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WIND TUNNEL DESIGN STUDIES AND TECHNICAL EVALUATION OF ADVANCED CARGO AIRCRAFT CONCEPTS

By

D.M. Rao

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PREFACE

This report describes the work performed (June 1975 through May 1976) under NASA Grant No. NSG-1135 at Langley Research Center in support of the National Transonic Facility Project Office.

The report is in three parts, as under:

Part I: Estimation of Aerodynamic Losses in the Tunnel Circuit.

Part II: 2nd-Turn Model Studies.

Part III: Proposed Circuit Modification for LN_2 Economy and Shell Cost Savings.

This report emphasises the basic motivation behind the problems tackled, and the main results and conclusions obtained. A more detailed presentation of the experimental data and analysis is deferred to a subsequent document.

ACKNOWLEDGEMENTS

The author is pleased to acknowledge the contributions of the following personnel at NASA Langley to various aspects of his work:

L. W. McKinney (Grant Monitor) and members of the Aerodynamic group, NTFPO -- for valuable discussions and helpful comments;

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W. G. Johnson Jr. and Ann B. Bell for executing the 2nd-turn and rapid diffuser experiments with skill and patience, and supplying results under a demanding time schedule.

The author would also like to acknowledge the assistance of Dr. Gene L. Goglia, professor and chairman, Department of Mechanical Engineering and Mechanics, Old Dominion University for administration responsibilities with respect to this grant.

SUMMARY

In support of aerodynamic studies relating to the design and performance prediction of the National Transonic Facility (NTF), the following main tasks were accomplished:

1. Estimation of aerodynamic losses of the tunnel circuit,
2. Refinement of the high-speed diffuser loss prediction method utilizing experimental data generated for the purpose,
3. Model studies of flow in the 2nd-turn and measurements of the fan inlet distortion and overall pressure loss,
4. Development of a shortened fan nacelle configuration of improved aerodynamic performance, and
5. Evolution through model studies of an efficient rapid-diffuser system as the key to a circuit-modification proposal to reduce volume and minimize liquid-nitrogen consumption, at the same time saving on the shell cost.

PART I

ESTIMATION OF AERODYNAMIC LOSSES IN THE TUNNEL CIRCUIT

1. Introduction

Reliable estimates of the aerodynamic losses in the tunnel circuit are needed at the project stage in order to:

a. Establish maximum fan power requirements,

b. Define the range of fan pressure ratio covering the tunnel operating envelope,

c. Identify circuit components having significant individual contributions to the total loss, where aerodynamic improvement would therefore be well worth the effort, and

d. Indicate the potential for achieving further economies in tunnel cost and energy requirements by aerodynamic refinement.

It was noted early in the NTF circuit loss calculations that the high-speed diffuser by itself was responsible for more than 50% of the total energy loss. On comparing estimates also made for Langley 8-ft and 16-ft transonic tunnels with available fan power measurements, it was concluded that diffuser losses were being grossly over-estimated (in relation to the precision needed for the present purpose) by the methods commonly in use (such as those described in refs. 1 and 2). A search was therefore made of the available diffuser literature for information and data from which to assemble a simple, more reliable method for diffuser loss estimation.

2. Diffuser Loss Calculation

Even a cursory look at the vast amount of published data reveals clear that the inlet boundary layer plays a vital role in determining diffuser performance. Sovran and Klomp (ref. 3) demonstrated that this was true for different diffuser geometries; and also that the pressure recovery of near-optimum diffusers correlated on the basis of the area blockage due to boundary layer displacement thickness (δ^*). The material presented in Reference 3 however does not readily lend itself to accurate calculation of the diffuser loss. The data reviewed earlier by Henry et al. (ref. 4), although rather sparse, was found to be more convenient to use for the present application.

The total pressure loss factor

$$K = \frac{H_2 - H_1}{H_1 - p_1} \times \frac{1}{(1 - 1/AR^2)}$$

where

H = Average total pressure
p = Static pressure
AR = Diffuser area ratio (>1)

for conical diffusors of total-angle 2θ around 5 to 6 degrees is plotted in figure I-1 as an empirical function of the inlet displacement thickness ratio δ^*/R_1 (from the data analysis of ref. 4). With this function, the loss in a diffuser preceded by a test-section length can be calculated using the inlet boundary layer thickness obtained (in the simplest approximation) from flat-plate turbulent boundary layer relations. In the calculation scheme (fig. I-2) the test-section and the diffuser are necessarily treated as a coupled system. Note that this procedure admits both Reynolds number and compressibility effects via the boundary layer thickness calculated from test-section stream parameters.

The pressure ratio $(H_1/H_2)^*$ thus calculated is compared with data measured in the Pilot Cryogenic Tunnel and the Diffuser Test Apparatus at Langley (figs. I-3 and I-4) from low subsonic speeds to $M = 1$. The agreement is good up to $M = 0.8$ beyond which the calculations increasingly fall short of the data (by about 10% at $M = 1$). The K-function in figure I-1 was based on incompressible ($M < 0.2$) data; although compressibility effect on K has been indicated in reference 4, a reliable factor to quantitatively account for it near $M = 1$ is lacking. Using a factor

$$K_{(M = 1)}/K_{(M = 0.2)} = 1.2$$

yields good agreement with the present $M = 1$ data. Pending further experimental verification, this factor is therefore adopted in the tunnel loss estimates.

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* H_2 was evaluated from exit pitot survey data integrated by the "mass-momentum" method described in NACA TN 3400.

The ability of the above method to predict the Reynolds number effect on circuit loss was tested against the Pilot Cryogenic tunnel data at $M = 1$ (fig. I-5). The calculated fan pressure-ratio gives a proper Reynolds number trend, but under-estimates the absolute values. In the calculation, the loss contribution of a cylindrical LN_2 injector bar mounted across the high-speed diffuser was based on two-dimensional uniform-flow drag coefficient data. Although it is expected that the cylinder drag will be magnified in the adverse pressure gradient of the diffuser flow, there is no ready means of accounting for it theoretically. An empirical adjustment by multiplying the cylinder drag coefficient by a constant to match the lowest Reynolds no. data point is found to yield good agreement with measurements over the Reynolds no. range.

3. NTF Circuit Loss Estimation

The component-wise break-up of the estimated NTF circuit losses for $M = 1$ and ambient stagnation conditions is shown in Table I-1.

4. Conclusion

A simple method has been assembled to calculated the aerodynamic loss of the test section and high-speed diffuser combination, as the most important item in the tunnel circuit accounting for nearly 60% of the total loss at $M \approx 1$. Comparison with experiments show that Mach number (0.2 to 1.0) and Reynolds number effects are reliably predicted by this method.

5. References

1. Pope, Alan. Wind Tunnel Testing. John Wiley, NY.
2. Pankhurst, R. C. and Holder, D. W. Wind Tunnel Technique. Sir Isaac Pitman, London.
3. Sovran, G. and Klomp, E. Experimentally Determined Optimum Geometries for Rectilinear Diffusers with Rectangular, Conical or Annular Cross-sections. Fluid Mechanics of Internal Flow Symposium, 1965, pp. 270-319.
4. Henry, J. R. et al. Summary of Subsonic-Diffuser Data. NACA RM L56F05, 1956.

Table I-1

NTF Circuit Loss Summary (M = 1, Stgn. Pr. = 14.7 psi, Stgn. Temp. = 635°R)

		ΔH psi	
1.	Test Section + High Speed Diffuser	0.995	
2.	Model Support Strut	0.125	
3.	1st Turn	0.057	
4.	2nd Leg	0.077	
5.	2nd Turn	0.040	
6.	Nacelle (Annular Diffuser)	0.184	
7.	3rd Leg Diffuser	0.087	
8.	3rd Turn	0.009	
9.	4th Turn	0.009	
10.	Rapid Diffuser	0.049	
11.	Screens (3 × 1q)	0.048	
12.	Cooling Coil (12q)	0.192	
	Total ΔH psi	1.680	(without cooler)
		1.872	(with cooler)
	Fan Pressure Ratio	1.129	(without cooler)
		1.146	(with cooler)

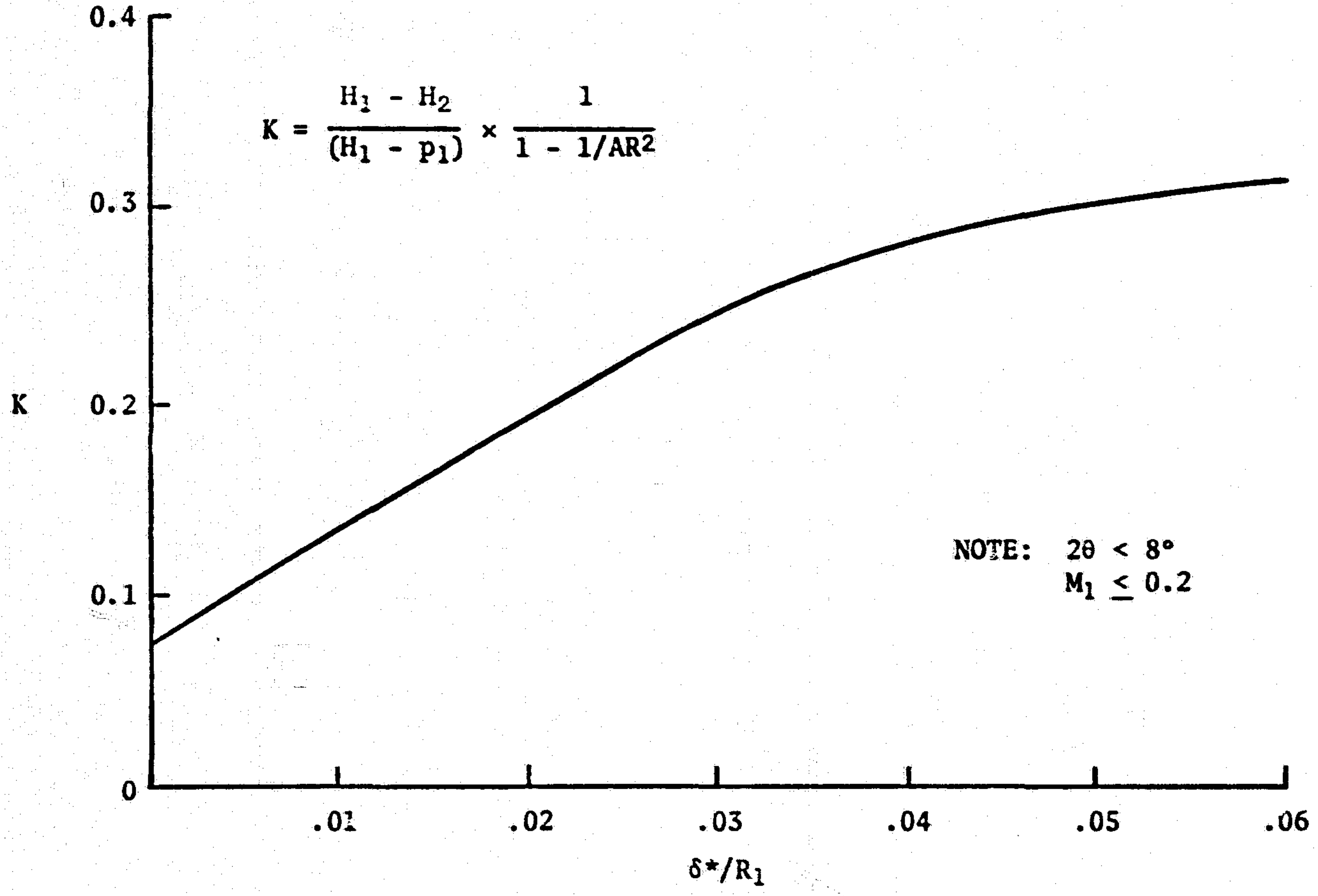

Figure I-1. Loss Factor for Conical Diffusers.

