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Idaho
National
Engineering
Laboratory

# Main Drive Selection for the Windstorm Simulation Center

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# ABSTRACT

Operated by the Partnership for Natural Disaster Reduction, the Windstorm Simulation Center (WSC) will be a structural test center dedicated to studying the performance of civil structural systems subjected to hurricanes, tornadoes, and other storm winds. Within the WSC, a bank of high-power fans, the main drive, will produce the high velocity wind necessary to reproduce these storms. Several options are available for the main drive, each with advantages and liabilities. This report documents a study to identify and evaluate all candidates available, and to select the most promising system such that the best possible combination of real-world performance attributes is achieved at the best value.

Four broad classes of candidate were identified: electric motors, turbofan aircraft engines, turboshaft aircraft engines, and turboshaft industrial engines. Candidate systems were evaluated on a basis of technical feasibility, availability, power, installed cost, and operating cost.

# EXECUTIVE SUMMARY

Operated by the Partnership for Natural Disaster Reduction, the Windstorm Simulation Center (WSC) will be a structural test center dedicated to studying the performance of civil structural systems subjected to hurricanes, tornadoes, and other storm winds. Within the WSC, a bank of high-power fans, the main drive, will produce the high velocity wind necessary to reproduce these storms. Several options are available for the main drive, each with advantages and liabilities. This report documents a study to identify and evaluate all candidates available, and to select the most promising system such that the best possible combination of real-world performance attributes is achieved at the best value.

To identify candidates, minimum performance criteria were developed, and a request for information was posted in four different sections of the Commerce Business Daily. The literature was surveyed, and phone calls were placed to a multitude of vendors.

Four broad classes of candidates were identified: electric motors, turbofan aircraft engines, turboshaft aircraft engines, and turboshaft industrial engines.

Candidate systems were evaluated on a basis of technical feasibility, availability, power, installed cost, and operating cost.

The application of turbofan aircraft engines was rejected on the basis of technical feasibility. These engines generate very high temperature airflows, and modifications to reduce the temperature to acceptable levels would be a lengthy and expensive process.

Electric motor systems are feasible, but have several disadvantages, ranking third overall. The entire system, including the power supply, motors, gearboxes, and propellers, would have to be built from scratch. Some re-invention of liquid rheostat controller technology may be necessary for appropriately sized motors, and the WSC may require significantly more structure to house the massive components. The lead time to bring such a system on-line may be three years or more, at an installed cost of $200M. Supplying energy to the facility would cost another $2M/month.

Application of industrial turboshaft (gas turbine) engines is attractive technically, but less so from a cost and schedule perspective, earning a rank of second. A wide variety of these compact, reliable, fuel efficient engines are available, yielding a broad choice of engine sizes and configurations. However, this would be a novel application for this powerplant, and a learning curve should be anticipated. Both propeller and gearbox would be specially designed and fabricated, requiring up to two years. Installed cost is estimated between $140M and $194M.

The result for aircraft turboshaft engines varied significantly from model to model. U.S. made engines appear to be highly optimized for military flight service, and are consequently somewhat expensive. Because the individual

engines deliver relatively low power, a large number would be required for the main drive, impacting feasibility, installed cost, and operational cost.

The NK-12MV, manufactured in Russia, offers a variety of attractive features. These units have a long service history, both in the air and on the ground, with good reliability statistics (Appendix E). Engines, gearboxes, and propellers are extant, and delivery could occur within months of an order. They produce 11.2 MW each, and run relatively cool, simplifying exhaust management. With modifications, they can burn natural gas if desired. Finally, the installed cost for these units is estimated at $32M, approximately $110M less than the next cheapest alternative. This combination of simplicity of application, low cost, and possibly rapid delivery earned the NK-12MV a ranking of first.

However, more detailed information about the operational characteristics, maintenance, and life cycle cost must be ascertained prior to the final decision to use this unit as the WSC main drive. It is recommended that

1. An in-depth investigation of the NK-12MV will be initiated, including ground-based operating characteristics, detailed life cycle costs, and availability.

2. WSC analysis, design, and project management studies assume a main drive system composed of NK-12MV units until the detailed analysis substantiates the unit's suitability for this application.

3. If the NK-12MV is determined to be unsuitable, then the industrial turboshaft engine should be investigated as the next logical choice.

4. Finally, the possibility of a hybrid system should be explored. In this case, a core of 2 – 4 electric motor driven fans might be placed in the center of the array, providing airflow for checkout and low-speed tests. This arrangement would avoid the large infrastructure costs of a purely electric system, while allowing a simple and rapid means of performing low velocity tests, calibration, and instrument check-out.

# ACKNOWLEDGMENTS

The authors would like to thank the many individuals who assisted us in identifying and investigating options for the Windstorm Simulation Center main drive. Their expertise and experience were invaluable to this effort. The names of these contributors are given in Appendix C.

We would also like to thank our technical review team for their perspective and insight, to which this document owes much. Reviewers were

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## 1. INTRODUCTION

The Windstorm Simulation Center (WSC) will be a structural test facility dedicated to studying the performance of civil structural systems subjected to hurricanes, tornadoes, and other storm winds. A bank of high-power fans, the main drive, will produce airflow at velocities up to 90 m/s (200 mph) at the test section. Because of the large power consumption expected of the main drive, costs associated with its installation and operation will be a significant portion of the overall facility costs. Therefore, a careful evaluation of all possible candidate systems is appropriate to ensure that the best possible combination of attributes is achieved in the final installed system.

This document reports the methodology and findings of a study to identify, evaluate, and rank candidate main drive systems. Candidates were evaluated by the technical feasibility, availability for installation, power, and order-of-magnitude installation and operating cost to achieve the published performance specifications for the WSC. Where appropriate, other data is included in the discussion and analysis. Because of the conceptual nature of the WSC design, life cycle cost data could not be applied as a measure of comparison.

## 2. SYSTEM DESCRIPTION

### 2.1 General

The conceptual design of the WSC,[1] developed by the Idaho National Engineering and Environmental Laboratory (INEEL), uses a straight-through, open circuit, open test section layout, as shown in Figure 1. Directly downstream of the bell-mouth inlet, a bank of fans produces the required airflow. Placement of the fans upstream of the test section protects them from debris that may be generated, by either injection into the airflow or failure of the test specimen. Fans will be individually ducted and faired to optimize efficiency. Airflow produced by the fan array flows through a contraction, to a

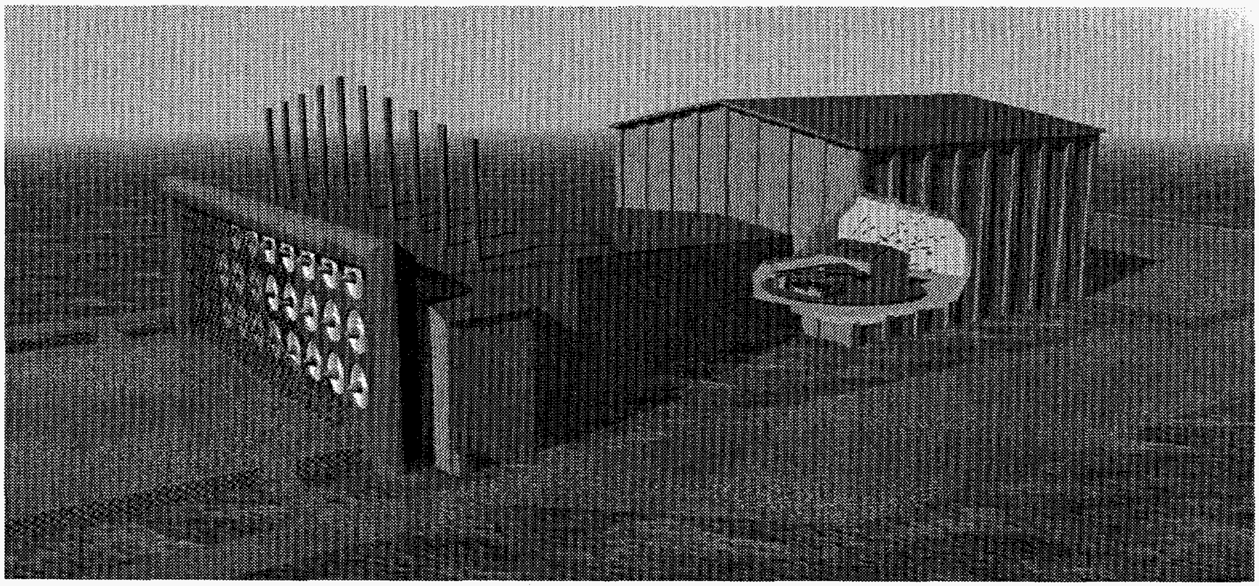

**Figure 1.** The Windstorm Simulation Center.

throat measuring approximately 24 m (80 ft) wide by 12 m high (40 ft), producing a high-velocity jet.

The jet then passes through an open test section area, where a test specimen rests on a 24 m (80 ft) diameter turntable, and then proceeds outdoors without further treatment.

Storm wind turbulence is produced in an active, mechanical manner. Longitudinal gusting is produced by individually controlling and cycling the thrust of the fans in the array. This turbulence is then intensified, and the lateral component added, by an active vertical airfoil cascade mounted at the throat of the contraction.

