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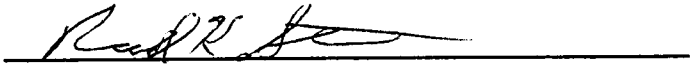
Signature 

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A Feasibility Study of a Transonic Adaptation of the AEDC 16-Foot Supersonic Wind Tunnel Facility

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Ronald K. Stonum

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ABSTRACT

The 16-Foot Supersonic Wind Tunnel (16S) at Arnold Engineering Development Center (AEDC) is one of the largest continuous flow supersonic wind tunnels in the world. However, because of the high energy costs required to operate it for testing, the facility does not get much usage. Consequently, the Air Force does not expend funds to keep the instrumentation and control systems at state-of-the-art status. However, the uniqueness of the facility prevents its demise, at least for now! To increase usage, I took another look at solutions that have been approached by various methods through the years at AEDC. If we can adapt 16S for transonic testing, we can increase its usage as well as relieve some of the work load of the 16-Foot Transonic Wind Tunnel (16T).

Many of the sources cited are from "Memos for Record" and operation reports which the contractor personnel have kept through the years. Additional data and ideas have been gathered by discussions with numerous facility engineers at AEDC. The facility descriptions are from a Test Facility Handbook as well as from instruction books provided by Westinghouse after the construction and initial checkout of the facility.

The solution of adapting 16S into a transonic facility can be implemented; however, it is not a low cost

undertaking. Because of this, I have broken down the solution into increments of work. This progresses from what I consider the bare minimum for a practical cost-effective solution up to a very effective test unit. The increase in usage of the modified facility undoubtedly will come, but a major commitment and investment by the government is required first.

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ABBREVIATIONS AND SYMBOLS

Abbreviations

AEDC . . . . . Arnold Engineering Development Center

AGARD . Advisory Group for Aerospace Research & Development

AOH . . . . . Air On Hour(s)

ARC . . . . . Ames Research Center

C-? . . . . . Main Compressor barrel number

CFD . . . . . computational fluid dynamics

CFM . . . . . cubic feet per minute

CFS . . . . . cubic feet per second

F . . . . . Fahrenheit

ft . . . . . foot (feet)

hp . . . . . horsepower

IDS . . . . . .Independent Drive System

IGV . . . . . inlet guide vanes

lb(s) . . . . . pound(s)

NACA . . . . . National Advisory Committee for Aeronautics

NASA . . . . . National Aeronautics and Space Administration

M-? . . . . . Main Drive System motor number

mph . . . . . miles per hour

PES . . . . . Plenum Evacuation System

psf . . . . . pounds per square foot(feet)

PWT . . . . . Propulsion Wind Tunnel

R . . . . . Rankine

rpm . . . . . revolutions per minute

sec . . . . . second

sq. ft. . . . . square feet

UOH . . . . . User Occupancy Hour(s)

4T . . . . . 4-foot transonic wind tunnel

16T . . . . . 16-foot transonic wind tunnel

16S . . . . . 16-foot supersonic wind tunnel

Symbols

A . . . . . cross-sectional area of stream tube

a . . . . . speed of sound

C_D . . . . . drag coefficient

C_L . . . . . lift coefficient

C_M . . . . . pitching moment coefficient

c . . . . . chord

C_p . . . . . pressure coefficient

L . . . . . body length

$\dot{m}$ . . . . . mass flow

M . . . . . Mach number

p . . . . . pressure

R . . . . . specific gas constant

R_s . . . . . radius of curvature of nozzle wall

T . . . . . temperature

u . . . . . x direction velocity component

$\tilde{u}$ . . . . . x direction perturbation velocity normalized by the speed of sound

V . . . . . speed of the flow

v . . . . . y direction velocity component

$\tilde{v}$ . . . . . y direction velocity normalized by the speed of sound

x . . . . . distance in streamwise direction

y . . . . . distance perpendicular to the flow axis

α . . . . . angle of attack

γ . . . . . specific heat ratio

Δ . . . . . change

ρ . . . . . mass density

$^\circ$ . . . . . degrees

Subscripts

f . . . . . force

m . . . . . mass

s . . . . . .sonic location on wall

t . . . . . total/stagnation conditions

0 . . . . . isentropic stagnation state

1 . . . . . conditions just upstream of a shock wave

2 . . . . . conditions just downstream of a shock wave

Superscripts

* . . . . . critical conditions (i. e. conditions where local speed is equal to the speed of sound)

1. INTRODUCTION

1.1 The Problem

Wind tunnels are like airplanes or any production equipment; they don't earn anything when they are not operating. As a matter of fact, they cost more money in upkeep while sitting idle. Wind tunnel facilities are also like any other equipment with electrical or mechanical parts; failure rates are significantly higher after the equipment has been idle for an extended period of time.

The 16-foot supersonic wind tunnel (16S) at Arnold Engineering Development Center (AEDC) is the largest continuous-flow supersonic wind tunnel in the United States, if not the world. However, because of the enormous cost of testing in the facility, only test programs with a significant budget can afford testing in the facility, and then normally only after doing preliminary testing in smaller facilities. Through the years there have been periods of renewed interest in supersonic testing of large models for various defense and space vehicle programs, but this interest comes and goes in cycles. One of the major impacts of only periodic testing in the facility is the cost that is incurred while getting the facility back in running order. As with any other equipment, the mechanical parts and electrical controls are in the best condition when they

are used regularly. To keep the tunnel ready to perform in lieu of regular testing requires high periodic maintenance costs. This periodic maintenance is often neglected, which causes a renewed concern about tunnel performance when a test is about to be run. Also, because of this low usage rate, the Air Force has not invested in modern instrumentation and control systems for the 16S tunnel. This results in inefficient and costly running of the facility because of the obsolescent technology used in its operation. However, the uniqueness of the facility and its capabilities requires that AEDC keep the facility available, even if only for periodic use.

Numerous users in the testing community have asked for an intermediate-size transonic wind tunnel at AEDC. Often they do not feel comfortable with the smaller model size and the resulting lower fidelity of the models tested in the AEDC 4-foot transonic tunnel (4T), but they don't like paying the high cost of testing in the 16-foot transonic facility (16T). Testing operations in the AEDC 16T facility are often 24 hours a day and seven days a week. A minimum of a six month wait is the norm for testing in that facility. There is a requirement to perform periodic maintenance on the complicated 16T system, but there is rarely an open time frame in the testing schedule to allow it.

The testing customers also want a tunnel that is compatible with their models that they test in other seven- and eight-foot commercial facilities across the country. These intermediate-size facilities are also available at the National Aeronautics and Space Administration (NASA) Centers; however, they currently do not run in a "production" mode as at AEDC. Previous studies at AEDC resulted in a proposal to build an 8-foot transonic facility to meet the additional testing needs, but this would result in the added costs required to build a whole new tunnel facility and its associated tunnel support equipment.

Transonic facilities are heavily used because most aircraft spend the majority of their flight time cruising in the transonic, i.e. high subsonic, speed regime. This is also the speed range where the transonic "drag rise" is taking place and thus the aircraft are paying the price in range performance. Since man also views time as money, we are usually willing to pay the extra cost for fuel in order to arrive at our destination faster. Transonic testing gives us the data for a trade-study of how much more we are paying to get there faster.

However, transonic testing has many problems associated with it. In a foreword written by von Karman, as well as in Goethert's introduction to his book on transonic wind tunnel testing [1], the difficulty in transonic testing is addressed. The speed range around Mach number one

creates difficulty in the design of airplanes and wind tunnels because of the characteristics of the flow. Transonic flow does not consist of only a single type of flow, as found in the subsonic and supersonic regimes. Instead, the transonic range has both types of flows mixed together, i.e. supersonic fields inside of subsonic flows and/or subsonic fields imbedded in supersonic flow.

This has caused difficulty in establishing transonic flow theories. In the purely supersonic or subsonic speed ranges, approximate solutions can be derived from linearized equations of motion. Therefore, rules of scaling and fundamental properties of the flows can be physically described and understood. On the other hand, it has been difficult, if not impossible, to establish simple transonic theories in order to predict the performance of aerodynamic vehicles or their components.

According to Shapiro [2], from admittedly incorrect linearized theory for two-dimensional flow with small perturbations, the disturbance caused by a body placed in transonic flow propagates laterally from the body with undiminished strength. Since these disturbances remain finite as the distance from the body increases, interference with the natural flowfield at large distances from the body can strongly influence the flow over the body. Therefore, the influence of boundaries very far from an object in transonic flow may not be negligible. This causes

difficulty in the interpretation of transonic wind tunnel data. However, other results from the linearized theory which are physically implausible are 1) inviscid drag is zero for a free stream Mach number slightly less than unity, but infinite for a free stream Mach number slightly greater than unity, and 2) the lift coefficient is infinite at Mach number one. One of the assumptions in small perturbation theory is that the local velocity is everywhere close to the speed of sound. This is invalid in most transonic flow. In spite of these limitations in the linearized theory, the result of a very small rate of decay of disturbances is indeed what occurs in real transonic flows.

In the transonic region, the rules and properties become dependent upon wind tunnel and model geometries and dimensions. The apparent shortage of similarity laws and scaling rules in transonic flow causes a greater dependence on aerodynamic testing and experiments for vehicle design information. But before the results of the wind tunnel tests can be realistically applied to a vehicle design, the reliability and limits of testing at the various speeds need to be understood. Because of the mixed supersonic/subsonic flows at transonic speeds, many of the transonic wind tunnels are very sensitive to the wall boundary layer control mechanisms and model geometry. This was demonstrated in a test for one wing's profile drag. The test showed a rapid increase in drag as the tunnel speed

approached sonic conditions. However, upon further investigation, it was revealed that the speed at which the increase occurred and the magnitude of the increase were more dependent on the characteristics of the wind tunnel than on the wing profile.

Now that we have established that transonic flow is very sensitive to disturbances, let's look at what is going on in the wind tunnel test section as we traverse the speed regime. When the flow field is still subsonic in the test section, local regions of supersonic flow, with accompanying shock waves, are produced in the vicinity of bodies placed in the flow. Local shock waves will be generated when the flow reaches or exceeds its critical Mach number for that particular body. These shock waves can reflect off the tunnel walls and impinge upon the model or its support system causing the model to vibrate; of course, this also affects the forces and moments acting on the body. Attempts are made to decrease this transonic interference through the use of various wave cancellation techniques such as porous walls.

As the flow gets even closer to sonic speeds, other shock waves can start forming from irregularities in the tunnel wall. Pressure surges and "noise" in the air flow can cause the airspeed to vary in the test section and affect the resultant data.

When supersonic flow is established, the movement of

the model in the test section can cause problems. If the flow is too close to sonic, changing the model attitude causes a change in the tunnel blockage. This can cause the shock to move forward out of the diffuser which results in serious problems not only in the data, but also in possible damage to the model and its instrumentation.

Two techniques used to counter these problems are plenum suction and Mach number selection. Plenum suction control in combination with porous walls will help control the local pressure distribution along the test section wall and the resulting local velocity. It also helps control shock reflection off the walls onto the model and support system. The other technique involves not testing at a Mach number close to one. Experienced testing personnel prefer to avoid Mach numbers between 0.95 and 1.05. This gives them some "breathing room" for setting conditions. Some facilities have problems maintaining stable conditions at test section Mach numbers between 0.95 and 1.05. The data is then interpolated between these Mach numbers using various techniques that have been developed through the years.

Figure 1 is an overhead schematic of the AEDC Propulsion Wind Tunnel (PWT) complex which encompasses 16T, 16S, and 4T. It is readily apparent that it is a scheduler's nightmare at times because different facilities in the complex require the usage of the same assets. The

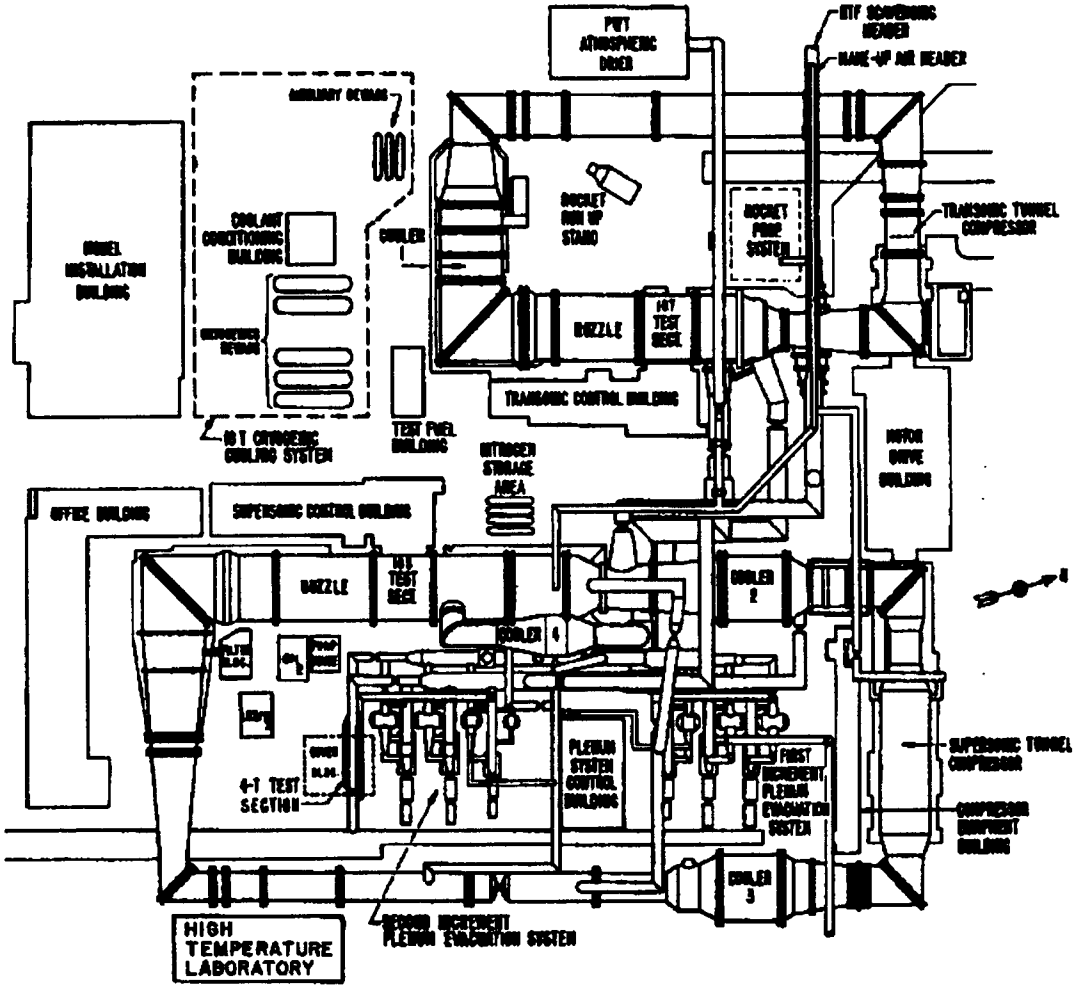

Figure 1. PWT Facility Layout

Source: Arnold Engineering Development Center "Test Facilities Handbook (Eleventh Edition)", June 1979.

