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Recent Productivity Improvements to the National Transonic Facility

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ABSTRACT

Productivity gains have recently been made at the National Transonic Facility wind tunnel at NASA Langley Research Center. A team was assigned to assess and set productivity goals to achieve the desired operating cost and output of the facility. Simulations have been developed to show the sensitivity of selected process productivity improvements in critical areas to reduce overall test cycle times. The improvements consist of an expanded liquid nitrogen storage system, a new fan drive, a new tunnel vent stack heater, replacement of programmable logic controllers, an increased data communications speed, automated test sequencing, and a faster model changeout system. Where possible, quantifiable results of these improvements are presented. Results show that in most cases, improvements meet the productivity gains predicted by the simulations.

INTRODUCTION

The National Transonic Facility (NTF) is a closed circuit, high Reynolds number, pressurized, cryogenic wind tunnel used by the aircraft industry for its ability to accurately simulate the full scale, in-flight performance characteristics of large transport aircraft at transonic speeds. The NTF can match the flight Mach number and the high flight Reynolds numbers (typically between values of 50 million and 100 million) associated with these aircraft. Aircraft designs can be optimized when wind tunnel data is obtained at flight Reynolds numbers. If the aircraft manufacturer's guaranteed aerodynamic performance is off by a small amount, the result is a significant increase in fuel cost for airlines. Missing the guaranteed performance margins result in either reduction in future sales or the manufacturer having to reimburse the airline for lack of performance. The NTF is a vital tool for assuring predicted flight performance matches actual flight performance.

The unique capabilities inherent in the NTF performance envelope ensure continued applicability throughout all high Reynolds number wind tunnel test programs well into the future. Reduction of the operating costs of the NTF is vital in maintaining this segment of the national wind tunnel testing capability. To determine how the NTF could be a more cost effective element of the wind tunnel testing strategy for various federal and commercial programs, a team considered ways of reducing the NTF operating cost with the concurrent benefits of increased efficiency and annual data production. The primary concerns addressed by the team were efficiency of the test operation, ability to provide sustained annual throughput, and operating cost. The output from this team included the following goals:

Polars per user occupancy hour	2
Cost per polar	$5,000
Polars per year	1,200

The NTF productivity goals are based on fifteen data points per polar, conventional cryogenic testing, and sting mounted models which use the existing model access housing system.

PRODUCTIVITY ENHANCEMENTS

A study was performed to identify constraints to the NTF's productivity using an existing simulation program for the NTF testing process from model installation, through testing, to removal of the model from the test section. Sensitivity analysis of this simulation suggests areas for improvements. The results show that the amount of liquid nitrogen (LN_2)

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available limits cryogenic testing and the LN_2 consumption during testing drives the cost per polar. Decreasing the time per data point reduces cost per polar by using less LN_2. Increased annual throughput (polars/year) and test throughput (polars per user occupancy hour) can be achieved by increasing efficiency of LN_2 use and reducing time for all test activities. Other activities having the greatest potential for improvements include downtime related to reliability issues, subsystem maintenance, and model changes. Specific subsystems were selected for improvements based on the NTF process simulation:

Liquid Nitrogen Supply System The simulation showed a significant loss in productivity due to two major limitations of the current LN_2 supply system. These drawbacks were the relatively small onsite LN_2 storage capacity and the slow refill rate. Losses were inccured when the facility runs out of LN_2 during cryogenic testing, and had to wait for replenishment. Secondary losses take place due to tunnel warm up and cool down cycles. Equipment failures from extended cold soak effects also occur.

Fan Drive System The complex, aging drive line has required significant maintenance and has caused substantial unscheduled downtime. Also, the drive control system was shared with another transonic tunnel, at times limiting the power available for the NTF to operate.

Vent Stack Heaters Discharge of cold vapor from the tunnel circuit is necessary during normal facility operations. If atmopheric conditions are unfavorable, the vapor cloud can fall to the ground, reducing visibility. This condition has forced the NTF to halt operations.

Tunnel Programmable Logic Controller (PLC) The operating sequences and safety interlocks of the facility systems resided in a slow and obsolete PLC. A failure of this outmoded system has put the tunnel at risk for long periods of unscheduled downtime.

High Level Control System Communications, Measurement, and Automatic Test Sequencing. Significant losses were pinpointed to the process control microprocessor interfaces, data transfer, and test parameter loading and sequencing.