Because test time in the WSC will be quite valuable, a construction facility will be provided nearby. There, test articles will be constructed and instrumented before being transported into the WSC. Once a test article is mounted on the turntable, sensors can be connected to the data collection system, and checked out prior to testing. This approach ensures efficient, cost effective use of the facility, and offers high potential throughput.

## 2.2 Main Drive Configuration

The main drive array may be either of two basic configurations: direct drive, or remote drive. In the "direct drive" configuration, each fan is directly mounted to the output shaft of an engine, which is mounted in the array shown in Figure 1. In the "remote drive" configuration each fan is attached to a gearbox mounted in the array. The gearbox is driven by a shaft from a motor or engine mounted in a room below the fan array.

Direct drive systems have the advantage of simplicity of design, fabrication, and installation, and require less structure to house. Thus the initial cost would be lower. Engine overhauls or significant maintenance may require that fans be removed from the array by crane.

Remote drive systems require more structure and machinery, but offer a wider array of options for type and size of motor, and may offer the option of driving multiple fans from each motor.

# 3. MAIN DRIVE REQUIREMENTS

The Partnership for Natural Disaster Reduction has developed a set of functional requirements for the WSC[2,3,4] for full-scale structural wind testing. In summary, the WSC is required to reproduce Category 5 hurricane wind and rain on full-scale two-story residential structures, and other structures or components of similar size, in a controllable, repeatable manner. This, in turn, generates requirements specific to the main drive. These requirements are listed and discussed in the following paragraphs.

## 3.1 Airflow

### 3.1.1 Test Section Airflow Speed

The WSC shall be capable of generating a sustained wind speed of 70 m/s (160 mph), with a maximum of 90 m/s (200 mph) averaged across the 300 $m^2$ (3,200 $ft^2$) test cross section, producing a maximum volumetric flow rate of 27,000 $m^3$/sec (57.2 million cfm). Airflow is expected to pass through a contraction from the fan section to the throat to achieve this speed. The contraction ratio is currently not specified, although a ratio near unity is preferred to maintain the lateral turbulence content of the flow. Initial calculations (Appendix A) indicate that the power required to achieve this airflow will fall between 250 MW and 300 MW, depending on the outcome of ongoing design optimization studies.

### 3.1.2 Test Duration

To simulate the passage of a storm, the WSC shall be able to produce hurricane intensity wind for up to 6 hours, and lower intensity wind for up to 12 hours, without interruption.

### 3.1.3 Airflow Turbulence

The WSC shall be capable of reproducing turbulence representative of surface winds. This requirement is to be applied only across those ranges of frequency and mean velocity pertinent to structural response. (35–90m/s [80–200 mph], 0.1–20 Hz). The main drive system is expected to contribute to the longitudinal wind speed variation by varying the thrust of each fan in a controlled fashion.

### 3.1.4 Airflow Temperature

The temperature of the airflow at the test cross section shall be substantially uniform, and remain less than 40°C. A water spray system, designed for rain injection, will be available to cool abnormally high temperature airflows for brief periods.

### 3.1.5 Noise

Noise at the test section shall be limited such that functionality of instruments on or near the test article is not impacted, and the behavior of the test article is not affected. It is anticipated that noise reduction technology will be employed in the contraction and test section; however, detailed information on the acoustic energy produced by candidate main drive systems will be required for design and evaluation of these systems.

## 3.2 Environmental Considerations

### 3.2.1 Combustion Products and Airborne Pollutants

Production of combustion products and airborne pollutants shall be limited to levels deemed acceptable by the INEEL and the state of Idaho, without resort to special waiver.

### 3.2.2 Process Waste Products

Waste streams produced by candidate main drive systems shall be identified so that suitable treatment and associated costs may be determined. Examples of waste products might be coolants, lubricants, cleaning agents, or other substances used during the normal operation and maintenance of the main drive system.

### 3.2.3 Environmental Noise

Excessive noise outside the WSC building may adversely affect local fauna, occupants of neighboring facilities, or travelers on the adjacent Highway 20. Therefore, sufficient information on noise generated by candidate systems is required to characterize the noise in the surrounding area.

## 3.3 Construction, Maintenance, and Operations

### 3.3.1 Availability

The current construction schedule requires delivery of the main drive system to start in mid-2000 and end in early 2001. Requisition is not expected to occur until 1999, leaving a maximum of two years to prepare and deliver the main drive. This short schedule is driven by the needs of the facility's potential customers.

### 3.3.2 System Control Issues

Preliminary model studies indicate that a minimum of six fans may be required to create the velocity profiles and turbulence content required of the WSC. As the array increases, finer control will be available to manipulate the airflow. However, costs associated with system construction, maintenance, operation, and reliability can be expected to increase significantly with the number of fans. In lieu of a parametric study to determine the optimum number of fans, this report will simply recognize that system feasibility will become problematic for candidates requiring a very large array.

# 4. METHODOLOGY AND CONSIDERATIONS

## 4.1 Candidate Identification

In early March of 1997, an extensive search was initiated to identify and characterize main drive candidates. An announcement was published in four different sections of the Commerce Business Daily (Appendix B) in June requesting information from vendors. Reference texts, such as Jane's Aero Engines,[5] proved invaluable to develop much of the information on aircraft based turbomachinery. However, most information was gathered by phone conversations with system vendors and engineers. These contacts are listed in the References and in Appendix C.

## 4.2 Ranking Criteria

Systems that could reasonably be expected to meet the requirements listed above were evaluated by the following criteria.

- Technical Feasibility: High marks were given to candidates that currently exist and require no, or only slight, modifications for this application; followed by candidates designed and fabricated by vendors with significant experience in wind tunnel drive applications. Low marks were given to candidates that would require extensive modification with low confidence in the resulting performance.

- Availability: This category represents the lead time to procure and install the candidates. It is assumed that main drives must begin to arrive on-site in mid-2000.

- Installed Cost: This includes the purchase price of the main drives, and energy supply systems to support them.

- Operating Cost: Operating Cost was calculated assuming the main drive will operate for 30 hours per month at an average of 70% full power.

Other life cycle cost data, such as reliability, maintainability, and emissions are reported where available. But, because this information is not consistently available for all systems, it was not included as a factor in the analysis.

## 4.3 Propellers and Drive Gears

As critical components of the main drive system, the cost of propellers and reduction gearing from the engine/motor to the propeller must be considered. With the exception of aircraft turbofans, all power sources discussed in the following sections will require a gear and propeller system. For special design systems, the cost to design and fabricate new propellers and gears must be included in the installed cost. Production gears and propellers are available for aircraft-derived systems at significantly less cost and quicker delivery, although they may not be optimized for ground test applications.

Propellers would be fabricated from aluminum in smaller sizes (less than 17 ft) or composites in larger sizes, and are expected to cost between $3M and $4M per set. Variable pitch control does not affect this cost significantly. Propellers in the size range contemplated typically require 1 to 2 years to deliver the first set, with subsequent sets following more rapidly.[6]

Reduction gears are necessary to transmit engine power, typically at 3,000–5,000 rpm, to the propeller at a much lower speed. Stress considerations limit propeller speed to approximately 700 rpm. Single-stage reduction gears transmitting 100,000 ft-lb of torque (11.2 MW @ 700 rpm) have been estimated to cost $130,000 per set, and require 38–40 weeks to deliver.[7]

# 5. ELECTRIC MOTORS

## 5.1 Description

Electric motors are traditionally the first choice main drive for wind tunnel applications.[8] Electric motor driven wind tunnels range in size from table-top models to the 40 ft × 80 ft/ 80 ft × 120 ft facility at Moffett Field operated by NASA Ames Research Center (Figure 2). Electric systems offer control and reliability at the cost of large supporting infrastructure and system size.

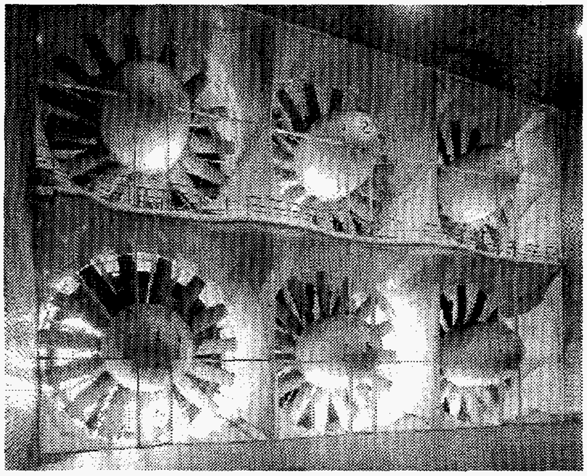

**Figure 2.** Electric Fan Array at NASA Ames 40 ft × 80 ft wind tunnel.[a]

## 5.2 Application

An electric motor-driven system would be specially designed and fabricated for the WSC. Therefore the properties of the system cannot be comparatively discussed in this document. However, very large electric motors are currently used in wind tunnels and other applications around the world, and the general properties of these systems are well known.

