Recent Enhancements to the National Transonic Facility (Mixed Mode Operations)

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Abstract:
The U.S. National Transonic Facility continues to make enhancements to provide quality data in a safe, efficient and cost effective method for aerodynamic ground testing. Recent enhancements discussed in this paper include the development of a Mixed-mode of operations that combine Air-mode operations with Nitrogen-mode operations. This implementation and operational results of this new Mixed-mode expands the ambient temperature transonic region of testing beyond the Air-mode limitations at a significantly reduced cost over Nitrogen Mode operation.

Recent Enhancements to the National Transonic Facility: Mixed-Mode Operation

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The National Transonic Facility continues to make enhancements to provide quality data in a safe, efficient, and cost-effective method for aerodynamic ground testing. Recent enhancements discussed in this paper include the development of a mixed-mode of operations that combine air-mode operations with nitrogen-mode operations. This new mixed-mode operations capability expands the ambient temperature transonic region of testing beyond the air-mode operation limitations at a significantly reduced cost over nitrogen-mode operation.

Nomenclature

Anz	=	LN_2 injector nozzle area
Av	=	LN_2 injection valve area setting
CMRO2	=	change in mass ratio of oxygen
Cp	=	specific heat at constant pressure
FanPower	=	fan power
h	=	heat of vaporization of liquid to a gas
K_i	=	control law gains
M	=	Mach number
MRO2	=	mass ratio of oxygen
$\dot{m}_{LN2}$	=	liquid nitrogen mass flow
N_2	=	nitrogen gas
LN_2	=	liquid nitrogen
O_2	=	oxygen gas
P_S	=	static pressure
P or P_T	=	total pressure
ΔP	=	differential pressure
Re	=	Reynolds number
T or T_T	=	total temperature
T_{STAG}	=	stagnation temperature

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T_{SET}　　= 　set point temperature
T_{SUMP}　= 　cooling water sump temperature
X_{LN2}　 = 　LN_2 injection valve command
X_W　　 = 　water bypass valve command

I.　Introduction

The National Transonic Facility (NTF) is a fan-driven, closed-circuit, continuous-flow pressurized wind tunnel used to obtain aerodynamic data on sub-scaled vehicles at subsonic and transonic speeds up through full-scale Reynolds numbers for most flight vehicles. The NTF can operate as a conventional pressurized wind tunnel using dry air as the test medium, where the free stream temperature is controlled by water-fed cooling coils located at the upstream end of the settling chamber. Additionally, the NTF can operate as a cryogenic pressurized wind tunnel using gaseous nitrogen as the test medium, where liquid nitrogen (LN_2) is injected into the circuit flow just upstream of the fan to control free stream temperature. These two modes of operation (air and nitrogen) allow the tunnel to operate at temperatures between -250 °F and 130 °F and total pressures from 15 psia to 130 psia. Using the combination of pressure and temperature, the NTF has the ability to produce high Reynolds number conditions. The compressor fan consists of a fixed pitch, single stage fan with variable inlet guide vanes. The fan drive system is powered by a variable speed motor (maximum power is 101 MW) and can operate up to 600 rpm to achieve the desired Mach number (from 0.2 up to 1.2 (currently 1.1 in air)). The fan inlet guide vanes are varied to achieve the desired fan compression ratio to obtain fine Mach number control. Figure 1 shows an operational schematic of the NTF. Shown are the unique feature of the NTF that allow it to obtain high Reynolds numbers, the LN_2 storage and injection systems, cooling tower and cooling coils, vent stack and pressure control valves.

The standard operational envelope for cryogenic nitrogen-mode operations at T=-250 °F is shown in Figure 2. This figure shows the operational range of the NTF to obtain data at high Reynolds numbers and dynamic pressures

Figure 3 shows the air-mode operational envelope for 120 °F. In air-mode, the water-cooling capacity of the cooling coils limits the ability to maintain constant tunnel free-stream temperature with some seasonal variation (typically 40 to 45 MW).[1] In this figure the maximum Reynolds number (Re) is limited to the tunnel maximum pressure limit (130 psia) for Mach numbers (M) less than 0.5. For Mach numbers above 0.5, this Re limit is due to the ability of the tunnel to maintain/control free stream temperature.

There are many transonic testing situations when the air-mode limit is reached, so in order to achieve the desired test conditions and maintain high data quality, the tunnel is switched over to the more costly nitrogen-mode of operation.

In an effort to improve tunnel performance and capability, a new concept of mixed-mode operation was developed. The purpose of the mixed-mode operation is to allow for higher Reynolds number testing at transonic speeds than available in air-mode operation and at less cost than in nitrogen-mode. Mixed-mode uses the combination of the water cooling capacity of air-mode with the cooling capacity of LN_2 injections of nitrogen-mode for free-stream temperature control.

II.　Mixed-Mode Operation

Mixed-mode operation combines the air-mode temperature control laws with a limited LN_2 injection algorithm to provide a controllable and stable free-stream temperature. No changes were required for the pressure or Mach number control laws.

A. Mixed-Mode Temperature Control Laws

The final mixed-mode design requires that the water bypass valve (See Fig. 1) under the air-mode control laws retains authority for fine temperature control at all times and the LN_2 injection provides only the necessary cooling in order to maintain the water bypass valves authority. The air-mode temperature control law is dictated by the water bypass valve command (X_w) as shown below:[2]

$$X_W = K_p(T_{STAG} - T_{SET}) + K_I \int (T_{STAG} - T_{SET}) + K_F \frac{FanPower}{(T_{STAG} - T_{SUMP})}$$

This water bypass valve command *(X_w)* consists of a proportional and integral feedback control algorithm with the addition of feed-forward fan power. Historically the air-mode temperature control law could maintain temperature control continuously for conditions up to 40 to 45 MW. Beyond these conditions, the tunnel

temperature is no longer controlled and quickly rises as heat can no longer be sufficiently removed by the cooling coils.

For the water bypass valve to remain active, the LN$_2$ injection must remove sufficient heat from the tunnel to allow the cooling water system to work near maximum cooling capability (around 43 MW). Because of the LN$_2$ systems enormous potential mass flow (1000 lb/s) and cooling power (100 MW) the mixed-mode control laws limit when and how much LN$_2$ can be injected into the tunnel. These LN$_2$ injection limits ensure operations safety and take full cost advantage of using as much of the water cooling capacity as possible. The necessary amount of LN$_2$ injection is determined when the fan power exceeds the *MaxWaterCooling* (set to 43 MW) using the following equation:

$$\dot{m}_{LN2} = K \frac{FanPower - MaxWaterCooling}{(CpT_{STAG} + h)}$$

This amount of LN$_2$ injection can then be related to the LN$_2$ injection valve area setting (*Av*) based on the LN$_2$ injector nozzle area (*Anz*) and the pressure differential between the tunnel pressure and LN$_2$ supply pressure (*ΔP*). The necessary amount of LN$_2$ flow into the tunnel can be mathematically described using the following equation:

$$\dot{m}_{LN2} = \sqrt{\Delta P} \sqrt{\frac{Av^2 Anz^2}{Av^2 + Anz^2}}$$

The relation between LN$_2$ injection valve area setting (*Av*) and the control valve command (X_{LN2}) in percentile is:

$$Av = 135(\frac{X_{LN2}}{100})^3$$

Therefore the LN$_2$ control valve command can be expressed as:

$$X_{LN2} = 100 \sqrt[3]{\frac{1}{135} \sqrt{\frac{(Anz)^2(\dot{m}_{LN2})^2}{\Delta P(Anz)^2 - (\dot{m}_{LN2})^2}}}$$

Using the above equations it is possible to determine the cooling capacity of LN$_2$ for a given LN$_2$ control valve command, nozzle valve area, tunnel pressure and temperature. From this the proper LN$_2$ injection nozzle area (*Anz*) can be determined to limit the LN$_2$ injection thereby limiting its cooling capacity. Figure 4 shows the current limitation for LN$_2$ injection where the LN2 injector nozzle area is limited to 28 individual injectors (*Anz*=14.4 lb/s/psid$^{0.5}$). Figure 4 clearly shows that the cooling capacity of the LN$_2$ injection is limited to around 30 MW (160 lb/s of LN$_2$ injection) when the LN$_2$ control valve is near fully open. Therefore during mixed-mode operations the tunnel operational limit at higher Mach numbers is the combination of 43 MW of cooling water and up to 30 MW of LN$_2$ injection cooling allowing the tunnel to operate up to 70 MW under normal conditions.