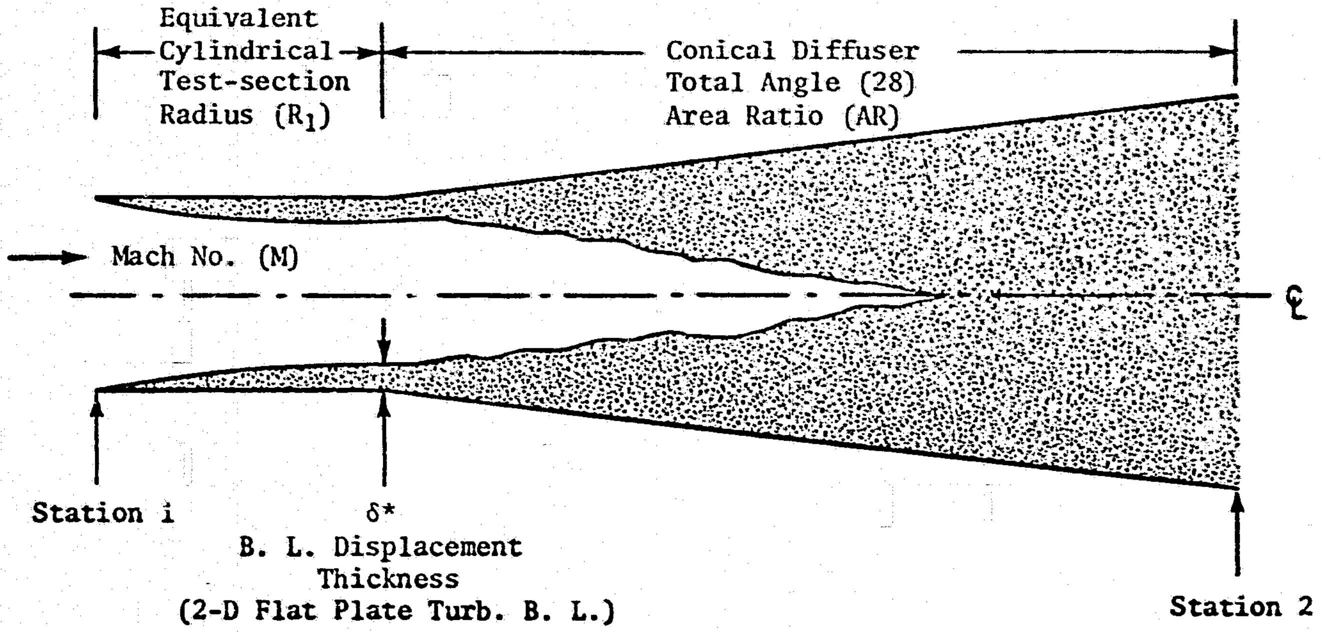

Figure I-2. Calculation of Diffuser Loss.

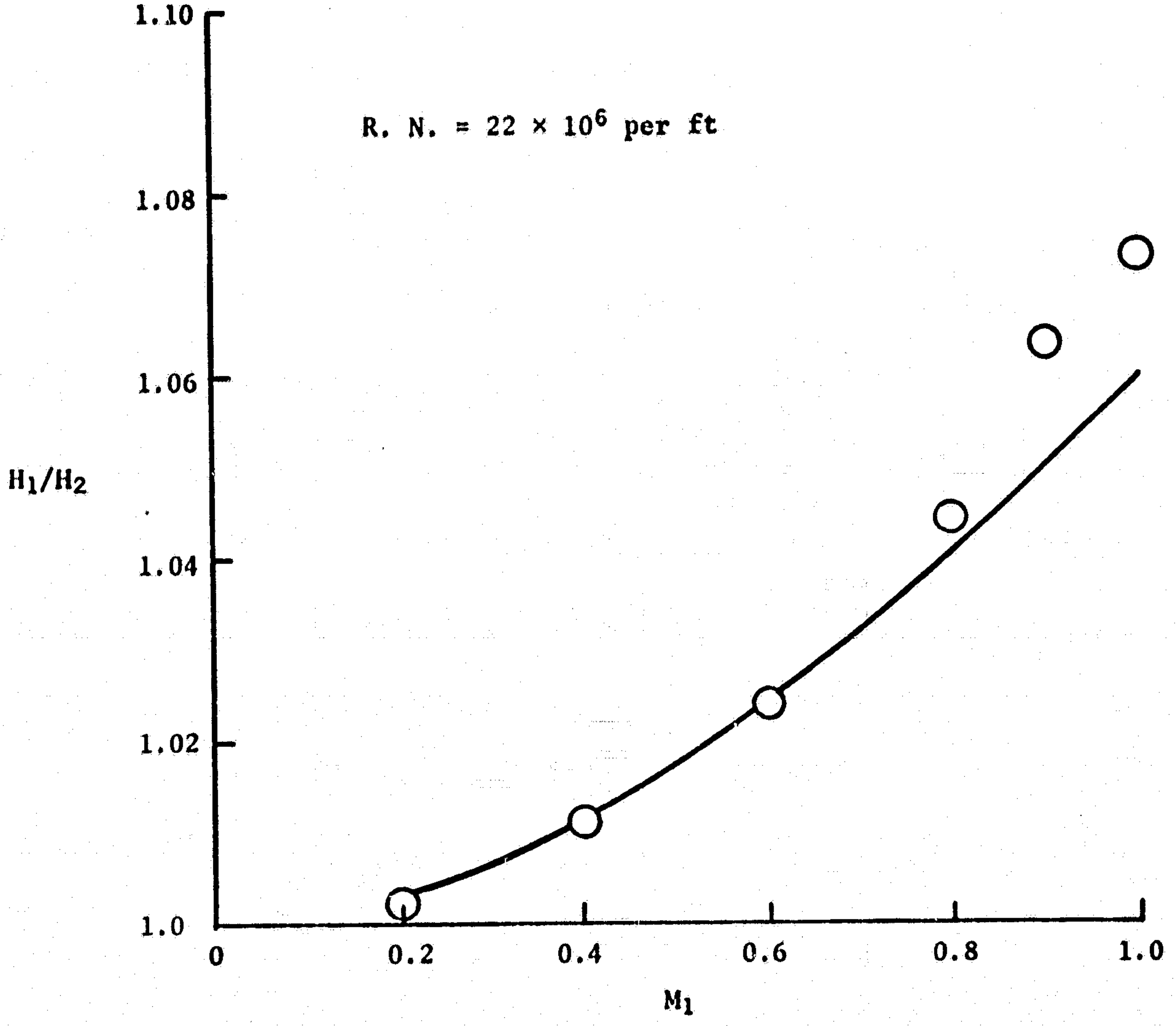

Figure I-3. Comparison of Estimated and Measured Loss Data-Pilot Cryogenic Tunnel.

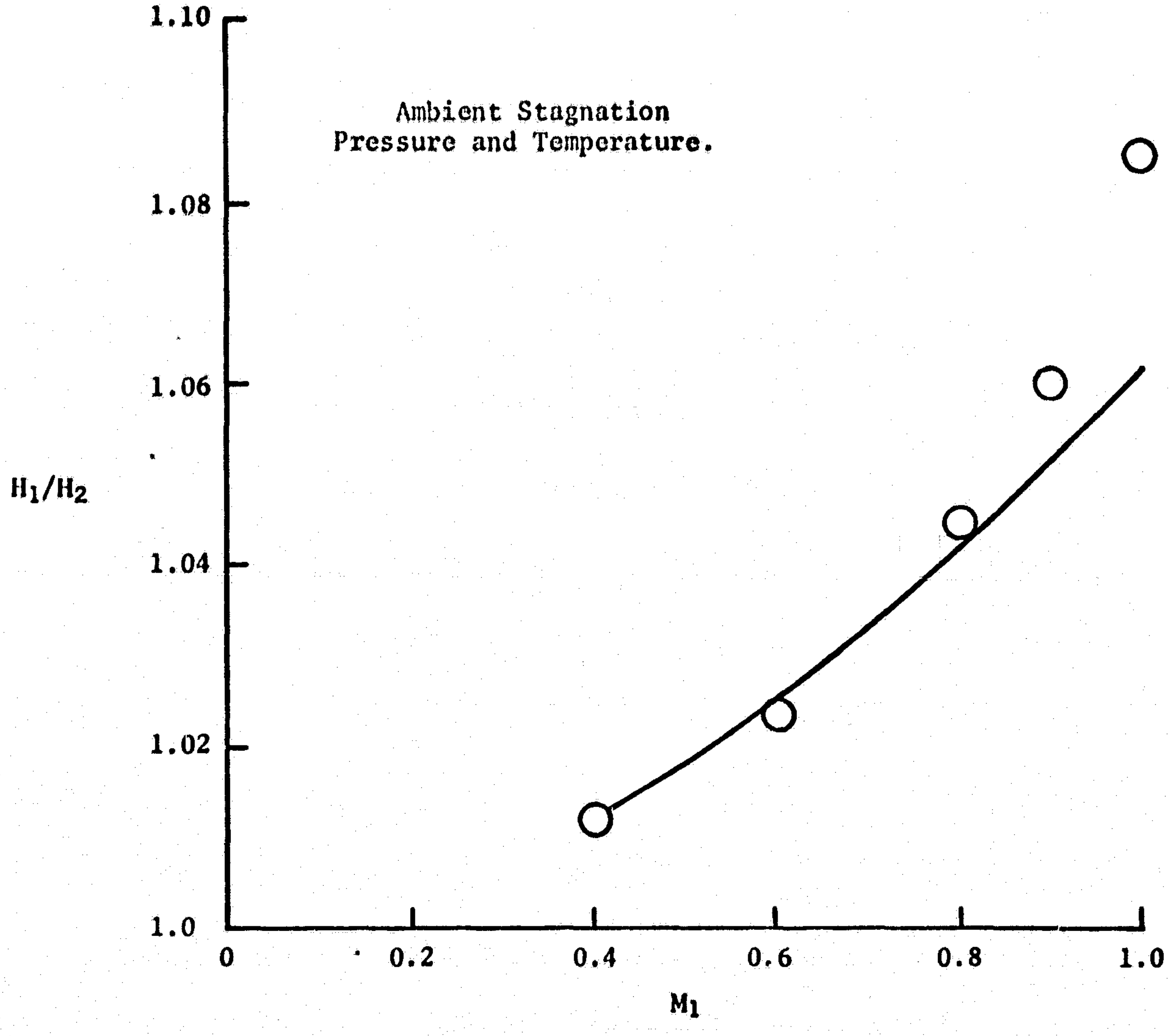

Figure I-4. Comparison of Estimated and Measured Loss Data-Diffuser Test Apparatus.