While form factors are not fixed, electric motors are typically dimensionally large and massive in comparison with combustion engines of similar output. A typical 10,000 hp (7.5 MW) coupled synchronous motor weighs between 45,000 and 70,000 lb.[9]

General Electric[10] has provided AC motors for wind tunnel applications at sizes up to 19 MW. These motors typically cost approximately $250/kW. These large systems have in the past employed liquid rheostat technology for the controller, which has since been abandoned in favor of the Load Commutated Inverter (LCI) controller. While LCI motors are more economical, they do not permit the power levels achievable with liquid rheostat motors. Because the technology for liquid rheostat control is in essence lost, new drive motors could be limited to 10,000 hp (7.5 MW) each, without some technology development effort. It is estimated that these motors would cost $2M each.

Because of the large size and extreme weight of the electric motors, they would be placed below grade. A remote drive configuration (drive shaft to gear box to propeller) would be used in this instance.

## 5.3 Infrastructure

The energy required by electric motors may be supplied by transmitting power from a remote site, or by generating and conditioning the power locally (cogeneration).

### 5.3.1 Power Transmission

The Idaho Power Company Planning Department investigated the possibility of supplying power to the WSC at levels between 120 MW and 300 MW.[11,12] While the analysis of the power supply infrastructure assumes a peak demand of 300MW, very large motors can draw up to 7 times their rated current when first started (locked rotor current). Without proper consideration, this effect could cause severe voltage sag in both the local and surrounding regions. Detailed analysis is required to confirm the peak demand, which may be greater than 300 MW.

Existing lines into the INEEL could not support this load, so a new transmission line would be required from the Brady Substation at American Falls to the Antelope Station at INEEL, a distance of 56 miles, and new line from there to the WSC site. These lines would be either 230 kV or 345 kV, depending on the outcome of detailed analysis. Upgrades would be required to both the Brady and Antelope substations, along with a new substation at the WSC site. Idaho Power estimates the total installation cost at $30M for 230kV line, and $40M if a 345kV line is necessary.

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[a] J. Allmen, "Aeroacoustic Wind Tunnel Modification Underway," National Aeronautics and Space Administration, http://ccf.arc.nasa.gov/wind tunnel/article.html July 8, 1997.

Sufficient cheap hydroelectric power is anticipated to be unavailable to supply the anticipated demand, making more expensive coal-generated power necessary. This is reflected in the estimated electric power cost of \$0.05/kWhr. The facility would also be charged a demand fee on the peak power demand of \$5.00/kW per month. Idaho Power estimated that the monthly cost could range as high as \$3.6M/month.

Idaho Power was not certain that 300 MW of power is available in the region to supply the facility. With very little margin available, future demand growth in the region could have a serious negative impact on the operation of the WSC.

Approximately 3 years would be required to place the transmission system: up to 2 years to site, permit, and acquire the route, and one year to construct the facilities.

### 5.3.2 On-site Power Generation

Rather than bringing electric power in from the outside, a power generation facility could be sited near the WSC. One option is to use 2 or 3 large gas turbine engines to generate the required power.

A survey of available gas turbine engines, developed by Turbine Systems Engineering, Inc.[13] is shown in Appendix C. This survey shows that the purchase cost of gas turbines with output between 40 and 60 MW average around \$300/kW. Conversations with General Electric, Salt Lake City[14] confirm this estimate. GE estimates that the gas-turbines alone (such as the 7FA) would cost \$96M. Idaho Power estimates the cost of the associated substation at \$10M–\$15M, placing the installed cost to \$106–\$111M.

A previous project at the INEEL[15] sought to design and build a rail-car mounted mobile generating station. In cooperation with Stewart and Stevenson, a system was developed to deliver 40–50MW of electricity. Each rail-car unit would have cost \$15M. This confirms the above estimate of \$300/kW. Operating cost, including amortization over 15 years, was between 7 and 12 cents/kWh, with fuel accounting for approximately 4¢ of that. At the time the project was halted, no customers had been identified on the INEEL site for the power, although the market appeared to be strong on a nationwide scale.

No upcoming projects at the INEEL have been identified which would share the costs to bring this amount of power to the site.

## 5.4 Summary

Because an electric motor driven system would be a special design-build project, the performance characteristics could be tailored to meet the WSC requirements exactly. Disadvantages are the large system size, which would require larger facilities and subsequent costs, and long lead time to procure. The installed cost for an electric motor system is expected to fall between \$173M and \$240M, with operating costs between \$20M and \$25M per year (Table 1).

# 6. AIRCRAFT TURBOFAN ENGINES

## 6.1 Description

A variety of modern high-bypass turbofan aircraft engines are available in the power ranges of interest. These engines, developed for large commercial transport aircraft, boast high power, energy efficiency, and reliability in a compact, lightweight package. They typically have a diameter less than 3 m and weigh less than 4 tonnes, producing 25 to 60 MW of power.

The modern turbofan engine is essentially a turbojet with an oversized stage 1 compressor. This fan compresses air flowing into the engine (core flow), and also pushes air around the outside of the engine (bypass flow). By using turbine power to drive a large mass of bypass air, the overall exit velocity is reduced, increasing propulsive efficiency and decreasing noise. Typically, the ratio of bypass flow to core flow (the bypass ratio) ranges between 5 and 8 in newer turbofans.

**Table 1.** Summary evaluation of electric motors.

| **Summary Analysis** | Electric Motors | |
|---|---|---|
| **Feasibility on scale of 0-4** | **2.75** | |
| Installation practical | 4 | Units are commonly used in smaller wind tunnel applications |
| Vendors exist | 4 | GE, Westinghouse are only identified vendors capable of the size required |
| Technology available | 2 | Some re-invention of starter technology may be necessary |
| Resources available | 1 | Power may not be available. May require on-site generation. |
| **Availability / Installation Schedule** | 3 years | Power infrastructure critical |

| **Installed Cost** | Unit Cost Range | | Unit | System Quantity | System Cost Range ($M) | | |
|---|---|---|---|---|---|---|---|
| Engine/Motor | $250 | $350 | kW | 300,000 | $75 | $105 | |
| Transmission/ gearing | $10 | $15 | kW | 300,000 | $3 | $5 | |
| Propeller | $3,000,000 | $4,000,000 | each | 20 | $60 | $80 | |
| Remote Drive Costs | $5,000,000 | $10,000,000 | each | 1 | $5 | $10 | |
| Fuel /Energy Supply | $30,000,000 | $40,000,000 | power | 1 | $30 | $40 | |
| **Total ($M)** | | | | | **$173** | **$240** | |
| **Operating Cost (per month)** | | | | | | | |
| Maintenance | $10,000 | $50,000 | month | 1 | $0.010 | $0.050 | No Data |
| Fuel /Energy | $0.035 | $0.050 | kWHr | 6.30E+06 | $0.221 | $0.315 | |
| Demand Fee | $5 | $5 | kW | 300,000 | $1.500 | $1.500 | |
| **Monthly Cost ($M)** | | | | | **$1.73** | **$1.87** | |

**Assumptions:**

20 - 15MW motors driving array of 20 fans @ 2.9 million cfm each

Run time 30 hours/month at an average of 70% full power: 6,300,000 kWhr/month

To increase fuel efficiency, modern designs use very high combustion chamber temperatures, which in turn lead to high exhaust temperatures. Estimates for the averaged exit air temperature, including bypass air, range from 800K to 1000K (525–725°C).

## 6.2 Infrastructure Requirements

Turbomachinery requires an infrastructure to supply energy much as electric systems do. This infrastructure includes the tankage, supply lines, pumps, temperature control, and truck depot facilities necessary to transport, store, condition, and deliver fuel to the engines. These systems are common to all liquid fueled turbomachinery discussed in this and following sections.

Reference 1 considered the cost to construct the fuel storage, delivery and truck depot facilities necessary to support a liquid fueled main drive system. It was calculated that a capacity for 200,000 gal of fuel was required initially, with a capability to expand to 400,000 gal if desired in the future.

The conceptual facility design included

- Two 100,000 gal tanks
- Concrete foundations and curbs to prevent spills

- Tank heaters and insulation to maintain fuel temperature

- A continuous recirculation pump system to provide 600 gpm fuel flow with 25% return flow at maximum engine consumption

- Heated 4 in. fuel lines

- Fuel control valving

- Tank truck depot.

The associated cost, detailed in Table 2, summed to $2.2M, including overhead and procurement fees. Addition of tankage, lines, and pumps for a 400,000 gal capacity would add $1.8M for a total of $4M. Fuel costs for turbomachinery have been estimated by other INEEL projects[15] at approximately $0.04/kWhr, which compares favorably with electric power.

**Table 2.** Fuel supply infrastructure costs.

| Infrastructure Construction: 200,000 gal Fuel Storage with Environmental Protection | |
|---|---|
| Sitework—excavation/backfill | $21,225 |
| Concrete—pads/foundation | 65,000 |
| Metals—pipe stand and guard post | 26,000 |
| Thermal and moisture protection—insulation | 125,440 |
| Finishes—painting, etc. | 80,000 |
| Special construction—pump house | 6,500 |
| Mechanical—tank, piping, pumps, etc. | 1,821,397 |
| Electrical—control system | 60,000 |
| Total, 200,000 gallon capacity | $2,205,562 |
| Additional 200,000 gallons | 1,821,397 |
| Total, 400,000 gallon capacity | $4,026,959 |

It is also possible to fuel internal combustion systems with natural gas. Upon request, Intermountain Gas Company[16] developed an estimate of the cost to deliver natural gas to the INEEL site. A line would be laid from the Northwest pipeline at the Aberdeen Tap, near the city of American Falls, 69 miles to the INEEL Central Facilities Area (CFA), and thence to the Disaster Prevention Center site.

