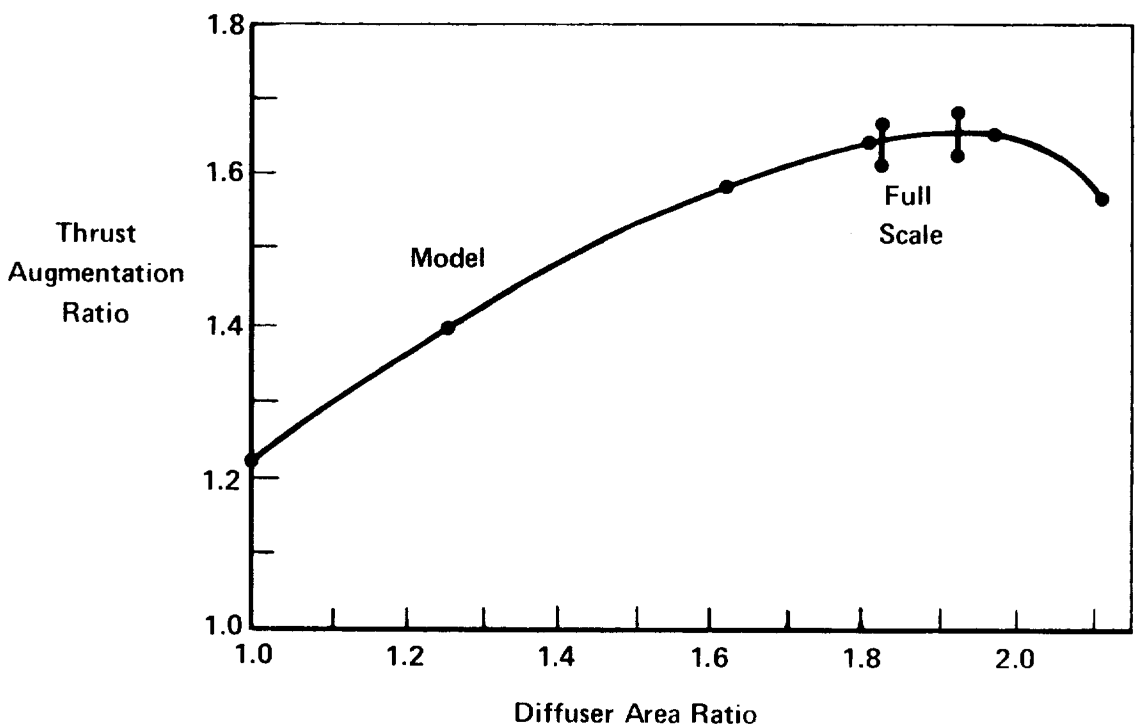

Figure 8. Comparison of measured thrust augmentation ratio at prototype and model scales.

This result suggests that apparent scale effects in previous tests were probably related to differences in internal ducting, primary jet temperature, method of construction, and other features that were not scaled. However, the present results should not be taken as proof that there are no scale effects. For example, in modeling the characteristics of jets, it is necessary that the Reynolds number be held constant. This is because small scale eddy motions are affected by Reynolds number; however, it is the large scale eddies that control the rate of entrainment and these are independent of Reynolds number. Thus, if the Reynolds numbers for both the original and model jets are large enough to insure that the flow is turbulent, equality of Reynolds number is not necessary to scale jet entrainment. On a more elementary level, the "square-cube law" for scaling implies that frictional effects are greater in small ejector models, because the model has greater wall surface (L^2) in relation to volume (L^3) than a full scale ejector. As long as the model is not made too small, frictional forces are almost negligible and may not reduce the augmentation significantly. Since the effect of increasing the temperature of the primary jet is to reduce the augmentation, these effects may have been equal and opposite in the present tests.

CONCLUSION

With the use of physical reasoning and mathematical analysis, scale model testing can be used for initial development of prototype scale ejectors. However, further study of ejector scale and temperature effects is needed to separate extraneous influences from true scale effects.

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