Model Change Improvements Model configuration changes in the test section require tunnel downtime. Model filler setup time and instrumentation pressure tubing connections were targeted as areas where new technologies could be applied to reduce the downtime required.

LIQUID NITROGEN SUPPLY SYSTEM

Expansion of the LN_2 supply system was made to increase storage capability and provide faster refill time. A new 900,000 gallon LN_2 storage tank combined with the existing 250,000 gallon run tank increases the onsite storage capability. When testing depletes the run tank, a new transfer system provides quick refill from the new storage tank, minimizing tunnel warm-up caused by the replenishment delay. The new system can refill the existing tank in 3 hours. This increases the NTF's continuous run time from 1.5 hours to 3 hours at a nominal injection rate of 2,800 gallons per minute (560 tons per hour).

LN_2 Storage and Transfer

The expanded LN_2 storage and transfer system design includes several major components. Of these, the 900,000 gallon LN_2 storage tank is the most significant. The new tank is now the primary receiving tank from the existing supply plant. The inner vessel of the tank is constructed from ASTM A240 type 304 stainless steel. The outer vessel is made of carbon steel. The volume between the two vessels is filled with expanded perlite insulation yielding a maximum heat leak of 0.25 precent per day. The cylindrical inner vessel height is 78 feet and has a diameter of 47 feet. (See Figure 1 for facility location.)

The new tank fill line is tied into the existing run tank fill line. Either tank can be filled from the LN_2 supply plant at a rate of 250 gallons per minute; however, only one tank can be filled at a time. Included onsite with the new LN_2 storage tank is a 1,300 gallons per minute transfer pump with a redundant back up pump. The existing run tank is capable of being filled simultaneously from both the LN_2 supply plant and the new tank transfer pump. This configuration gives a maximum combined fill rate to the run tank of 1,550 gallons per minute which is six times faster than previously possible. (See Figure 2 for the LN_2 system schematic.)

Vaporizer

A new LN_2 vaporizer reduces the time necessary to remove LN_2 from the tunnel's injector torus ring. Draining the torus is required to safely access the model while in the tunnel. The previous method of draining the torus was time consuming. After the final wind off zero, the fan drive was brought up to 100 rpm and the LN_2 injectors opened to drain approximately half the torus into the tunnel circuit.

Next, the torus drain valve was opened and the remaining LN_2 drained out. This draining operation could cause undesired ground fogging close to a highway. When fogging occurred, torus draining had to be slowed down to minimize the fog. The new vaporizer can convert 700 gallons in 30 minutes, eliminating the need to bring up the drive system and prevent ground fogging. Sized to handle the total quantity of the torus, the new vaporizer will reduce test section access time by a minimum of 15 minutes.

FAN DRIVE SYSTEM

The NTF was originally configured with two motors from a decommissioned wind tunnel, an existing speed control system, and a synchronous motor coupled by two gear boxes to achieve the tunnel's desired fan speed/torque requirements. The total short-term overload power was roughly 92 MW. This was slightly below the design requirement of the tunnel due to higher than anticipated losses.

Much of the NTF's unscheduled downtime was logged to the fan drive system, but it was not possible to pinpoint a single element that was the major cause of the delays. A detailed analysis of the facility downtime logs revealed issues related to operation, breakdowns, repairs, and extensive maintenance of this drive system. The lost hours were grouped into three major catagories; which were failure of complicated rotating machinery, awkward system operation, and limited design power.

1. The sheer complexity of the drive system contributed the majority of logged hours. These were associated with the mechanical and rotating elements of the drive line, such as bearing, couplings, clutches, and oil supplies. The calculated drive line Mean Time Between Failures (MTBF) was 84 hours, with a Mean Time To Repair (MTTR) of 5.1 hours. The aging Kramer speed control system MTBF was 107 hours, with a MTTR of 11.7 hours. Consequently, multiple failures could be predicted to occur during any given test.

2. The limitations in speed/power envelopes for different Mach number conditions required constant drive line configuration changes. Each change meant gearbox clutching, switching between liquid rheostat and Kramer speed control loops, and synchronizing the constant speed synchronous motor in and out of the drive lineup. These manipulations required additional start/stop cycles, lost time, and subsequent loss of productivity. Losses increased when the tunnel was configured for high pressure cryogenic tests due to LN_2 consumption costs.