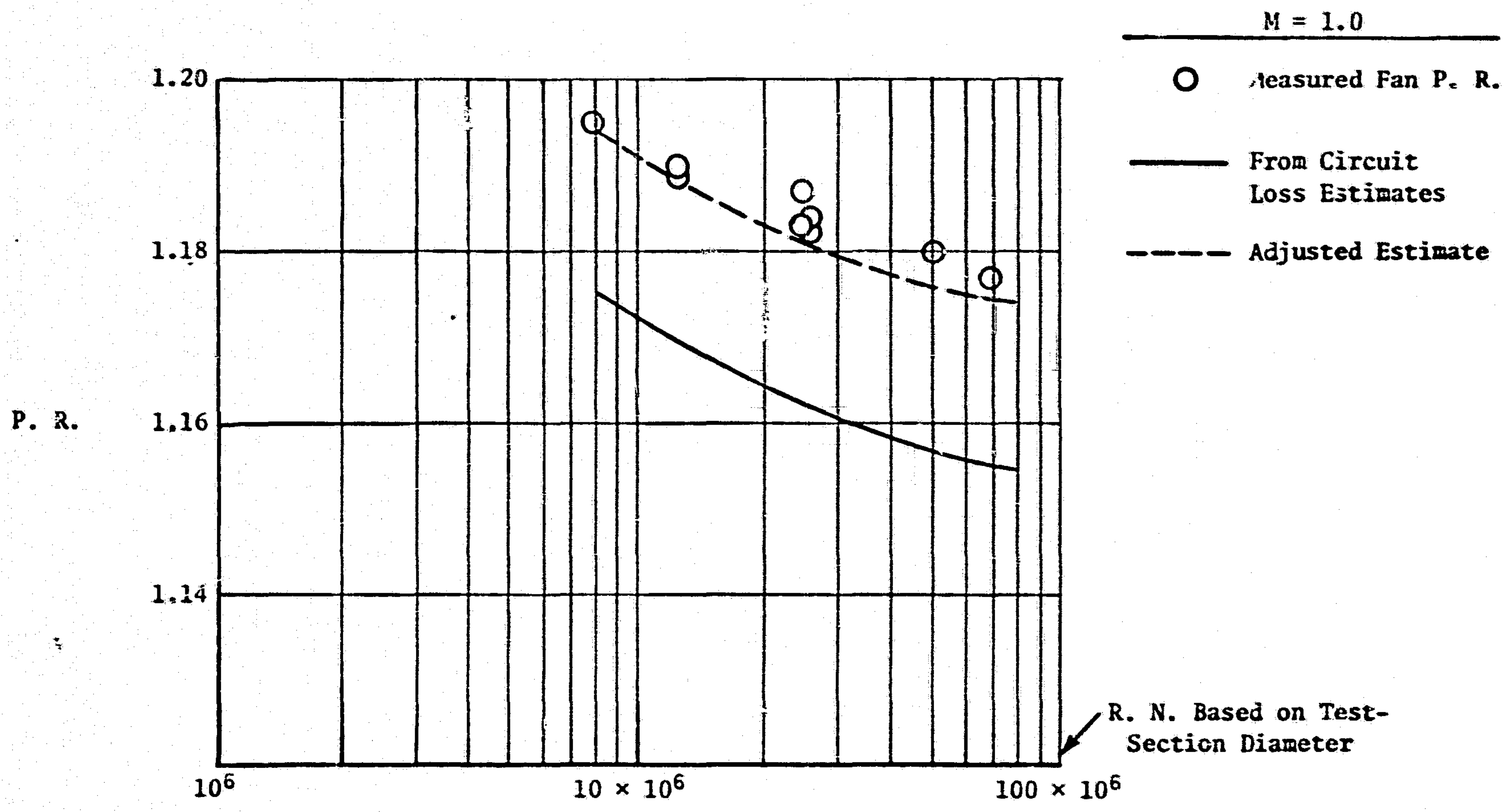

Figure I-5. Prediction of Reynolds No. Effect on Pilot-Cryogenic Tunnel Pressure Ratio.

PART II

NTF SECOND-TURN MODEL STUDIES

1. Introduction

The 2nd-turn presents a complex geometry, incorporating a center-body which through a 90-degree turn becomes the fan-nacelle; an airfoil fairing over the fan shaft also turning through 90 degrees; and four struts supporting the nacelle from the outer shell (fig. II-1). With so many complicated and aerodynamically-interfering surfaces present, the resulting flow distortion in the fan-annulus is of concern, to be determined and controlled if possible in order to limit fan noise, vibration and dynamic loading on the blades.

Tests were conducted on a 1/12 scale model rig (fig. II-2) for:

a. Velocity survey around the fan annulus,

b. Tuft visualisation of flow,

c. Surface pressure measurements, and

d. Total pressure survey across a downstream station to evaluate overall loss.

The annulus downstream of the fan station around the tailcone essentially acts as a diffuser, as opposed to the common practice of designing the tailcone as a "streamlined body" as in external-flow aerodynamics. From an annular diffuser viewpoint,* the original NTF tailcone length was found to be overly conservative, and it appeared that a shorter shape might be adopted for its practical advantages and for possibly improved aerodynamics. The opportunity offered by the 2nd-turn model program was accordingly utilized to develop a new tailcone geometry.

2. Discussion of Results

a. Fan Station Survey: The circumferential variation of the core-flow velocity in the fan annulus is shown in figure II-3. The salient features in the distribution are the sharp velocity drop locally in the strut wakes. The wake of the fan-shaft fairing is more diffused at this station, as expected. Also noted is a shallow region of reduced velocity** between the inside-struts, attributable

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* See reference 3 of Part I.

** This feature is also noticeable in the downstream pressure-loss surveys, see figure II-5.

to the increased resistance of the more closely-spaced turning-vanes on the inside of the turn.

b. Nacelle Tailcone: The static pressure recovery in the tailcone annular diffuser (from outer wall measurements) is shown in figure II-4. The original as well as the 20-foot-shortened tailcone shapes are also indicated (the outer wall was unchanged). The tailcone geometry was constrained by the preference for single-curvature surfaces for ease of fabrication. The modified shape employed a single-row of vortex-generators just upstream of the break in the cone.

The data comparison of figure II-4 shows that the shortened tailcone achieved a faster rate of pressure recovery in the annular diffuser, as intended. Note that a higher maximum pressure occurs at the exit of this tailcone (in accordance with increased area-ratio); to take advantage of this feature, the outer shell should be suitably modified to eliminate an area contraction downstream of the tailcone. Comparison of the static pressure at the downstream station (where the area ratio is constant at 1.7 for both cases) indicates a 6% improvement in static pressure recovery with the shortened tailcone, which translates to a 10% decrease in loss approximately (using one-dimensional flow relations).

The downstream total-pressure loss profiles (typical plane-of-turn surveys shown in fig. II-5) are also considerably improved, primarily due to the reduced wetted area (and friction-loss) of the shortened tailcone. A more uniform flow is produced at the entry to the 3rd-leg diffuser, whose performance is expected to improve as a result. The vortex-generators, whose effect is confined to the body wake, provide relatively little further benefit to an already attenuated wake.

From integration* of the downstream profiles (measured along four 45° - spaced diameters), the overall loss of the 2nd-turn model with the original tailcone was 0.784 q_o.** The shortened tailcone reduced the loss to 0.706 q_o, i.e., a 10% improvement, as already inferred from static pressure data.

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* Performed by B. B. Gloss, of NASA Langley.

** q_o measured at Station 0 indicated in figure II-2.

3. Conclusions

A shortened tailcone for the NTF fan nacelle, amounting to a 20-foot (or 40%) reduction over the original length was designed and tested. A 10% reduction in the total pressure loss of the 2nd-turn was thereby achieved. The accompanying improvement in the downstream flow uniformity is anticipated to benefit the 3rd-leg diffuser performance also.