assets that are the "show stoppers" are Main Drive, the Plenum Evacuation System (PES), and cooling water. AEDC can now run 4T and the 16 foot facilities concurrently under some tunnel conditions with the advent of the 4T Independent Drive System (IDS). However, the current conditions under which Main Drive can be used for concurrent 16T and 16S tunnel operations are extremely limited and this is rarely done. Additionally, the reliability of the Main Drive system has deteriorated significantly, since it is a high horsepower motor system that has been in regular use for almost forty years. A major overhaul/replacement of the main drive motor is overdue and has been recommended by the National Research Council [4].

The costs of building and maintaining large-scale test facilities are very prohibitive to all but the largest aeronautical companies in the nation. Even large companies like Boeing, Pratt and Whitney, and General Electric are negotiating testing alliances with AEDC to avoid spending the huge sums of money required to build or upgrade their own corporate testing facilities. The companies will undoubtedly keep their smaller research tunnels for initial research and development, or for computational fluid dynamic (CFD) code validation. But when it comes to full fledged performance testing, they will still look to the larger facilities, which are government-owned because of the high costs associated with them. There is a call from the

aircraft industry for the government to provide state-of-the-art testing facilities, either at military facilities such as AEDC or at NASA centers. With this in mind, we can see that at least one additional transonic-testing facility at AEDC will be required for future activities. Combine this with the need to keep the large-scale supersonic facility (16S) available for intermittent use, and we can appreciate the utility in this revived proposal for a solution. There are other facilities that the aircraft industries are calling for, such as a national high Reynolds number test facility, but these facilities are beyond the scope of this thesis.

1.2 Preliminary Look At A Solution

The adaptation of the 16-foot supersonic facility into a transonic one will allow more regular use of the facility and its equipment. This will reduce the base operating cost of keeping the facility in a standby status between the periodic large-scale supersonic model tests. An additional expenditure to replace the Main Drive Motor System will greatly increase the number of hours that 16T and the retrofitted 16S/16x13T will be available for testing. However, even without the 16S retrofit, a major overhaul/replacement of the main drive motor is overdue. This is necessary in order to provide more reliable system

availability for future testing in the two 16 foot facilities. The proposed upgrade to the current Main Drive Motor System is discussed in greater detail in section 3.5.

The adaptation of 16S to a transonic facility is not a trivial task. The issue of facility flow quality is as important as that of the availability of the test unit. An Advisory Group for Aerospace Research & Development (AGARD) report in 1982 [3] addressed the issue of flow quality and its relationship to test data. The group specified the accuracy requirements for the wind tunnel data in relation to: 1) A given configuration's predicted performance and operating characteristics, 2) The evaluation of performance changes due to small configurational changes, and 3) The assessment of computational codes. AGARD stipulated that the data accuracy and flow quality requirements were applicable to transport-type aircraft in the high-speed regime. They also added that drag was considered the most important aerodynamic parameter to be determined. The report gave the accuracy requirements for lift, drag, and pitching moment, "as stated by various research and industry sources" as:

Lift coefficient	$\Delta C_L = 0.01$
Drag coefficient	$\Delta C_D = 0.0001$
Pitching-moment coefficient	$\Delta C_M = 0.001$

These accuracy requirements are for data repeatability and incremental effects caused by minor configuration changes.

Based on these data accuracy requirements, the report gave some guidelines as to the flow quality required in temporal and spatial terms. An example of a temporal uniformity requirement for flow quality is for Mach number control while measuring drag. At the drag divergence boundary, the free-stream Mach number must be determined and kept constant to within $\Delta M=0.001$ for at least one α-sweep. For data repeatability and minor configuration changes, they assert that the flow uniformities are not important as long as they are consistent over long periods of time.

The report quotes more stringent spatial flow quality requirements for doing assessments of major configuration changes and model comparisons. In this case, we are not just incrementing data, but are establishing baseline performance databases and thus require the more stringent flow quality. These requirements also depend upon the changes to the model size or geometry. The desired drag accuracy drives the maximum allowable pressure variation along the model axis. Assuming a ratio of 0.1 between the body cross-section and the wing area, we have a limit of $\Delta c_p=0.001$ over the length of the model. The accuracy of the flow angle has a greater impact at the tail surface location due to the pitching-moment coefficient requirement. Assuming a tail volume of 0.1 and $(dC_L/d\alpha)_{tail}$ of 0.1/deg, this yields the tolerance of $\Delta\alpha=0.1°$ at the tail location. The group adds that the total pressure and temperature

variation over the span and length of the model should be kept within 1/2% and ±1° K, respectively.

To summarize, according to the AGARD panel, the most stringent flow quality requirements to meet the C_D accuracy requirements are:

Flow angularity	≤ 0.01°
Flow curvature {[d(v/V)]/[d(x/c)]}	≤ 0.03°/chord
Spanwise variation in flow angle	≤ 0.1°
Mach gradient {dM/[d(x/L)]}	≤ 0.0006 M

Note that the calibration measurements for flow quality are normally done in an "empty" test section and would be influenced by the presence of a model or model support mechanisms. These flow quality parameters take statistical error propagation into account when determining their values. The errors or data uncertainty in themselves could result in accuracy errors greater than one drag count. The absolute accuracy of ΔC_D=0.0005 is considered adequate since it is about what one can achieve in flight testing. However, these previous flow quality parameters are the goals that the wind tunnel designer needs to strive for in order to aid the aerodynamics engineer. Reference [3] is a detailed report on the subject of flow quality and data accuracy interaction and should be reviewed by all wind tunnel testing engineers. A preliminary look at the flow in the modified 16S nozzle test section as well as suggested further investigations are described in Section 4.

2. JUSTIFICATION AND MOTIVATION

2.1 Tunnel Usage Statistics

The 16S wind tunnel was first brought on line for production testing in the early 1960's. I could readily find operational information only for the 23 years since 1970.[1] These records, summarized in Table 1, show that there have been 108 tests for about 8000 User Occupancy Hours (UOH) and 4840 Air On Hours (AOH) in 16S. User Occupancy Hours are the number of hours that the tunnel is available for actual testing or productive work such as model changes or instrumentation setup. Downtime is any time that productive work or testing cannot be done because of User or AEDC problems. Downtime charged to AEDC problems is not counted as part of the UOHs; however User downtime is charged as UOHs if the facility is ready to produce data.

Now let's put this into perspective. Because of the shared resources that have been required to run 16T, 16S, and 4T, we'll assume that, at the minimum, 16S would be available an average of eight hours per day five days per week. This is very conservative since some testing conditions permit more than one of the PWT facilities to operate at the same time. Remember, however, that 16T and

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[1] Calspan AEDC Operations Branch, "Test Unit Utilization Report Spreadsheet", January 1993.

Table 1. PWT 16 Foot Test Cells Utilization

	16S			16T		
Fiscal Year	No. of Tests	UOH	AOH	No. of Tests	UOH	AOH
70	16	844.2	610.3	31	2097.1	1337.7
71	14	1088.8	748.1	27	2020.5	1189.8
72	13	1187.9	725.6	31	1730.3	1031.9
73	10	689.5	448.5	31	2458.8	1443.5
74	3	707.5	476.7	23	1767.1	876.7
75	7	563.5	372.4	45	2724.7	1425.8
76	6	311.2	172.1	44	3481.8	1658.5
77	1	76.3	43.6	40	2853.9	1397.4
78	3	59.0	24.8	43	2608.5	1369.8
79	3	34.5	23.1	41	1480.9	943.1
80	7	475.4	328.3	40	1818.9	1206.9
81	2	151.5	84.2	68	1890.6	1057.7
82	0	0.0	0.0	25	1289.6	744.9
83	1	38.3	20.5	22	1674.4	846.9
84	4	272.7	81.6	22	1957.4	899.8
85	1	221.4	0.0	22	3462.4	1405.9
86	2	76.7	37.6	20	2457.8	1143.5
87	4	94.0	42.9	23	2892.2	1203.0
88	2	167.3	51.6	23	2829.1	1192.6
89	2	161.2	110.8	26	3716.7	1574.6
90	1	177.3	80.1	22	3159.6	1353.3
91	3	284.6	177.3	14	1807.7	716.6
92	3	314.9	180.3	17	2464.7	972.7
Total	108	7,997.7	4,840.4	700	54,644.7	26,992.6

Adapted from Calspan AEDC Operations Branch, "Test Unit Utilization Report Spreadsheet", January 1993.

16S rarely operate at the same time. An additional conservative aspect of this estimate is that the tunnels have operated seven days a week at times due to heavy testing requirements. On the other hand, there have been some catastrophic failures of the 16S testing circuit which have caused the test unit to be unavailable for extended periods. Taking all of these factors into consideration, we can see that 16S could have operated for approximately 47,320 (UOH) in the period from January 1970 to October 1992.

These figures reflect that the 16S wind tunnel was only operated or occupied for 17 percent of the time that it was available during this period. Compared to this, the 16T occupancy rate during the same time frame was 115 percent of the time available.

2.2 Instrumentation Issues

One of the "fallout" problems associated with the low usage rate is the low level of equipment investment in the 16S facility. The prevailing view is that if a facility is not used very often, one should not spend "corporate" dollars on keeping the instrumentation and control systems state-of-the-art or even of the current generation. To combat this deficiency in 16S instrumentation, some of the instrumentation is often moved back and forth between 16T

and 16S. Additionally, some of the instrument racks that are not moved have patch panels between the facilities. This results in additional wire length that causes any number of problems. The instrumentation, whether moved or cross-patched, must be "retuned" for use in each tunnel.

There is inefficiency in this system that has been used for about ten years. Since one has to wait for the other large tunnel to complete its testing before beginning instrumentation setup, the time required for test installation and checkout prior to running is large. If the independent instrumentation was available in both tunnels, concurrent running and installation could be done in both 16 foot facilities. My experience has shown that it takes approximately 72 working hours to move the instrumentation from one facility to the other. Two thirds of this time could be converted into testing time with additional instrumentation. A side issue that goes with this is the loss of useful instrument life caused by moving it from place to place.

The instrumentation that I have addressed here is the basic type that is common to the force and pressure tests that are carried out in any wind tunnel. I recognize that there are some instrumentation or sensor systems which are low usage and do not warrant multiple setups. However, the basic instrumentation for each facility should be independent.

2.3 "Getting Back In The Groove"

This is a term that is used in wind tunnel facilities across the country. The term refers to the rhythm that comes in the production of data. You check the model, bring the tunnel on condition, collect the data, shut down the tunnel, change the model, check the model, . . . and keep doing it over and over until the end of the test. If equipment has been sitting idle for an extended period, it often malfunctions when called upon to operate again. AEDC's 16T, a very high production facility, has this problem when it is down for a few days between tests. Multiply this by the number of days that 16S is down between test entries and you can see the magnitude of the problem in getting such a complex facility to operate reliably again.

When a customer comes to test in 16S after it has set idle for months, they "cross their fingers" and hope that the facility gets back "in the groove" quickly to preclude high additional testing costs. They realize that testing is risky anywhere, but this low usage phenomenon is another reason that some customers hesitate to use the 16S facility. They know that the facility has unique capability but that this capability is sometimes at its own whim.

2.4 How Others Have Modified Their Tunnels

There are other facilities that have been adapted to various speed ranges within the circuit. Pope [5] shows how the insertion of venturis within a test section can increase the top speed of the tunnel test section by a factor of up to six times the normal speed. The increase in test section speed by the use of inserts is common because most large facilities were built for low speed testing. With the advent of higher speed requirements, these modified facilities were more cost effective than building all-new tunnels and provided the required experimental information.