3. To achieve the maximum power indicated above, drive motors, cables, and transformers had to operate above their design limits. Delays caused by the subsequent equipment cooldown periods further reduced productivity.

To eliminate all of these problems, a new fan drive system was designed. The inherent features of the new system are a less complicated configuration, dedicated power system, and variable speed capability throughout the operating envelope of the tunnel. Currently, the most prevalant concept for low speed, high power applications like NTF (600 rpm, 135,000 hp) is a synchronous motor driven by a Load Commutated Inverter (LCI). The single drive/motor installation met design requirements by:

1. Reducing the mechanical complexity by implementing a single motor prime mover. Improving drive electrical efficiency (lower operating cost) and reducing the number of personnel required to operate and maintain the drive line by using a solid state speed control LCI. The original drive line MTBF and MTTR compare poorly with sychronous machines driven by LCI having a MTBF of 40,000 hours and a MTTR of 4 hours.

2. Improving tunnel test duration by eliminating operational envelope limitations imposed using gear boxes, power/speed envelope limitations, and slow acceleration/ deceleration times.

3. Providing maximum power on a continuous basis, without short term overload ratings. Unrestricted operation is now possible without interference from other tunnels because of the new dedicated electrical feeder and switchgear.

Drive System Design

Originally designed for the continuous duty applications in the oil and gas industries, large adjustable speed drives have dramatically increased in power levels and reliability since their commercial introduction in the 1970s. Power levels up to 60 MW are typical; however, the 100 MW required for the NTF make this the largest adjustable speed drive system in the world. The NTF configuration consists of a two-channel LCI frequency converter connected to a synchronous motor with dual stator windings, as shown in Figure 3.

The main components of the NTF's fan drive system are the synchronous motor, LCI, transformer, and harmonic filter. The LCI takes power from the supply network at constant voltage and frequency and converts it to variable voltage and frequency. The synchronous motor converts this electrical energy to fan power with a shaft speed proportional to the input frequency. The synchronous machine can be accelerated (motor mode) and decelerated (generator mode) at any speed within the operating speed range of the NTF fan, as shown in Figure 4.

The synchronous motor has two electrically isolated stator windings with a salient pole rotor. Due to the 30° electrical phase shift between the two stator windings, the rotor shaft pulsating torques are reduced with consequent reduction of the mechanical stress on the fan shaft. This is required to assure the mechnical stress levels do not get too high, and to smooth the torque output. A torque limiting coupling is used to connect the motor to the existing fan drive shaft to protect the fan from over stress due to transient overload conditions.

The LCI consists of two independent channels, resulting in a total of four identical three-phase bridges. Redundancy (n+1 design) is built in the thyristor bridges, to increase system availiablity. Therefore, one thyristor may fail per branch, and the drive is still able to run at full load continuously. The bridges are cooled by a closed loop deionized water circuit. The LCI is housed in a conditioned, enclosed structure to remove heat losses and protect personnel and equipment.

Incoming power is provided from LaRC's primary substation and routed to the NTF via an underground gas-filled, high voltage feeder cable. A four winding input isolation transformer reduces the voltage to the LCI. Because of the electrical distortion generated when firing thyristors, a harmonic filter is required to meet the industry guidelines for feeding harmonic distortion back through the local power system. The damped filter is connected to the transformer tertiary winding and is split into four series-resonant circuits tuned to the 3rd, 5th, 11th, and 13th harmonic frequencies. In all NTF operating conditions the power factor and harmonic distortion are kept within specified limits.

Operation

Commissioning tests and operations to date of the wind tunnel suggest that the simulation improvements should be realized when the facility is returned to full operation. The high effficiency of the LCI/synchronous motor provides approximately a 5 percent improvement over the old Kramer (slip energy recovery) speed control, and substantially more for liquid rheostat speed control. This results in more than $200,000 per year in electrical energy cost savings, based on past years' energy consumption.

The new drive acceleration time is 36 seconds to 360 rpm, and another 48 seconds to 600 rpm. This exceeds the old system acceleration time of 5 to 7 minutes to 360 rpm. The new drive deceleration time is 60 seconds from 600 rpm to zero speed. This exceeds the previous deceleration of 8 minutes from 360 to zero rpm. LN_2 consumption is reduced by as much as 90 percent when cryogeninc wind-off zero test measurements are made with the improved acceleration and deceleration times.

