THEORY AND PRACTICE OF EJECTOR SCALING

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ABSTRACT

Procedures are described for utilizing scale models for the development of thrust augmenting ejectors. Physical reasoning and the methods of dimensional analysis are used to argue that the Mach numbers must be matched, but that the Reynolds number is not a relevant parameter if its value is large. Numerical analysis is used to show that almost no change in performance may be expected from the use of cold air jets. Experimental data is presented to support these results. Thus, it is concluded that scale model ejectors powered by cold jets provide a close approximation to the performance of full size ejectors powered by hot jet exhaust flows.

INTRODUCTION

Scale model testing of thrust ejector systems and their associated components provides a convenient low cost alternative to full size test and development programs. The applicability of model scale test data in the prediction of conventional aircraft performance through the use of certain scaling laws has long been accepted practice. Unfortunately, the development of full size thrust ejector systems utilizing model scale testing is not as universally accepted.

Inconsistencies in the results of available ejector scaling studies imply that we cannot simply scale an ejector model geometrically and assume that its performance will be representative of its full size counterpart. However, by the use of physical reasoning and mathematical analysis, a scaling rationale for the design of useful model tests has been developed. Applying physical reasoning and the laws of dimensional analysis, it will be shown that the performance of model scale ejectors driven by cold air jets should approximate the performance of their full size counterparts driven by aircraft gas turbine propulsion systems.

Utilization of this rationale in conjunction with highly controlled specific test procedures and methods has resulted in providing substantiation for utilizing model scale ejectors in the development for full size ejector systems.

Ejector Scaling Rationale

In order to set up a meaningful test, the fundamental parameters on which the thrust augmenting force depends must be identified. If it is assumed that this force is a function of the jet thrust, the ejector shroud geometry, and the physical properties of the fluid, dimensional analysis yields for the scaling law

$$F/T = f(Re, M, L/W, \delta)$$

in which the force coefficient, F/T, is the ratio of the augmenting force to the jet thrust, Re and M are the jet Reynolds number and Mach number, and L/W and δ give the length to width ratio and divergence angle of the ejector shroud. The force coefficient also depends on the surface roughness and ambient turbulence level, but these parameters should be controlled to insure that their effect is small. Temperature effects are usually assumed to be implicit in the variation of the Mach and Reynolds numbers; however, an additional effect of temperature on the turbulent mixing will be discussed separately.

The geometry of a scale model can easily be made to duplicate the full size prototype, but it is not possible to simultaneously match the Mach and Reynolds numbers of the prototype; for example, if the Mach numbers are matched, then the change in scale means the model Reynolds number will be smaller. Similarly, if the Reynolds numbers are matched by increasing the model velocity, then the model Mach number will be larger. However, because the velocity of the prototype jet is large ($M > 1$), the Reynolds number is also large ($Re \cong 10^6$), so that the flow is turbulent and the effects of viscosity are small. In this case, changes in the Reynolds number only affect the very smallest scales of the turbulence, which do not interact directly with the main flow. According to this principle of asymptotic invariance, the Reynolds number is not a relevant parameter if its value is large.

Therefore, if the Mach numbers are matched and the Reynolds numbers are large, scale model tests can be used to determine the variation of ejector thrust with nozzle geometry and diffuser angle for a given ejector configuration. On the other hand, the angle at which the flow separates, and other phenomena which relate to the exact details of the viscous stresses, are dependent on the Reynolds number. Thus, unless the Reynolds number is matched, model values of the separation angle cannot always be used to predict full size separation angles. Typically,separation will occur at a smaller angle on the scale model due to the predominance of the viscous stresses resulting from the lower value of Reynolds number. Therefore, the assumption that the full size ejector separates at the same angle as the scale model should be a conservative estimate.

As previously noted, the first order effects of temperature on the physical properties of the jet (density, viscosity, and compressibility) are implicit in scaling the Mach and Reynolds numbers. In particular, the Mach number ($M \cong V/a$) is independent of temperature, since both the jet velocity, V, and the speed of sound, a, have the same dependence on temperature:

$$\text{jet velocity} \qquad V = \left[\frac{2\gamma}{\gamma - 1} RT_0 \left(1 - \left(\frac{P}{P_0}\right)^{\frac{\gamma - 1}{\gamma}}\right)\right]^{\frac{1}{2}}$$

$$\text{speed of sound} \qquad a = \left(\gamma RT_0\right)^{\frac{1}{2}}$$

The jet thrust is also independent of temperature, since the velocity increase is balanced by a decrease in density. The variation of Reynolds number with temperature is shown in Figure 1. The effect of reducing the jet temperature by 1000°F, as in the present case, does not change the order of magnitude of the Reynolds number.

The effect of temperature on the rate of turbulent mixing is not as straightforward. For small density differences, the mixing rate is proportional to the velocity difference between the two streams. If the density difference is large, the mixing rate is proportional to the momentum difference. Thus, a small temperature difference will probably increase the mixing rate ($\Delta V \sim T_0^{\frac{1}{2}}$) while a large temperature change will probably decrease mixing ($\Delta \rho V \sim T_0^{-\frac{1}{2}}$), although this has not been proven.

The net effect of the 1000° temperature decrease used for these scale model tests was calculated with the TKE program to be a .03 increase in augmentation. This is almost within the accuracy of the calculation procedure; however, the available data seem to support this result.[1-4] This is shown in Figure 2. Although all the data except that of Lockheed also included a scale or configuration change, the trend is consistent. Thus, a small increase in performance may be expected as a result of using cold jets in the scale model testing. However, for the temperature range of interest, the temperature effect is almost within the range of computational and experimental error.

Therefore, based on theoretical arguments, if primary flow Mach numbers are matched while Reynolds numbers are held large enough to assure turbulent flow, it may be concluded that model scale ejectors powered by cold jets should approximate the performance of large scale ejectors powered by hot flow jets.

A study of ejector scale effects performed at Pennsylvania State University indicated that the thrust augmentation increases with ejector scale. However, aircraft scale ejectors built by both Boeing and DeHavilland produced less augmentation than the laboratory models from which they were developed. While initially these results appear inconclusive, it is believed that the inconsistencies may relate to differences between the model scale and full size tests. Model construction techniques, primary jet temperature, and test procedures all must be accounted for during investigations of ejector scale.