B. Mixed-Mode Safety

The combining of air-mode and nitrogen-mode operations at the NTF presented several potential safety issues that needed to be addressed in its implementation to avoid any potential dangers to the facility.

To ensure safety, the facility is set up for full nitrogen operations in terms of facility oxygen monitoring, tunnel and building access procedures. New mixed-mode procedures and processes were developed and implemented that allowed the cooling water systems and the LN2 systems to operate together under specific tunnel constraints.

The injection of LN$_2$ into the tunnel presented the potential for large temperature gradients and the remote potential for freezing of the water in the cooling coils. To avoid these potential problems mixed-mode control laws limit the injection of LN$_2$ to specific tunnel conditions. Mixed-mode is only available when the free-stream temperature is above 100 °F and the fan power is greater than 43 MW. With these conditions, there is enormous heat (43 MW) and mass flow (over 1000 lb/s) in the circuit, therefore the limited LN$_2$ injection (less than 160 lb/s) has such a smaller enthalpy therefore the stream only sees a few degrees of cooling from nominal 120 °F. Hence, as

long as fan power is greater than 43 MW and the LN_2 mass flow is no more than 160 lb/s, eliminates the possibility of freezing water in the cooling coils and reduces the possibility of temperature gradients.

C. Mixed-Mode Operation

For mixed-mode operations, the tunnel is brought on-line and pressurized using dry air to the pressure set point. The tunnel is then thermally conditioned with dry air until the temperature set point is achieved (typically 120 °F) using 5 to 10 MW of fan power. Once the tunnel reaches thermal equilibrium, data runs are performed using the dry air in-bleed to control pressure and the cooling water bypass valve to control temperature. As the data runs continue to higher Re or M, the cooling water bypass valve runs out of authority (40 to 45 MW) and any further increase of power results in a rapid temperature rise.

Upon reaching 43 MW, the mixed-mode control laws automatically start injecting limited amounts of LN_2 into the tunnel in addition to the dry air. The entire process is monitored using the display screen shown in Figure 5. LN_2 injection is limited to sufficiently offset the additional heat in order to return temperature control authority to the water bypass valve. Limited LN_2 injection continues to increase as the tunnel power increases up to 70 MW. As the fan power decreases, the LN_2 injection decreases and eventually is stopped as the tunnel power drops below 43 MW.

Figure 6 shows the increased capability of mixed-mode operations to achieve higher Re than air-mode operations. The section labeled "Water Cooling" is the capability of the air-mode that is limited to 43 MW. It can be seen how mixed-mode provides increased Reynolds number capability at transonic speeds.

III.   Mixed-Mode Data Computations

The NTF has been hitherto restricted to work in either air-mode (with ~80% nitrogen and ~20% oxygen), or nitrogen-mode (with 100% nitrogen). In mixed-mode, the nitrogen volume percentile is allowed to vary from 80% to 100%, and consequently oxygen will vary from 20% to 0%. The instantaneous changes in the N_2/O_2 concentrations need to be measured and accounted for in applying real gas corrections to tunnel parameters.

To measure this oxygen level change a high performance compact paramagnetic oxygen analyzer (California Analytical Instruments® Model 110P Oxygen Analyzer) is used at the NTF. Using this O_2 content information the data reduction program calculates the tunnel reference quantities using the proper real-gas corrections based on the actual test gas composition. These corrections are for molecular weight of the test gas mixture, Equations of State Constants (using Beattie-Bridgeman Equation of State), viscosity, thermal conductivity and several other parameters. The corrections are determined by performing a linear interpolation between the constants for nitrogen and the constants for dry air based on the change of the mass ratio of oxygen (CMRO2) as described in Reference 3 where:

$$CMRO2 = \frac{(MRO2_{air} - MRO2_{mixture})}{MRO2_{air}}$$

$MRO2_{air}$ is the mass ratio of O_2 in air and $MRO2_{mixture}$ is the mass ratio of O_2 in the mixture test gas.

To show the effects of the decreasing oxygen content in the test gas on the tunnel reference quantity calculations, data reduction trial computations were performed at constant tunnel conditions (P_T=50 psia, P_S=30 psia, and T=120 ºF) while decreasing the oxygen content from 21% (dry air) down to 0% (pure nitrogen). The table below shows the effect of the decreasing oxygen content on the molecular weight, the Beattie-Bridgeman constants, the viscosity, and the thermal conductivity using the CMRO2 for a linear interpolation between air and nitrogen.[3]

Data Reduction Trial – P_T = 50 psia, P_S = 30 psia, T = 120 ºF						
	Air	*15% O₂*	*10% O₂*	*5% O₂*	*1% O₂*	*Nitrogen*
Molecular Weight (g/mole)	28.960	28.695	28.468	28.241	28.059	28.0134
CMRO2	0.0	0.27867	0.51527	0.75569	0.95082	1.0
Beattie-Bridgeman Constants	A_0 = 1.30120 a = 0.01931 B_0 = 0.04611 b = -0.01101 C = 43400	A_0 = 1.3133 a = 0.02122 B_0 = 0.04732 b = -0.00987 C = 43010	A_0 = 1.3235 a = 0.02285 B_0 = 0.04835 b = -0.00890 C = 42679	A_0 = 1.3339 a = 0.02449 B_0 = 0.04940 b = -0.00791 C = 42342	A_0 = 1.3424 a = 0.02583 B_0 = 0.05025 b = -0.00711 C = 42069	A_0 = 1.34450 a = 0.02617 B_0 = 0.05046 b = -0.00691 C = 42000
Viscosity (kg/cm-sec)	0.17416	0.17295	0.17193	0.17089	0.17004	0.16983
Thermal Conductivity (kW/cm-ºK)	0.24514	0.24492	0.24473	0.24454	0.24437	0.24434

There are also thermodynamic property equations for entropy, enthalpy, specific heats at constant volume and constant pressure, which are used to calculate the Mach number, Reynolds number, and dynamic pressure. They are not presented here as they are beyond the scope of this document and these equations are not directly affected by the mixed-mode of operation.

Figure 7 and 8 show how this variation in oxygen content effects the calculations for Mach number and Reynolds number. For this particular case of tunnel conditions, the Mach number started at M=0.88572 at the 21% O_2 and dropped to M=0.88561 at the 0% O_2. Only a change of 0.00011 in Mach number or about a 0.0124% decrease occurred. This slight variation in the Mach number is due to real-gas effects at the elevated pressures. For Reynolds number, the Reynolds number started at Re=13.445 million/ft at the 21% O_2 and increased to Re=13.56 million/ft at the 0% O_2 content. Only a change of 0.115 million/ft in Reynolds number or about a 0.855% increase occurred. This change though small, does make sense physically because nitrogen has a slightly lower viscosity and a slightly higher density than air, so the Reynolds number will increase as the oxygen content decreases.

The effects of the decreasing oxygen content at near ambient temperatures are very small on Mach number and Reynolds number; however, it is still a correction that needs to be applied. The effects on other tunnel parameters were also examined but are not presented because the differences were also very small.

A similar analysis was performed using actual tunnel data acquired during a Check Standard test (Test 156), during the first implementation of mixed-mode operation. The data was acquired at tunnel conditions of M=0.8, P_T=45 psia, T_T=120 ºF, and Re=11.6 million/ft. When this data were acquired, the oxygen content was already down to about 6.5% and gradually decreased to about 1.5%. The corrections to Mach number and Reynolds number for decreasing oxygen content were again very small as shown in Figures 9 and 10. They were on the order of 0.0001 in Mach number and on the order of 0.08 million/ft in Reynolds number.

IV.   Mixed-Mode Operational Performance Analysis

Because of the extra cooling that is provided by the injection of LN_2 in mixed-mode, the operational envelope for ambient temperature operations at the NTF is expanded. Figure 11 shows a detailed version of the expanded NTF operational envelope. This figure shows several of the total pressure curves, the fan power curves, and the dynamic pressure curves, along with a series of conditions run for customers in mixed-mode in evaluation of the mixed-mode performance at Reynolds numbers between 13 and 14 million/ft.

A. Comparison of Mixed-mode and Nitrogen-mode

The major advantage of mixed-mode over warm nitrogen-mode is the savings in LN_2 used. To operate the NTF at fan powers of 43 to 70 MW in nitrogen-mode at ambient temperatures requires 200 to 350 lb/s of LN_2 injection to offset the fan power heat. In contrast, for mixed-mode operations only 0 to 160 lb/s of LN_2 injection is required

because the water cooling coils takes most of the burden of removing the fan power heat. Overall, the LN_2 injection flow rates in mixed-mode are about one-third of the flow rates in nitrogen-mode.