System design has incorporated troubleshooting tools such as alarm displays, drive shaft vibration analysis tools, and extensive operator interface to quickly and accurately pinpoint problems and recommend solutions to speed repair and minimize unscheduled downtime.

An added benifit of the new drive system design is an increase in the NTF operating envelope. Figure 5 shows a significant increase in test capability at high transonic Reynolds numbers. Also, this design removes drive motor stoppage associated with changing gears. Using the new synchronous motor, Reynolds number and aeroelastic studies can be accomplished quickly over a wide range of power levels. This reduction in test time will increase the polars per user occupancy hour while reducing LN_2 consumption.

VENT STACK HEATER

NTF discharges gaseous nitrogen through a vent system during tunnel cooldown, depressurization, and testing for tunnel pressure control. The vent system is an ejector type, vertical stack that uses forced draft provided by four 350 horsepower fans having a combined flow capacity of 240,000 cfm. The vent stack is 11 feet in diameter and 120 feet in height.

When weather conditions are characterized by high relative humidity and low wind velocity, a plume touchdown can occur when the cold vapor cloud descends to the ground, limiting visibility in the surrounding area, which includes a nearby highway. Unfortunately, these events occur mostly during the evening and night time hours when visibility is naturally limited. Current philosophy is to restrict operations of the tunnel during these periods to prevent a plume touchdown. During calendar year 1994, the plume touchdown interrupted tunnel operations 11 times. This accounted for 20 percent of the total unscheduled downtime for the year. The solution was to stop operations while waiting for the weather to improve, resulting in additional unscheduled downtime of sufficient duration that a complete tunnel warm-up, purge, and cooldown cycle was required. This effort could consume as much as 450 tons of LN_2. When conditions are favorable for touchdown, facility personnel must continuously monitor the plume during the tunnel run. If the plume appeared likely to touchdown, testing was terminated. This was also a major source of customer frustration.

In studies dating back to the NTF's original design, the cold vent stack effluent has been characterized by negative buoyancy, so the plume tends to fall. The long term solution to compensate for negative buoyancy is to heat the vent flow stream. By increasing the effluent temperature, the plume can attain, as a minimum, neutral buoyancy. This eliminates the impact of ground level visibility effects.

A natural gas burner system was added to the vent stack to provide a heat source. The four burners were sized to provide enough energy to maintain an exit duct temperature of 750° F, eliminating a plume touchdown. The new design maintains the current 60,000 cfm air flow per burner, which is required to disperse the vapor into the surrounding atmosphere with nominal mixing effects.

PROGRAMMABLE LOGIC CONTROLLER

The NTF PLC governs the sequence of events for tunnel operation and contains interlocks to prevent equipment damage. The old NTF PLC averaged one system failure every 2 months. The PLC was based on 1970's computer technology, and replacement parts were no longer available. After a thorough market survey, a replacement system was selected from a stable product line with available spare parts. Selection factors included reliability, quality, programming ease, and market share. The latter correlates directly to the stability and long term availability of service and replacement parts. The system consists of four processors with local and remote I/O distribution. A local area network has been implemented for communication with remote input/output modules, and other intelligent subsystems. External communications were upgraded from RS-232 protocol to Ethernet drivers for high speed data transfer to the facility's process computer. See Figure 6 for communications block diagram.

With this planned system upgrade, the possibility of a crippling failure from obsolete hardware has been eliminated. The reliability of the installed system is extremely high. Other than infant mortality issues and commissioning failures there have been no system component failures to date. In addition, substantial spare parts were procured, and an increased inventory is maintained at the facility to minimize future hardware changeout downtime.

CONTROL INTEGRATION UPGRADES

The control system upgrades provide the greatest benefit to online cost savings as predicted by the simulation. Several areas of improvements were targeted; some have not been made fully operational, as they require online testing to commission. These are currently in the final stages of completion. A high speed communications network, SCRAMNet, is used to upgrade data communications between the process control microprocessors, PLCs, process computer system, and reseach data system. The configuration provides a 250 fold increase in the data throughput over the old RS-232 links.

A new process Mach number measurement system has replaced an obsolete system and standardizes all Langley's aerodynamic facilities to the same hardware. This improvement secures Mach number accuracy of ± 0.001 across the tunnel operating envelope while increasing data sampling to 10 Hz. A Mach number disturbance management system is also being developed to decrease off setpoint time which would reduce LN_2 consumption and increase obtainable polars per year.