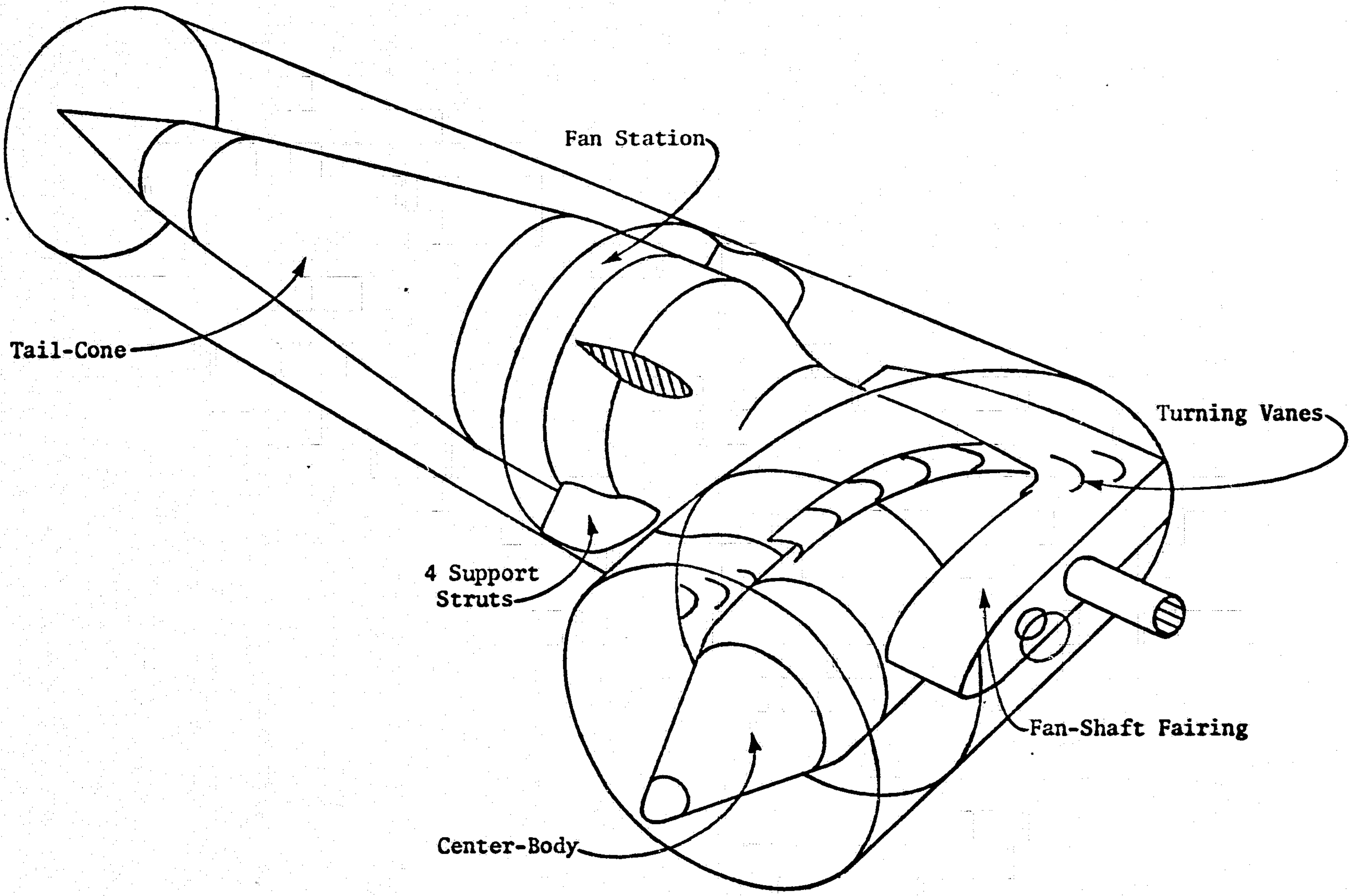


Figure II-1. N. T. F. 2nd-Turn Geometry.

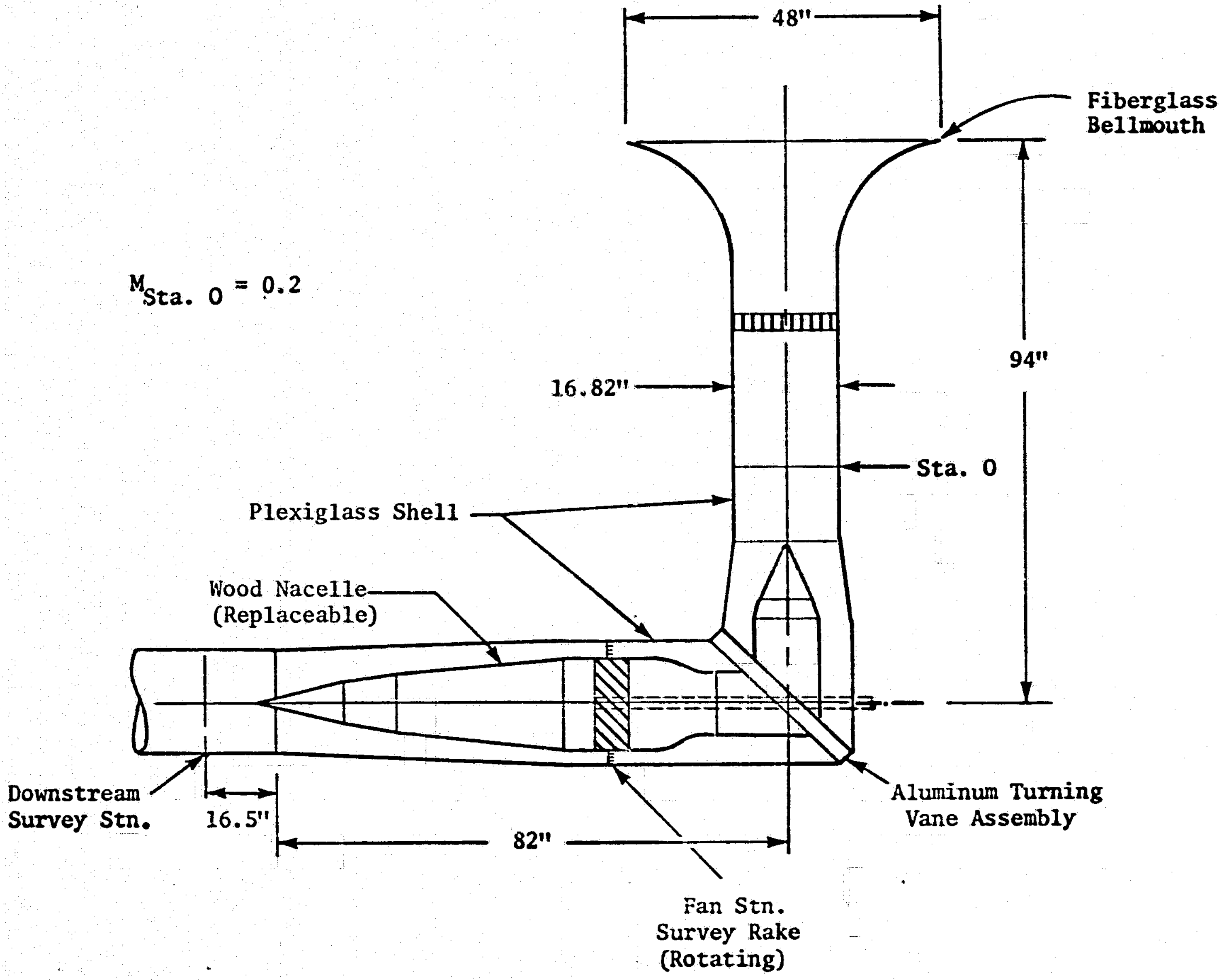


Figure II-2. N. T. F. 2nd-Turn Model (1/12 Full Scale).

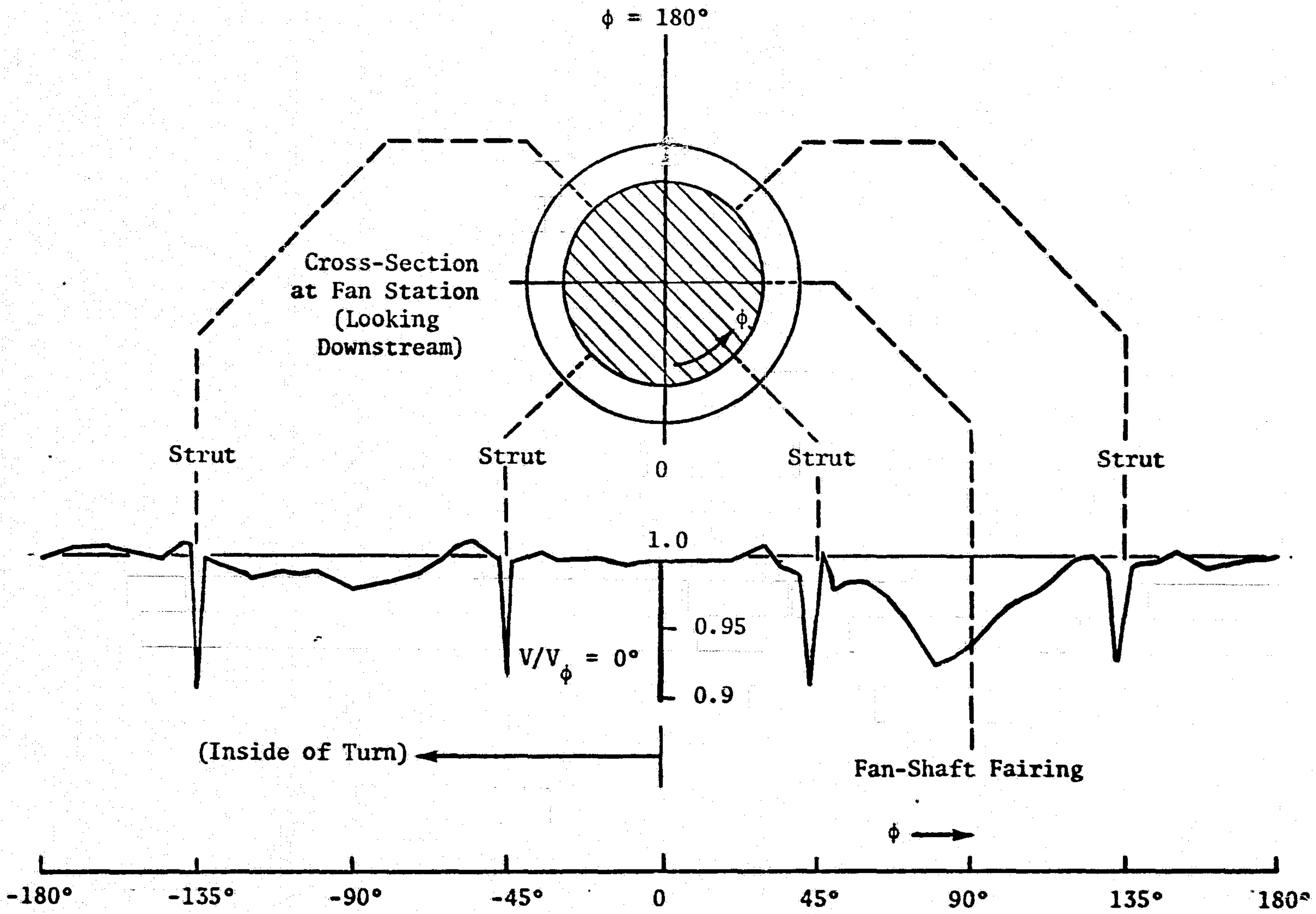


Figure II-3. Fan Annulus Circumferential Velocity Variation.