The lower LN2 flow rates translate to a lower total amount of LN_2 used to complete a series of runs. Figure 12 shows the total amount of LN_2 used to complete several run series during a test. It also shows the pre-test estimates of the amount of LN_2 needed to complete each run series in mixed-mode or in nitrogen-mode. Clearly, the LN_2 usage in mixed-mode is much less than what would have been required in nitrogen-mode for each run series. In fact, for the five run series shown in Figure 12, over 3100 tons of LN_2 were saved by running the series in mixed-mode instead of nitrogen-mode.

There was a concern by a customer on whether the force and moment data acquired in mixed-mode compared well with data acquired in nitrogen-mode. Therefore, a comparison data set was collected using the same model configuration at the same conditions (M=0.7, T_T=120 ºF, and Re=14 million/ft) for mixed-mode and nitrogen-mode. The mixed-mode runs were done 14 days after the nitrogen-mode runs. Figure 13 shows that these runs repeated very well as expected with each other. C_D repeated within 2 drag counts when plotted against C_L. Similar results were obtained for C_D, C_L and C_M when plotted against alpha.

B. Mixed-mode Performance

A series of tests were performed in 2005 to fully develop the capabilities of mixed-mode of operation and establish operational performance limits.   The analysis presented here is for a series of mixed-mode runs at 120 ºF, with Mach numbers between 0.84 and 0.94, and Reynolds Numbers between 13 and 14 million/ft. These conditions corresponded to fan powers from 60 to 75 MW which meant that the mixed-mode operation was pushed to its limits.

Figures 14 shows the tunnel conditions that were achieved during these runs and the variation in fan power, Mach number, pressure and dynamic pressure over a one hour period. The fan power during the runs is well above 60 MW and increases up to 76 MW, clearly these conditions could only be achieved with mixed-mode operations.

Figure 15 shows the cooling performance during these runs. Presented are tunnel free-stream temperature and the corresponding control valve commands. One can see that as the LN_2 control valve is opened the water bypass valve closes but continues to provide a smooth active control in order to maintain tunnel temperature (0% on the water bypass valve means maximum cooling capacity). There are some interesting observations that can be made. First, some of the runs went above 70 MW and the stream temperature was being held relatively constant. This was possible because these runs were done during autumn with cooler temperatures so the cooling coil had a slightly higher cooling capacity. Finally, the runs were sequenced in decreasing fan power requirements, so that the runs with the highest required fan power were done first before the tunnel and cooling tower warmed up, which ensured that the stream temperature would still be controllable. During the highest fan power runs (76 MW), the cooling coil was at its maximum cooling capacity and LN2 injection (140 lb/s) was at its maximum. This is evident in the water bypass valve plot and the LN_2 valve plot in Figure 15. Even with all of this cooling, the stream temperature did steadily rise during each run about 3 ºF.

Figure 16 shows the LN2 injection flow rate and the oxygen volume ratio during these runs. The oxygen ratio went from 21% to start all the way to 3% during the first run. The subsequent runs steadily dropped the oxygen ratio down to 0% meaning the tunnel was full of nitrogen. The LN_2 flow rate varied between 110 to 140 lb/s.

V.   Conclusions

Mixed-mode operation at NTF has been successfully implemented and used for customer testing. As shown in Figure 6 the mixed-mode operation provides an efficient method of obtaining higher Reynolds numbers at ambient temperature (120 °F) without the complexities and costs of nitrogen-mode operation.

VI.   Acknowledgements

VII.   References

[1]Kilgore, W. Allen, Balakrishna, S., Bobbitt. C.W., and Underwood, P.; Recent Enhancements to the National Transonic Facility (Invited), AIAA-2003-0754, 41st AIAA Aerospace Sciences Meeting and Exhibit, January 2003.
[2]Kilgore, W. Allen, and Balakrishna, S.: Controls of Large Cryogenic Wind Tunnels, Study of the National Transonic Facility Controls, NASA Contractor Report 194977, September 1994.

[3]Foster, Jean M., Adcock, Jerry B., "Users Guide for the National Transonic Facility Research Data System", TM-110242, April 1996.
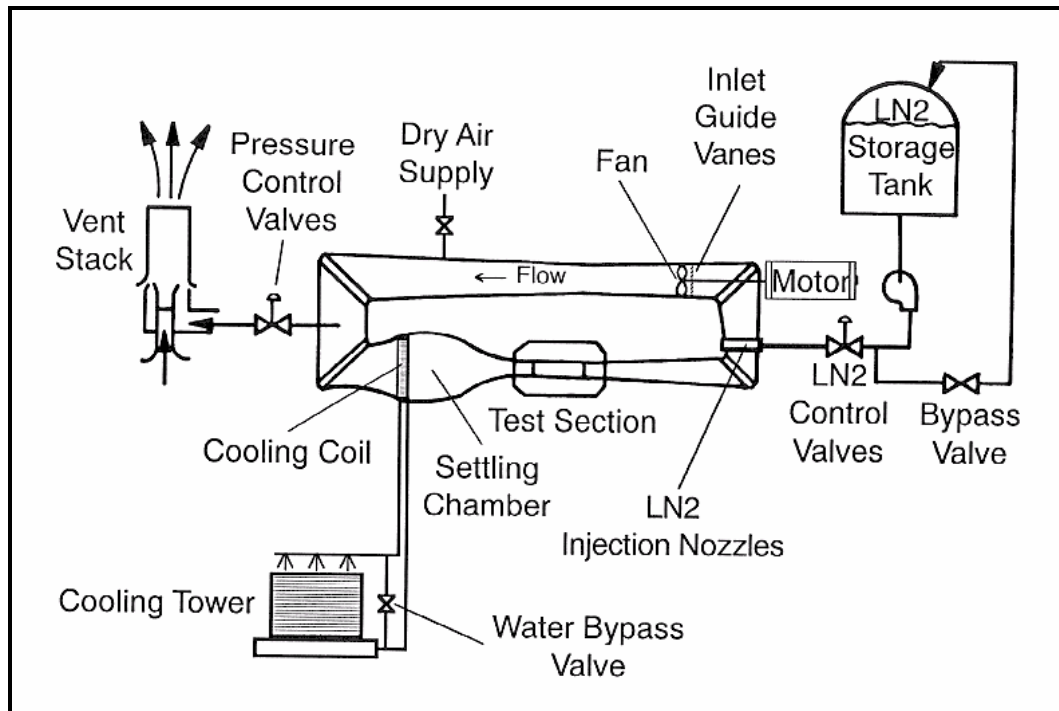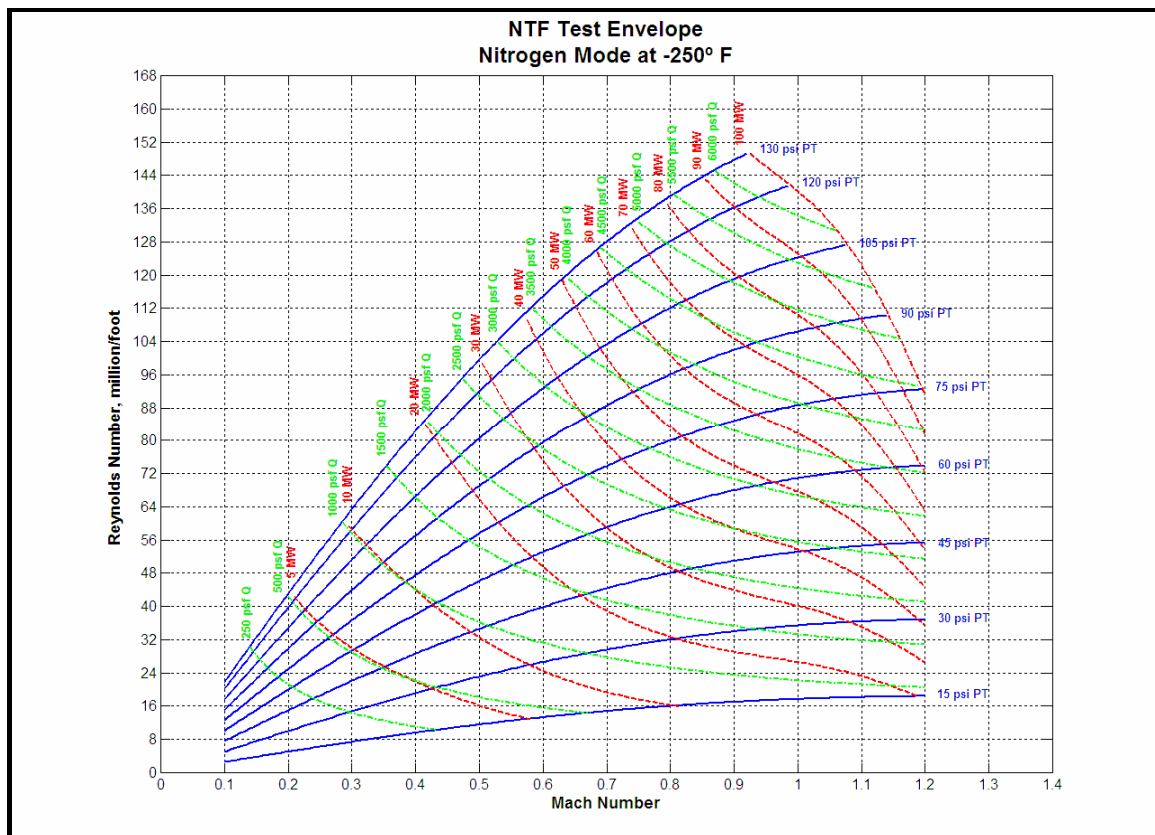