Ejector Test Techniques

In order to minimize the influence of experimental error which may in some part explain the observed inconsistencies in previous ejector scale investigations, attention must be given to developing well controlled test procedures and methods.

At Rockwell, scale model ejector tests are normally performed at the Columbus plant's thermodynamics laboratory utilizing test stands specially designed and fabricated for ejector test applications. Each test stand is basically a floating frame attached to an outer fixed frame through a set of load cells to measure the ejector's forces. Figure 6. Tension is maintained on the load cells with dead weight cable suspended preloads. Air flow is supplied from the laboratory's compressor via four individually controlled supply lines. The air supply system is equipped with particle filters and dryers in order to remove contaminants from the primary air supply. Excessive variations in air flow temperature are eliminated through the use of a compressor system cooling tower.

Each air supply line has a venturi meter with the necessary instrumentation attached to calculate mass flows using standard venturi meter equations. The four lines are fed to the diffuser, centerbody, elevon, and endwall blowers (BLCS) through four flexible 2-inch hoses. These flexible lines prevent excessive tare when bringing the lines across the metric part of the load stand.

Load cells, pressure transducers, and thermocouples are connected at appropriate test points on the load stand, model, and air supply system to monitor forces, pressures, and temperatures. These transducers are periodically calibrated using standard laboratory practice with calibration equipment traceable to the National Bureau of Standards.

The Thermo Lab's data system is capable of monitoring 48 channels of transducer analog output data and incorporates all signal conditioning and amplification prior to signal processing by an IBM 1800 computer. The data system also has the capability of performing an electrical test of the transducer's bridge integrity by use of a resistance calibration test (R-CAL). This is routinely done by the computer prior to each test run, and any drift in transducer excitation or signal amplification is automatically compensated for by the computer. Prior to each test run, the load cells are checked by preloading with calibrated lead weights, thus assuring their accuracy before collecting test data.

Data acquisition and reduction is handled by an IBM 1800 computer that contains a 48 channel multiplexer and a 14 bit plus sign analog to digital converter.

Data reduction is accomplished by appropriate user-written computer programs. Conversion constants for all transducers are contained in the software and utilized to convert transducer electrical outputs to equivalent engineering units. Appropriate equations are programmed to calculate augmenter air flow parameters such as isentropic thrust, flow coefficients, velocity Reynolds number, etc. A typical printout of relative ejector performance parameters is shown in Figure 3. Selected parameters are calculated and punched into cards for additional data analysis utilizing a timeshared IBM 370 computing system.

Data Error and Repeatability

Prior to applying model scale test results to the development of full size ejector systems, it is useful to develop an understanding of the test data accuracy and repeatability. The definition of augmentation ratio (ϕ), utilized in Rockwell's ejector development program is

$$\phi = \frac{\text{Ejector Lift (Thrust)}}{\text{Nozzle Isentropic Thrust}} = \frac{\text{Load Cell Measured Lift}}{(\text{Mass Flow})_{\text{Measured}} \; (\text{Velocity})_{\text{Isentropic}}}$$

Therefore, the fractional error in ϕ may be computed by:

$$\frac{\Delta\phi}{\phi} = \sqrt{\frac{\Delta\text{Lift}}{\text{Lift}}^{2} + \frac{\Delta\text{Mass Flow}}{\text{Mass Flow}}^{2} + \frac{\Delta\text{Velocity}}{\text{Velocity}}^{2}}$$

where the (Δ) symbol signifies the probable error in the parameter of interest.

A close examination of the calibration accuracies of the instrumentation utilized to isolate the major parameters in the augmentation ratio (ϕ) definition resulting in

Lift (load cell accuracy and hose tare corrections) = .25%

Mass Flow (calibration accuracy venturi and associated pressure transducers) = 1.29%

Velocity (calibration or pressure transducers) = .117%

Therefore:

$$\Delta\phi = \sqrt{(.0025)^2 + (.0129)^2 + (.00117)^2} = .0132$$

Therefore, an expected error in measured performance of 1.32% can be related to the accuracy of the instrumentation utilized during the scale model test program.

To determine the possible variation in augmenter performance over a short period of time and the possible error encountered by taking lift and pressure data at an instantaneous time slice, a series of runs were made comparing results where ten data samples were taken, averaged, and compared to results of a single sample data point. Figure 4 presents a comparison plot of single sample/data point vs. ten samples/per data point (@ one sec. time interval between samples). Results show that ϕ at any given time is comparable to ϕ over a period of ten seconds.

This sampling/averaging technique was further tested by increasing the time between samples from one sec. to ten secs. The lower plot on Figure 5 shows the results of one sample/sec. vs. one sample/ten sec. for a ten sample data point.

Based on these investigations the 10 sample-1 sample/sec. technique was incorporated as the standard sampling method in the data reduction routines.

Long term data repeatability was established by periodically restoring the model to a baseline configuration and examining its performance. Figure 10 presents a ϕ vs A_3/A_2 comparison of a four run series over a two week time period. The maximum scatter in ϕ was on the order of $\pm.013\ \Delta\phi$.

By collectively evaluating the experimental error due to instrumentation accuracy and the data repeatability, it is possible to establish a band of experimental data scatter. For the example discussed this band was about $\pm.02\ \Delta\phi$. Isolating and controlling the experimental data quality is an integral part of effective ejector scaling.

Experimental Data

A survey of large scale ejectors previously developed by Rockwell International provides substantiating evidence that model scale ejectors can be utilized in the design of prototype scale ejector systems. In general large scale ejector systems have performed as well as or slightly better than their model scale counterparts. Figures 7 and 8. In one case shown in Figure 9 where a great deal of attention was given to exact geometric scaling, the same level of augmentation ratio (ϕ) was achieved.

CONCLUSION

Through the use of physical reasoning, mathematical analysis, and carefully controlled test techniques, scale model testing can be utilized in the development of large scale ejector systems. Experimental data have been obtained which provide substantiating evidence that model scale ejectors powered by cold air jets provide a close approximation to the performance of full size ejectors powered by hot jet exhaust flows. Further study of ejector scale and temperature effects is recommended to establish scaling relationships for ejector systems.