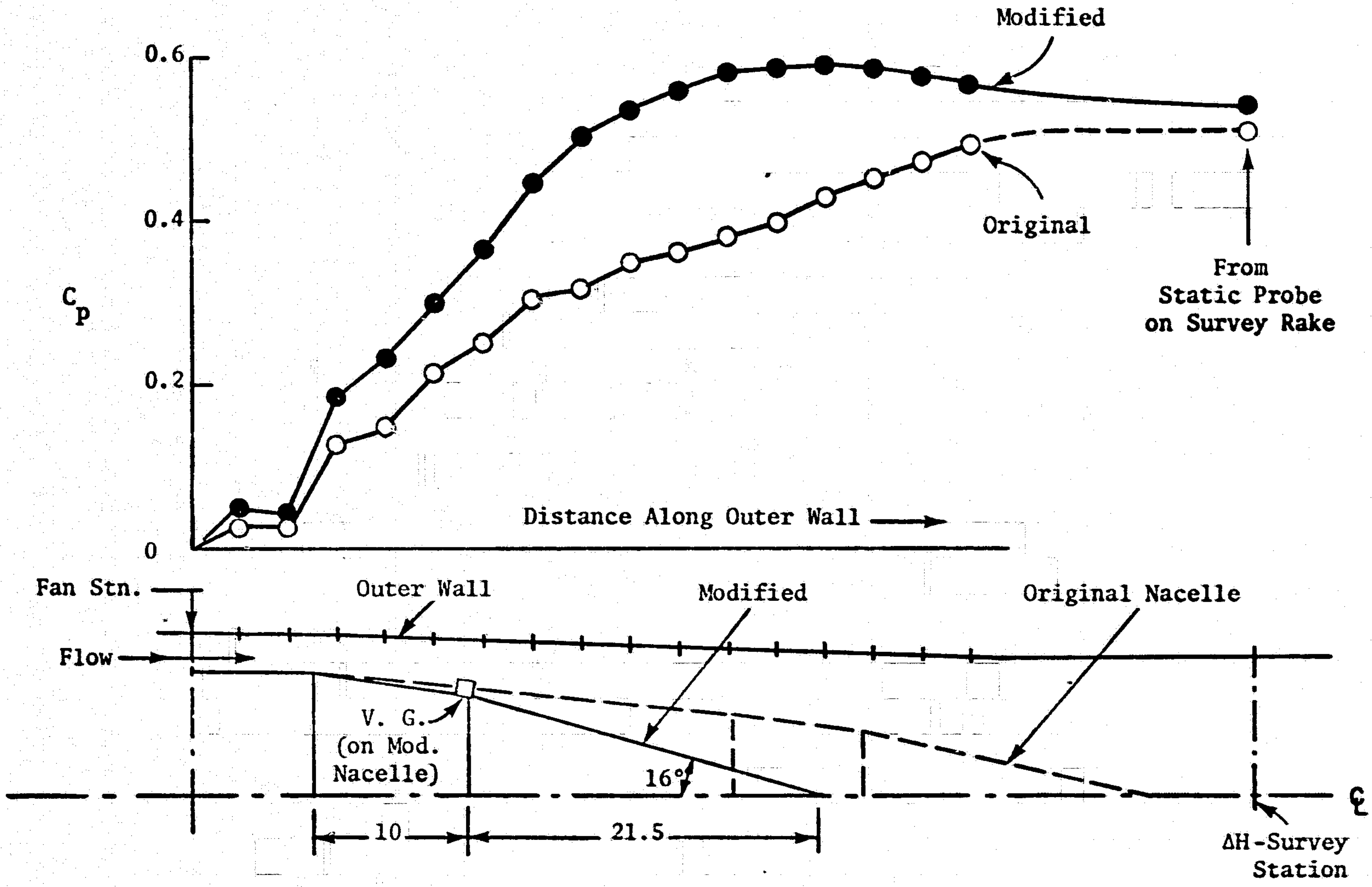
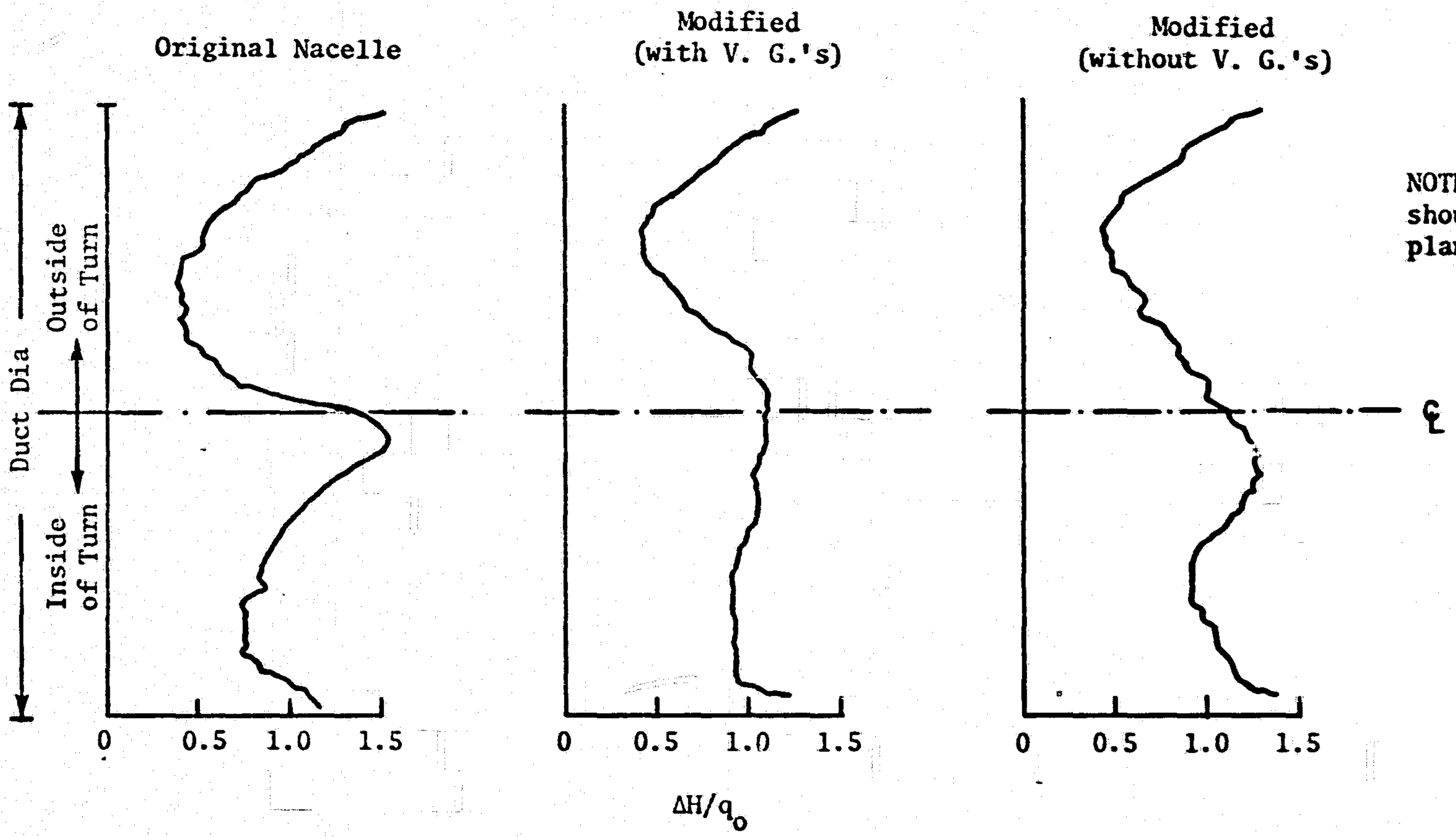


Figure II-4. Outer Wall Pressure Distributions with Original and Modified Tailcones.



NOTE: Surveys shown are in the plane of turn.

Figure II-5. Total Pressure Loss Profiles Downstream of Tailcone.

PART III

TUNNEL CIRCUIT MODIFICATION FOR LN_2 ECONOMY AND SHELL COST SAVING

1. Introduction

A unique feature of cryogenic wind tunnels is that the energy supplied directly to the fan is a rather small part of the total energy requirements. The major energy input is in the form of liquid nitrogen (LN_2), initially to cool the circuit to the low operating temperature and then to maintain this condition during a test program, by balancing the heat of compression at the fan and also the thermal losses through the shell. To achieve high energy efficiency requires not only an aerodynamically clean circuit design (in order to reduce the fan compression ratio, and for low turbulence and noise levels), but also a minimum circuit volume on which LN_2 consumption directly depends. Volume reduction without unduly compromising circuit aerodynamics poses a challenge, and an attempt is made here to propose a circuit modification for LN_2 economy and to evaluate its merits.

2. Proposed Circuit Modification

Inspection of the current NTF circuit, which is already a fairly compact one by conventional standards, suggests additional possibilities for volume reduction. For example, by substituting a constant diameter section for the 3rd-leg diffuser and maintaining this diameter all the way up to the rapid diffuser, a reduction of about 17,000 cubic feet results (fig. III-1). Calculations* for a typical NTF test program indicate that this 6% volume reduction is worth about 4% saving in LN_2 consumption. Additionally, there is a like saving in the tunnel time to complete the test program (taking into account the time for changing the stagnation conditions). The test time saved yields a direct saving in electrical energy of 4%, and contributes an increment to the annual productivity of the facility. The more compact shell resulting from this modification is estimated** to cost less by about $1.8 million (including savings in supports, foundation, insulation, etc.).

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* By E. S. Cornette of NASA Langley.

** By G. A. Wentland of NASA Langley.

The aerodynamic consequences of the proposed circuit modification will be:

a. Reduced loss through the constant diameter section replacing the diffuser,

b. Increased losses through 3rd and 4th turns due to increased mean velocity (although some alleviation may be expected due to a more uniform velocity profile produced at the 3rd turn by the cylindrical section), and

c. Increased loss through the rapid diffuser of larger area-ratio (viz. 4.5 versus 2 originally).

While items a and b can be reasonably well estimated, the rapid-diffuser loss is not easily calculated. There is also the question whether the desired level of settling-chamber flow uniformity is achievable with an area-ratio 4 rapid diffuser, without incurring undue loss penalty incurred through flow treatment. In order to establish with confidence the feasibility of the proposed circuit modification, experimental data on rapid-diffuser performance in a configuration pertinent to the present study is needed.

Yet another modification to the current NTF circuit suggested in figure III-1 consists of substituting a rapid-expansion (of a small area-ratio) for the conical portion of the high-speed diffuser (i.e., between the end of transition and 1st-turn entry). This takes advantage of the shortened fan-nacelle tailcone (see Part II) to reduce the overall tunnel by about 20 feet. The additional saving in circuit volume is about 8,200 cubic feet, to bring the total reduction to 9%. The aerodynamic loss penalty accruing from the high-speed diffuser modification has been roughly estimated (taking credit for the loss-reduction in a shortened 3rd-leg) to be less than 5%. However, for a more precise trade-off study experimental data for the particular configuration will be required; in its absence, this aspect will not be pursued further in this report.

3. Rapid Diffuser Experiments

A 1/12 scale test rig was used to obtain comparative data on rapid diffusers of area-ratio 2 and 4.5. The diffuser test configurations are shown in figure III-2. The "baseline-bell" diffuser conforms to the geometry currently adopted for NTF. The "baseline-conical" model represents an alternate shape for ease of manufacture. The remaining three models are area-ratio 4.5 and consist of 40- and 50-degree total-angle conical diffusers fitted with radial vanes, and a bell-shaped geometry designed* for constant wall pressure (following the theoretical procedure as used for the "baseline-bell" diffuser design).