It was assumed for this estimate that the WSC peak demand would be 15,000 therms/hour (1 therm = 100,000 BTU), and that the gas must be delivered at 300 psi to the INEEL site. This could be accomplished with a 12-in. line, at an approximate cost of $20M. If detailed analysis shows that a 16-in. line is required, the cost would rise to $30M. The accuracy of the estimate is plus or minus 15%.

If a gas line were supplied, the cost of natural gas is expected, at the worst case, to range near $0.25/therm, or $0.0085/kWhr.

## 6.3 Application

Table D-1 in Appendix D lists some of the significant engine families, along with power and cost ranges. Engineers from Boeing,[17] General Electric,[18] and Pratt & Whitney[19] (Figure 3) were contacted to discuss the applicability of these engines to wind tunnel operations.

These engines have been extensively optimized for aircraft use, and modifications required for this application would be extensive. Among several difficulties and re-design issues raised by the specialists was the assertion that it is not possible to duct the hot core exhaust away from the bypass flow without damaging the engine. Thus it is not possible to decrease the airflow temperature from the 800–1,000K range to within the required range of less than 310K.

## 6.4 Summary

Aircraft turbofans have been optimized over the years to produce very high thrust from a small, lightweight, and reliable package. Much of this progress has been made by developing new materials, coatings, and cooling schemes to survive increasingly hot exhaust gas temperatures. Although exhaust gas is mixed with a larger volume of bypass air, the average airflow temperature is still much hotter than acceptable in the WSC. Because all the airflow that passes

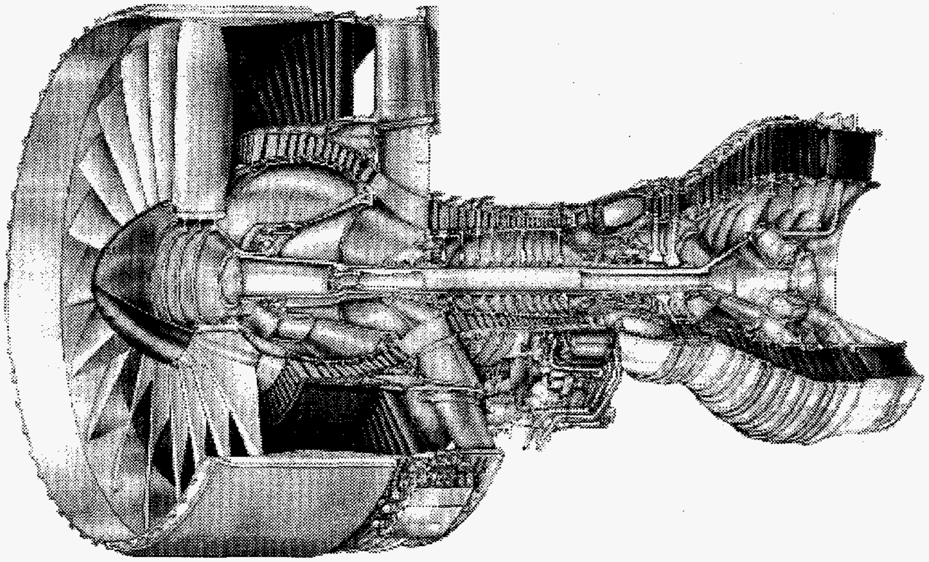

**Figure 3.** The Pratt & Whitney Series 4000 turbofan.

through the facility must pass through the main drive first, there is no opportunity to cool it by any other mixing. In addition, the intended strategy of cycling the main drive power continuously cannot be employed without cycling the engine rotational speed, which degrades the life of the engines. For these reasons turbofans do not meet the requirements of the WSC, and will not be considered further.

# 7. AIRCRAFT TURBOSHAFT ENGINES

## 7.1 Description

Aircraft turboshaft (commonly called turboprop) engines are another modification of the turbojet. In this case, turbine power is used to drive a shaft, to which a propeller set is attached. Residual thrust from the turbine exhaust typically accounts for approximately 5% of the total thrust, with the remainder attributable to the propeller. Bypass ratios for turboprop engines range around a value of 20. Thus, for a given power output and air mass flow rate, the outlet air velocity is lower, reducing noise and increasing efficiency, with respect to turbofans. In aircraft applications, these improvements come at the cost of lower aircraft speed, which accounts for their lack of popularity in western countries today.

A relatively new development in turboprop design is the propfan. In this case thrust is generated by a propeller with multiple (usually six or more) blades of exceptionally thin profile, sharp edges and a curved scimitar-like planform. For highest efficiency two such propellers counter-rotate. The propellers may be open or shrouded. Such an engine gives turboprop economy at jet speed. As a high-speed version of a turboprop, the propfan has all the advantages of a turboprop, with significantly higher power output. Most propfans are being developed in the Ukraine or Russia and employ state-of-the-art technology.

Thrust is usually controlled by a combination of the fuel flow and the pitch of the propeller blades, leaving the engine rotational speed relatively constant. This provides an advantage because thrust, or airflow, can be changed more quickly than with other aircraft engines. As mentioned previously, almost all exhaust gas energy is consumed by the power turbine, making exhaust gas management more tractable. U.S. Turbine Corp.[20] indicates that in industrial applications the exhaust from turboshaft engines is commonly ducted away with simple stainless steel ductwork. This removes the difficulty of overheating the airflow encountered with turbofans.

## 7.2 Candidates

Table D-2 in Appendix D shows the turboprop and propfan engines currently in development, production, or available as used from around the world. It is readily apparent that almost all high-power turboprop engine development is being performed in former Soviet bloc countries. Only two are manufactured in the U.S.: the Allison T56 and AE 2100. Costs for turboprop engines range from $75/kW for the Kuznetsov NK-12MV to $360/kW for the AE 2100.

### 7.2.1 U.S.-Made Turboprops

The Allison T56 series (Figure 4) has a long and distinguished record, serving as the powerplant of aircraft such as the Lockheed C-130 "Hercules" transport and variants since 1954. Power output ranges from 3,700 shaft horsepower (shp) in earlier models, to 4,500 shp in later models. One variant, the A-427, attained 5200 shp. Currently, the U.S. military is upgrading to the "J" series of the C-130, which employs the newer AE 2100 engine. Therefore, in early 1997, Allison[21] discontinued production of the T56 in favor of the AE 2100, and no longer has any T56 models available. In production, the T56 cost approximately $800,000 per unit. The WSC would require an array of 90 T56 engines to meet the expected peak power requirement.

The first Allison AE 2100 completed flight testing in 1990, making it the newest production turboprop available today. The engine produces thermodynamic power of 6,000 hp; however, all models currently in production have been derated to between 3,200 shp and 4,500 shp. The C-130J program employs the AE 2100D3 model, flat rated at 4,591 shp, with a Dowty Aerospace six-bladed R391 propeller. Cost is reported by Allison to be approximately $1.2M per unit, not including propellers.

It is not known whether a 6,000 shp rated version will be available in time to support the WSC. 68–6,000 shp engines or 90–4,500 shp engines would be required to meet the WSC peak power demand.

### 7.2.2 Russian-Made Turboprops

The Kuznetsov NK-12MV (Figure 5) is a large counter-rotating turboprop engine, in service in various configurations with the former Soviet Union for approximately 40 years. It is the most powerful conventional turboprop