In searching for other dual speed range or dual usage facilities, I found several at the various NASA Centers. Some of these were initially built as multi-speed or multi-use facilities, but some were also modified to provide dual-speed capability. NASA Ames Research Center (ARC) has a 40'x 80' facility that was originally built as only a low speed closed circuit facility (Figure 2). They added an 80'x 120' leg to it that changes part of the 40'x 80' closed circuit into an open circuit past the compressors. In addition to that facility at Ames, the Unitary Plan wind tunnel (Figure 3) has one main drive motor that alternatively powers three different test circuits. The circuit to the left is the 11'x 11' transonic leg. It is a high usage facility at ARC and has a Mach number range

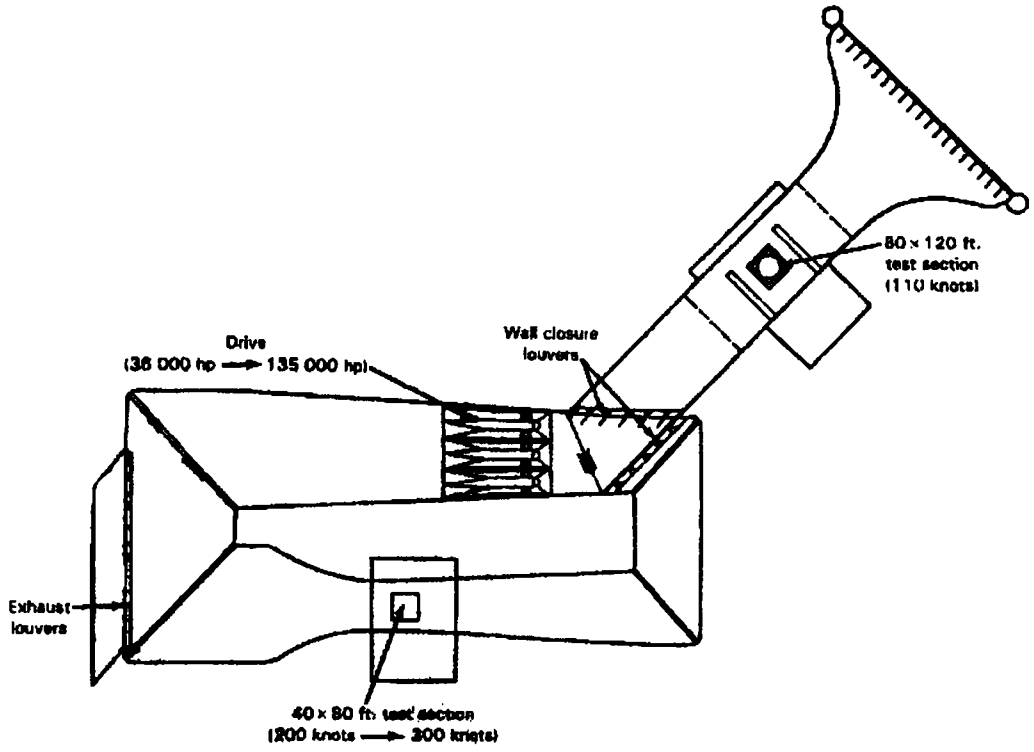

Figure 2. NASA Ames Research Center 40x80x120 Wind Tunnel

Source: Baals, Donald D. and Corliss, William R., "Wind Tunnels of NASA", National Aeronautics and Space Administration, Washington, D.C., 1981.

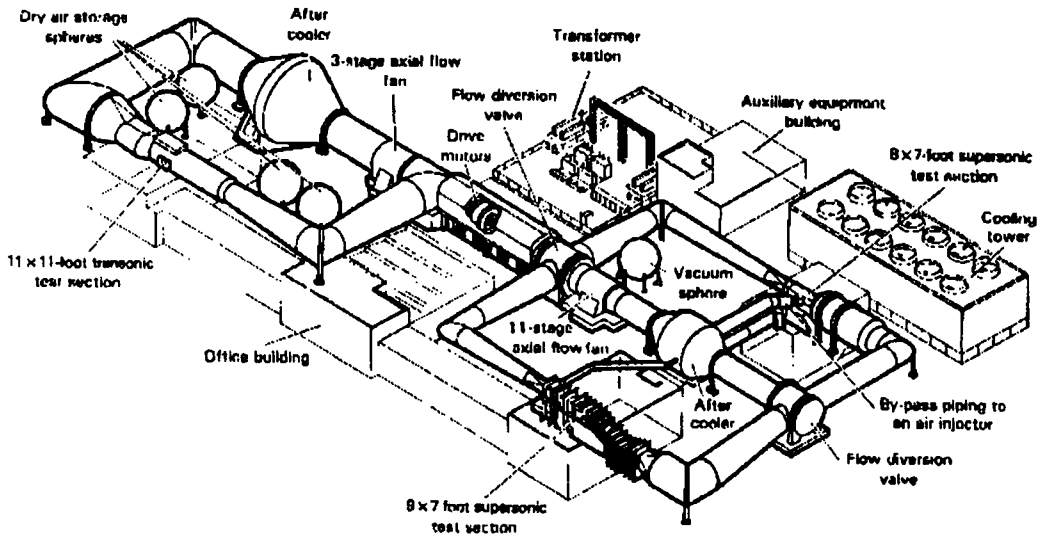

Figure 3. NASA Ames Research Center's Unitary Wind Tunnel

Source: Baals, Donald D. and Corliss, William R., "Wind Tunnels of NASA", National Aeronautics and Space Administration, Washington, D.C., 1981.

from 0.4 to 1.4. The main drive unit powers a three stage compressor to produce the speed regime. The circuit in the lower right is the 9'x 7' supersonic leg and the one in the upper right is the 8'x 7' supersonic leg. These two legs share a common 11-stage axial flow compressor that is powered by the central main drive unit. Large ball valves, with built in turning vanes, are located on each end of the center compressor leg of the circuits and are positioned to direct the air flow to the appropriate test section. This is an excellent example of using a common compressor drive motor to power multiple-speed-regime tunnels [6].

NASA Lewis has a dual-purpose facility in which the transonic/supersonic test section is in the main leg of the circuit [7]. It can test at Mach numbers from 0.4 to 2.0 in its 8'x 6' test section that is 23 feet long. This leg can also be configured as an open circuit to permit testing of propulsion systems. On the return leg of the circuit, there is a 9'x 15' test section that is 28 feet long and can test at speeds up to 175 miles per hour (mph). This was one of the configuration options that I originally considered, but after looking at all of the "plumbing" and other test support equipment for all of PWT, not just 16S, it lost its appeal as a viable option.

3. THE FACILITY TODAY AND TOMORROW

3.1 The Facility As It Is Today

The 1979 edition of the AEDC Test Facility Handbook gives a general description of the PWT Facilities [8]. It describes 16S as a continuous-flow, closed-circuit tunnel whose original design envelope was from Mach number 1.50 to 6.00. The tunnel has been operated at test section Mach numbers from 1.50 to 4.75. At Mach numbers above 3.40, the Main Drive and PES compressors must be operated in series. The plant configuration changes required for these higher Mach numbers must be made while the tunnel is operating and consume a significant amount of test time to accomplish. The Mach number range in 16S is obtained through the use of a flexible-wall, Laval-type nozzle. The nozzle of 16S is adjusted by 58 sets of hydraulically driven actuators. These actuators are automatically positioned for the various Mach number contours with a digital-computer setpoint and guidance input system.

Air-to-water heat exchangers are located upstream and downstream of the compressor. These allow the test section stagnation temperature to be controlled in the range from 100 to 600 degrees Fahrenheit. The minimum temperature is a function of outside air temperature and cooling water temperature, which might be coming from the local reservoir

instead of the cooling tower system. The upper temperature range is a function of the number of main drive compressors that are being used to provide the Mach number.

The extraction of tunnel air for tunnel pressure-level control during aerodynamic tests in all of the tunnels in the PWT complex is done by using the Plenum Evacuation System (PES) compressors as exhausters. The PES consists of two increments which can be operated in parallel or independently depending upon the requirements. It can perform the function of plenum suction with either one or both of the increments, as well as the simultaneous functions of plenum suction and tunnel pressure control. Each PES increment contains five 9-stage compressors which can be operated in parallel or staged in series for two-stage operations. Additionally, there is a 7-stage machine in each increment which can be used for either 2- or 3-stage operations. The horsepower rating of each increment is 77,500-hp; however, a continuous service factor of 15 percent provides an available power of 89,000-hp. The importance of this PES system will be emphasized later as an additional equipment requirement necessary to realize fully the gains to be had by adapting the 16-foot supersonic circuit to do transonic testing.

The Main Drive Motor System is common to both 16T and 16S and currently has a total capacity of 226,000-hp. It consists of one 25,000- and one 35,000-hp wound-rotor

induction motors and two 83,000-hp synchronous motors. Three disconnect couplings permit the four motors to be operated with either 16T or 16S compressor. The main compressor of 16S consists of four axial-flow compressors (barrels), which are oriented such that any number from one to four barrels may be operated in series. The number of barrels operating in series is controlled by a system of iris valves and disconnect couplings located between each barrel. The compressor operates at a constant speed of 600 rpm with volume flow adjustment provided by the remotely controlled inlet guide vanes and stator blades of the first, second, and third barrels. The first three barrels are four-stage, axial flow compressors and the fourth is a six-stage compressor. The current configuration restrictions and proposed compressor and main drive modifications are discussed in Sections 3.4 and 3.5.

The test section of 16S is 16 feet in cross section and 40 feet long. The entire test section and supporting structure are constructed as a separate unit, called the test section cart. There are three separate 20-ft-long carts available for testing throughout the design temperature range of 16S. In 16S, the carts are used in pairs to form the 40-ft-long test section. Each cart may be used in either the forward or aft position in the test section. These test section carts are completely enclosed in a plenum chamber when in the tunnel circuit and can be

evacuated. The test section carts can be moved to a model installation building where the test article and associated equipment are installed.

3.2 The Nozzle and Test Section

Before I can propose to change the configuration of the 16S wind tunnel nozzle and test section, I must make sure that flow analysis indicates that it is viable. First let's establish the assumptions for the following nozzle equations:

1. Compressible flow.
2. Adiabatic and inviscid flow (isentropic).
3. Thermally and calorically perfect gas.
4. One-dimensional or quasi-one-dimensional flow.

Based on these assumptions, from the NACA Report 1135 [9], we will use the continuity equation of a stream tube. In addition to the above basic assumptions for the flow, if we assume that the density and speed are uniform across the stream tube, we get the following relationship:

$$\rho VA = constant = \rho^* a^* A^* \qquad (1)$$

As a result of this relationship, the following equation has been previously derived and is again stated in [9]:

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

We want to rearrange this equation to find the area of the throat for a given supersonic Mach number in the test section. Reference [8] indicates that the minimum Mach number in the 16S test section is 1.5. This minimum Mach number for the normal testing envelope is the result of the maximum achievable distance between the nozzle plates in the tunnel. The 16'x 16' test section gives us an area of 256 sq. ft. and the specific heat ratio (gamma) is assumed to be 1.4. We substitute the following values into equation 2

$$M = 1.5$$
$$A = 256\ sq.\ ft.$$
$$\gamma = 1.4$$

which yields the following equation:

$$A^* = 256\left\{\left[\frac{(1.4+1)}{2}\right]^{\frac{(1.4+1)}{2(1.4-1)}} 1.5\left[1+\frac{(1.4-1)}{2}(1.5)^2\right]^{-\frac{(1.4+1)}{2(1.4-1)}}\right\} \qquad (3)$$

The result of these substitutions is that the maximum normal area of the nozzle (or throat) is 218 sq. ft. at the start-up Mach number. Since the top and bottom surfaces do not contract from the nozzle to the test section, we can divide this number by the test section height of 16 feet to give us a throat width of 13.6 feet. These dimensions determine the size of the test-section insert required to provide a continuous operating envelope below Mach number 1.0. This insert from the nozzle throat to the diffuser provides a constant-area flow channel through the test section. Since the flow will not be expanded past the nozzle throat, the

flow will stay sonic or below. For it to stay subsonic, we need to keep the pressure rise in the main compressor low enough to preclude sonic flow at the throat. Attaining supersonic flow will be addressed later in this section.

There have been numerous studies through the years to increase the speed regime of the 16S facility; these studies were driven by interim testing requirements. Some of these studies addressed increasing the speed envelope, but there were also studies addressed to decreasing it. Some of these slower speed studies were focused on just using the facility as it is physically. They involved configuring the PES, main drive, test section nozzle and diffuser to extend the lower operating speed. After many iterations, the Mach number range of 0.04 to 0.61 was all that could be achieved.

Another set of studies was done in 1963 by Estabrooks and Maxwell. The first considered having a fairing go from the throat to the test section wall positions.[2] The second one also proposed modifying the 16S test section carts to position the test cart walls inward as far as they would go to match up with the fairing from the first study.[3] Since

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[2] Estabrooks, B.B. and Maxwell, H., "Feasibility of Operating the PWT 16-Ft Supersonic Tunnel in the Transonic Mach Number Range", ARO, Inc., Arnold AFS, TN, Memo for Record, January 21, 1963.

[3] Maxwell, H., "Feasibility of Operating the PWT 16-Ft Supersonic Tunnel in the Transonic Mach Number Range", ARO, Inc., Arnold AFS, TN, Memo for Record, February 25, 1963.

this area was still greater than the nozzle throat area and would result in supersonic flow, they had the additional requirement to build up the top and bottom walls of the test cart. Figures 4 and 5 come from the Memos for Record that were produced and provide a rough sketch of their plans.

This method is close to what I envision doing to the test section. I would keep the top and bottom walls of the test section intact. I propose building up the sidewalls with a framework that would support the installation of porous walls that are similar in design to those now in use in 16T. The resulting test section would be approximately 16'x 13'. Figure 6 is a sketch of my proposed modifications in the 16S circuit from the nozzle throat to the diffuser.