An alpha/beta model position control algorithm has replaced the conventional pitch and roll model control loop to increase speed and accuracy in achieving the customer's setpoints.

A computer controlled automatic test sequencing (ATS) system automatically sets tunnel test conditions and performs data polars without operator intervention. The ATS integrates the research computer with the process control microprocessors to sequence from drive on, through polar sets, to drive off. By minimizing the operator response time in the test loop, an increase in polars per user occupancy hour is realized. ATS works in conjunction with the on-setpoint status indicator to determine when tunnel conditions and model parameters are within specified tolerances following setpoint changes.

Facility performance measurement is automated using a new monitoring system which can access data being acquired by the research and process computer systems. This data can be used to show real time performance capability of the facility. It also provides customers with the current status of consumable resources. This capability enhances facility maintainability by establishing a performance database which can be used for comparative analysis.

MODEL CHANGE IMPROVEMENTS

Model Filler Model changes consume a large portion of the testing process. A significant reduction in model change time has been achieved by changing the material used to fill model fastener holes. The baseline model filler material was a two part epoxy mixed with small carbon spheres to match the thermal expansion of the metal model. The cure time for this material was 8 hours, and the resulting average surface finish was 64 microinch rms (root mean squared). After extensive study, an ultraviolet light cured product mixed with high purity quartz was found to be the most successful candidate to replace the existing model filler. The cure time was reduced to 15 seconds, and the average surface finish improved to 11 microinch rms. The new material requires very little hand work to match model surfaces tested in NTF, which typically have a surface finish between 8-16 microinches rms.

Cryogenic Pressure Tube Quick Disconnects A set of cryogenic pressure tube quick disconnects are in use for model configurations that require rapid pressure instrumentation changes. Conventional pressure tube quick disconnects often leak under cryogenic test conditions. A mechnical quick disconnect was developed using cryogenic seal material to prevent leakage. This reduced the time to exchange an electronically scanned pressure module from 3 hours required to retube a module to 15 minutes to replace a quick disconnect module. Another advantage is the time saved sealing pressure tubes across the model balance when converting from pressure testing to force and moment only testing. By placing a cap on the end of the quick disconnect, the wing pressure tubes can be sealed in 15 minutes rather than sealing each individual tube, which can take up to 4 hours.

RESULTS AND SUMMARY

Results Baseline values for NTF operations have been established from the facility process simulation models. The recent improvements at the NTF have increased the tunnel productivity substantially. The effects of the improvements have been incorporated in the model simulator and impact on future productivity determined. With these improvements, the long term productivity goals are approached. One measure of productivity, polars per user occupancy hour, increases from 0.70 to 1.06. Cost per polar decreases from $12,000 to $7,700. Annual output is predicted to increase from 860 to the goal of 1,200 polars per year. Customer satisfaction is increased as test cycle time is reduced. Efforts are continuing to identify areas of further improvement and cost reduction.

Summary Recent facility improvements at the NASA LaRC NTF have increased the wind tunnel productivity. The new 900,000 gallon LN_2 tank provides sufficient nitrogen to perform customer test programs. The new drive system increases system reliability and reduces test cycle time by rapidly obtaining fan speeds throughout the tunnel operating envelope. The addition of vent stack heaters has removed a safety hazard and allows tunnel operation to continue during inclement weather. Replacement of an obsolete PLC has eliminated a crippling maintenance problem and increased operating flexibility. Upgrades to the controls integration system increases communication between microprocessors and has automated functions to shorten test time. Several new techniques applied to model changes in the test section reduce tunnel downtime. The combined effect of all these enhancements allow facility operations to reduce customer test cycle time.

ACKNOWLEDGEMENTS

The results presented in this paper are a culmination of many individuals working to achieve success for the NTF and LaRC. These indivduals represent many different organizations and outside contractors. The team made the events described in this paper happen in a very timely and successful manner.