Figure 1 – NTF Operational Schematic

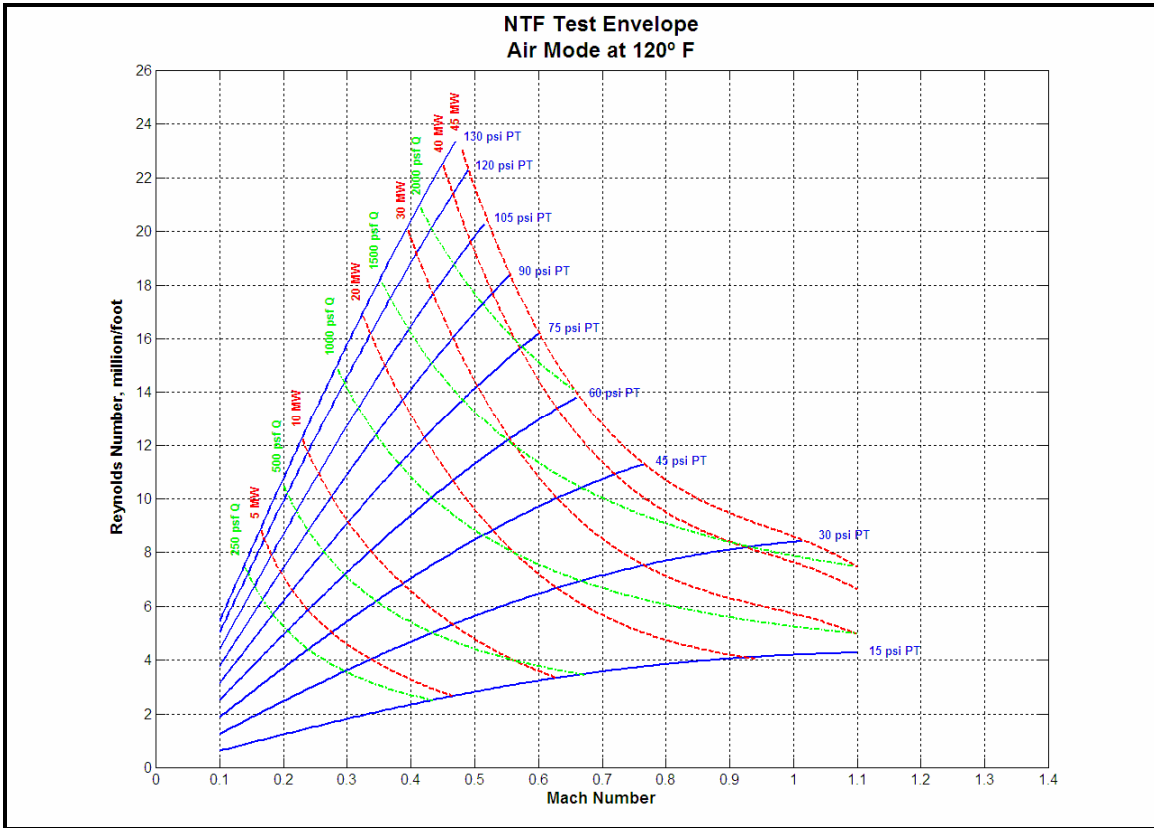**Figure 2 – NTF Test Envelope for Nitrogen Mode**

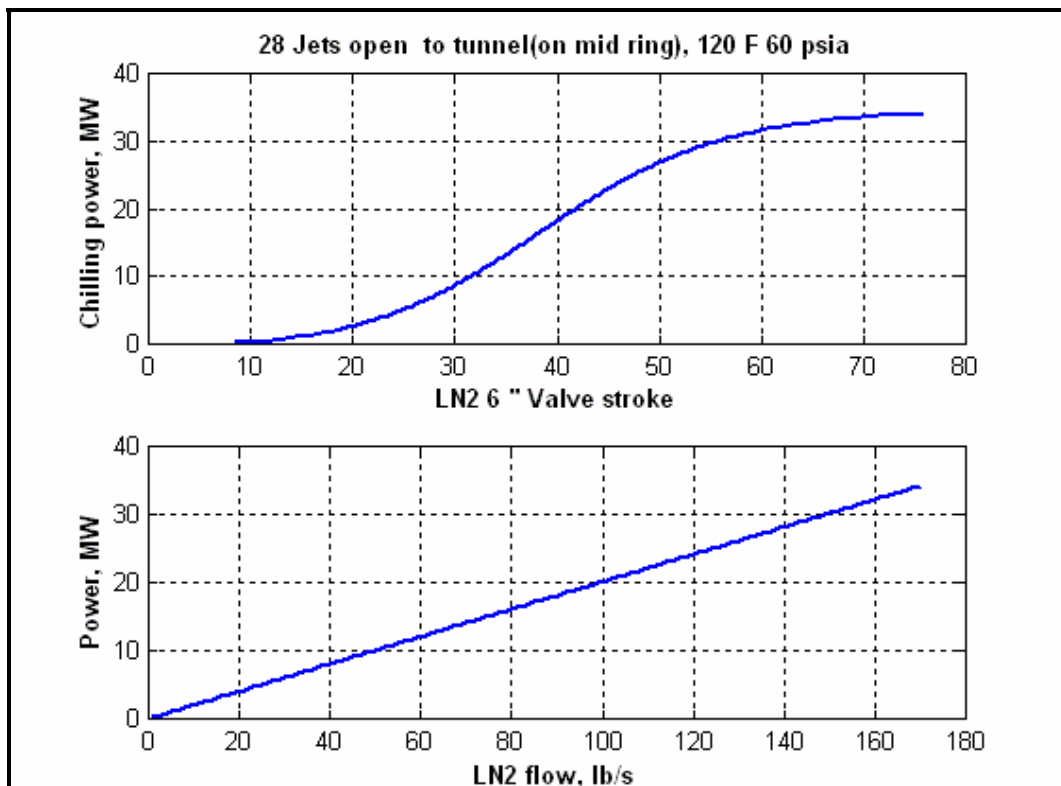**Figure 3 – NTF Test Envelope for Air Mode**
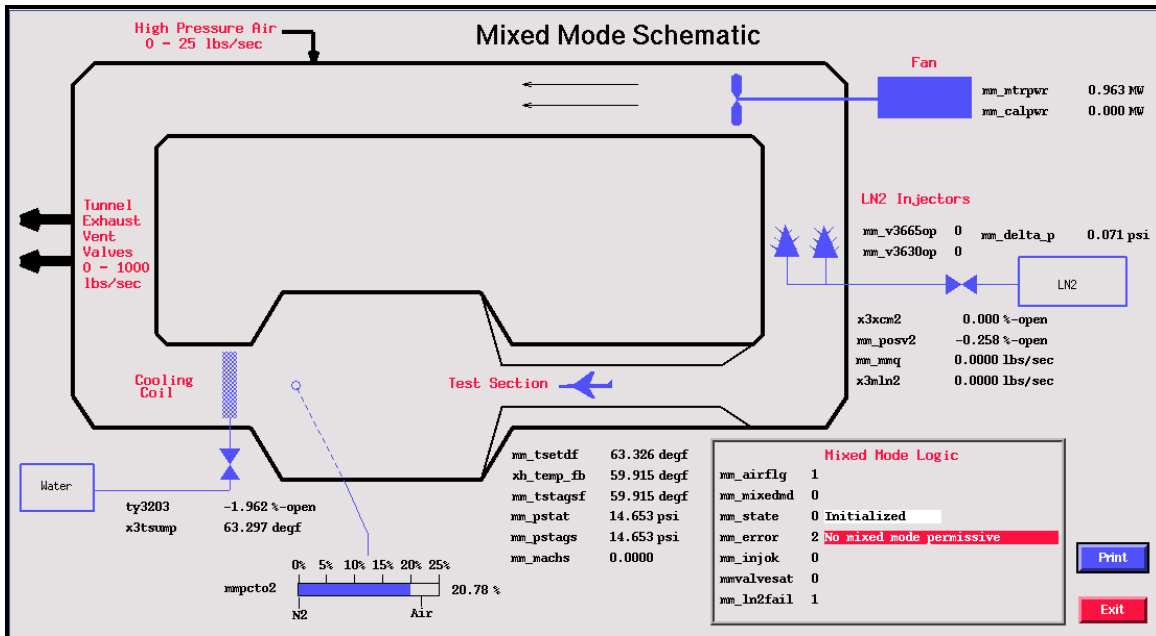