REFERENCES

1) Phillips, J. D., Temperature and Pressure Effects on Thrust Augmentation, M.S. Thesis, The Ohio State University, 1975.
2) Dejneka, R., Influence of Driving Air Temperature on Thrust Augmenting Ejector Performance, NADC-PE-41, August 1980.
3) Gates, M. F., Cochran, C. L., Evaluation of Annular Nozzle Ejector, ARD-280, November 1980.
4) Rabeneck, G. L.; Shumpert, P. K.; and Sutton, J. F., Steady Flow Ejector Research Program, Lockheed Aircraft Corporation, Georgia Division, Final Contract Report NONC-3067(00), December 1980.
5) Fought, D. E., Test and Analysis of a Coanda Thrust Augmentation Nozzle, (A Thesis in Aeronautical Engineering), The Pennsylvania State University, January 1960.
6) Wang, T.; Wright, R.; and Mahal, Design Integration and Noise Studies for Jet STOL Aircraft, The Boeing Company, NASA CR114286, May 1972.
7) Whittley, D. C., Augmenter-Wing Technology for STOL Transport Aircraft, DeHavilland Aircraft of Canada, Ltd., High Lift Technology Course, Univ. of Tenn., 27 October 1975.
8) Mefferd, L. A.; Alden, R. E.; and Bevilaqua, P. M., Design and Test of Prototype Scale Ejector Wing, Paper at Workshop of Thrust Augmenting Ejectors, NASA Ames Research Center, June 1978.

REYNOLDS NUMBER

$R_N = \frac{\phi V}{\mu}$

ρ DECREASES AS T^{-1}

V INCREASES AS $T^{\frac{1}{2}}$

μ INCREASES AS $T^{\frac{1}{2}}$

$R_N \sim T^{-1}$

REYNOLDS NUMBER DECREASES WITH INCREASING TEMPERATURE

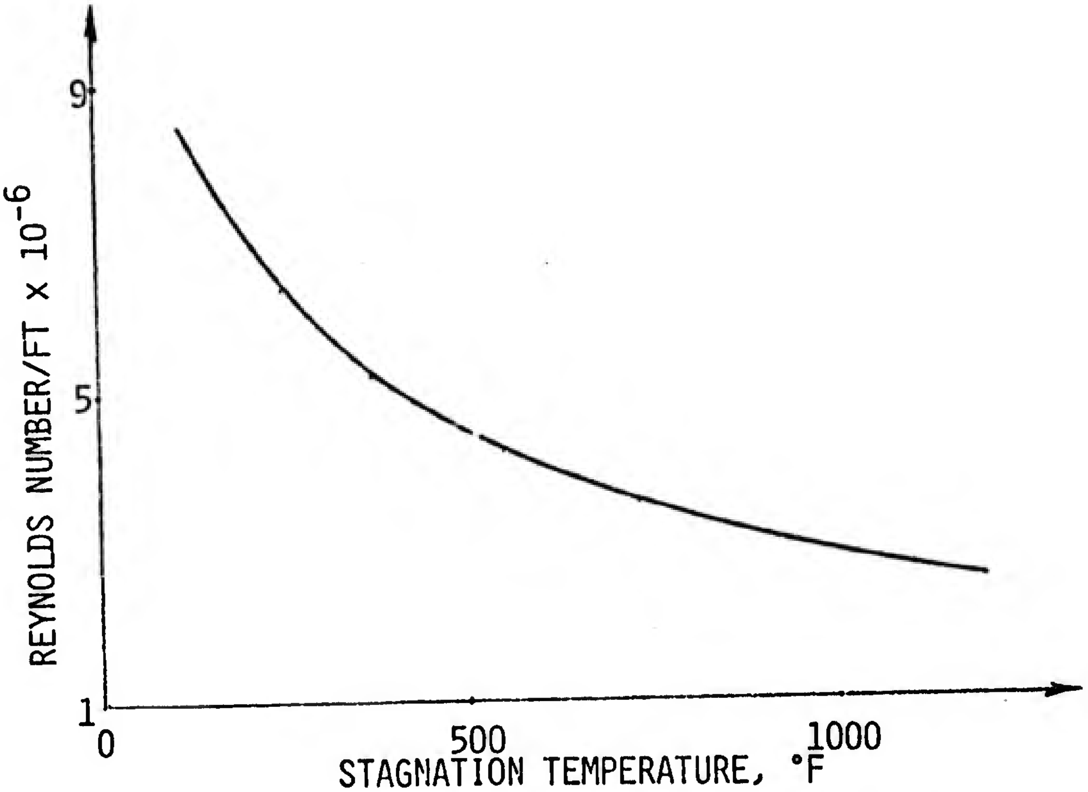


Figure 1.