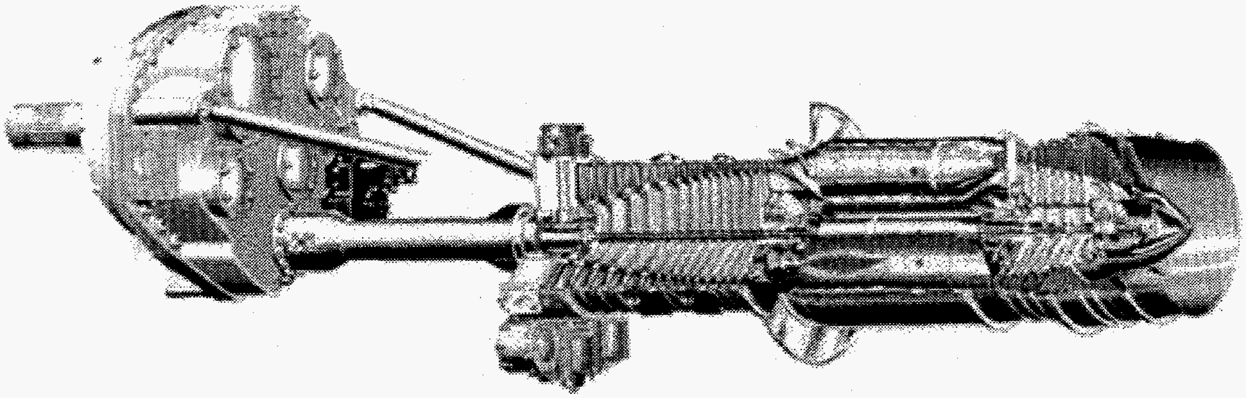

**Figure 4.** Cutaway view of the Allison T56.

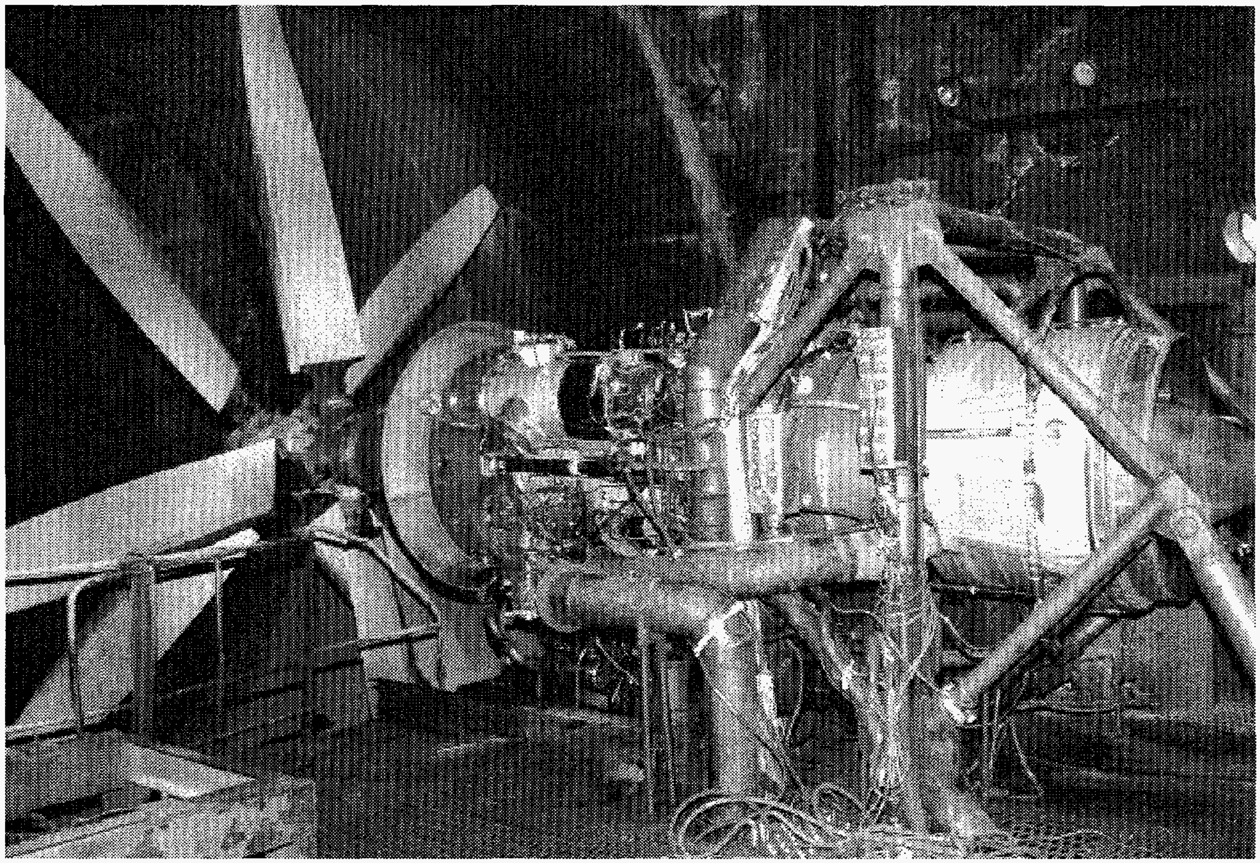

**Figure 5.** NK-12MV on test stand.

aircraft engine in the world, rated at 14,750 shp. Variants of this engine—up to 30,000 shp—have been built for powerplant and pipeline pumping applications.

At 14,750 shp, 28 units would be required to meet the predicted WSC peak power demand.

The MV design has been used extensively on both military and civil aircraft. Typically, a 6.2m (20 ft-4 in.) reversible pitch propeller set is used in military applications, while civilian applications employ a 5.6m (18 ft-4 in.) propeller set. All propeller configurations employ two sets of four variable pitch blades on independent counter-rotating coaxial shafts (The counter-rotating and independent nature of the propellers is appealing in this application because it provides a simple means of controlling the vorticity and subsequent lateral turbulence content of the airflow).

The NK12-MV also has prior experience as a wind tunnel main drive. Kuznetsov factory representatives[22] report that a wind tunnel was built to test the NK93 propfan (discussed below) that was driven by a single NK12-MV. This effort produced valuable data on engine ground test properties including propeller behavior, reliability data, and operating costs. Some effort will be required to predict life cycle costs for U.S.-based operation from the Russian-based cost data.

The problem of noise with turboprop engines appears to be exacerbated somewhat in the NK-12. Factory reported sound pressures for indoor operation reach 143 dB at the engine outlet. While engine outlet noise would be significantly reduced by ducting the exhaust out of the airflow, further effort will be required to determine whether engine noise would affect WSC operations.

It is reported that this engine has been modified to burn natural gas rather than liquid jet fuel with positive results. This modification requires replacement of fuel orifices, fuel pipelines, and fuel delivery controllers.

Information from the U.S. Defense Technical Information Center and extrapolation to include civilian applications indicate that in excess of 3,000 NK-12MV series engines have been produced. Ongoing disarmament activities have caused a large supply of these engines to be available, however, firm data is not yet available on the delivery time for 28 units.

The Dvigatel NK-93 is the most powerful propfan known to be under development anywhere in the world. This engine generates 22.4 MW (30,000 shp), which is over twice the power output of the NK-12MV. The NK-93 has a front fan with 8 blades (40% power) and a rear fan with 10 blades (60% power) which counter-rotate similar to the NK-12 turboprop. The high power of the NK-93 points to an array one-half the size of the preliminary design.

Unfortunately, this and other large propfans are still in development phase and not ready for production at this time. The designer indicates that, because of a protracted budget shortfall, development will continue to lag behind schedule, and the engine will not enter production in time to support this program.

## 7.3 Summary

Table 3 summarizes the analysis of turboshaft engines as main drive candidates. The system-installed cost of the candidates shows a very large range: from $32M to $221M. This range reflects the difference between the NK-12MV and its lighter, flight optimized American counterparts. The use of turboprop engines is attractive for a variety of reasons: high power output, direct drive compatibility, long service history, and low cost. Although the most attractive candidates are manufactured overseas, a U.S. supplier has been identified[23] to develop and deliver complete main drive systems from the basic engines.

**Table 3.** Summary evaluation of turboshaft aircraft engines.

| | | |
|---|---|---|
| **Summary Analysis** | Turboprop Aircraft Engines | |
| **Feasibility on scale of 0-4** | **3.75** | |
| Installation practical | 4 | Previous experience as windtunnel prime mover. |
| Vendors exist | 3 | Few vendors with large enough engines. Very high interest in supporting the program. |
| Technology available | 4 | No technology development issues identified. |
| Resources available | 4 | Engines, fuel and qualified mechanics are likely available |
| **Installation Schedule** | 3 mo - 2 yrs | Single Kuznetsov NK12-MV available 90 day after order. Time for following engines underternined. |

| **Installed Cost** | Unit Cost Range | | Unit | System Quantity | System Cost Range ($M) | | |
|---|---|---|---|---|---|---|---|
| Engine/Motor | $82 | $350 | kW | 300,000 | $24.6 | $105.0 | |
| Transmission/ gearing | $0 | $0 | kW | 300,000 | $0.0 | $0.0 | included with engine |
| Propeller | $180,000 | $4,000,000 | prop | 28 | $5.0 | $112.0 | |
| Fuel /Energy Supply | $2,200,000 | $4,000,000 | power | 1 | $2.2 | $4.0 | |
| **Total ($M)** | | | | | **$31.8** | **$221.0** | |
| **Operating Cost (per month)** | | | | | | | |
| Maintenance | $10,000 | $50,000 | month | 1 | $0.010 | $0.050 | Limited Data for one engine (NK-12Mv) |
| Fuel /Energy | $0.035 | $0.050 | kWHr | 6.30E+06 | $0.221 | $0.315 | |
| Demand Fee | $0 | $0 | kW | 300,000 | $0.000 | $0.000 | |
| **Monthly Cost ($M)** | | | | | **$0.23** | **$0.37** | |

**Assumptions:**

Run time 30 hours/month at an average of 70% full power: 6,300,000 kWhr/month
28 - 11MW engines in an array

# 8. INDUSTRIAL TURBOSHAFT ENGINES

## 8.1 Description

Industrial turboshaft engines, or gas-turbines (Figure 6), are ground-based derivatives of aircraft turbofan or turboprop engines. Employed in a wide variety of mechanical drive and power production applications, they feature high power, high efficiency, low exhaust emissions, and installation flexibility. Table D-3 in Appendix D shows a sampling of gas-turbines on the market.[13] Many of the engines surveyed are designed to operate on either liquid or natural gas fuels, further enhancing their flexibility.