Now assume that new test section must provide Mach numbers from 0.4 to 1.5. Additional equations from [9] are:

$$a_t = \sqrt{\gamma R T_t} \tag{4}$$

$$\left(\frac{V}{a_t}\right)^2 = M^2 \left(1 + \frac{\gamma - 1}{2} M^2\right)^{-1} \tag{5}$$

Since T in equation 4 is in degrees Rankine, we can adjust this for the input in degrees Fahrenheit and solve for the velocity in feet per second. The equation then becomes:

$$V = M \sqrt{\frac{[\gamma R (T_t + 459.6)]}{\left(1 + \frac{\gamma - 1}{2} M^2\right)}} \tag{6}$$

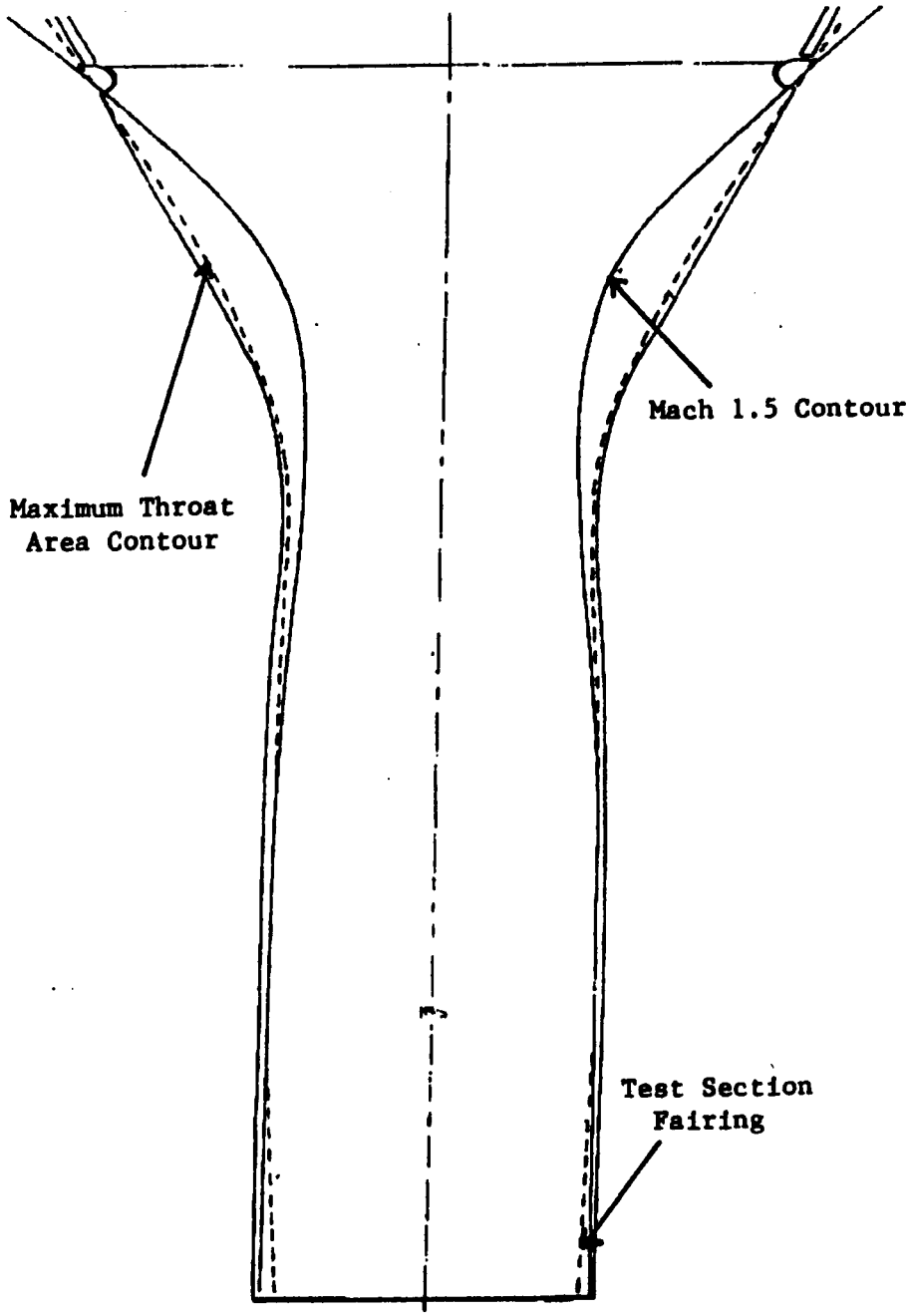

Figure 4. 16S Nozzle Geometry for Transonic Testing

Adapted from Estabrooks and Maxwell, "Feasibility of Operating the PWT 16-Ft Supersonic Tunnel in the Transonic Mach Number Range", ARO, Inc., Arnold AFS, TN, Memo for Record, January 1963.

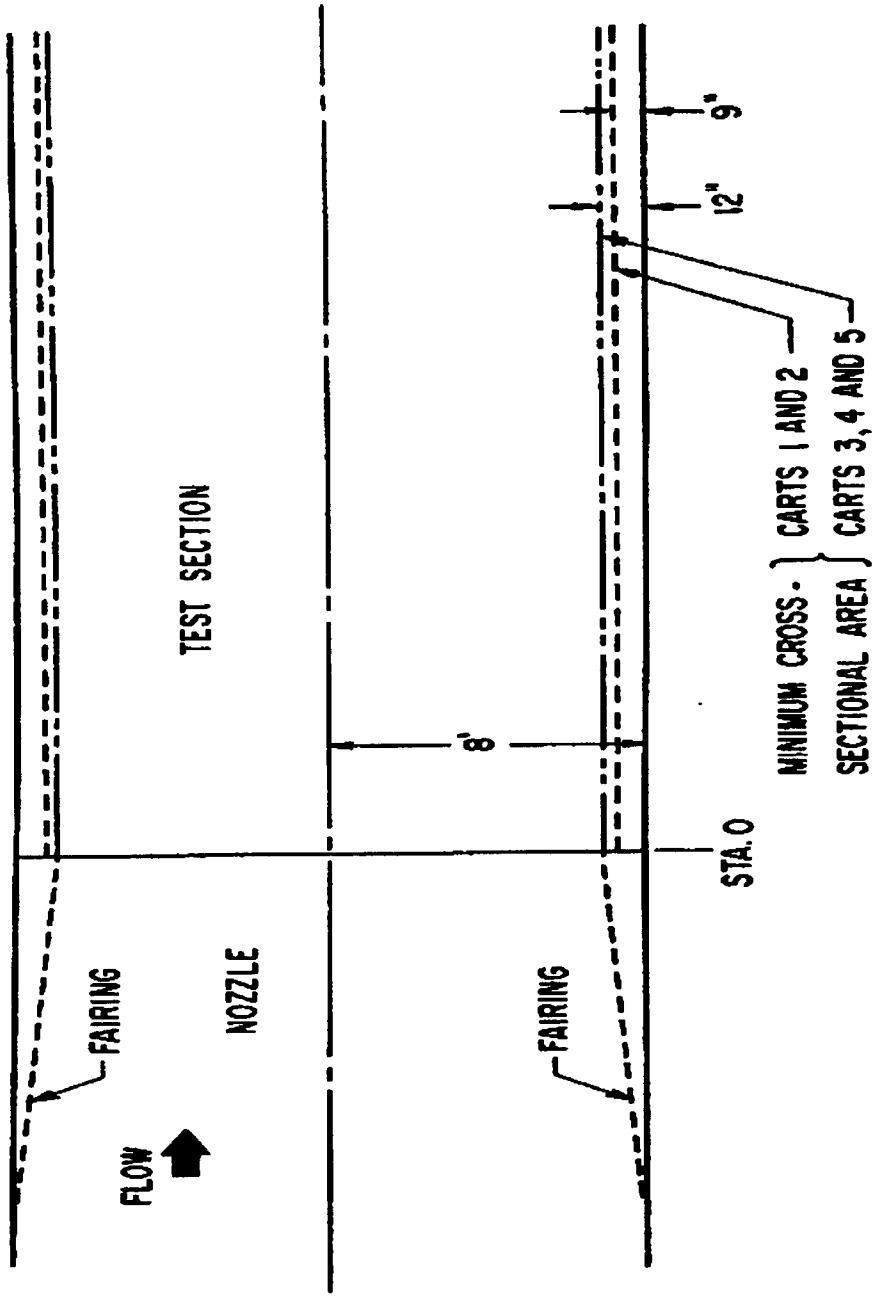

Figure 5. 16S Test Section Sidewall Positions For Transonic Testing

Source: Maxwell, H., "Feasibility of Operating the PWT 16-Ft Supersonic Tunnel in the Transonic Mach Number Range", ARO, Inc., Arnold AFS, TN, Memo for Record, February 1963.

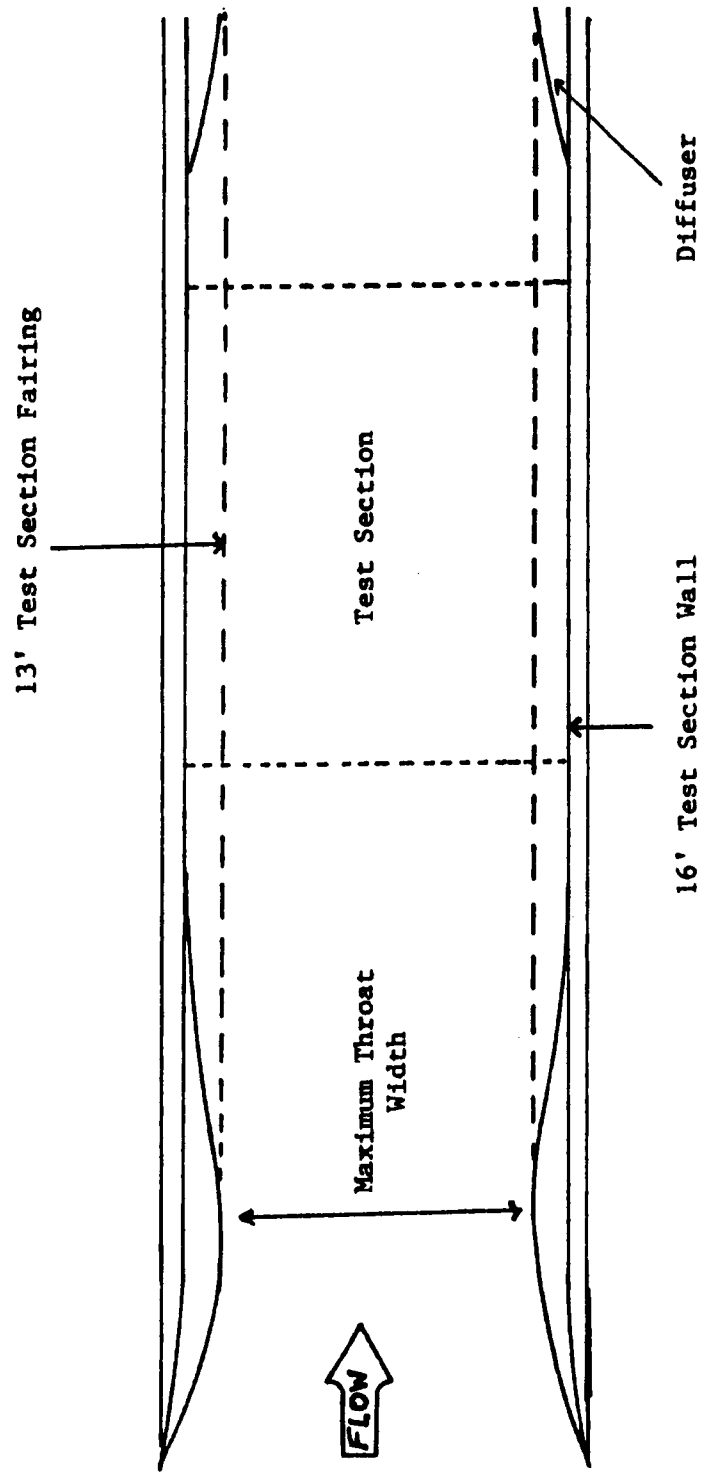

Figure 6. Proposed 16S Modification for Transonic Testing

Substituting the following values:

$$T_t = 100^\circ\ F$$
$$\gamma = 1.4$$
$$R = 1716\ (ft \cdot lb_f)/(slug \cdot {}^\circ R)$$

We get the following equation:

$$V = M \sqrt{\frac{[(1.4)\ (1716)\ (100+459.6)]}{\left(1+\frac{\gamma-1}{2}\ M^2\right)}} \qquad (7)$$

Substituting a Mach number of 0.4 into equation 7, we get the velocity to be about 450 ft/sec. The new test section dimensions would yield an ideal, no-loss air flow of about 98,000 cubic feet per second (CFS). But what about the air flow for the supersonic case? The equations used previously do not allow for a normal shock in the flow, so for the supersonic case we need to use a few more relationships.

Anderson [10] gives the following relationship for the mass flow of a calorically perfect gas through a choked nozzle:

$$\dot{m} = \frac{p_t\ A^*}{\sqrt{T_t}} \sqrt{\frac{\gamma}{R}\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}} \qquad (8)$$

For the new test section of 13'x 16', from equation 2 we would get the new throat area for Mach 1.5 in the test

section. That value and other assumed values for the test section are:

$$p_t = 1500\ psf$$
$$A^* = 176.9\ sq.\ ft.$$
$$T_t = 100^\circ F$$
$$\gamma = 1.4$$
$$R = 53.29\ (ft \cdot lb_f) / (lb_m \cdot {}^\circ R)$$

We would then get the following equation:

$$\dot{m} = \frac{(1500)\ (176.9)}{\sqrt{(459.6+100)}} \sqrt{\left[\frac{(1.4)\ (32.2)}{(53.29)}\right]\left[\frac{2}{(1.4+1)}\right]^{\frac{(1.4+1)}{(1.4-1)}}} \qquad (9)$$

This yields a value for the choked nozzle mass flow of about 5970.5 lbs/sec. The isentropic relationships that I have been using are only good on either side of a normal shock, not across it. Because of this, I will use relationships for a shock wave. The first is:

$$M_2 = \sqrt{\frac{(\gamma-1)\ M_1^2 + 2}{2\ \gamma\ M_1^2 - (\gamma-1)}} \qquad (10)$$

From this equation and the value of Mach 1.5 for M_1 in the test section we get M_2 to be .70 behind the shock at about the engine exhaust scoop area immediately downstream of the test section. Actually the shock is usually farther downstream in the diffuser, past the "second throat", so the diffuser efficiency is somewhat larger than assumed here. Therefore, the results of the following analysis are

somewhat pessimistic.