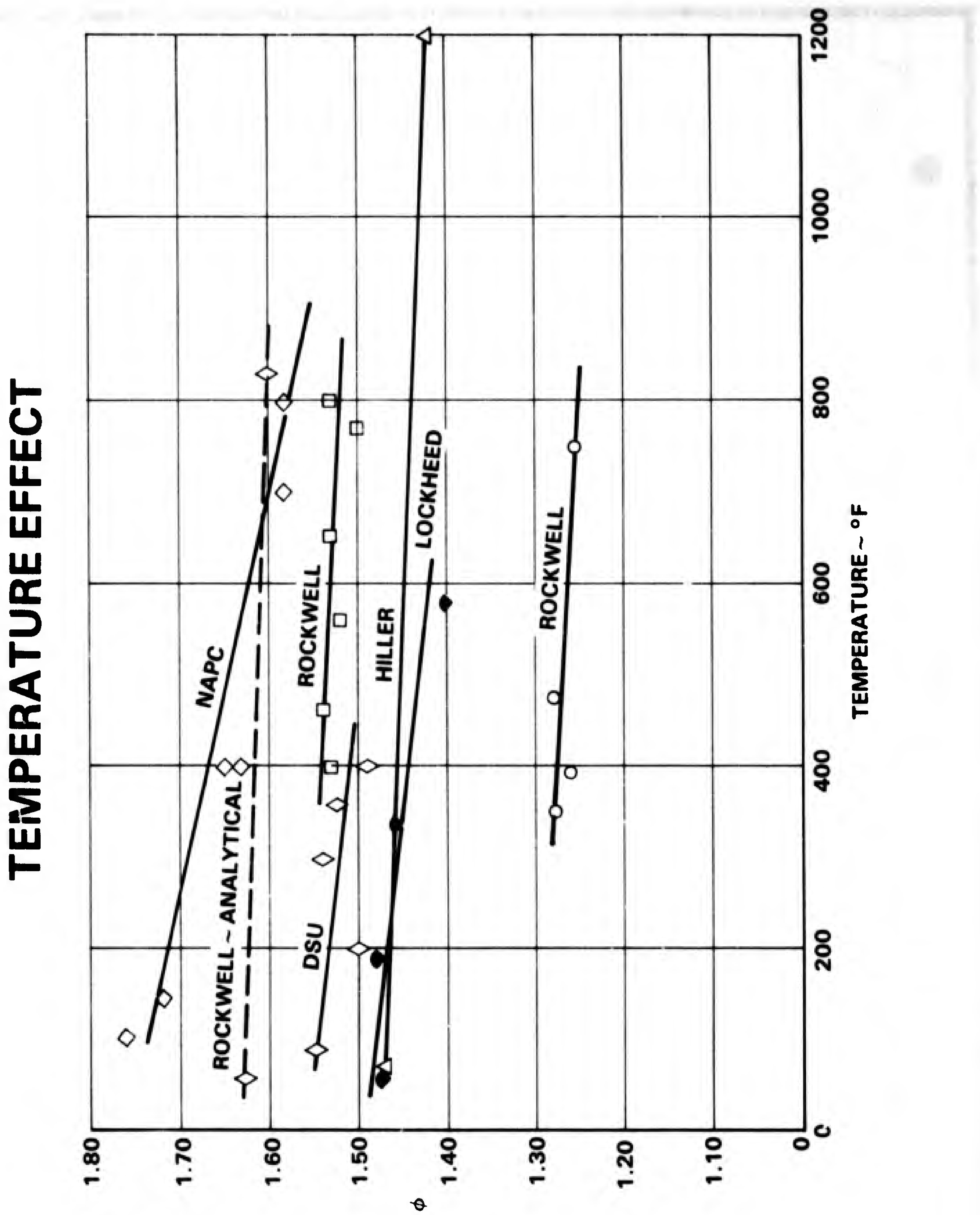

TEMPERATURE EFFECT
NAPC
ROCKWELL ~ ANALYTICAL
ROCKWELL
DSU
HILLER
LOCKHEED
ROCKWELL
φ
1.80
1.70
1.60
1.50
1.40
1.30
1.20
1.10
0
0
200
400
600
800
1000
1200
TEMPERATURE ~ °F

Figure 2.

```
TEST 278        RUN  985       DATE   08 MAY 80      TIME 17.28         RECOMP NO.  0       DISK  9         PAGE  7

JOB NO.  5          LDGR ACCT 31511      CONTRACT    356      SUB ACCT   1001                ACO DATE  8 MAY 80 17.25

MOD 924 0.2 RECT WG,15EL CRUC BT HT=1.60,CBA=0,F=24,(ORIG),EX=11.37,   TH=5.019,A3/2=2.265,CB TAPS OFF,FRNGS

PT   3                                FWD COANDA      CENTERBODY       AFT COANDA        BLC

            PHI             TFGI           FGI1           FGI2            FGI3            FGI4           FGI5
         1.6543         126.0674        22.6879        75.0328         22.9383          5.4084     ***********
          TFEJC            AVCDN           CDN1           CDN2            CDN3            CDN4           CDN5
       208.5585           0.9879         1.0113         0.9777          1.0224          0.8841     ***********
           TWFN                            WFN1           WFN2            WFN3            WFN4           WFN5
         3.6179                          0.6359         2.1728          0.6354          0.1736     ***********
           TWFV             PHIL           WFV1           WFV2            WFV3            WFV4           WFV5
         3.5710           1.6543         0.6431         2.1246          0.6496          0.1535     ***********
                                          PWFV1          PWFV2           PWFV3           PWFV4          PWFV5
                                        18.0107        59.4955         18.1931          4.3004     ***********
          DELTF            AVPRN           PRN1           PRN2            PRN3            PRN4           PRN5
        24.0000           2.1988         2.1942         2.2006          2.1982          2.1958     ***********
          DELTD            TAREA          AREA1          AREA2           AREA3           AREA4          AREA5
        90.0000           5.0005         0.8812         3.0006          0.8788          0.2400         0.0000
           PBAR                           VELN1          VELN2           VELN3           VELN4          VELN5
        14.2802                       1135.8420      1137.1628       1136.8634       1133.9904     ***********
          CLIFT            ULIFT           MNN1           MNN2            MNN3            MNN4           MNN5
       208.5585         207.5764         1.0000         1.0000          1.0000          1.0000     ***********
          CSIDE            USIDE           PTN1           PTN2            PTN3            PTN4           PTN5
         0.0000           0.0000        31.3344        31.4263         31.3912         31.3577     ***********
          CDRAG            UDRAG            PS1            PS2             PS3             PS4            PS5
         0.0000           0.0000        89.8149        42.3319         91.8718         33.1919     ***********
 LFT LD CELL-NTH  LFT LD CELL-STH          RNV1           RNV2            RNV3            RNV4           RNV5
       109.4089          98.1674      0.776E 06      0.194E 07       0.788E 06       0.185E 06      0.000E 00
 DRG LD CELL-EST  DRG LD CELL-WST           PV1            PV2             PV3             PV4            PV5
         0.0000           0.0000       113.3789       110.1443        113.2390        113.6570     ***********
 SDE LD CEL-N.E.  SDE LD CEL-S.E.          DPV1           DPV2            DPV3            DPV4           DPV5
         0.0000           0.0000         2.2578         7.4836          2.3645          0.1291     ***********
 SDE LD CEL-N.W.  SDE LD CEL-S.W.           TV1            TV2             TV3              T4            TV5
         0.0000           0.0000       534.0676       533.5381        533.9327        531.8807     ***********

       CH-SAT1    CH-SAT2    CH-SAT3    CH-SAT4
          0          0          0          0
```

Figure 3.