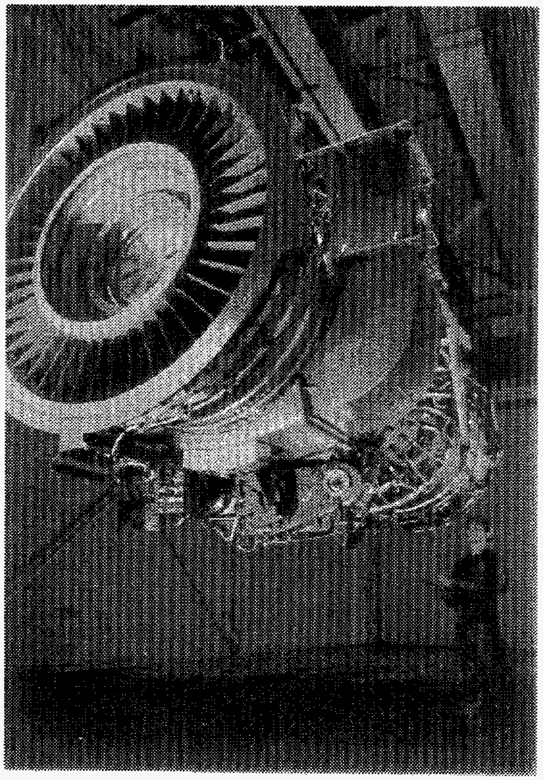

**Figure 6.** The 45 MW GE LM6000 gas turbine engine

## 8.2 Application

The application of gas turbine engines is quite flexible. They may be installed in a remote drive configuration as with electric motors, or, depending on engine and gearbox dimensions, they may be set up in a direct drive configuration. The availability of engines over a wide power output range would simplify the design of the main drive array, and the balance of the WSC. Drive gears and propeller sets would be specially designed and built to match the operating characteristics particular to the selected engine. Because these engines are designed to operate at constant speed, airflow speed control would require variable pitch propellers. As noted in Section 4.3, this technology is readily available and would not add significantly to the system cost. Infrastructure costs would be similar to those enumerated in Section 6.2 for turbofan engines.

To our knowledge, gas turbines have not been used in a wind tunnel application. It is therefore difficult to estimate the life cycle costs for the unique application envisioned for the WSC.

## 8.3 Summary

Gas turbine engines appear to be well suited for this application. They offer the power, compact size, low exhaust emissions, and application flexibility to facilitate the design, permitting, construction, and operation of the WSC. Countering these advantages are the lack of history in this application, high initial cost, and long lead time to procure. The specific cost ($/kW) of these systems is 3 to 5 times greater than that for select aircraft turboshaft engines, while delivery time is constrained by propeller design and fabrication to two years (Table 4).

# 9. CONCLUSIONS

## 9.1 Feasibility

The aircraft turbofan is the only candidate determined to be infeasible for this application. While it would be possible to overcome the exhaust temperature and power cycling issues, the cost and development time associated with the effort would be similar to that for a new

**Table 4**. Summary evaluation of industrial gas turbine engines.

| **Summary Analysis** | Industrial Gas Turbines | |
|---|---|---|
| **Feasibility on scale of 0-4** | **3.5** | |
| Installation practical | 3 | Installation and operation similar to electric motors, speed control may be an issue |
| Vendors exist | 4 | Several vendors exist. Those contacted show interest in supporting this project |
| Technology available | 3 | May require cycling engine speed to change flow rate |
| Resources available | 4 | Engines, fuel and qualified mechanics are likely available |
| **Availability** | 2 years | Limited by propellers and reduction gears |

| **Installed Cost** | Unit Cost Range | | Unit | System Quantity | System Cost Range ($M) | | |
|---|---|---|---|---|---|---|---|
| Engine/Motor | $250 | $350 | kW | 300,000 | $75 | $105 | |
| Transmission/ gearing | $10 | $15 | kW | 300,000 | $3 | $5 | |
| Propeller | $3,000,000 | $4,000,000 | prop | 20 | $60 | $80 | |
| Fuel /Energy Supply | $2,200,000 | $4,000,000 | power | 1 | $2 | $4 | |
| **Total** | | | | | **$140** | **$194** | |
| **Operating Cost (per month)** | | | | | | | |
| Maintenance | $10,000 | $50,000 | month | 1 | $0.010 | $0.050 | No Data |
| Fuel /Energy | $0.035 | $0.050 | kWHr | 6.30E+06 | $0.221 | $0.315 | |
| Demand Fee | $0 | $0 | kW | 300,000 | $0.000 | $0.000 | |
| **Monthly Cost ($M)** | | | | | **$0.23** | **$0.37** | |

**Assumptions:**

20 - 15MW motors driving array of 20 fans @ 2.9 million cfm each

Run time 30 hours/month at an average of 70% full power: 6,300,000 kWhr/month

product line, and not compatible with the construction schedule of the WSC. Turbofans will not be discussed in the comparisons to follow.

The remaining candidates—electric, aircraft turboprop, and industrial turboshafts—are all technically feasible. However, they differ in the quantity of technical development required, and the risk associated with the development effort.

The use of electric motors would not be simple for this particular application. Current motor control technology appears to have a power limit of 7.5 MW, above which development would become much more involved. The real limitation, however, appears to be the infrastructure requirements to deliver power to the system. The WSC's large predicted power demand, combined with the proposed site location relative to major power sources, make the cost of power prohibitive. Electric motors rank third in this category.

Aircraft turboshafts are well suited to this application. No significant modifications are necessary prior to installation. And the systems are well understood: they have logged millions of hours coupled with the gears and propeller sets that would be used in the WSC. The NK-12 has prior application as a wind tunnel main drive. This historical information would facilitate the prediction and solution of installation issues and maintenance requirements, and improve the accuracy of predicted lifecycle costs. Aircraft turboshafts rank first in this category.

Industrial turboshaft engines also appear to be well suited for this application. While no obstacles or significant modifications are foreseen, this would be a novel application for these systems, and a learning curve can be expected in developing appropriate propeller sets and operating parameters. Thus, industrial engines rank second in feasibility.

## 9.2 Availability

Electric motors will depend upon the electric power delivery infrastructure, which has been predicted to take as long as 3 years. Aircraft turboshafts have a distinct advantage in availability. Because the engines, gears, and propellers are currently extant and in storage, the delivery time for a single fully operational engine is advertised to be six months. Gas turbines are constrained by design and fabrication of the propellers, which could take up to 2 years. Thus aircraft turboshafts lead this category, followed by industrial engines and electric motors.

## 9.3 Power

In the category of power output, electric motors again rank third. While it is theoretically possible to build electric motors in any size, current controller technology appears to set a practical upper bound of about 7.5 MW per unit.

Industrial gas turbines not only provide the most power of any of the candidates, but also provide a wide range of options, from less than 1 to over 50 MW output. This range provides great flexibility in the facility design, allowing the selection of unit power after the balance of the facility has been designed and characterized. This flexibility earns a first place ranking.

Aircraft turboprops do not exhibit the power range of industrial engines. The maximum is represented by the NK-12MV at 11 MW, earning a rank of second.

## 9.4 Installed Cost

In general, all systems investigated would cost between \$250/kW and \$350/kW, plus supporting infrastructure costs. Infrastructure for an electric system was calculated to be \$30–\$40M, while that for liquid fueled systems was \$2–\$4M. An exception to this trend was the NK-12MV aircraft turboshaft, costing less than \$100/kW with the propellers included. The installed cost for an array of these units is estimated to be \$32M (Table 3), while the next candidate, industrial gas turbines, will cost a minimum of \$140M (Table 4). Thus aircraft turboprops rank first, followed by industrial turboshafts and electric motors.

## 9.5 Operating Cost

Operating cost data, as shown in the summary tables, is currently limited to estimated fuel/energy costs based on a fixed output per month. While reliability information is available for some extant candidates (Appendix E), it is difficult to meaningfully extrapolate what the reliability of novel combinations of engine/motor/gear/propeller might be. Therefore, ranking is not performed in this category.

## 9.6 Rank

Aircraft turboshaft engines are ranked first overall, having earned first in the categories of feasibility, availability, and installed cost, and second in power. This ranking is almost entirely due to the remarkable combination of attributes found in the NK-12MV.

Industrial turboshaft engines rank second, having placed first in power, and second in all other categories.

Electric motors are third choice, being a feasible, but difficult and expensive solution for this application.

Finally, aircraft turbofans are ranked last, as they do not appear to be a viable option.

## 9.7 Recommendations

In the course of this investigation the remarkable attributes of NK-12MV have become readily apparent. These units have a long service history, both in the air and on the ground, with good reliability statistics (Appendix E). They are already built, and can be overhauled and begin delivery to the WSC site within months, rather than years. They produce very respectable power, at 11.2 MW each, and run relatively cool, simplifying exhaust management. Finally, the installed cost for these units is approximately $110M less than the next alternative.

However, more detailed information about the operational characteristics, maintenance, and life cycle cost must be ascertained prior to the final decision to employ this unit as the WSC main drive.