Figure 4 – Mixed Mode - Liquid Nitrogen Flow Limits
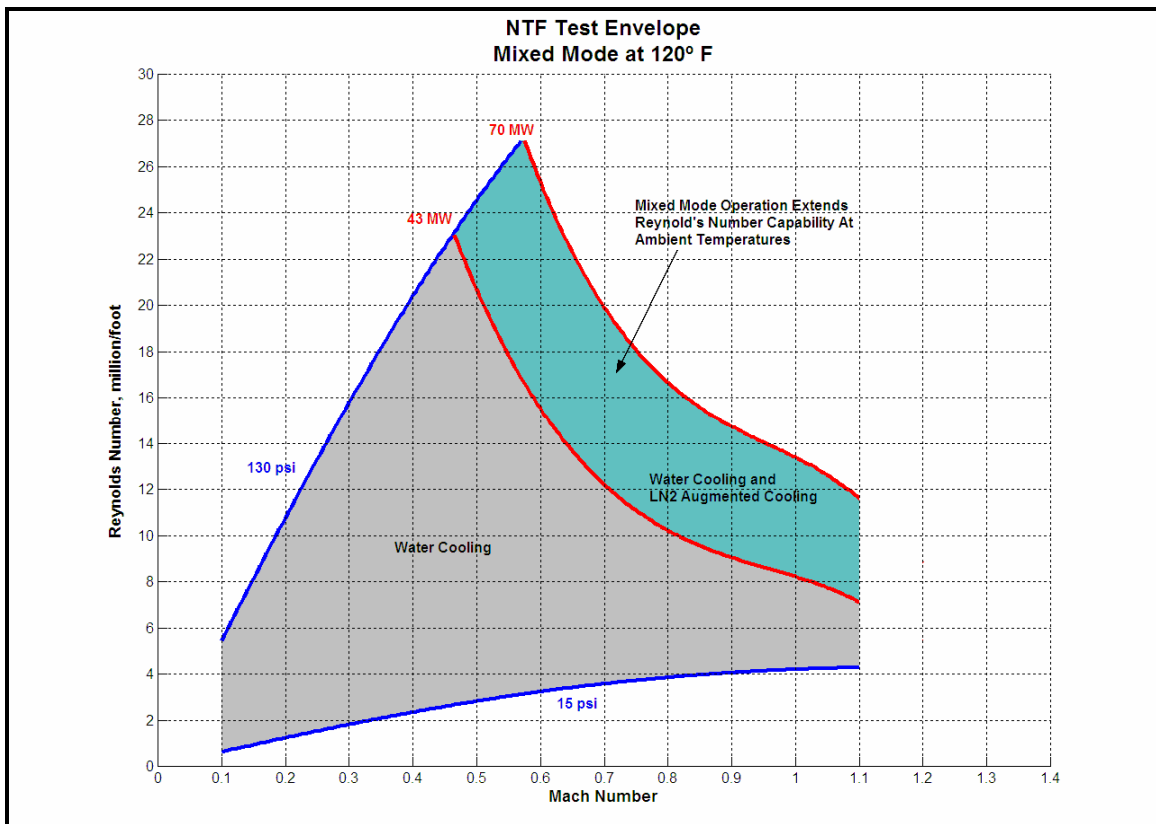
8