DATA REPEATABILITY ~ SHORT TERM

ϕ VERSUS NPR

SCBT15-1, A_2/A_0 = 20.1 L/D = 1.5

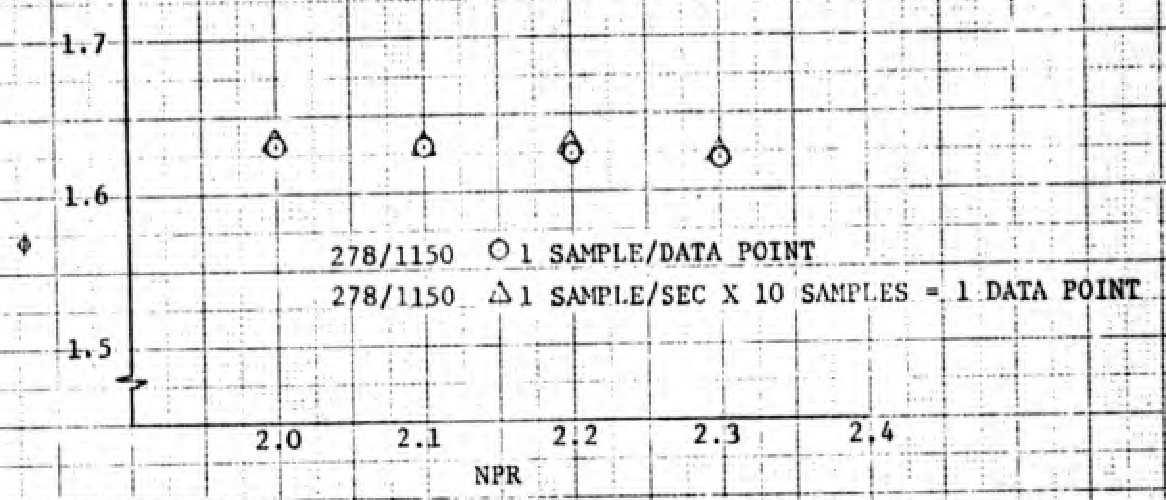


Figure 4.

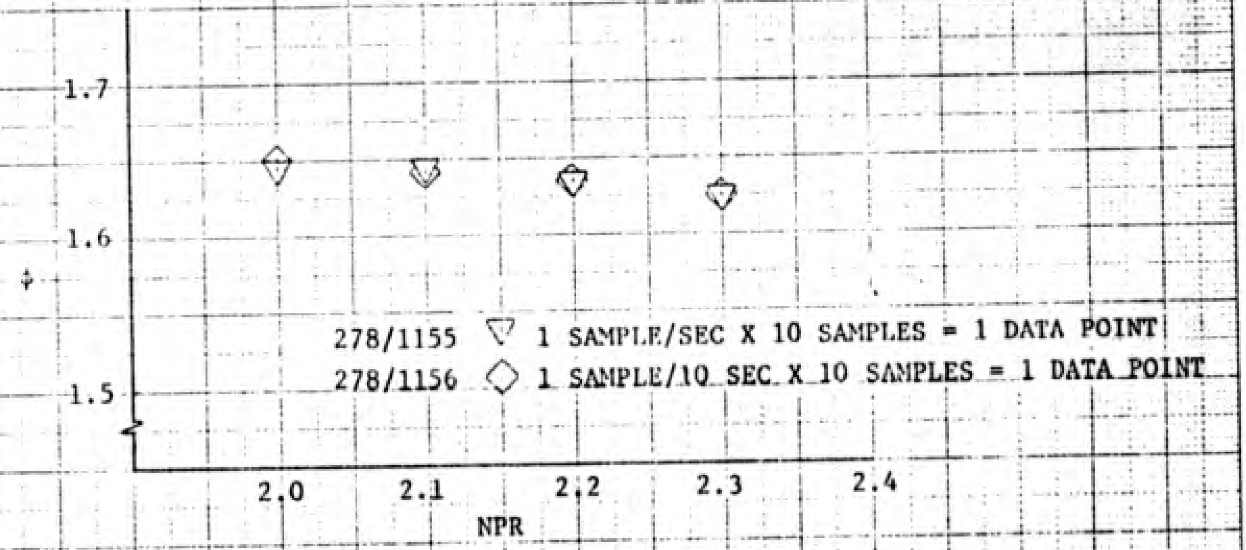


Figure 5.