It is recommended that

1. An in-depth investigation of the NK-12MV be initiated, including ground-based operating characteristics, life cycle costs, and availability.

2. WSC analysis, design, and project management studies assume a main drive system composed of NK-12MV units until the recommended detailed analysis substantiates the unit's suitability for this application.

3. If further investigation reveals that the NK-12MV is not suitable, then the industrial turboshaft engine should be investigated as the next logical choice

4. Finally, the possibility of a hybrid system should be explored. In this case, a core of 2–4 electric motor driven fans might be placed in the center of the array, providing airflow for checkout and low-speed tests. This arrangement would avoid the large infrastructure costs of a purely electric system, while allowing a simple and rapid means of performing low velocity tests, calibration, and instrument check-out.

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# Appendix A

## Conceptual Windstorm Simulation Center Main Drive Power Calculations

# Wind Tunnel Flow Losses and Power Requirements

4/1/97
J. M. Lacy

**References**:

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**Design Parameters :**

Max airflow speed at test section $V_{test} \equiv 200 \cdot mph$

Jet Width $W_{jet} \equiv 80 \cdot ft$

Jet Height $H_{jet} \equiv 40 \cdot ft$

Propeller efficiency $\eta := 80 \cdot \%$

**Assumptions, Definitions, and Properties**:

Intake air is still
Incompressible fluid flow

Density of air $\gamma := 11.8 \cdot \frac{newton}{m^3}$ $\rho := \frac{\gamma}{g}$ $\rho = 1.203 \cdot \frac{kg}{m^3}$

Dynamic Viscosity (T=80F) $\mu := 3.85 \cdot 10^{-7} \cdot lbf \cdot \frac{sec}{ft^2}$ $\mu = 1.843 \cdot 10^{-5} \cdot \frac{kg}{m \cdot sec}$

Units: $kPa \equiv 1000 \cdot Pa$ $MW \equiv 10^6 \cdot watt$

**Section Definitions** (see attached figure)

Volume 1: Bell mouth contraction to fans
Volume 2: Fan exit contraction to jet
Volume 0: High bay/test section flow
Section 3: High bay exhaust to ambient

**Test Section Characteristics**

Test Section Area $A_{test} := W_{jet} \cdot H_{jet}$ $A_{test} = 297.29 \cdot m^2$ $A_0 := A_{test}$

$V_{test} = 89.408 \cdot \frac{m}{sec}$ $V_0 := V_{test}$

Volumetric Flow Rate $Q := A_{test} \cdot V_{test}$ $Q = 2.658 \cdot 10^4 \cdot \frac{m^3}{sec}$

Jet Dynamic Pressure $q0 := \left[\frac{1}{2} \cdot \rho \cdot \left(V_{test}\right)^2\right]$ $q0 = 4.809 \cdot kPa$

## Velocity Profile through Tunnel

Bellmouth entrance (1)

$V_1 := 50 \cdot \text{mph}$ $\qquad A_1 := \frac{Q}{V_1}$ $\qquad A_1 = 1.189 \cdot 10^3 \cdot \text{m}^2$ $\qquad \sqrt{A_1} = 113.137 \cdot \text{ft}$

Entrance to Fans (2)

Assume an array of 20' Diameter fans. Exit area is equal to array of 20' squares:

$N_{fan} := 28$

$A_2 := N_{fan} \cdot 400 \cdot \text{ft}^2$ $\qquad A_2 = 1.041 \cdot 10^3 \cdot \text{m}^2$ $\qquad V_2 := \frac{Q}{A_2}$ $\qquad \sqrt{A_2} = 105.83 \cdot \text{ft}$

High Bay

Open Section Area is normally 4x the jet area:

$A_3 := 4 \cdot A_0$ $\qquad A_3 = 1.189 \cdot 10^3 \cdot \text{m}^2$ $\qquad V_3 := \frac{Q}{A_3}$ $\qquad \sqrt{A_3} = 113.137 \cdot \text{ft}$

Equivalent Diameter of Sections

$$D := \overrightarrow{\sqrt{4 \cdot \frac{A}{\pi}}} \qquad D = \begin{bmatrix} 19.456 \\ 38.911 \\ 36.398 \\ 38.911 \end{bmatrix} \cdot \text{m} \qquad V = \begin{bmatrix} 89.408 \\ 22.352 \\ 25.545 \\ 22.352 \end{bmatrix} \cdot \frac{\text{m}}{\text{sec}}$$

## Energy Loss By Section and Volume

### Bellmouth entrance (section 1)

Loss Coefficient $\quad C_{L_1} := 0.35$

Pressure Drop $\quad \Delta p_1 := \gamma \cdot C_{L_1} \cdot \frac{(V_2)^2}{2 \cdot g}$ $\qquad \Delta p_1 = 0.137 \cdot \text{kPa}$

$K_{0_1} := \frac{\Delta p_1}{q0}$ $\qquad K_{0_1} = 0.029$

### Contraction from Fans to Jet (volume 2)

Section Length $\quad L_{sec} := 190 \cdot \text{ft}$

Avg Velocity $\quad V_{avg} := \frac{V_0 + V_2}{2}$ $\qquad V_{avg} = 57.477 \cdot \frac{\text{m}}{\text{sec}}$

Characteristic Length $\quad L := \frac{D_2 + D_0}{2}$ $\qquad L = 27.927 \cdot \text{m}$

Reynold's No. $\quad R := \frac{\rho}{\mu} \cdot V_{avg} \cdot L$ $\qquad R = 1.048 \cdot 10^8$

Skin Friction (Table Lookup based on R, Rouse) $\quad \lambda := 0.001$

$K_{0_2} := \frac{0.32 \cdot \lambda \cdot L_{sec}}{D_0}$ $\qquad K_{0_2} = 9.525 \cdot 10^{-4}$

$\Delta p_2 := K_{0_2} \cdot q0$ $\qquad \Delta p_2 = 0.005 \cdot \text{kPa}$

## Jet Losses in open test section

$L_{sec} := 160 \cdot ft$

$\lambda := 0.08$ From Rae & Pope

$K_{0_0} := \dfrac{\lambda \cdot L_{sec}}{D_0}$ $K_{0_0} = 0.201$

$\Delta p_0 := K_{0_0} \cdot q0$ $\Delta p_0 = 0.964 \cdot kPa$

## High Bay Exhaust to Ambient (section 3)

*Note: This assumes the length of high bay is not enough to extract much energy. Therefore loss is calculated assuming full jet velocity.*

$C_{L_3} := 1.0$

$\Delta p_3 := \gamma \cdot C_{L_3} \cdot \dfrac{(V_0)^2}{2 \cdot g}$ $\Delta p_3 = 4.809 \cdot kPa$

$K_{0_3} := \dfrac{\Delta p_3}{q0}$ $K_{0_3} = 1$

## Summary of Losses

Total Pressure Drop

$$\Delta p = \begin{bmatrix} 0.964 \\ 0.137 \\ 0.005 \\ 4.809 \end{bmatrix} \cdot kPa$$

$\sum \Delta p = 5.916 \cdot kPa$

Total Loss Coefficient

$$K_0 = \begin{bmatrix} 0.201 \\ 0.029 \\ 9.525 \cdot 10^{-4} \\ 1 \end{bmatrix}$$

$\sum K_0 = 1.23$

Tunnel Energy Ratio

$ER := \dfrac{1}{\sum K_0}$

$ER = 0.813$

Composite Energy Ratio

$ER_{comp} := \eta \cdot ER$

$ER_{comp} = 0.65$

**Static Pressure Profile Through Tunnel**

$P_{atm} := 1 \cdot atm - \gamma \cdot 5000 \cdot ft$ $\qquad P_{atm} = 83.342 \cdot kPa$

$v_{atm} := 0 \cdot \frac{m}{sec}$

$$\frac{v_1^2}{2g} + \frac{p_1}{\gamma} + z_1 + h_p = \frac{v_2^2}{2g} + \frac{p_2}{\gamma} + z_2 + h_l$$

$p_0 := \left[ v_{atm}^2 - (V_0)^2 \right] \cdot \frac{\rho}{2} + P_{atm} + \Delta p_3 + \Delta p_0$ $\qquad p_0 = 84.306 \cdot kPa$

$p_2 := \left[ v_{atm}^2 - (V_2)^2 \right] \cdot \frac{\rho}{2} + P_{atm} + \Delta p_0 + \Delta p_2 + \Delta p_3$ $\qquad p_2 = 88.728 \cdot kPa$

$p_1 := \left[ P_{atm} + \left[ v_{atm}^2 - (V_2)^2 \right] \cdot \frac{\rho}{2} \right] - \Delta p_1$ $\qquad p_1 = 82.812 \cdot kPa$

Fan Power: $P := \frac{(p_2 - p_1) \cdot Q}{\eta}$ $\qquad P = 196.551 \cdot MW \qquad P = 2.636 \cdot 10^5 \cdot hp$