Figure 5 – Mixed Mode Operation Display
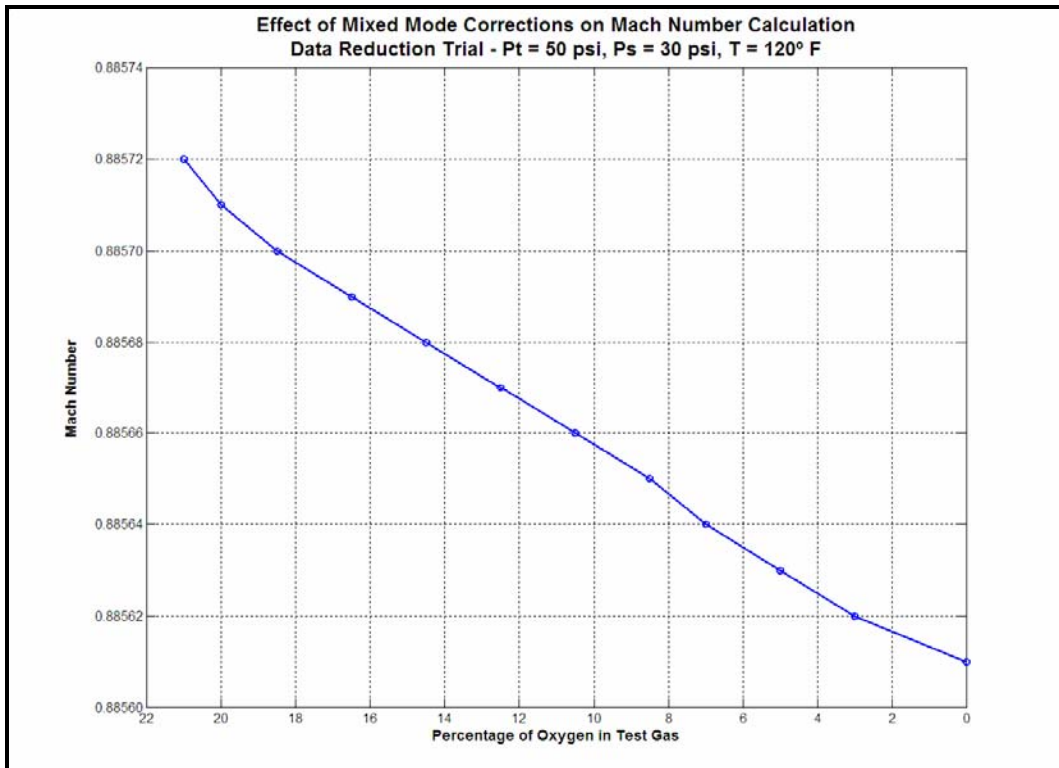

Figure 6 – NTF Test Envelop for Mixed Mode

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Figure 7 – Change in Mach No. for Percent of Oxygen
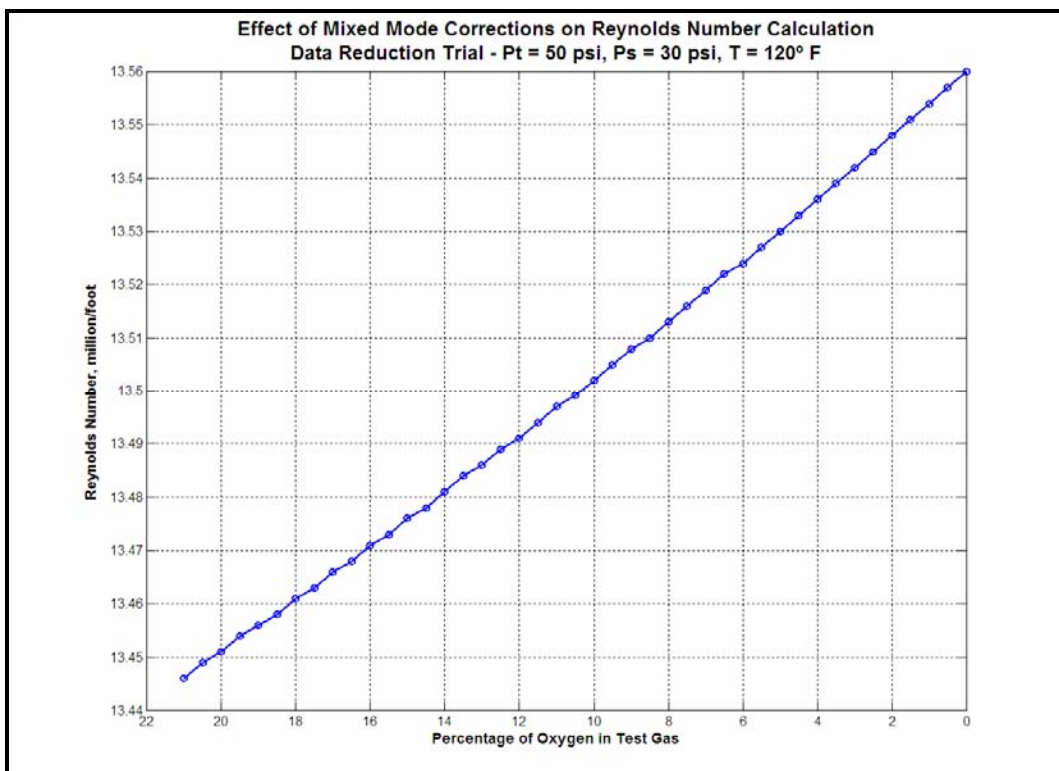
Figure 8 - Change in Reynolds No. for Percent of Oxygen
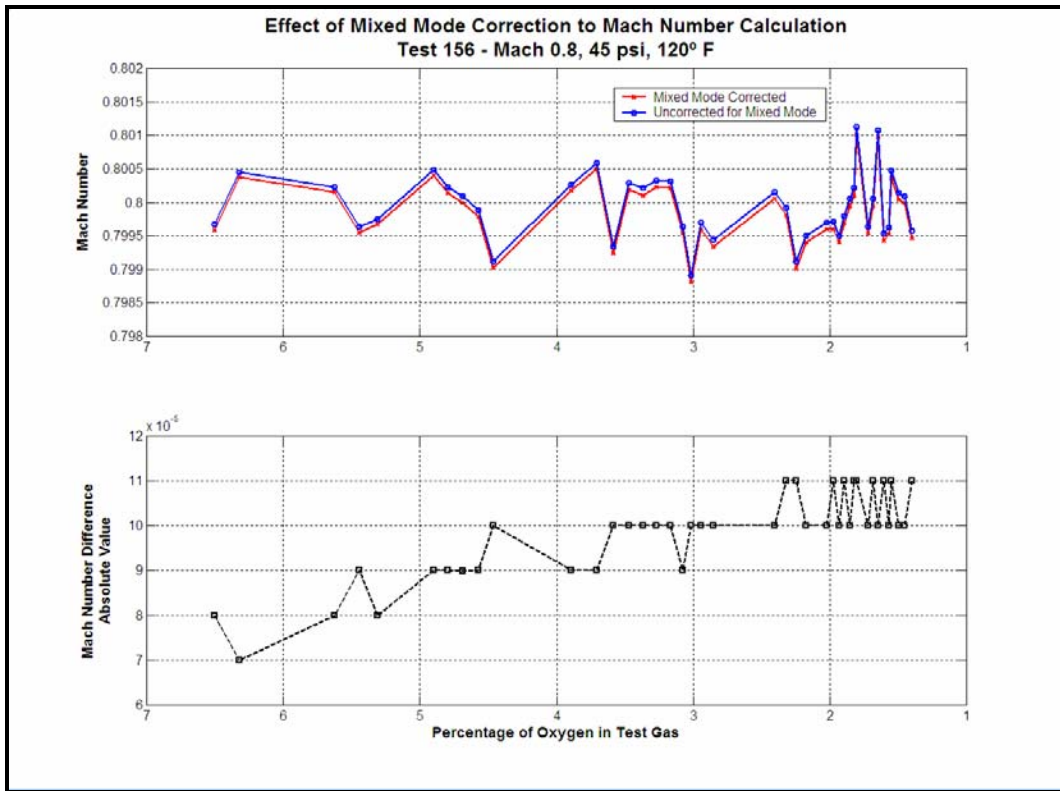
Figure 9 – Mixed Mode Corrections to Mach No.