The radial-vane concept was originally proposed as a low-loss flow-spreader for rapid conical diffusers of large area ratio (up to 15), as commonly employed in blowdown tunnels (see refs. 1, 2, and 3). Briefly described, the diffuser is compartmented over its full length by means of several equally spaced radial vanes. A small disc (of about 2% area blockage) placed on the vane leading-edge intersection forces separation of flow in the inner corners of the compartments. The inlet flow is displaced radially outwards by the corner separation bubbles, remains attached to the diffuser wall and is divided equally into the vane compartments. Within the compartments, the bubble closure is accompanied by continuous flow diffusion as evidenced by a substantial pressure rise. A relatively flat exit velocity profile is attained following the merging of the flows leaving the compartments.

While the previous work on the vane-diffusers was concerned mainly with effective flow spreading in large area-ratio expansions, the present object was to develop a combined system of moderate area-ratio rapid diffuser and flow treatment for a specified level of settling-chamber flow uniformity with minimum energy loss. A quantitative definition of this minimum loss was then needed to evaluate the feasibility of the circuit modification, as already discussed.

The geometrical variables tested for loss-minimisation were the disc diameter and the vane recess depth (fig. III-3). An optimum combination of the two was critical also with respect to the downstream flow uniformity.

4. Discussion of Results

The effects of radial vanes alone and with disc in the 40-degree diffuser are illustrated in figure III-4. Vanes by themselves show a relatively minor effect on the highly distorted ΔH profile delivered by the clean diffuser across the settling chamber. Addition of an optimum disc to the vanes not only improves markedly the flow uniformity, there is actually a small reduction in the loss.

An increased static pressure recovery in the diffuser further reflects the beneficial corner-bubble type of flow produced within the vane compartments by the disc (fig. III-5).

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* By J. B. Peterson Jr. of NASA Langley.

Interestingly, with an optimum vane-disc combination the final pressure recovery actually exceeds the value reported in literature* for plain conical diffusers having the same angle as the compartment equivalent cone-angle. The appearance of a suction-peak near the start of the diffuser unmistakably indicates attached wall flow induced by the addition of the disc to the vanes (even though the disc in this case was located 5 inches into the diffuser).

The distribution of total-pressure loss (relative to diffuser inlet total pressure) distribution across the settling-chamber, in terms of $\Delta H/\overline{\Delta H}$** (where the bar denotes an average value) is shown in figure III-6 for all the test configurations. The topmost curve for each case represents the best uniformity achieved. These comparisons show that the flow uniformity with 40-degree conical vaned-diffuser exceeds that of all the other models. With comparable effort devoted to vane-disc optimisation in the 50-degree diffuser, it is believed that this diffuser will prove to be at least equally efficient.

A static-pressure recovery of nearly 50% of the ideal was obtained in the settling chamber with the optimum 40-degree vaned-diffuser. For comparison, according to reference 4, to produce uniform downstream flow with rapid diffusers utilising screens would require overall resistance corresponding to zero pressure recovery. Thus, the radial vane concept represents an advance in rapid-diffuser technology by significantly reducing the associated energy-loss penalty.

The overall performance of the various diffuser models is summarised in figure III-7. From this comparison it is concluded that:

a. The baseline-bell diffuser was not superior to the baseline-conical model, both requiring exit-resistance to run full.

b. Flow uniformity better than the baseline case was achieved with area-ratio 4.5 radial-vaned conical diffusers. The penalty was an increased loss by a factor of 2.5.

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* e.g., see reference 4 of Part I.

** Since $\overline{\Delta H}/H_1$ in all cases was close to 1%, $\Delta H/H_1 = .01 \times \Delta H/\overline{\Delta H}$.

To put the above loss comparisons in proper perspective, it may be pointed out that to attain the same quality of downstream flow uniformity with the baseline diffusers will require increased exit-resistance. At the same time, since the vaned-diffusers are not dependent on exit resistance for flow spreading, the loss penalty in this case can be partially alleviated by using less resistance without significantly compromising flow quality (as already noted in the case of 50-degree diffuser, fig. III-6). Also, the "tuning" of the disc-vane combination was not carried to the limit due to time limitations in the present tests, and some additional improvement is considered possible. Finally, the vane-diffuser loss being largely made up of skin-friction, a favorable Reynolds no. effect may be expected.

5. Conclusions

The experimental data discussed in the foregoing were used to estimate the NTF circuit losses in the baseline and the "low-volume" alternate configurations (fig. 8). The alternate circuit shows a loss increase by 6% over the baseline when operating at $M = 1$ and ambient stagnation conditions. Under cryogenic (viz., high Reynolds no.) conditions, its impact on the fan-energy is diminished by the time-saving due to reduced circuit volume, as discussed in Section II. The final effect of LN_2 consumption taking into account the opposing influences of volume reduction and fan-energy increase (due to increased circuit loss) will depend heavily on the pattern of facility utilisation. This aspect requires a more detailed study of the energy trade-off and costs, which is outside the scope of this report. However, if the proposed circuit volume-reduction is found to be cost-effective, then the results of the present study provide confidence that by the application of optimised radial-vane rapid diffuser, no penalty need be paid in terms of tunnel flow quality.

6. References

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2. Belyanin, B. V. et al. "Study of Flow Characteristics Behind Diffusers with Large Angles of Flare." FTD HT-23-586-73.

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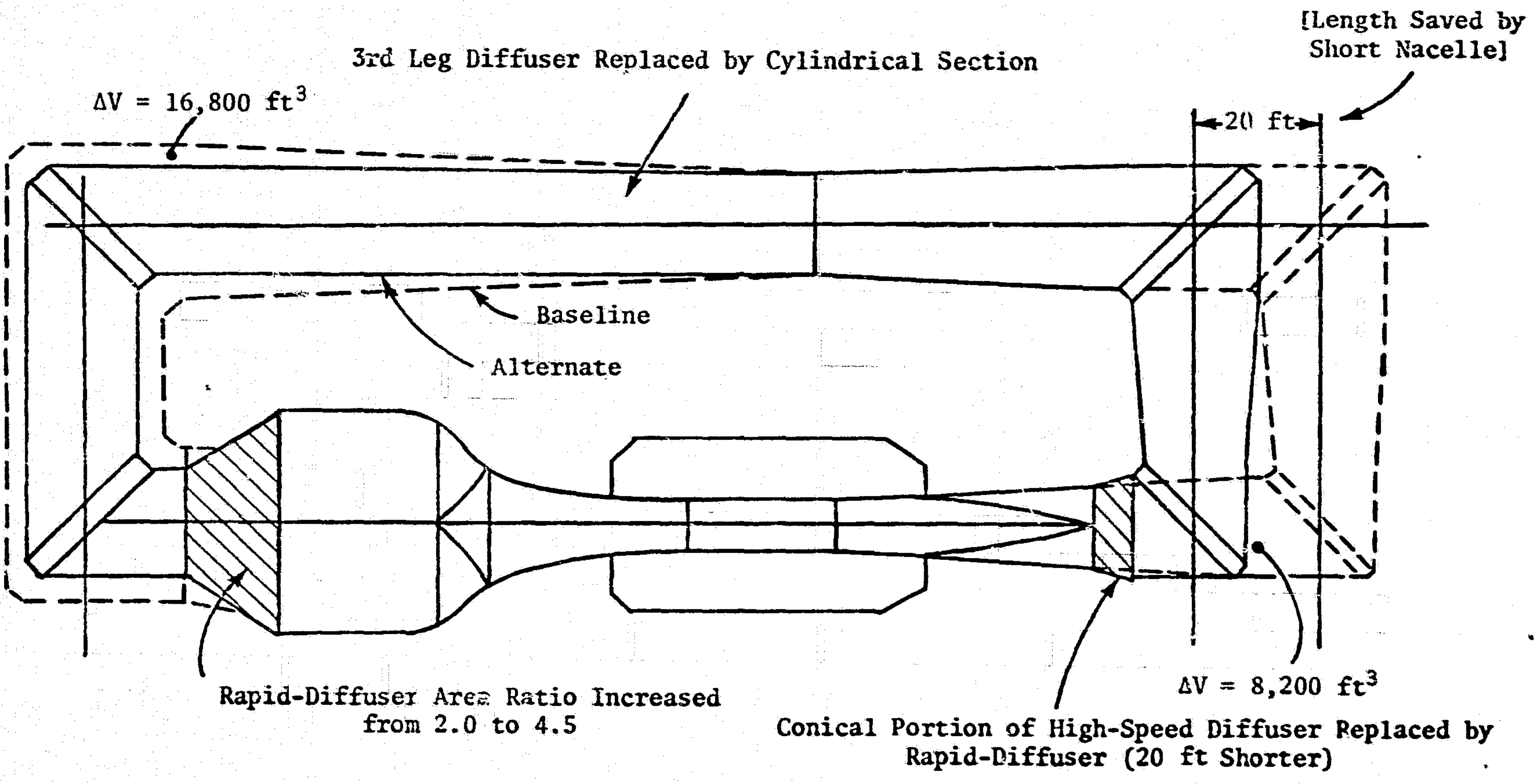
4. Ewald, B. "Low Speed Tunnels with Tandem Test Sections, A Contribution to Some Design Problems." AGARD CP 174, Paper no. 7, 1975.



Total Circuit Volume Reduced About 9%

Figure III-1. N. T. F. Circuit Volume Reduction Potential.