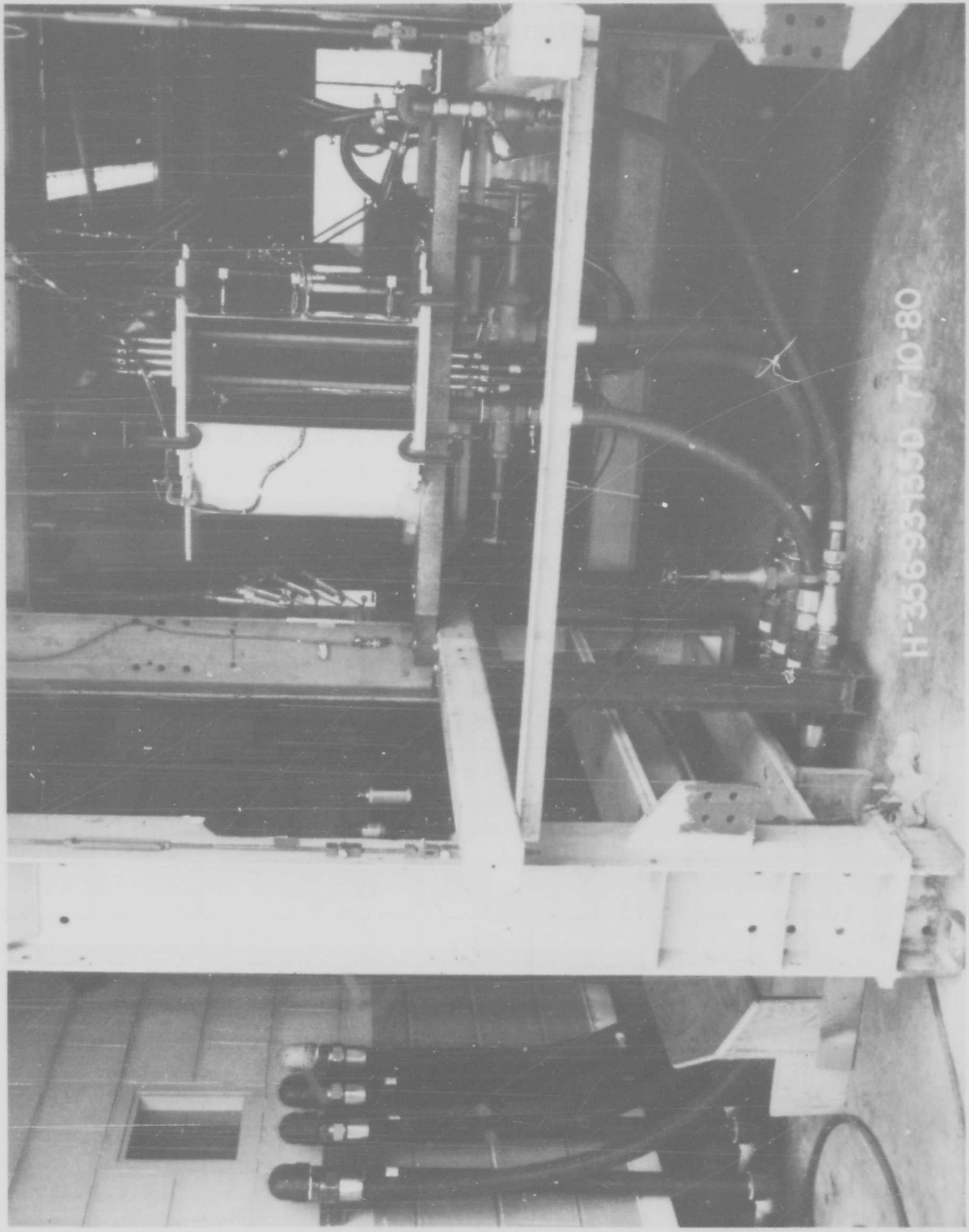


Figure 6.