Since we have choked flow at the throat, we can use the following relationship:

$$\dot{m} = \rho^* A^* a^* = \rho_1 A_1 V_1 = \rho_2 A_1 V_2 \tag{11}$$

The volumetric flow behind the shock that will be entering the compressor is:

$$\frac{\dot{m}}{\rho_2} = A_1 V_2 \tag{12}$$

To find the density behind the shock, we can use various methods. I will solve for the parameters in:

$$\rho_2 = \frac{p_2}{R T_2} \tag{13}$$

These values can be found readily using the following equations in [9]:

$$\frac{p_2}{p_{t_1}} = \frac{2\gamma M_1^2 - (\gamma - 1)}{\gamma + 1}\left[\frac{2}{(\gamma - 1) M_1^2 + 2}\right]^{\frac{\gamma}{\gamma - 1}} \tag{14}$$

$$\frac{T}{T_t} = \left(1 + \frac{\gamma - 1}{2} M^2\right)^{-1} \tag{15}$$

Substituting the values for the test section ahead of the normal shock into equation 14 and rearranging, we get:

$$p_2 = 1500\left\{\frac{[(2.8)(1.5)^2] - (.4)}{2.4}\left[\frac{2}{(.4)(1.5)^2 + 2}\right]^{3.5}\right\} \tag{16}$$

$$p_2 = 1004.5 \; psf$$

Since total temperature is constant across a normal shock, we will use the isentropic equations with the Mach number that we found from equation 10. So substituting into equation 15 and rearranging we have:

$$T = 559.6\left[1 + (.2)(.7)^2\right]^{-1}$$
$$T = 509.7^\circ R = 50.1^\circ F \tag{17}$$

Now we will combine equations 12 and 13 and solve using these values that we have arrived at from our assumptions.

$$A_1 V_2 = \frac{\dot{m} R T_2}{p_2} = \frac{(5970.5)(53.29)(509.7)}{(1004.5)} \tag{18}$$

This equation results in a volumetric flow of 161,444 CFS. Although this is greater than the 150,000 CFS design point, Figure 7 from reference [11] shows that it is well within the capabilities of the compressor.

One way of achieving supersonic flow is by extracting mass flow through the walls in a constant area test section. This is equivalent to increasing the area ratio of the test section. Achieving Mach number 1.5 using only plenum suction would require removing 1050.8 lb_m/sec mass flow. An assumed total temperature of 100° F and a plenum pressure of 500 psf would require plenum pumping of about 62,600 CFS to achieve Mach number 1.5 in the test section. This is almost three times the current pumping capacity of one PES increment. Even if PES had the capacity, care would have to be taken to provide a provide a suitable test section

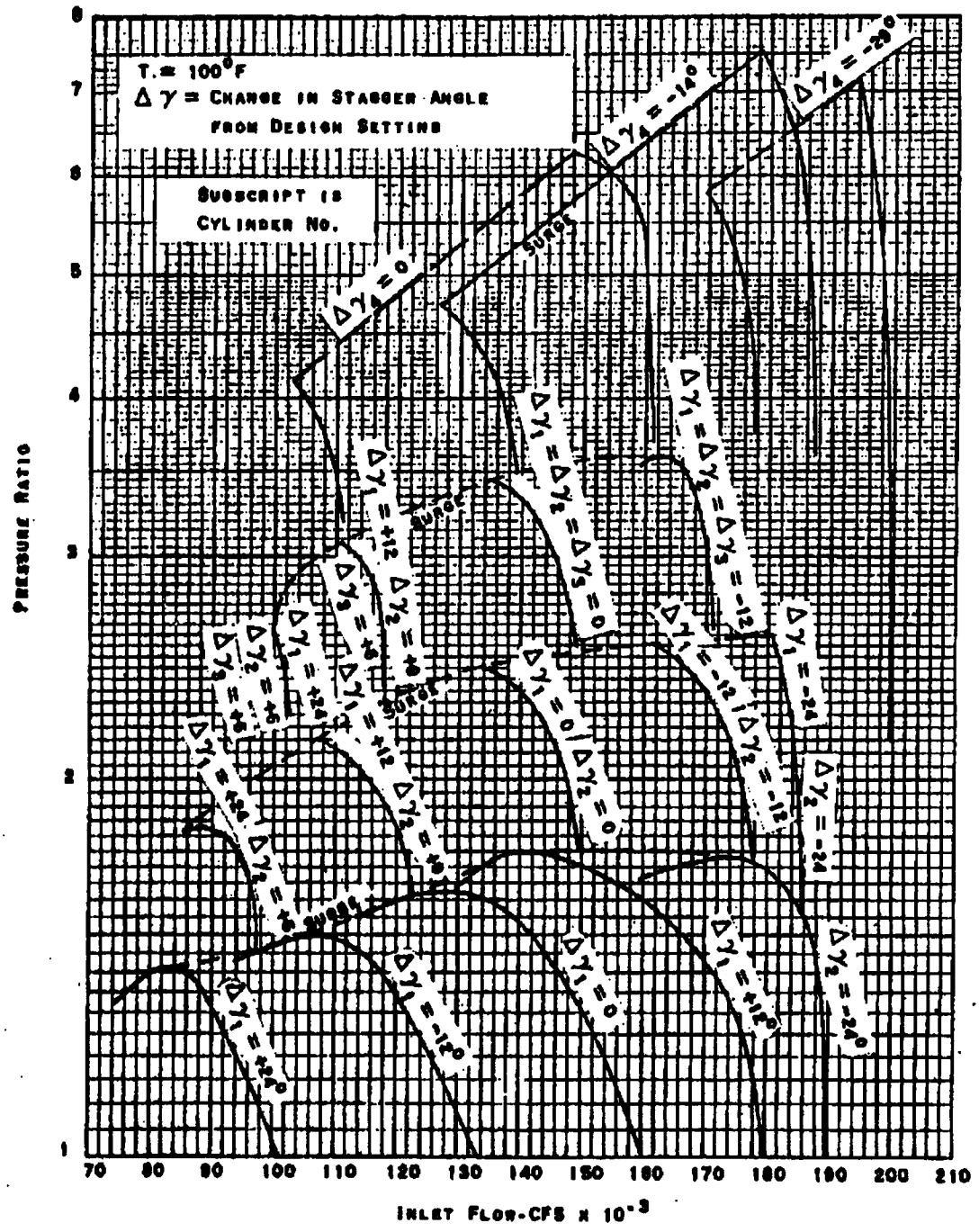

Figure 7. Supersonic Compressor Expected Performance

Source: Westinghouse Electric Corporation, "Instruction Book-Volume 4, Main Drive Equipment for the Propulsion Wind Tunnel, Supersonic Compressor", 1960.

pressure distribution in order to provide acceptably uniform test-section flowfield.

3.3 The Diffuser

The 16S diffuser has a variable-geometry section that is rectangular in cross section and is followed by a fixed geometry that includes a transition to a circular cross section. The walls are moved by hydraulic actuators to form a diffuser second-throat with the desired area ratio. The second-throat area is increased for supersonic flow establishment and then decreased to improve the diffuser efficiency. The diffuser panel placement is at less than the most efficient contour so that the shock can be located downstream of the second-throat. This prevents the shock from moving upstream too far when the model is repositioned in a manner that increases the test section blockage. The leading edge of the diffuser is positioned so that there is about a one inch gap between the diffuser and test cart wall to allow the pressure to equalize between the plenum and the tunnel circuit.

The initial rectangular area has the top and bottom panels at a fixed distance of 16 feet. The walls are divided into five panels that are hinged together. These panels are 24, 20, 16, 16, and 24 feet long. The downstream panel has a sliding joint in it to allow the change in

length required when the walls are moved to different locations. Figure 8 is a sketch of the diffuser section.

The area ratio within the diffuser is complicated by the presence of the propulsion-testing scavenging scoop. The cross sectional area of the ogive shape increases to 96 square feet toward the end of the diffuser. Geometrically the first panel of the diffuser has an angle of 5.58 degrees, however, the effective angle of divergence is only 1.25 degrees. This is based upon a cross section adjusted for the removal of the scavenging scoop area in the two-dimensional diffuser. The supersonic divergence angle is a function of the contour being used to generate the particular test-section Mach number. As the Mach number is increased, the diffuser contour is changed to move the second throat forward to allow more divergent-section length for pressure recovery. The effective angle of divergence for Mach number 1.5 would be 0.14 degrees past the second throat with the same geometric divergence angle at the intersection of panels two and three. This is caused by the scavenging scoop being a constant area in the vicinity of these panels.

If the walls were moved inward at the beginning of the diffuser for the new configuration, the actual diffuser angle would be 9.19 degrees for the first panel. However, the effective diffuser angle would be only be 4.83 degrees for the panel. Since the 16S tunnel is rarely used for

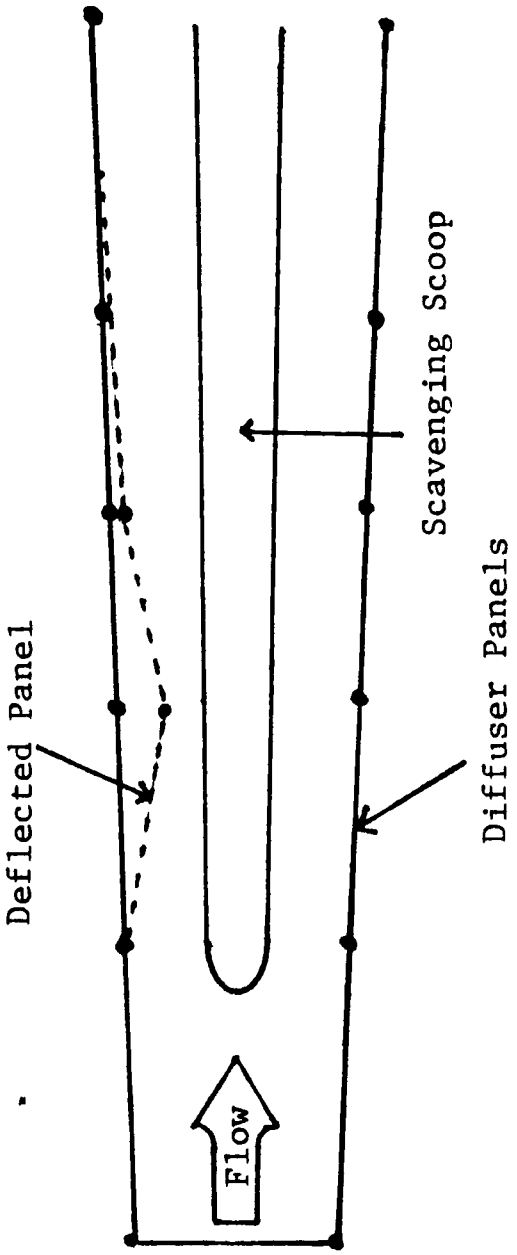

Figure 8. Current 16S Diffuser Section

propulsion testing, consideration should be given to making the scavenging scoop and associated tunnel ducting removable. This might facilitate further enhancements in diffuser performance during subsonic and transonic operations.

3.4 The Compressor

The following general physical description is quoted from the instruction book for the compressor [11] and is shown in Figure 9. It gives the original information available at construction and checkout of the 16S facility. The parts of the description that have changed and the modifications proposed will be addressed in a later part of this section.

> The Supersonic Compressor consists of four compressors arranged in tandem and designated C-2, C-3, C-4, and C-5 on the end of the drive motor shafts. The downstream three compressors C-3, C-4, and C-5 are housed inside an enlarged section of the tunnel known as the by-pass shell. Located between each of the compressors is a flexible gear type coupling which can be remotely controlled to connect and disconnect three combinations of compressors from the drive system. The compressor

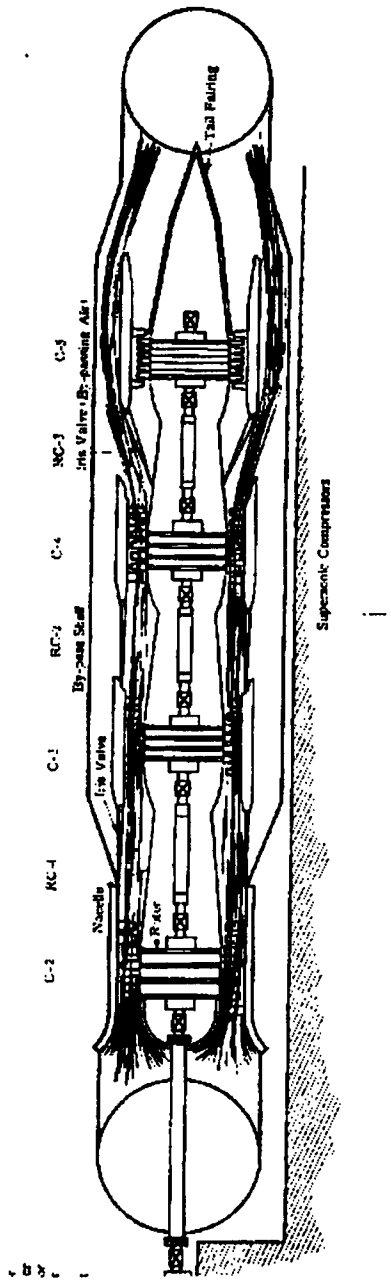

Figure 9. Compressor System

Adapted from Westinghouse Electric Corporation, "Instruction Book-Volume 1, Book 1, Main Drive Equipment for the Propulsion Wind Tunnel, Main Drive System", 1960.

combinations that can be disconnected at any one time are C-5; C-4 and C-5; and C-3, C-4, and C-5. Located between the four compressors are three iris valves for diverting the flow of air into the by-pass area around any combination of compressors that have been disconnected from the drive.