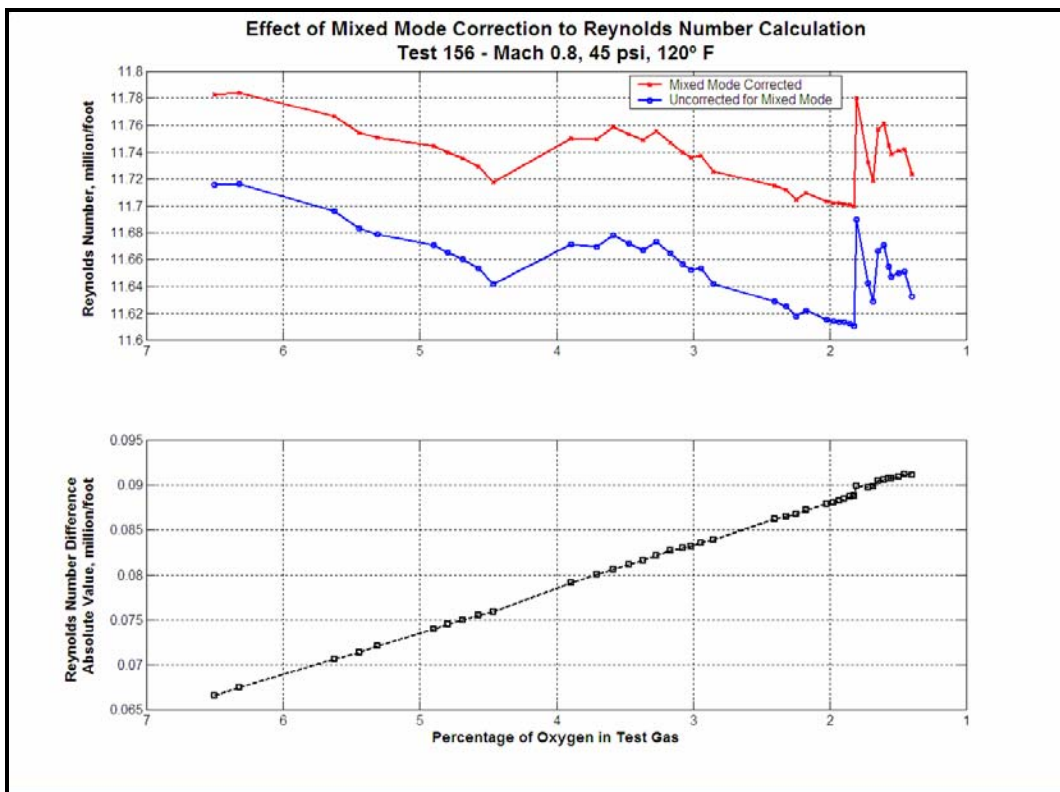
Figure 10 – Mixed Mode Correction to Reynolds No.
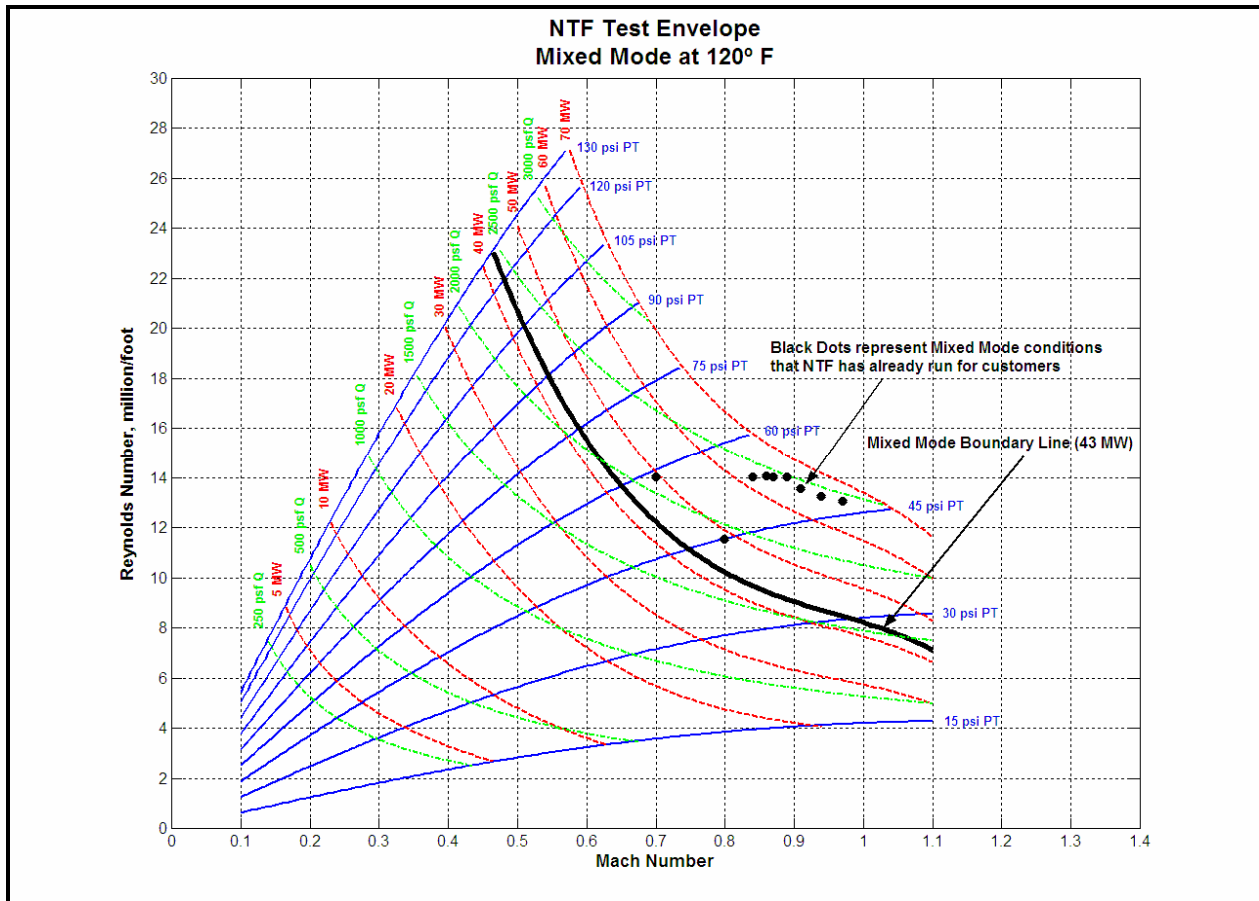
Figure 11 – Detailed Mixed Mode Test Envelope
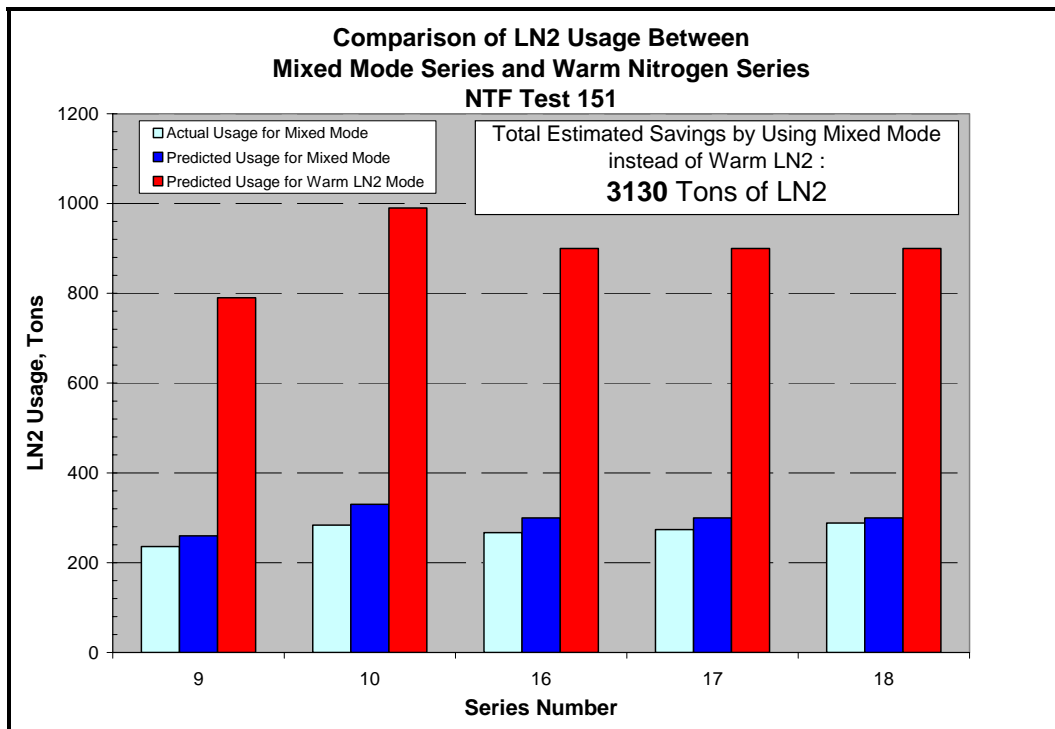
Figure 12 – Mixed Mode Nitrogen Usage Savings
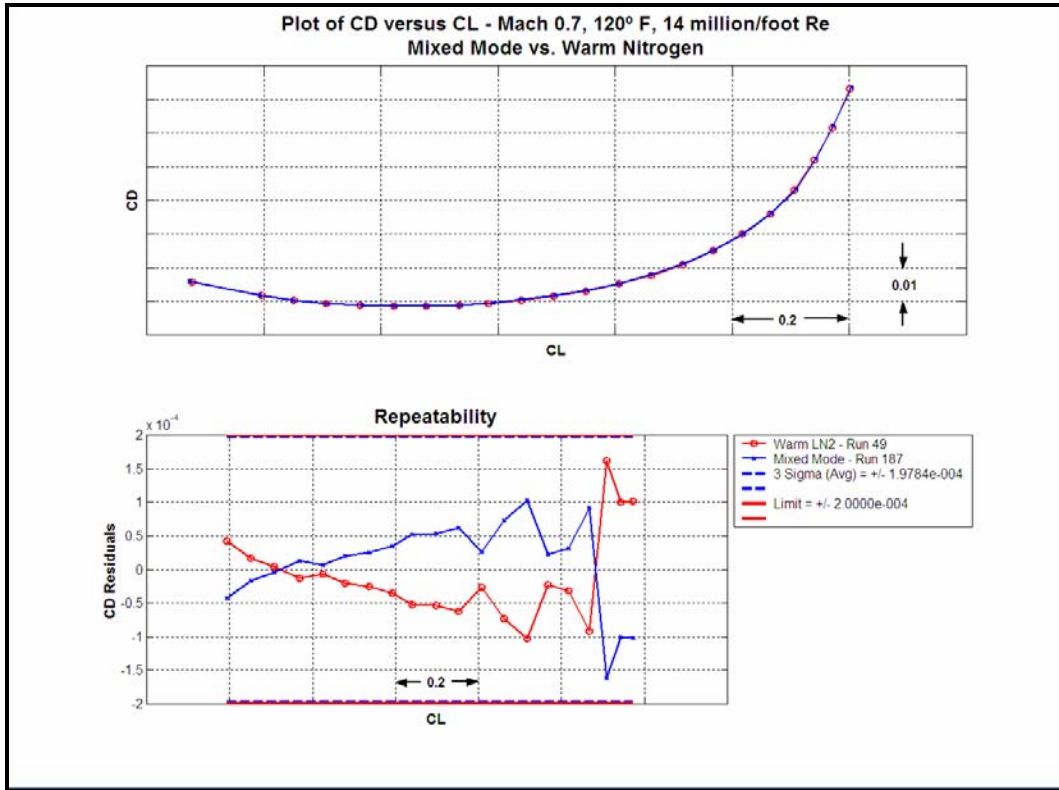
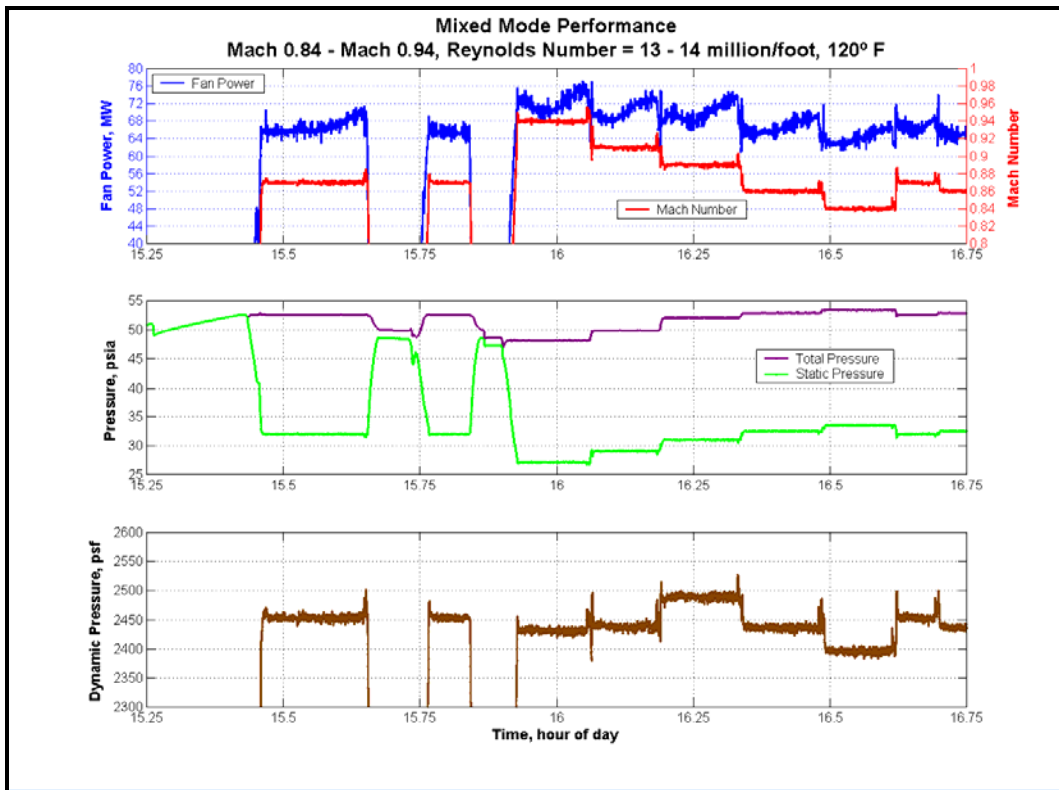**Figure 13 – Aerodynamic Data Comparison between Mixed Mode and Nitrogen Mode**