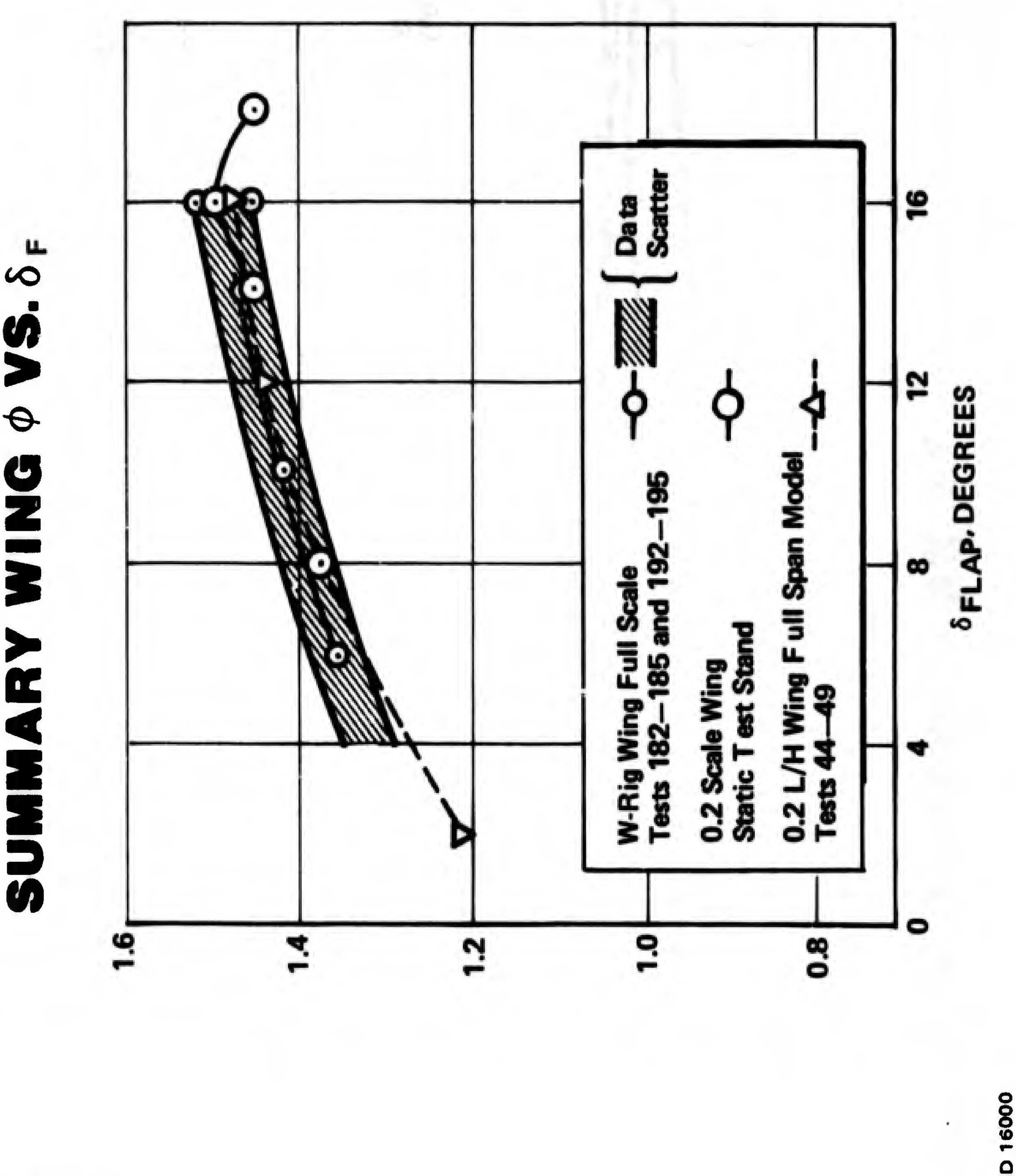
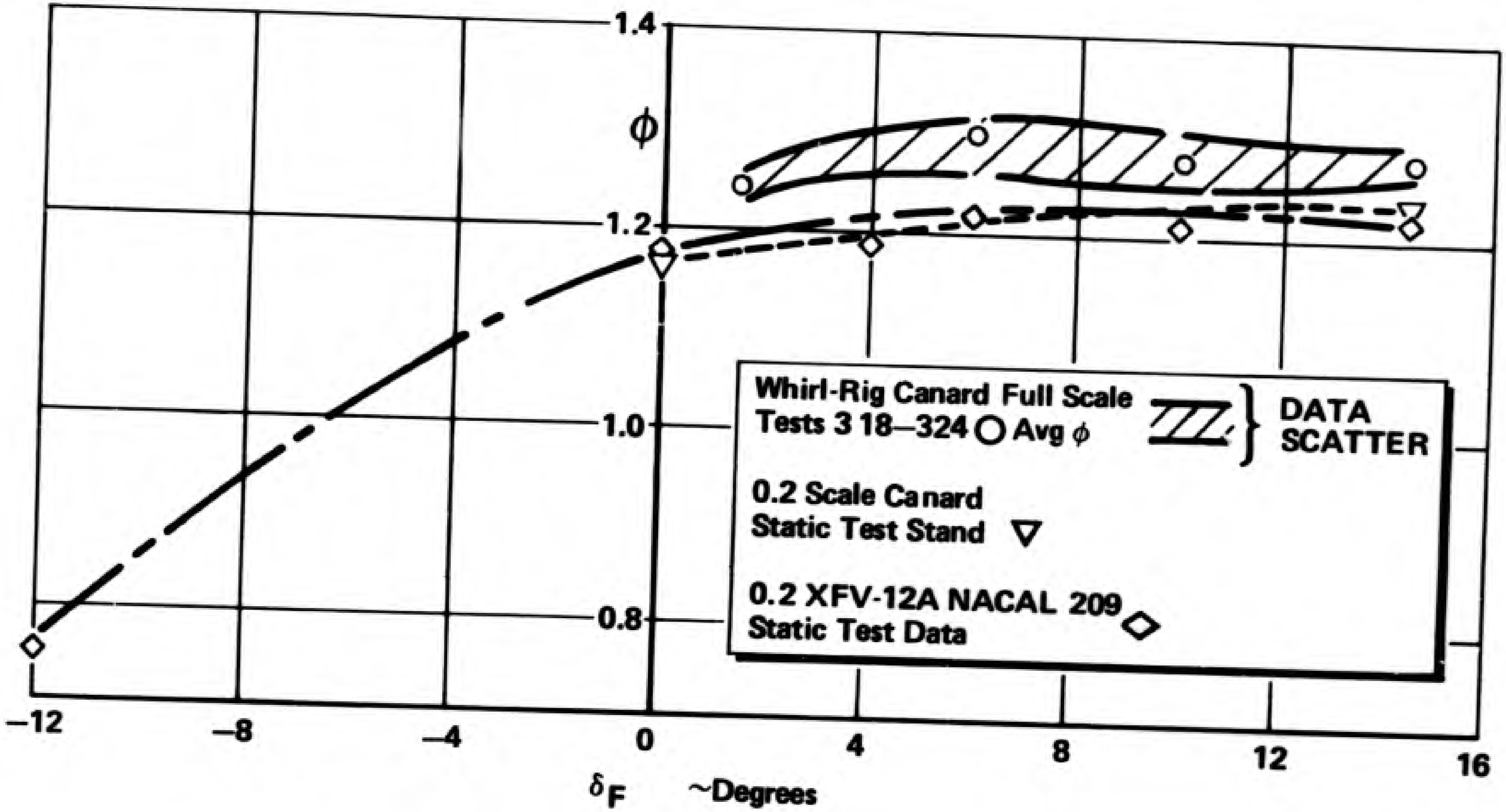