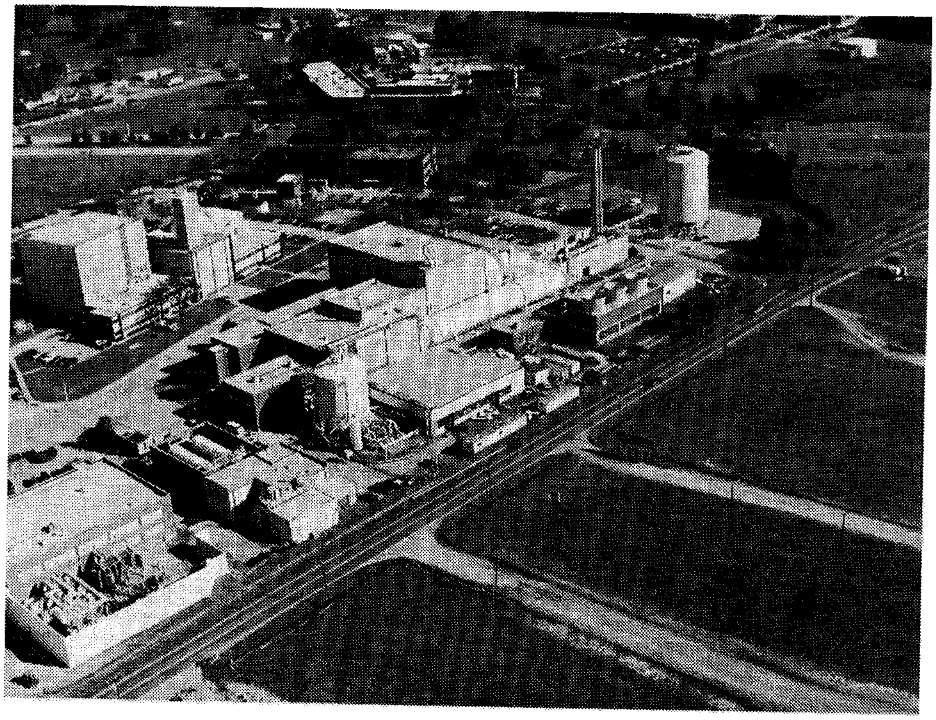

Figure 1. The National Transonic Facility, new LN_2 Storage Tank upper right.