Figure 14 – Mixed Mode Performance Data (Fan Power, Mach No., Pressure, Dynamic Pressure)
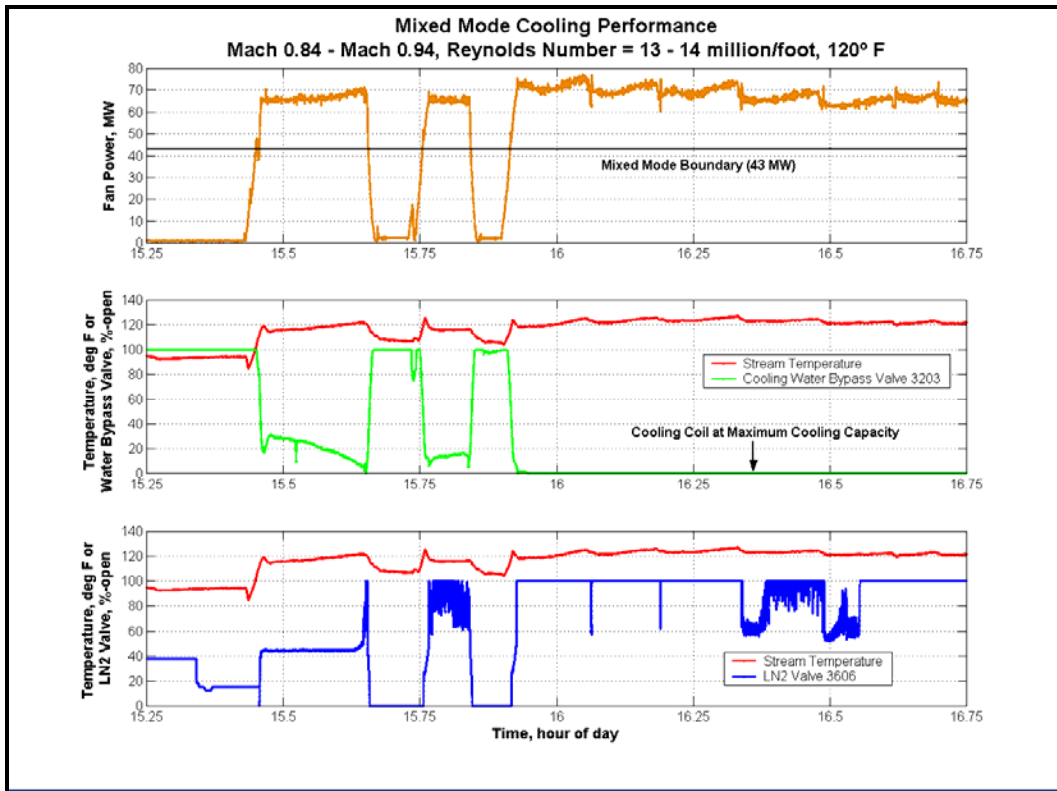
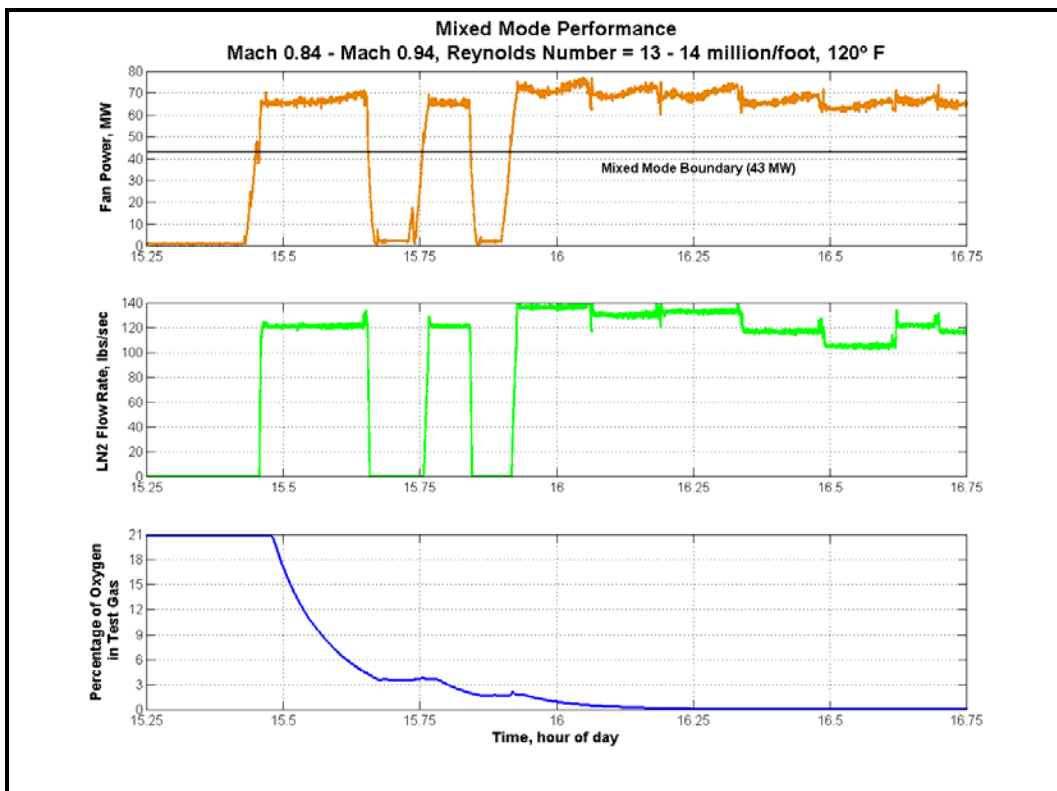**Figure 15 - Mixed Mode Performance Data (Power, Temperatures, Valve Positions)**

Figure 16 - Mixed Mode Performance Data (Power, LN$_2$ Flow, Percentage of Oxygen)