The Supersonic Compressor is a constant speed machine operating at 600 rpm.

It is designed for a volume flow of 150,000 CFS at a compression ratio from 1.20 with one compressor operation to 7.58 with four compressor operation. Compressors C-2, C-3, and C-4 are designed to control flow by adjusting the angle of attack of the stator blades.

Compressor C-5 has fixed blading of the free vortex axial flow type. . . .

The Supersonic Compressor and shafting have been designed to provide for repowering.

The downstream end of the C-5 rotor has been provided with a coupling flange for the addition of another shaft to pass through the tunnel corner

immediately downstream from the C-5 compressor. This repowering would consist of removing the present drive motor, M4, and moving it to the Northeast corner of the supersonic tunnel attaching a new shaft to the coupling flange on C-5 and passing it through the tunnel corner to the drive motor. The present M4 motor would be replaced by a new M4 of 180,000-hp capacity.

Since that writing, there have been some modifications to the 16S compressor that are worth mentioning. The first is as the result of an incident in the compressor where the iris valve between C-2 and C-3 failed. Since AEDC determined that C-2 rarely was used without C-3 in the supersonic speed regime, the iris valve between C-2 and C-3 was "hard wired" open, and the coupling between the two compressor barrels was made a fixed connection. It might be more energy efficient for the transonic adaptation if the iris valve and coupling were restored to their original capability. A trade-off study should be conducted to see if less electrical power usage and wear on the main drive motors would result from the restoration.

After the transonic adaptation is done, an additional trade-off study should be done to see if reblading the C-2 compressor would be more cost effective for the lower Mach numbers. It should consider the options of switching the

blades in C-2 out as required, or redesigning the blades in the first two or three barrels and not requiring the blades to be changed when switching between speed regimes. This might be considered a cost-effective alternative if the Main Drive System is replaced with a variable rotational speed system.

As evidenced in the aforementioned quote, there were preplanned upgrades in the original design to allow operating envelope expansion in the future. Although even today a 180,000-hp capacity is something of a pipe dream for one motor, they did make provisions for enhanced capabilities. In the next section, the Main Drive System used to power the 16-foot tunnels will be considered.

The following quote is also from [11], in the section concerning aerodynamic characteristics of the compressor. It gives information about the original concepts employed to allow operation over a large performance envelope.

> The compressor design for the Supersonic Circuit of the Propulsion Wind Tunnel was designed especially to meet the performance field defined by the United States Air Force . . . . In order to effectively cover the range of flows and pressure ratios specified, a four cylinder compressor system was used. By means of disconnect shaft couplings and iris valves, from

one to four cylinders can be used to obtain the desired pressure ratios. Controllable stator blades are utilized in the first three cylinders to achieve the necessary range of flows. The aerodynamic design of the four compressor cylinders is such as to provide a high level of efficiency over the range of stator blade angles used. . . .

. . . The compressor system must cover flows from about 130,000 to 190,000 CFM and pressure ratios from 1.4 to 7.5. Such a wide range of pressure ratios cannot be effectively obtained from a single compressor; therefore, four compressor cylinders in series were used. The design pressure ratios and inlet volume flows for the various number of cylinders in operation are listed below:

No. of Cylinders	Pressure Ratio	Inlet Volume Flow
1	1.55	150,000 CFM
2	2.34	150,000 CFM
3	3.32	150,000 CFM
4	5.45	150,000 CFM

The pressure ratio and flow shown for four cylinders is the design point with the fourth cylinder stator blades set at their design stagger

angles. In the Supersonic compressor the fourth cylinder stator blades were set at -14° from the design angles in order to obtain higher pressure ratios at high inlet volume flows. . . .

C-2, C-3, and C-4 use the "Constant Mean Swirl" (CMS) velocity diagram for the stage design. The CMS design requires that the mean swirl velocity through the stator blades is constant over the blade height. Inlet guide vanes are necessary to produce the proper prerotation into the first row of rotor blades of each cylinder. Outlet guide vanes remove the swirl following the last row of stator blades. The CMS blading design has several advantages over other types of blading, especially when controllable stator blades are used for flow control. Efficiency is high during design and off design operation, the variation in axial velocity over the blade height is not excessive, and stator blade control is effective in varying flow. . . .

Care must be taken to control the stator blades with such technique that no stage is forced to stall. In general, when increasing flow, adjust the first stages first. When decreasing the flow, adjust the last stages first. However, while the

unit is in operation, no single row should be adjusted more than 3° without adjusting the rest of the rows by a corresponding amount according to the test results.

In a high pressure ratio compressor of this type, optimum performance at off design volume flows is obtained with different angle changes for different stages. Because a change in pressure ratio usually accompanies a change in flow, the volume flow entering the last stage will be a different proportion of the inlet volume flow than it was at the design blade setting and pressure ratio. Therefore, the last stage blade angles must be changed by a different amount than the first stage blade angles.

Before I go any further, there is a question that I have posed to many of my co-workers. Namely, the flow volume is quoted as cubic feet per second (CFS) in some places and as cubic feet per minute (CFM) in others. We have agreed that, based upon the performance of the 16S wind tunnel, the terms must be in CFS.

The above quotes show the wide flow regime that the compressor was originally designed for with a Main Drive System providing a constant 600 rpm. However, I showed

previously that the volumetric flow for Mach number 0.4 would be about 98,000 CFS for the modified configuration. Why run inefficiently at the higher rotational speed in 16S as well as in 16T? This gives more credence to my proposal for the changes to the Main Drive System.

3.5 Main Drive

The Main Drive System shown in Figure 10 has four motors in tandem on a shaft with a coupling on each end of the motor system and one between motors two and three [12]. Although the system was originally designed to use only two of the motors to run either 16T or 16S, this configuration is rarely run. The normal mode is to have all of the available motors run either one tunnel or the other.

The tunnel is normally brought "on conditions" in a multi-stepped process. First, the operating configuration is determined and selected in the Main Drive Control Room. This causes interlocking and relay groups to be selected and must be satisfied before the main motors can be started. When the main motors are ready to be started, and the tunnel closed, the tunnel density (pressure) is reduced. At a predetermined pressure level, the wound-rotor induction motors (M2 and M3) are started to spin the main drive and compressor up to 600 rpm. At 600 rpm, the synchronous machines (M1 and M4) are synchronized with the remainder of

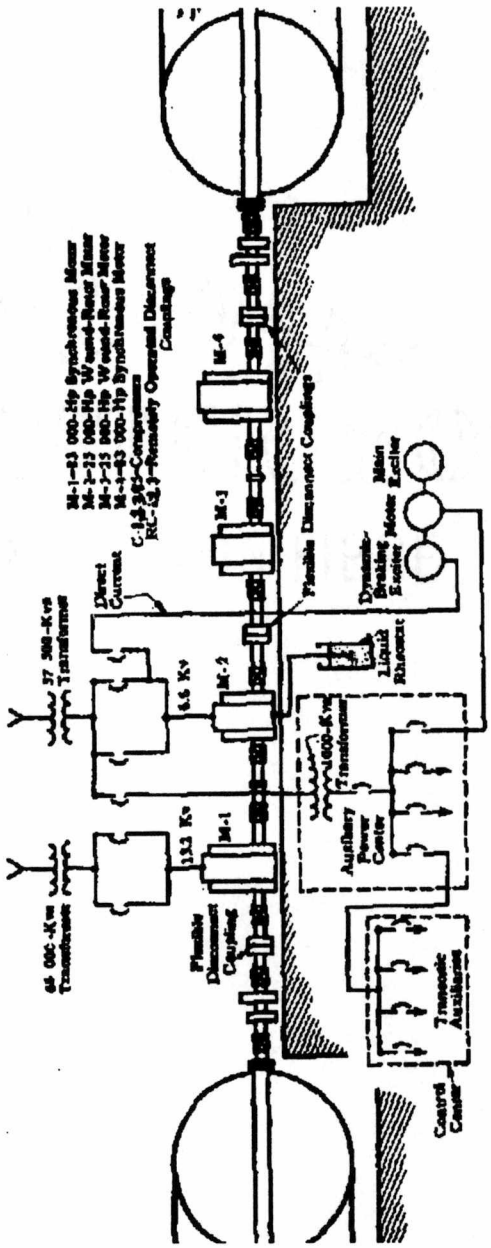

Figure 10. PWT Main Drive Motor System

Adapted from Westinghouse Electric Corporation, "Instruction Book-Volume 1, Book 1, Main Drive Equipment for the Propulsion Wind Tunnel, Main Drive System", 1960.

the drive system. After the main drive is synchronized, the electrical loads of M2 and M3 are reduced. Then the tunnel density is increased to the desired testing conditions.

The National Research Council, in its report on AEDC's future requirements, recognized the importance of the main drive system [4]. I would like to quote one of its main recommendations, which is repeated in several places in the final report.

> Because of the importance of 16T and 16S, the current demands on 16T, and the high cost of replacing the drive system (currently estimated by AEDC at several hundred million dollars for a complete replacement), the committee recommends that AEDC develop a 16T and 16S replacement main drive design, funding plan, and implementation strategy to ensure the continuing availability of these facilities. Also, a means of closely monitoring the integrity of the present drive system should be incorporated to minimize the risk of catastrophic failure.

The Council mentions in their report that replacement motors of this size require a lead time of about three years. We can see that a catastrophic failure of the main drive would be devastating to the 16 foot facilities and to the economy

of AEDC as a whole. The Council also says that the main drive system may be approaching the limit of its useful life. Additionally, they mention that the shared drive system approach has worked in the past only because of the low work load in 16S. However, they state that if the aerodynamic development of a high-speed transport vehicle came to 16S, the 16T tunnel could not maintain its current heavy work load. So we can see two reasons for developing a new Main Drive System; the need for a more reliable system, and the need for a system that can simultaneously support both 16 foot tunnels. The additional versatility of adapting 16S into a transonic facility during its low usage periods will add even more fuel to the justification fire.

What I propose for the Main Drive System is the replacement of all four main drive motors with four 100,000-110,000-hp variable-frequency motors. Between each of the motors, and between the motors and the compressors, I suggest placing couplers. This configuration would allow numerous options for running or for coping with malfunctions. In its most basic configuration, two motors would provide the power to run one of the adjacent tunnels with the middle coupler disconnected. If one of the motors were down for maintenance or malfunction, it could be removed from the drive system, a stub shaft installed, and additional adjacent motor(s) coupled as required for running the selected tunnel. If any additional motor(s) were

required in any operating condition for either tunnel, they could be coupled to the select compressor. This proposed system would be much more "robust" in its options than the current configuration.

In addition to the increase in the configuration options, there is an increase in power efficiency possible. The current configuration is dependent on the system turning at a constant 600 rpm. This means that the efficiency of the compressor is reduced at off-design conditions. This off-design envelope is quite extensive in both tunnels because of their broad speed and pressure ranges. With a variable-frequency motor, a constant rotational speed for such a broad operations band is not required. One can vary the rotational speed and power usage as required to meet the testing conditions with less off-design conditions in the compressors. This could lead to significant power-cost reductions because of the lower power consumption at on-design testing conditions. The amount of Inlet Guide Vane (IGV) and stator blade adjustments would be less, since the air flow volume would be controlled more by the rotational speed of the compressor than by the swirl of the flow going into or out of the compressor. This swirling of the inlet flow costs efficiency in the compressor power consumption. Instead of just one constant rotational speed at which to operate the drive system, the variable-frequency motor system would allow the system to operate at several discrete

rotational speeds appropriate for the Mach number and pressure ranges of each compressor.