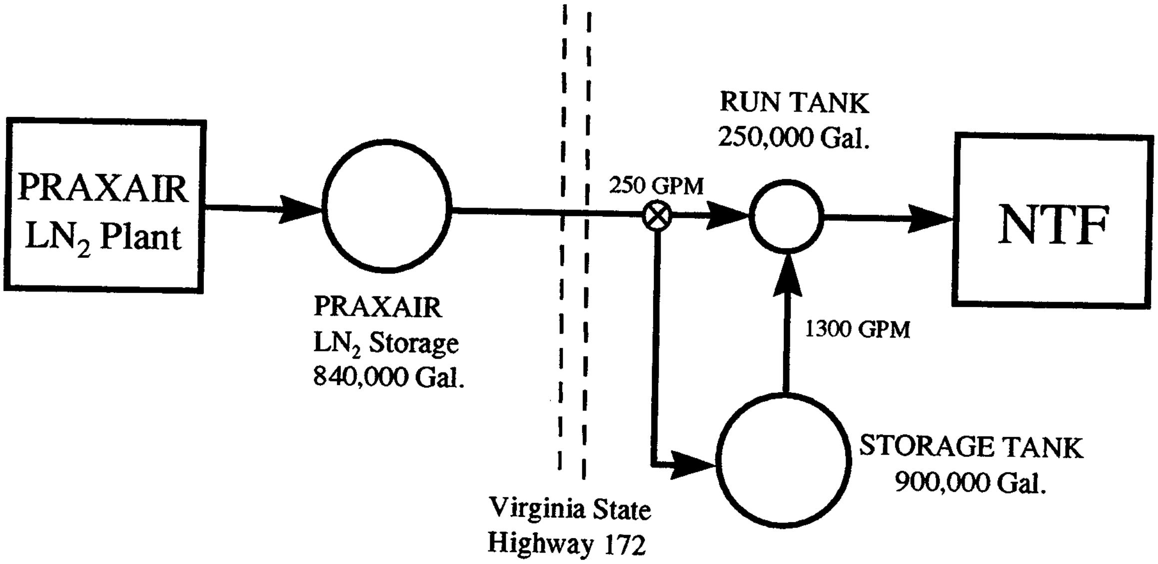

Figure 2. LN_2 System Schematic

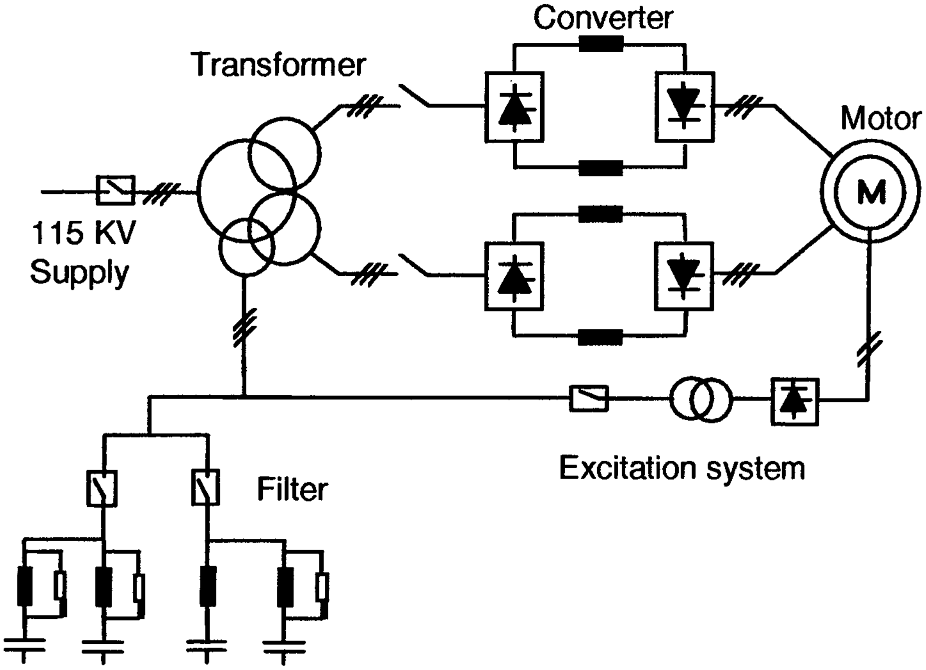

Figure 3. Fan Drive System One Line Diagram

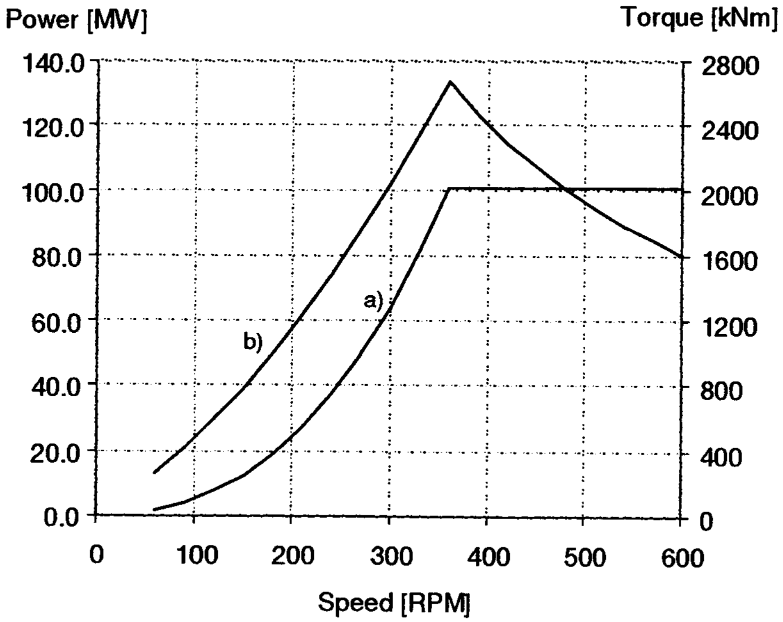