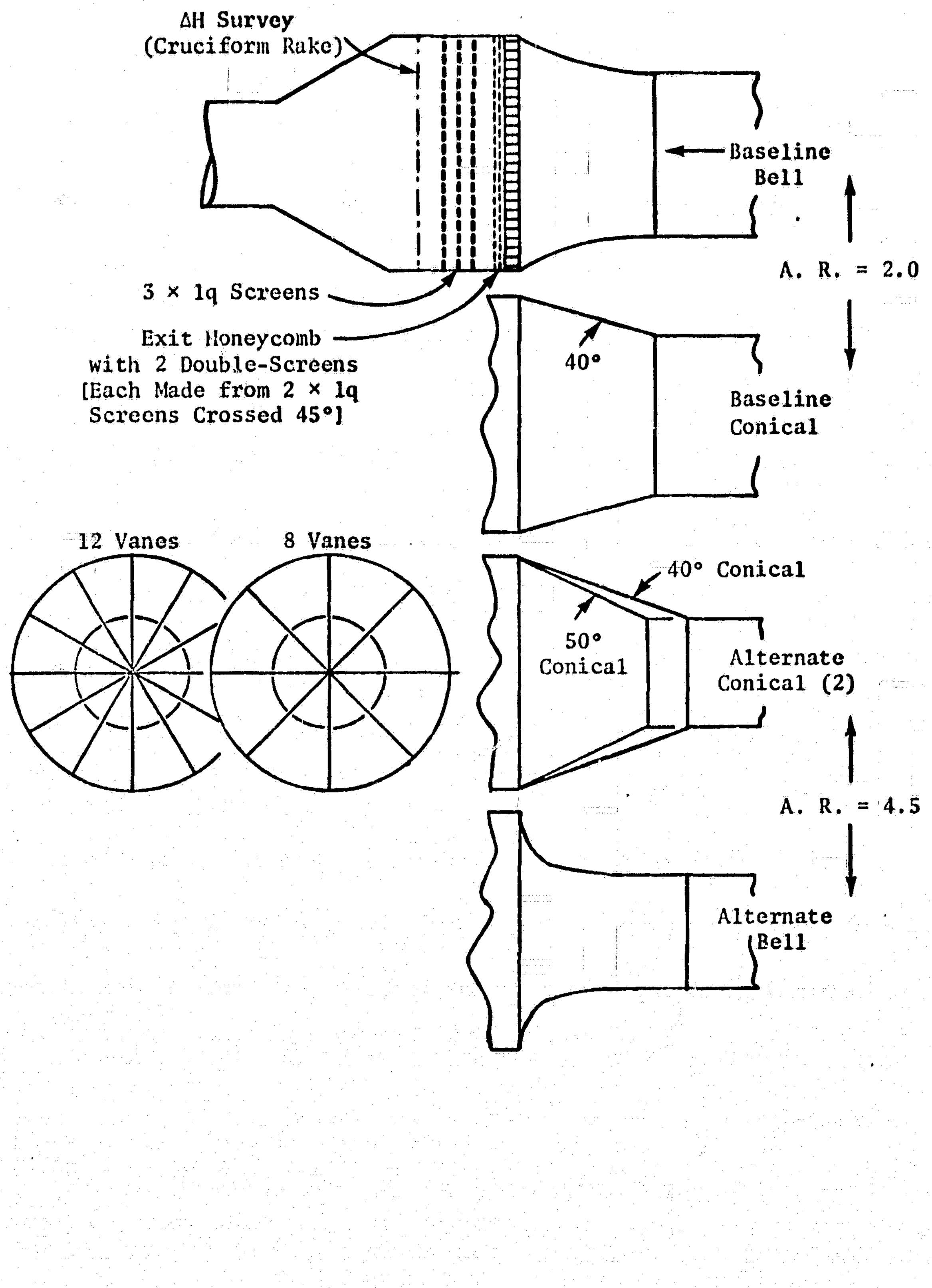


Figure III-2. Rapid-Diffuser Test Models.

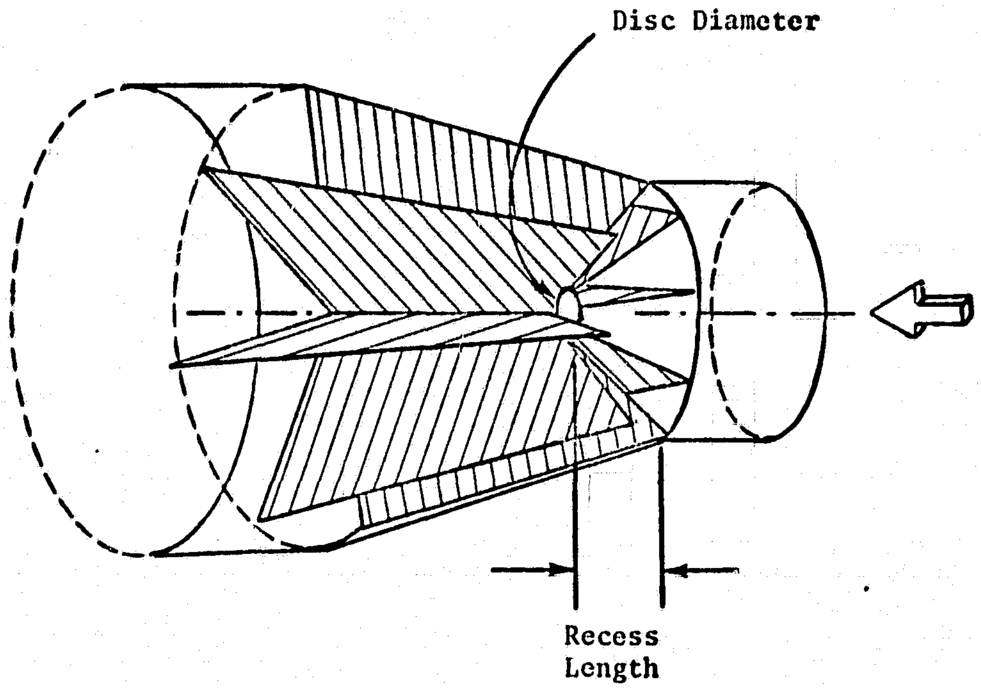


Figure III-3. Splitter Geometry (40° Conical Diffuser) Showing Variables Tested.

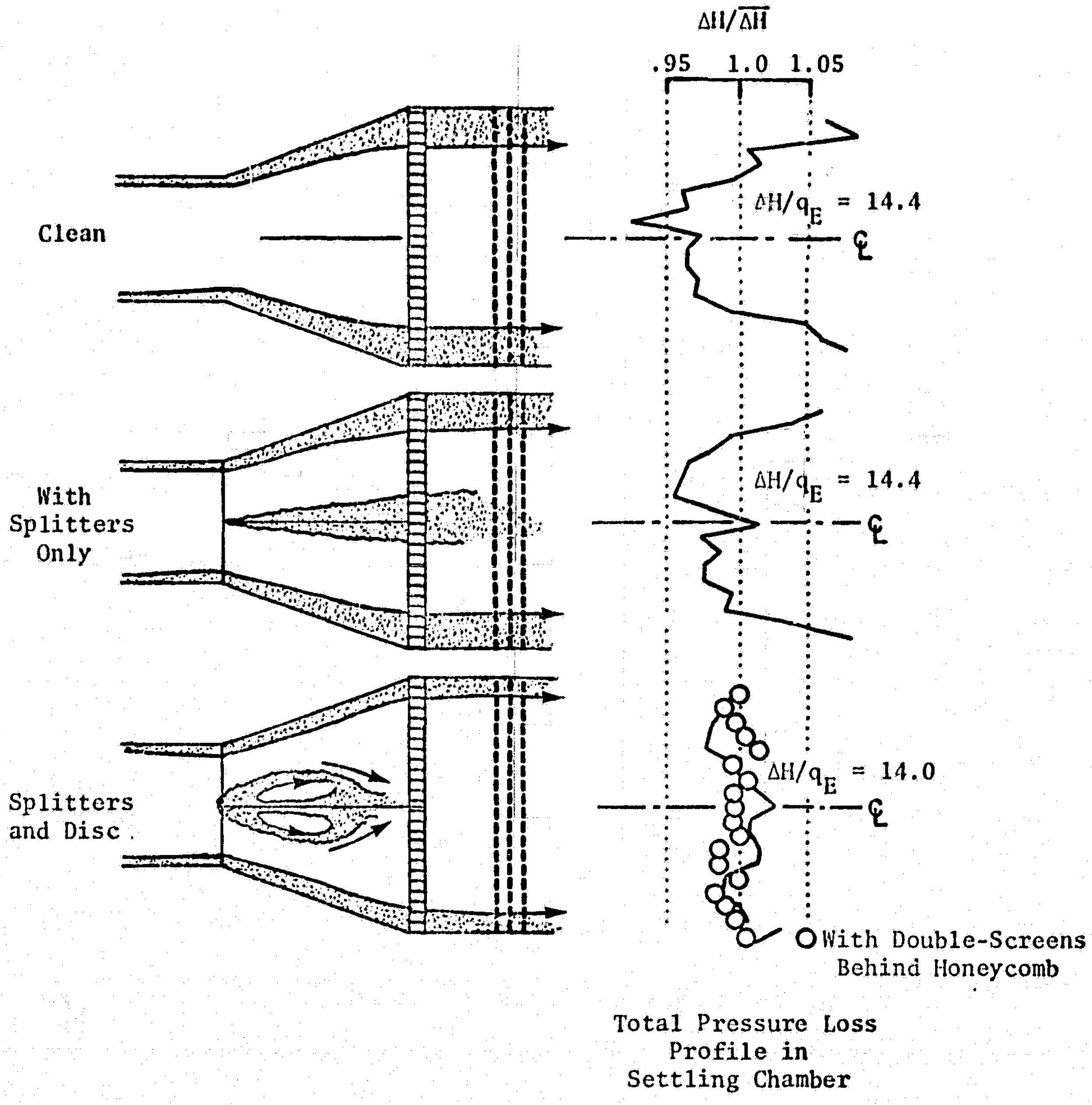


Figure III-4. Effects of Radial Vanes and Disc on Flow Uniformity Downstream of 40° Conical Diffuser.

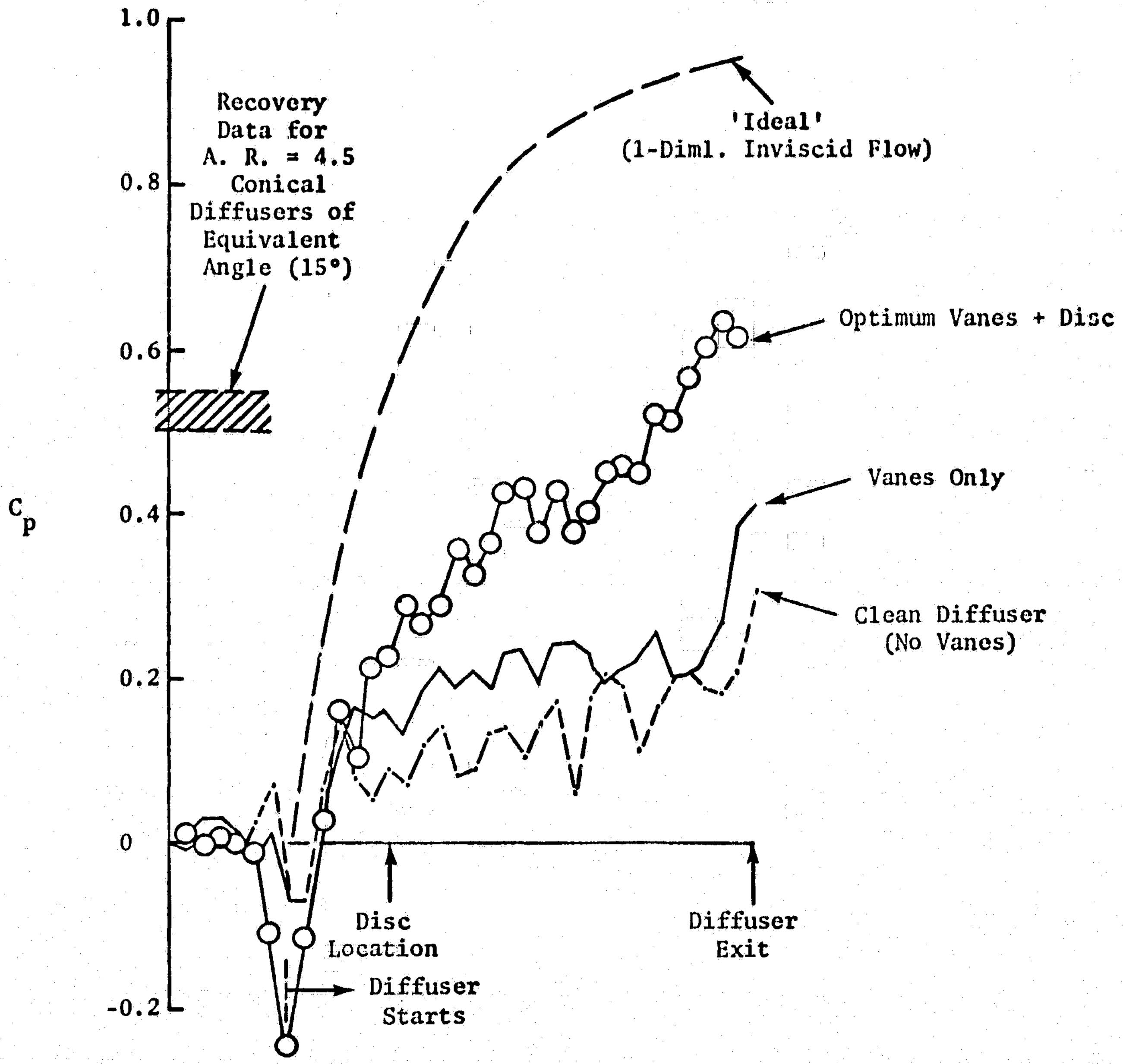


Figure III-5. Pressure Recovery in 40° Conical Diffuser (Wall Pressure Measurements).