An additional benefit of the new Main Drive System would be the enhanced operating envelope that not only 16S would realize but also 16T. Figure 11 is the 16T performance chart found in [8]. The irregular area below Mach 0.6 is the result of the requirement to use the less powerful wound-rotor induction motors for these conditions. The proposed motor system would eliminate these discontinuities as shown in Figure 12. This figure shows an initial estimate of the operating envelopes in the 16 foot facilities with the number of motors required for each condition. The total operating envelope is expanded in Figure 12 because a third 110,000-hp motor can be connected if needed to reach the upper pressure limits in the charts. The tunnel's limiting factor then is the maximum pressure that the PES ducting can handle as well as the C-1 compressor limits in the 16T circuit. The envelope for the 16'x 13' facility would be similar since the speed range and pressure restrictions would be similar. Attention would also have to be given to the amount of torque that the drive shaft was exposed to during start-up and operation at higher pressures. The system limits would shift from electrical to structural and mechanical. Performance charts would need to be developed for both 16T and 16S/16x13T. These charts would have operating bands annotated on them representing

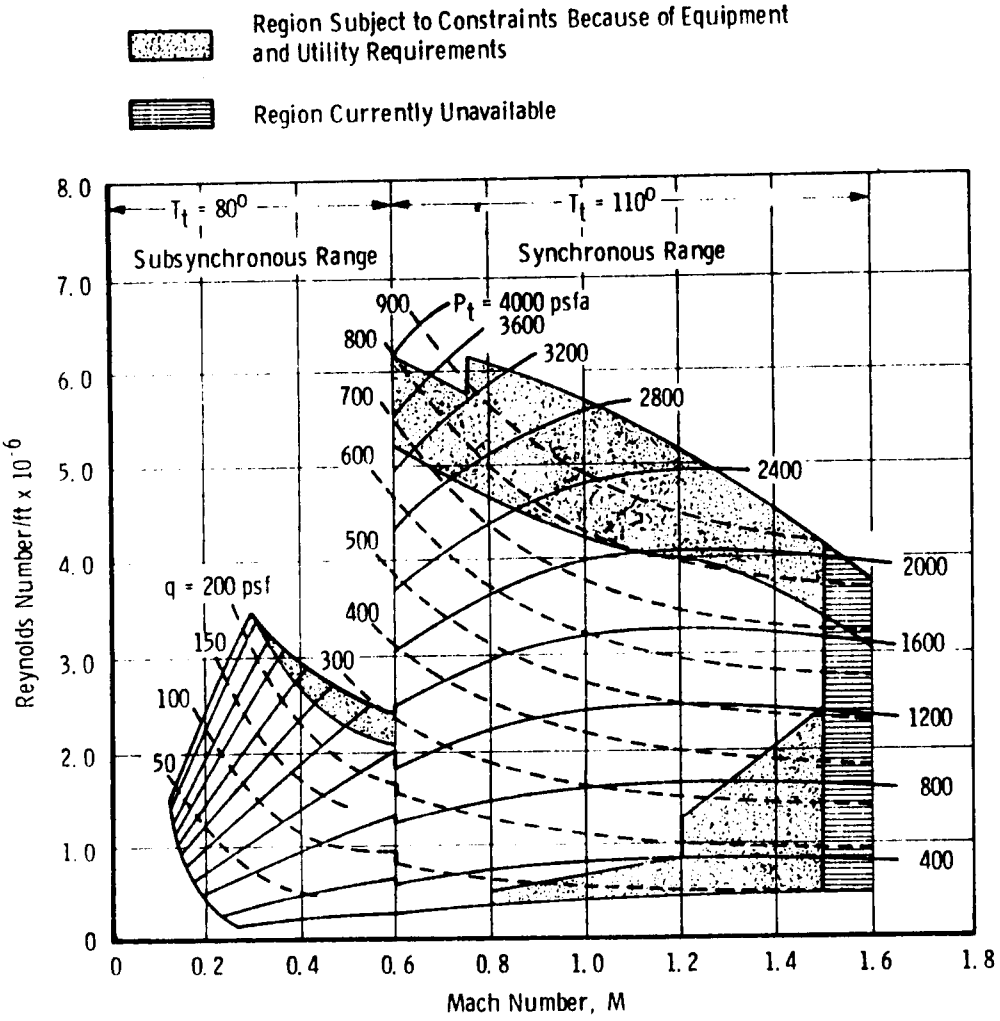

Figure 12. Performance of Tunnel 16T

Source: Arnold Engineering Development Center, "Test Facilities Handbook (Eleventh Edition)", June 1979.

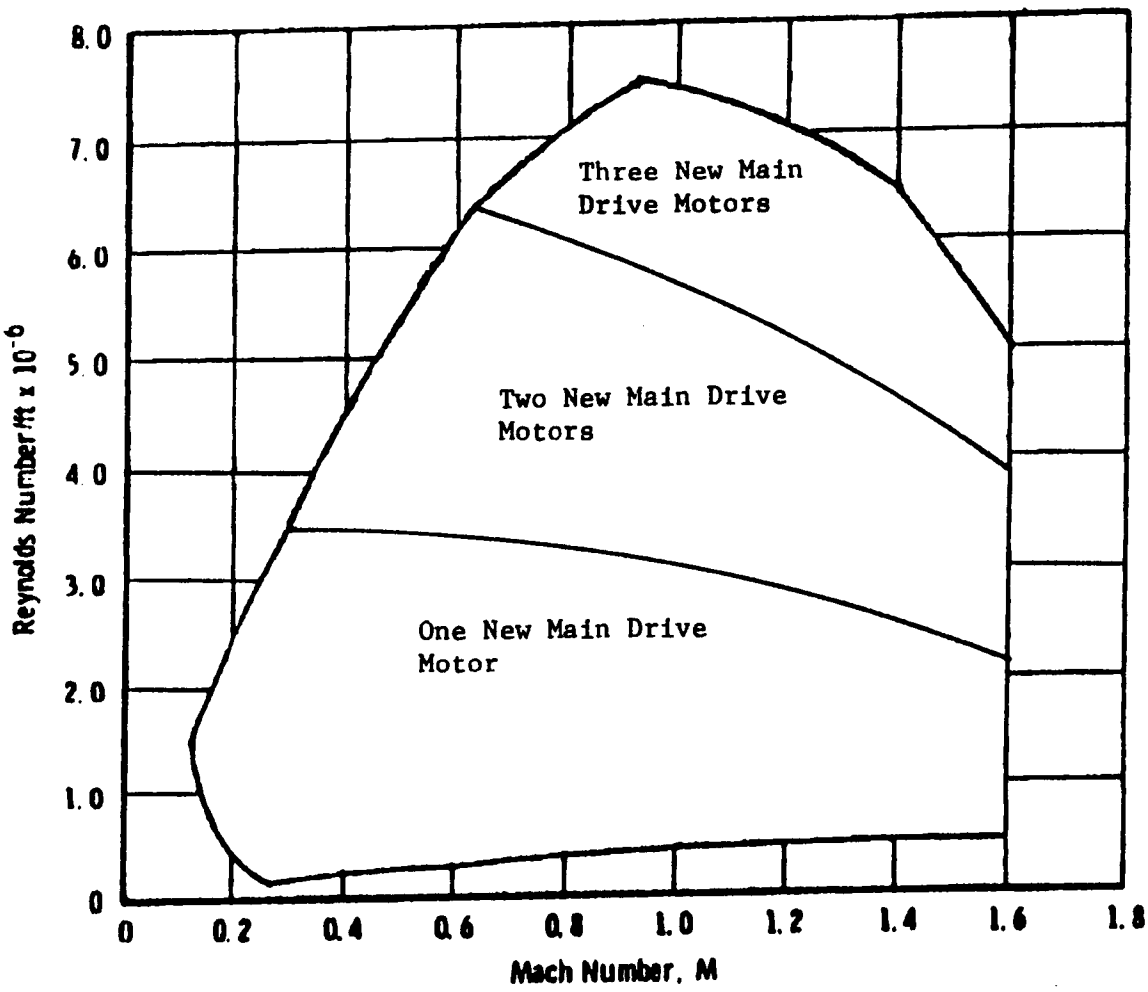

Figure 11. 16T and 16x13T Performance With New Drive Motors

Source: Arnold Engineering Development Center, "Test Facilities Handbook (Eleventh Edition)", June 1979.

the capabilities based on the number of motors connected to the compressors as demonstrated in Figure 12. Even if the decision is made not to adapt 16S for transonic use, the Main Drive System needs to be replaced with the more powerful variable frequency motors.

3.6 The Plenum Evacuation System

Even with the advent of the independent drive system (IDS) for the 4T facility, usage of PES is a scheduling problem at times. Tunnel pressurization or plenum suction required for operating just two of the PWT facilities at a time is sometimes hard to arrange. Add these requirements for the third facility in the complex, and we have a major exercise in asset utilization.

The PES recently underwent upgrading of its motors to a variable-frequency system. This allows the motor system for the PES compressors to be brought on-condition much faster. However, also recently, cracks were found in the PES compressors. During the period when the compressors were being repaired, the dependency on the PES was even more evidenced.

In order to realize the true operating potential of the additional transonic configuration of 16S, an additional compressor system for uses similar to that of the current PES needs to be built. Its primary support would be for

16T, and it could be located inside of or adjacent to the current 16T circuit. It should, however, also be interconnected to the current PES plumbing to allow usage in case of failure of the old or new PES system. In addition to the new system being built, the old PES needs to have a major refurbishment or replacement. With all of the pressurized air support required in the PWT complex, as well as the possibility of high Reynolds number facilities in the future, consideration should be given to a centralized pressurized air facility. This method of air supply is used at NASA Lewis for providing vacuum or compressed air to over 100 test cells [7]. One way or another, the PES system will need to be enhanced in the future.

3.7 Cooling Water

With all the heat that is generated in the compressors of the various wind tunnels in PWT and the nearby engine testing facilities, I would be remiss if I didn't mention the requirement for additional cooling water. For many years, the restricting factor in running various facilities at AEDC was the lack of capacity in the electrical power substation. However, that problem has been relieved with a power station upgrade. The problem that has now arisen is the lack of cooling water.

The center currently has two cooling water systems that

are used. The first one is a raw-water cooling system that uses water from Woods Reservoir. The problem with this system is the amount of water that has to be pumped and the head pressure required by the system. The heat dissipation capacity of this system is not as great as that of the other system, the cooling towers. There is a project currently in the planning stages to increase the capacity of the cooling-tower system in order to meet some of the future needs of AEDC. This project will double the capacity of the current cooling tower system.

4. NOZZLE FLOW ANALYSIS

Section 3 is based on a system-level viewpoint, but what about the flow that will result in the modified tunnel? Currently, the flow quality in 16S is considerably less than the requirements stated in Section 1.2. The National Research Council recommended that a modernization plan for 16S be developed to improve flow quality, including flow uniformity, low noise level, and low turbulence level [4]. The following preliminary analysis is based upon the assumption of uniform conditions at the approach to the throat, so the results should not be taken out of context.

The first step was to determine the coordinates for the Mach number 1.5 convergent contour and to fit them with an equation. These coordinates from [13] are shown in Table 2. Station zero is at the upwind edge of the forward test cart. The station numbers then increase toward the nozzle with the values given in feet, and the Y value is the distance from tunnel center line to the wall. I did a third order polynomial curve fit of the (X,Y) data from station 15 to station 27. Some points which will be under the fairing were included to get a smoother fit in the vicinity of the throat. The resulting polynomial equation for the wall contour in the vicinity of the throat is:

$$Y = (3.3074 \times 10^{-4}) X^3 - (5.743 \times 10^{-2}) X^2 + (3.27) X - 54.183 \qquad (19)$$

Table 2. 16S Nozzle Coordinates for Mach Number 1.5 Contour

Station	X (ft)	Y (ft)
1	4.0025	7.9861
2	8.0049	7.9720
3	12.0074	7.9578
4	16.0098	7.9435
5	20.0123	7.9289
6	24.0147	7.9141
7	28.0172	7.8991
8	32.0196	7.8811
9	36.0219	7.8420
10	40.0234	7.7558
11	43.0235	7.6531
12	46.0222	7.5155
13	48.9359	7.3492
14	51.8483	7.1611
15	54.7606	6.9708
16	57.6742	6.8027
17	60.5899	6.6775
18	63.5076	6.6095
19	66.4259	6.6162
20	69.3424	6.7189
21	72.2486	6.9794
22	75.1215	7.4855
23	77.9213	8.3032
24	80.5992	9.4589
25	83.2031	10.9507
26	85.7305	12.5704
27	88.2074	14.2661

Adapted from Electric Boat Division General Dynamics Corporation, "Basic Contours for the Supersonic Circuit Nozzle, Propulsion Wind Tunnel. Revision A", December 1958.

Sauer's [14] small-perturbation transonic flow analysis, which is also described by Shapiro [2], was then used to determine the flow characteristics in the vicinity of the throat. Figure 13 shows the nomenclature used in the Sauer analysis. For the radius of curvature at the throat, the first and second derivatives of equation 19 were found at nozzle station 18. The equation used for the radius of curvature was:

$$R_s = \frac{[1+(dy/dx)^2]^{3/2}}{[d^2y/dx^2]} \tag{20}$$

With an x_s value of 63.51 feet for the y_s value of 6.61 feet, the resulting R_s value is 89.31 feet. We can now compute the approximate flow field in the vicinity of the sonic line.