SUMMARY WING φ VS. δF
1.6
1.4
1.2
1.0
0.8
0
4
8
12
16
δFLAP, DEGREES
W-Rig Wing Full Scale
Tests 182–185 and 192–195
Data Scatter
0.2 Scale Wing
Static Test Stand
0.2 L/H Wing Full Span Model
Tests 44–49
CAD 16000

Figure 7.

SUMMARY CANARD ϕ VS. δ_F



CAD 16031

Figure 8.

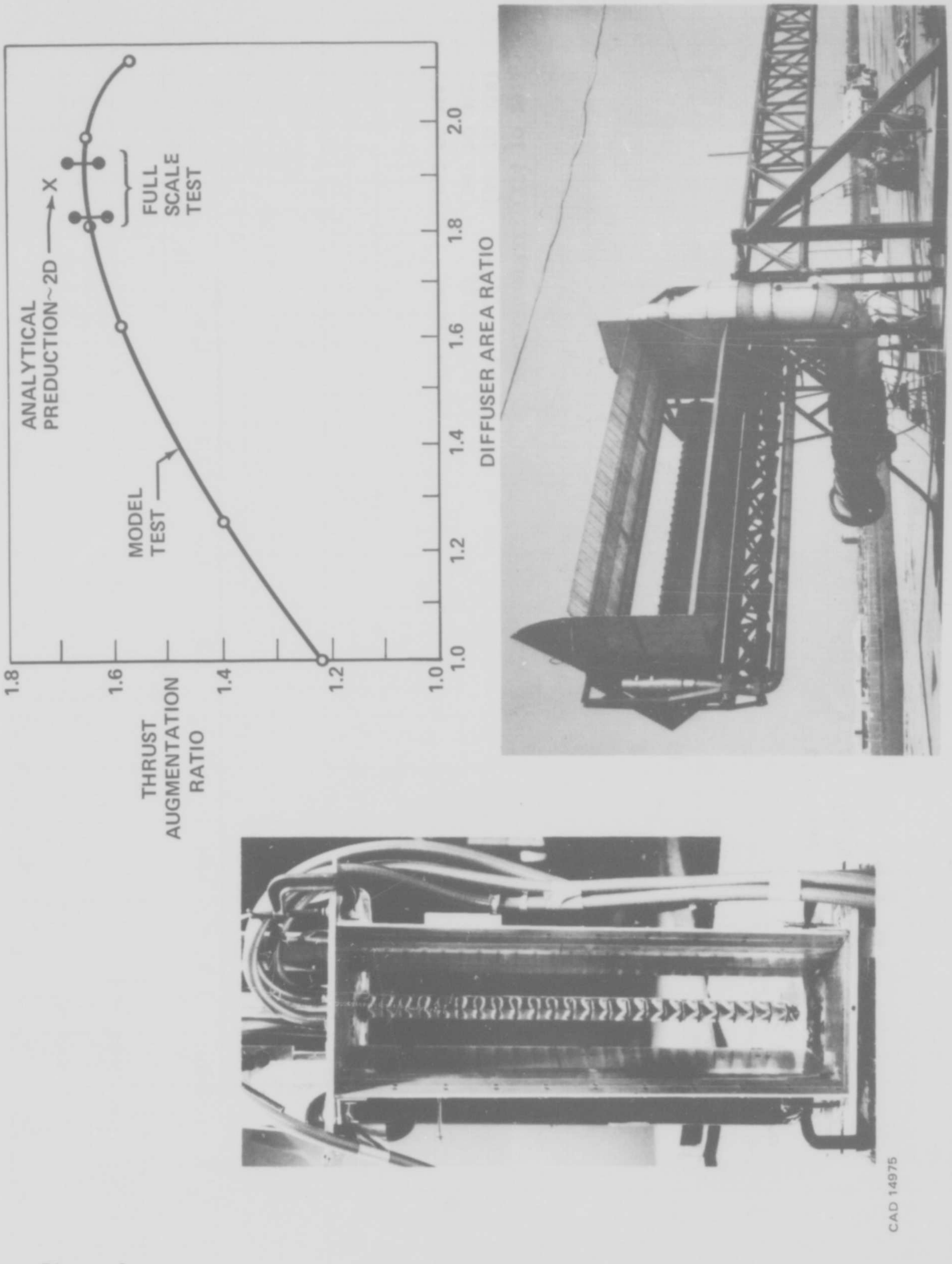

THRUST AUGMENTATION RATIO
1.0
1.2
1.4
1.6
1.8
1.0
1.2
1.4
1.6
1.8
2.0
DIFFUSER AREA RATIO
MODEL TEST
ANALYTICAL PREDUCTION~2D → X
FULL SCALE TEST
CAD 14975

Figure 9.

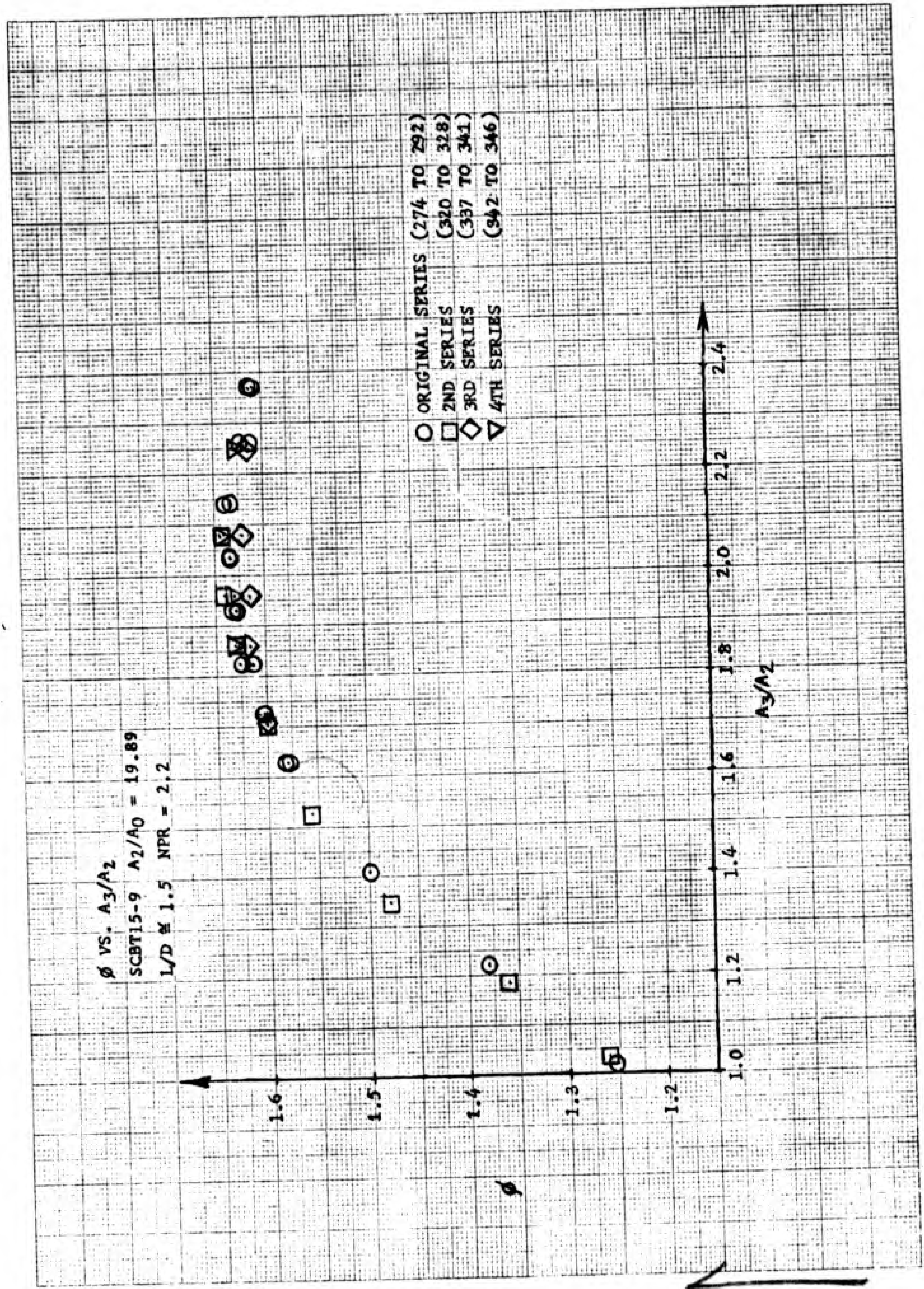

ϕ VS. A3/A2
SCBT15-9 A2/A0 = 19.89
L/D ≅ 1.5 NPR = 2.2
○ ORIGINAL SERIES (274 TO 292)
□ 2ND SERIES (320 TO 328)
◇ 3RD SERIES (337 TO 341)
▽ 4TH SERIES (342 TO 346)
ϕ
1.2
1.3
1.4
1.5
1.6
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
A3/A2

Figure 10.