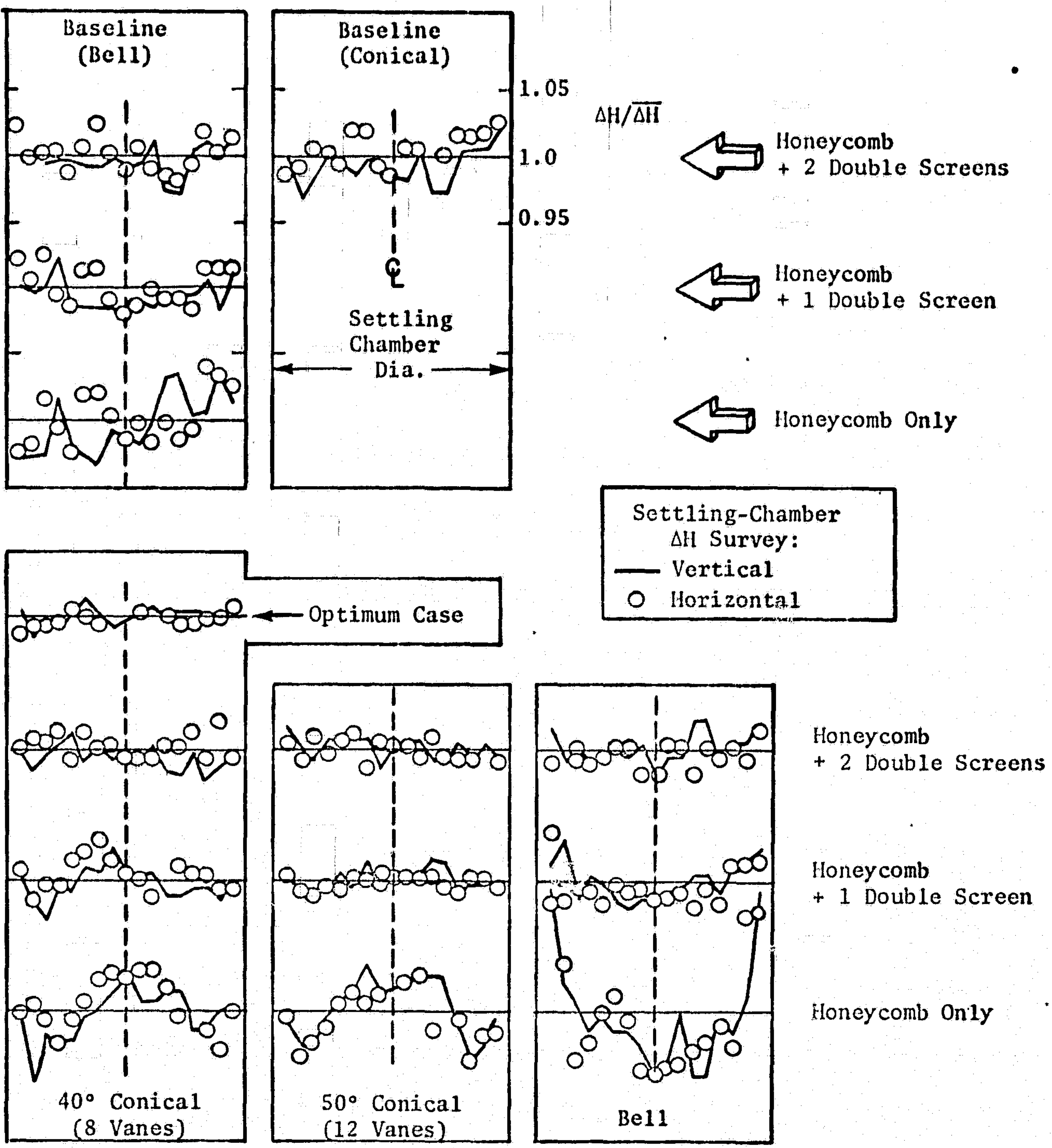
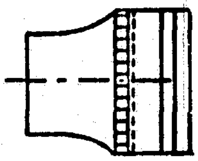
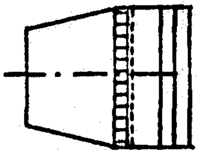
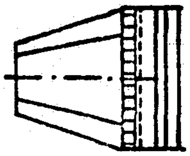
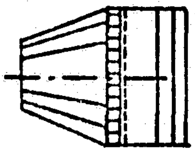
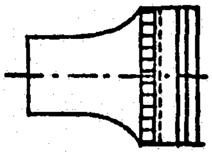


Figure III-6. Settling Chamber Flow Uniformity with Various Rapid-Diffuser Models.

Performance Parameter →

Test Configuration ↓

		Test Configuration	Uniformity $\frac{R.M.S.(\Delta H)}{\overline{\Delta H}}$ Percent	Turbulence $\frac{R.M.S.\ (U)}{\overline{U}}$ Percent	Loss $\frac{\Delta H}{q_{Exit}}$
A. R. = 2.0		Baseline (Bell)	1.26	0.68	5.40
		Baseline (Conical)	1.43	0.53	5.45
A. R. = 4.5		40° Conical 8 Vanes	0.88	0.97	13.60 ↓
		50° Conical 12 Vanes	0.83	1.10	14.64 ↓
		Bell	1.18	0.63	15.60

Arrows Indicate Potential Exists for Improvement

NOTE: Estimated loss due to honeycomb and all screens = 5q approximately.

Figure III-7. Rapid-Diffuser Experimental Study Summary of Results.

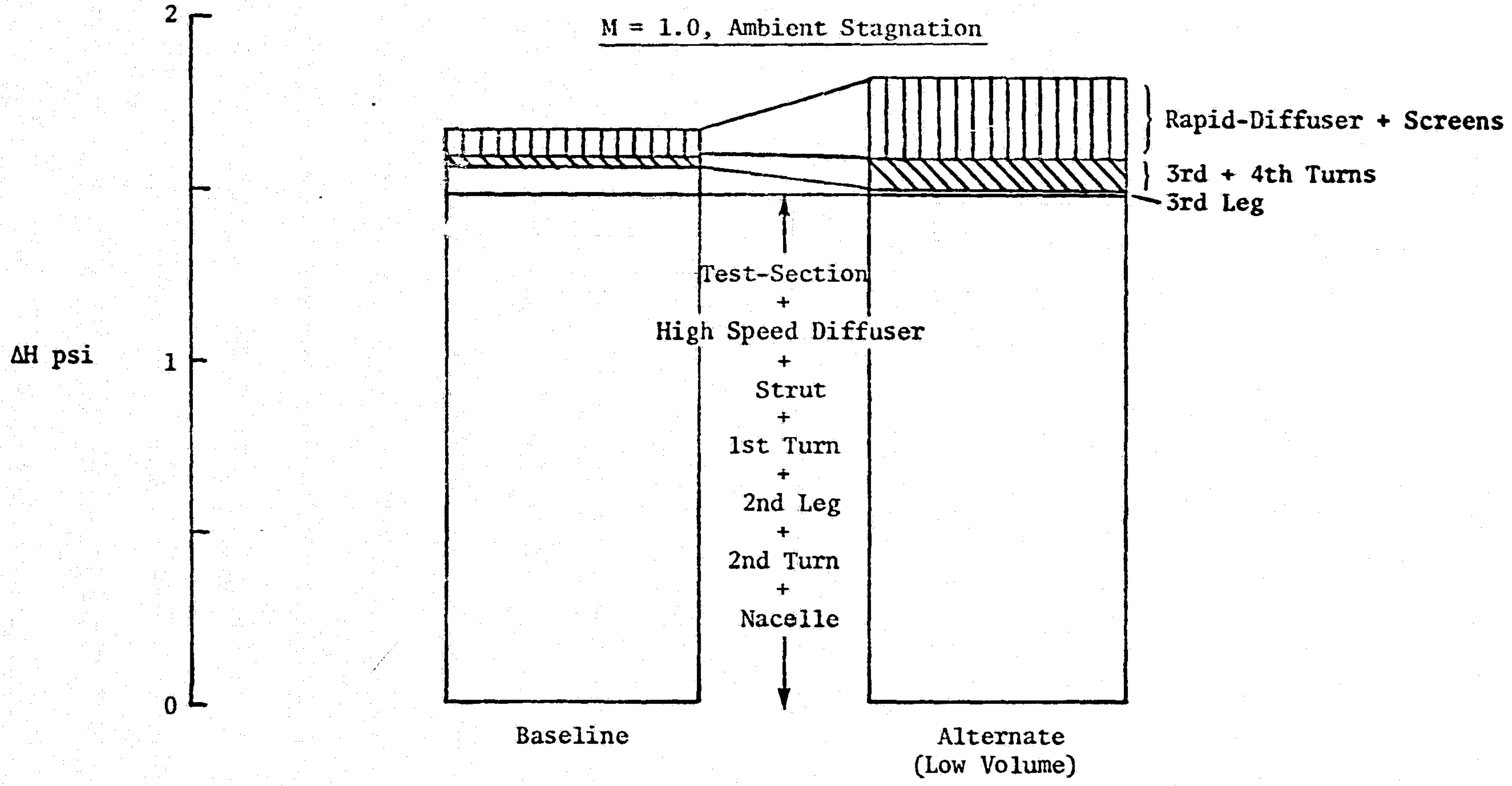


Figure III-8. Aerodynamic Loss Penalty Due to Circuit Modification.