The following equations from [2] will be used to determine the geometry of the sonic line in the throat area:

$$\frac{R_0^*}{y_s} = \sqrt{\frac{1}{(\gamma+1)}\,\frac{R_s}{y_s}} \tag{21}$$

$$\frac{x_s - x^*_{wall}}{y_s} = \frac{2\,(-x_s)}{y_s} = \sqrt{\frac{\gamma+1}{9}\,\frac{y_s}{R_s}} \tag{22}$$

$$\left[\frac{d\tilde{u}}{d\left(\frac{x}{y_s}\right)}\right]_0 = \sqrt{\frac{1}{(\gamma+1)}\,\frac{y_s}{R_s}} \tag{23}$$

where $\tilde{u}$ and $\tilde{v}$ represent the perturbation velocity components

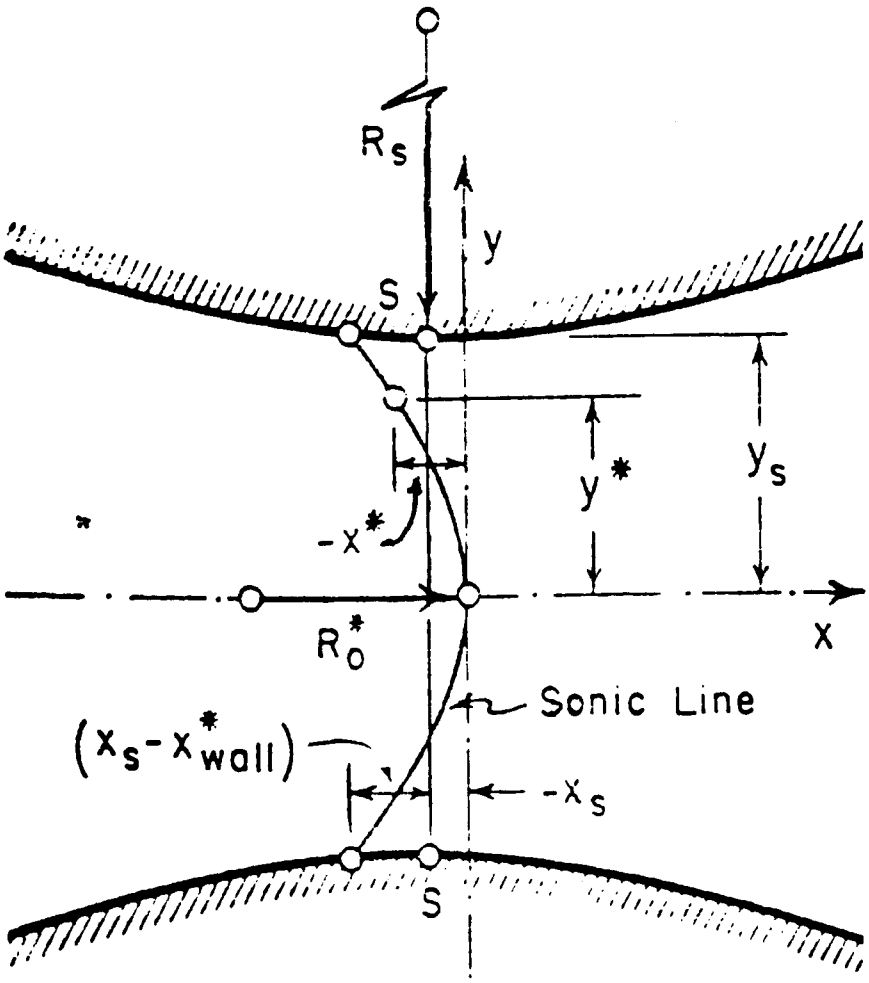

Figure 13. Nomenclature for Sonic Line in the Nozzle Throat Region

Source: Shapiro, Ascher H., "The Dynamics and Thermodynamics of Compressible Fluid Flow, Volume II", The Ronald Press Company, New York, 1954.

from a uniform, parallel flow at sonic conditions and are normalized by the speed of sound. From the current nozzle geometry, we get the values:

$$\left[\frac{d\tilde{u}}{d\left(\frac{x}{y_s}\right)}\right]_0 = 0.176 \text{ sec}^{-1}$$

$$\frac{R_0^*}{y_s} = 2.37$$

$$\frac{x_s - x^*_{wall}}{y_s} = \frac{2\,(-x_s)}{y_s} = 0.140$$

In the equations from [2] we will use the relation:

$$\left(\frac{d\tilde{u}}{dx}\right)_0 = \frac{1}{y_s}\left[\frac{d\tilde{u}}{d\left(\frac{x}{y_s}\right)}\right]_0 \qquad (24)$$

Evaluated at the minimum throat area location, $(d\tilde{u}/dx)_0$ is 0.0266 sec^{-1}. We then get the geometry of the parabolic sonic line.

Table 3 reflects the values computed from the various equations in [2] evaluated at the throat where x_s is equal to -0.4630 feet. The velocity distribution was computed along the nozzle throat plane. The equations used were:

$$\tilde{u} = \left(\frac{d\tilde{u}}{dx}\right)_0 x + \frac{(\gamma+1)}{2}\left(\frac{d\tilde{u}}{dx}\right)_0^2 y^2 + \ldots \qquad (25)$$

$$\tilde{v} = (\gamma+1)\left(\frac{d\tilde{u}}{dx}\right)_0^2 xy + \frac{(\gamma+1)^2}{6}\left(\frac{d\tilde{u}}{dx}\right)_0^3 y^3 + \ldots \qquad (26)$$

Table 3. Computed Velocity Profile Data

y_s (ft)	$\tilde{u}$	$\tilde{v}$	$\frac{V}{a^*}$	Flow Angle (deg)
0.0	-0.0123	0.0	0.9877	0.0
0.5	-0.0121	-0.0004	0.9879	-0.0227
1.0	-0.0115	-0.0008	0.9885	-0.0445
1.5	-0.0104	-0.0011	0.9896	-0.0648
2.0	-0.0089	-0.0014	0.9911	-0.0826
2.5	-0.0070	-0.0017	0.9930	-0.0971
3.0	-0.0047	-0.0019	0.9953	-0.1077
3.5	-0.0019	-0.0020	0.9981	-0.1135
4.0	0.0013	-0.0020	1.0013	-0.1138
4.5	0.0049	-0.0019	1.0049	-0.1079
5.0	0.0089	-0.0017	1.0089	-0.0950
5.5	0.0134	-0.0013	1.0134	-0.0745
6.0	0.0183	-0.0008	1.0183	-0.0458
6.5	0.0236	-0.0001	1.0236	-0.0083
6.61	0.0248	0.0000	1.0248	0.0012

$$\frac{V}{a^*} = \sqrt{(\tilde{u}+1)^2 + (\tilde{v})^2} \tag{27}$$

$$Flow\ Angle = Tan^{-1}\left[\frac{\tilde{v}}{(\tilde{u}+1)}\right] \tag{28}$$

The values in the table show the deviations of the flow velocity and angle horizontally across the nozzle throat, whereas the flow quality requirements stated in Section 1.2 are in the streamwise direction. We must also remember the following about these results:

1. They are based upon the assumption of uniform and parallel flow approaching the nozzle.

2. They are based upon a two-dimensional inviscid-flow analysis.
3. They do not take into account the corner vortex flows that actually occur a rectangular channel.

Figure 14 shows the sonic line's location based on [14].

This is only a cursory look at the ideal flow field in the proposed facility. With the flow-quality problems in the current 16S facility, I would recommend that AEDC determine the causes of this poor flow quality. This would involve interactive use of experimental measurements and CFD codes to generate the flow field in the current 16S tunnel. This would contribute to resolving the problems with today's flow, as well as provide a starting point for systematic analysis of the flow characteristics in the proposed adaptation. With the computing power and expertise that is at AEDC, the investment in CFD for this application would be small relative to the benefits achieved.

The next action would be to model the flow field in the transonic modifications. The first iteration would be based on a two-dimensional Euler method applied in the domain from the settling chamber through the nozzle to the end of the diffuser. Then a three-dimensional Euler code should be used to get more refined data. Finally, a full or parabolized Navier-Stokes solution should be obtained before the hardware modifications are finalized.

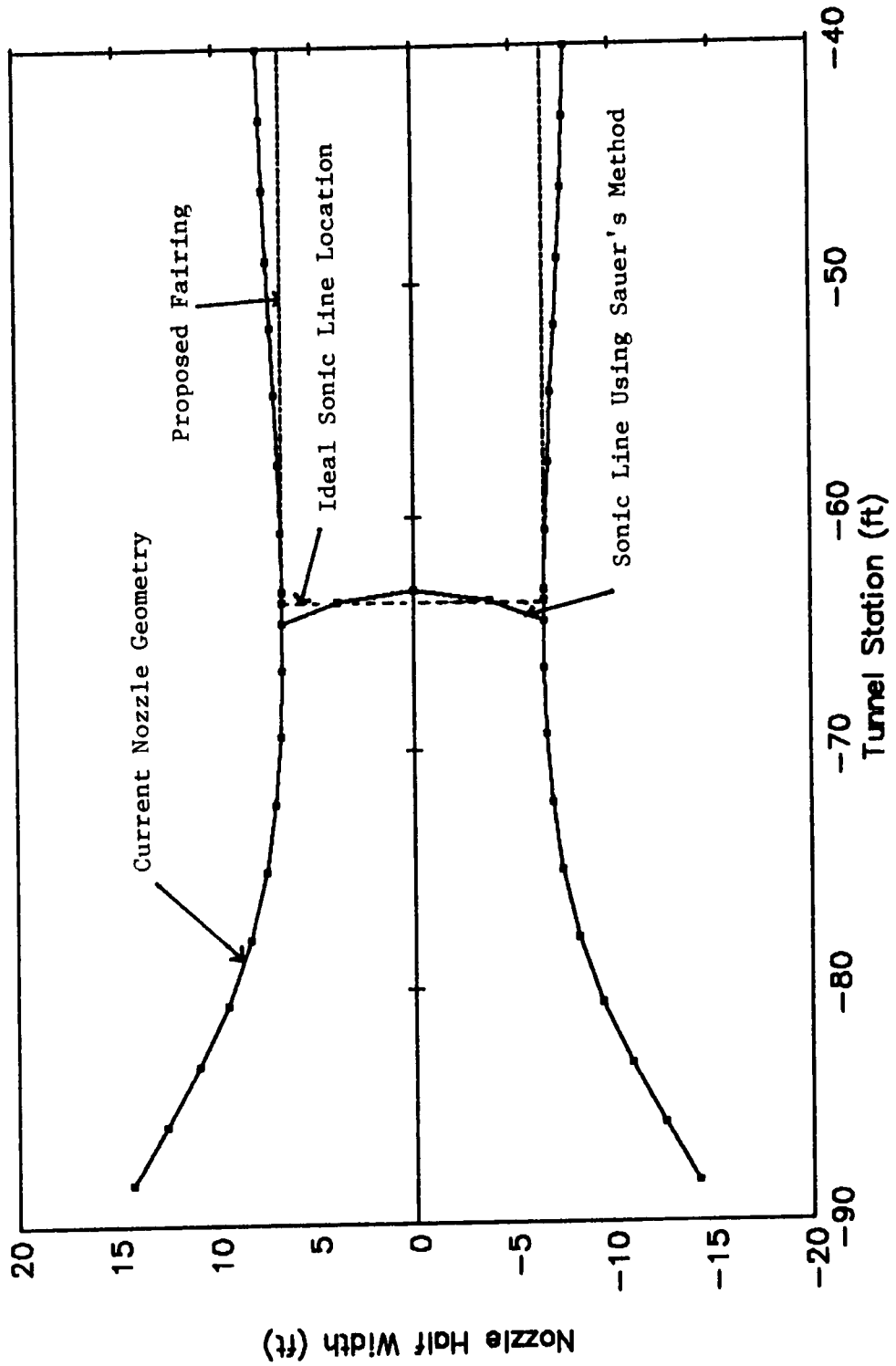

Figure 14. Sonic Line Location Based on Sauer's Method.

5. CONCLUDING REMARKS

Roepke et al. [15] give some desirable features in an optimum transonic wind tunnel that can be met by my proposed adaptation of 16S into a transonic facility. A few of these are: 1) A test section width of seven feet or more for conventional aerodynamic testing. 2) The walls must be ventilated, preferably with variable-porosity walls. 3) A continuous-operation wind tunnel is desired. They also state in their clarifications at the beginning of the paper that the average useful life of a wind tunnel facility without major refurbishment is about 25 years. However, instrumentation and computer systems have a life-cycle of about 5 years. From these assumptions, we can see that the 16S facility is long overdue for improvement, in more ways than one.

The first step that needs to be done before modifying the facility to do transonic testing is to find out what is causing the flow quality problems that exist today. There isn't any reason to change a facility when the result might be a test unit with flow quality that is poorer than the testing industry will tolerate. AEDC initially needs to implement a detailed CFD model of the facility as it is today. They also need to do serious air flow calibration and mapping at various locations in the circuit to validate and calibrate the CFD solutions and increments. After the

modeling and calibration, they can use the CFD model to investigate ways to improve the flow quality by modifications such as installing honeycombs in the settling chamber, etc.

Once the baseline flow quality in 16S has been improved, they need to continue the CFD analysis with the modeling of the constant-area channel that I am proposing. These CFD studies should concentrate on such things as the flow quality in the test section, including the pressure distribution and Mach number variations. This initial investment of manhours and computer time could save dollars and embarrassment if, without such studies, the transonic facility flow quality turns out to be unacceptable and cannot be corrected.

After the baseline facility has been improved and the CFD solutions have validated the proposed transonic adaptation, the actual changes can be implemented in the following order of importance, not cost. First, adapt the facility to transonic capabilities using the nozzle and test section inserts that will make it into an approximately 16'x 13' test facility. Next, in order to be able to run both of the 16 foot facilities at the same time and realize the benefits of increased reliability, replace the Main Drive System with the configuration that I proposed in Section 3.5. Then, preferably at the same time as when replacing the main drive system, increase and improve the capacity of

the PES. If the additional cooling towers have not yet been built, or if the cooling system is still lacking, the situation must be remedied next. After that, consider the reblading of the compressors, since the main drive replacement has possibly warranted it for increased power efficiency. Finally, improvements in the diffuser and the settling chamber should be considered.

In summary, this proposal is not a small or inexpensive undertaking. However, with the decreasing number of commercial transonic testing facilities and the need to keep 16S available as a national asset, it is a proposal whose time has come.

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VITA

Ronald K. Stonum was born in Covington, Kentucky on April 14, 1953. He attended school in Newport, Kentucky and graduated from Newport High School in 1971. In July of that same year, he entered the United States Air Force and served at various locations, both in the United States and at overseas locations, before being assigned to Ohio State University in 1983, under the Air Force Institute of Technology's Airman Education and Commissioning Program. He received the degree of Bachelor of Science in Aeronautical Engineering in March, 1986 from Ohio State University. Immediately following his commissioning as a second lieutenant, he was assigned to the National Aeronautics and Space Administration's Ames Research Center where he did research and development testing on numerous programs. He entered The University of Tennessee Space Institute in 1989, from which he graduated with a Master of Science degree in Aerospace Engineering in May, 1993.

Still on active duty, he is presently assigned to the Arnold Engineering Development Center, Directorate of Flight Dynamics Testing, Arnold Air Force Base, Tennessee.