Figure 4. Fan Drive Capability; a) shaft power, b) torque

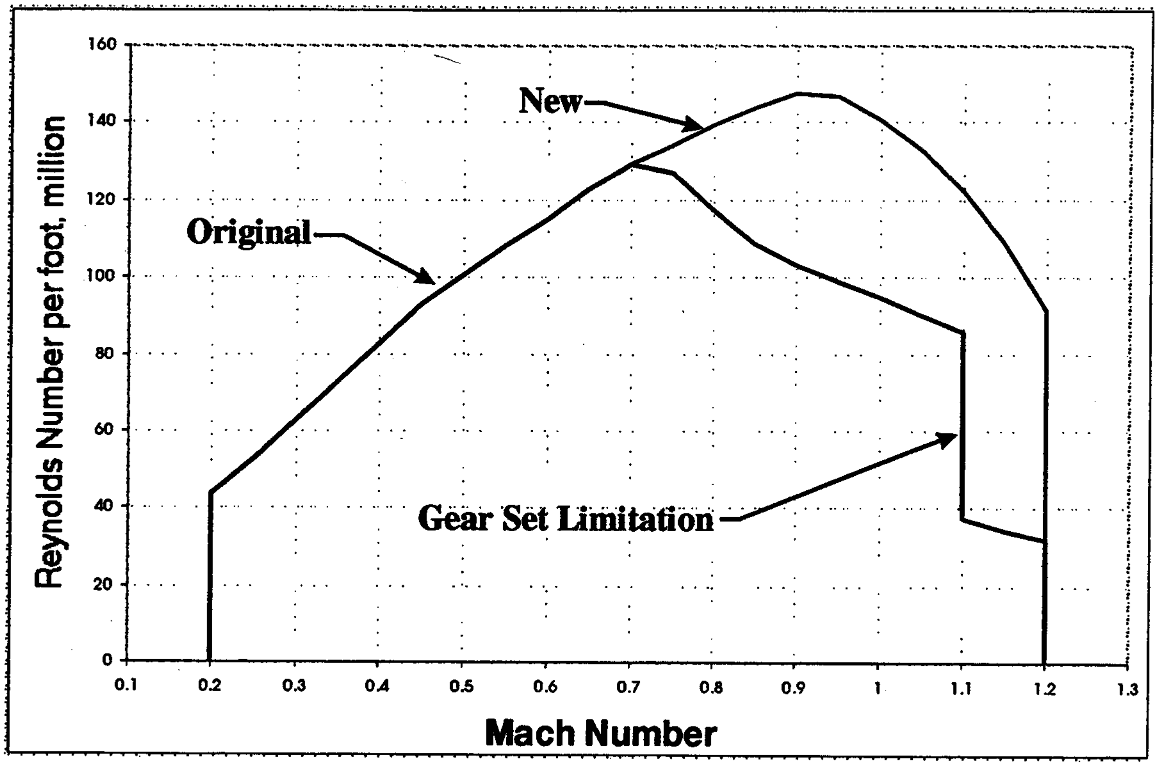

Figure 5. Test capability with new drive system.

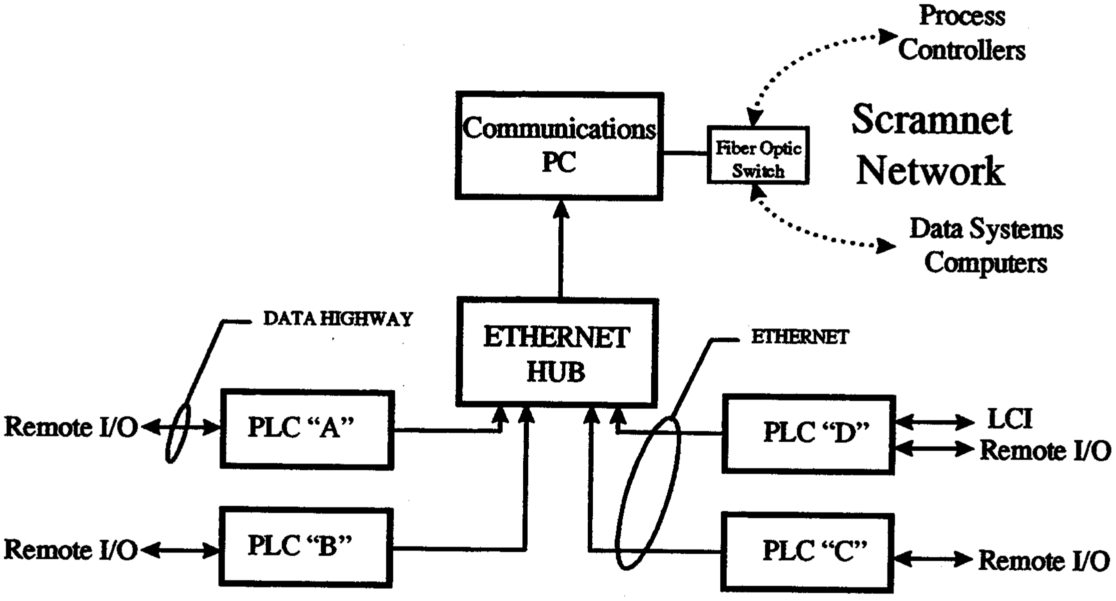

Figure 6. Communications Block Diagram