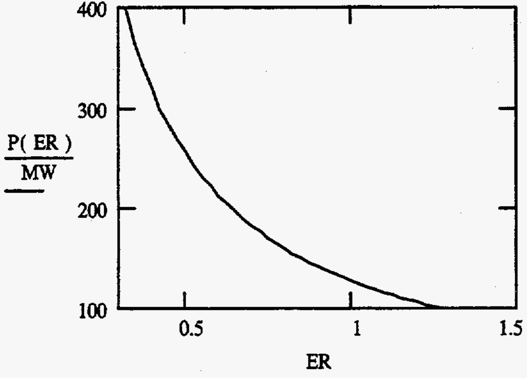
Required Shaft Power per Fan: $P_{fan} := \frac{P}{N_{fan}}$ $\qquad P_{fan} = 9.414 \cdot 10^3 \cdot hp$

A review of the literature indicates that an Energy Ratio greater than 0.5 may be difficult to achieve. Examine the power required assuming the composite ER ranges between 0.3 and 0.8

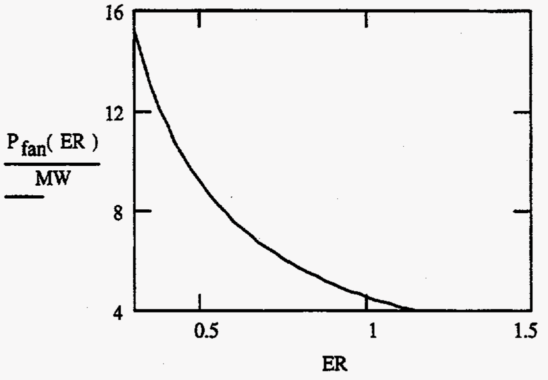
$ER := 0.3, 0.325 .. 1.5$

Required Composite Power $$P(ER) := \frac{.5 \cdot \rho \cdot A_{test} \cdot V_{test}^{3}}{ER} \qquad P(0.5) = 255.664 \cdot MW$$

Required Shaft Power per Fan: $$P_{fan}(ER) := \frac{P(ER)}{N_{fan}} \qquad P_{fan}(0.5) = 9.131 \cdot MW$$



*Required Total Power (MW) vs. Energy Ratio*



*Required individual fan power (MW) vs. energy ratic assuming 28 fan array*

The design baseline assumes the use of 28 Kuznetsov NK-12MV turboprop engines. These engines are rated at 14750 shp (11.0 MW) each. Therefore this configuration can be expected to deliver the required jet velocities for energy ratios down to approximately 0.4. Design enhancements, such as the addition of an exhaust diffuser, that increase the composite ER from 0.4 to, for example 0.55, would decrease power requirements by 87MW.

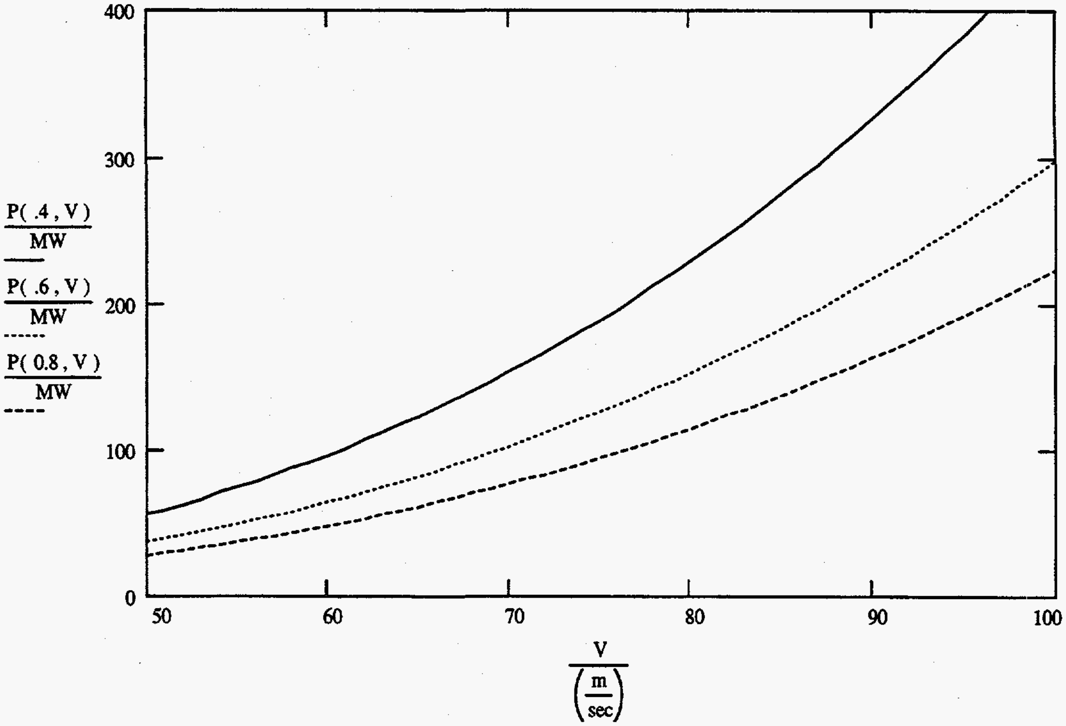
Power required as a function of energy ratio and jet velocity

$$P(ER, V) := \frac{.5 \cdot \rho \cdot A_{test} \cdot V^3}{ER}$$

*Test section area*
$A_{test} = 297.29 \cdot m^2$

$$V := 50 \cdot \frac{m}{sec} .. 100 \cdot \frac{m}{sec}$$

*Composite power vs. test section velocity at energy ratios of 0.4, 0.6, and 0.8*



# Appendix B

# Request for Information
Commerce Business Daily

[Commerce Business Daily: Posted June 17, 1997]
From the Commerce Business Daily Online via GPO Access
[cbdnet.access.gpo.gov]

PART: U.S. GOVERNMENT PROCUREMENTS
SUBPART: SUPPLIES, EQUIPMENT AND MATERIAL
CLASSCOD: 99--Miscellaneous--Potential Sources Sought
OFFADD: Lockheed Idaho Technologies Company, P.O. Box 1625, Falls, ID 83415-3521
SUBJECT: 99--HIGH POWER FANS FOR WIND TUNNEL APPLICATION
SOL cbdO78
DUE 071897
POC Jeff Lacy
DESC: Lockheed Martin Idaho Technologies Company (LMITCO), a management and operating contractor for the Department of Energy (DOE) at the Idaho National Engineering & Environmental Laboratory (INEEL) is seeking sources only. There is no solicitation available. The Idaho National Engineering and Environmental Laboratory is developing a design for a large-scale structural wind test facility as a critical activity of the **Partnership for Natural Disaster Reduction.** The conceptual design for this facility is an open-circuit, open-test section wind tunnel, with fans mounted in an array upstream of the test section. An airflow of 90 m/s is required over a throat area of 300 sq. meters. It is estimated that between 250 and 300 MW will be required to provide this airflow, subject to design optimization of the facility. Current schedule will require delivery of fan system in early 2000. Sources are sought for candidate propulsion systems to provide the described airflow. There is currently no restriction on type of power source, however, the ability to prescribe and vary the longitudinal large scale turbulence produced is required. It is expected that an array of fans will be employed, with numerical limits imposed by control and maintenance issues. Interested firms with either pre-existing or proposed design solutions are invited to respond within 30 days of this notice. Responses should include candidate physical dimensions, power, efficiency and reliability and maintainability statistics, as available.

LINKURL: http://www.inel.gov/procurement/litco/index.html
LINKDESC: LMITCO Procurement area
EMAILADD: lcy@inel.gov
EMAILDESC: Jeff Lacy
CITE: (W-168 SN085782)

# Appendix C

# List of Contacts

# Appendix C

## Contact List

| Company | Contact | Phone No. | Location | Notes |
|---|---|---|---|---|
| **Aiolos Engineers** | | | **Toronto, Canada** | |
| | Elfstrom, Gary | 416.674.3017 | | |
| **Allison** | | **317.230.2000** | **Indianapolis, IN** | |
| | Lindsey, Tom | 317.230.6375 | | Program Manager AE2100 |
| | Eddy, Bill | 317.230.3232 | | T56 Program Manager |
| | Mosser, Dean | 317.230.2323 | | AE2100 - T56 |
| | Owens, Jim | 317.230.3740 | | Industrial Sales |
| **Aviaexport (Russia)** | | | **Moscow, Russia** | Export firm for Russian engines |
| | Aliaev, Sergei | 095.417.0144 | | Director, Engine Division |
| | Khrenov, Alex | 095.417.0435 | | Chief Specialist, Engine Division |
| **Boeing** | Mohageh, Mike | 206.234.0200 | | Structures |
| | Honomen, Art | 206.717.0616 | | Structures |
| **Bosch Aerospace** | | **205.882.9394** | | Markets Kuznetsov engines in U.S. |
| | Boschma, James | 205.882.9394 | | Technical Director |
| **CFM International** | | **513.552.3300** | **Cincinnati, OH** | |
| | Calendar, John | 513.552.3404 | | |
| **Dowty (UK)** | | **01235 559999** | **Abingdon, Oxfordshire, Great Britain** | No Contact |
| | Hansen, Jeff | 44.1452.711.422 | | Director, Engine Division |
| **Dresser-Rand Turbo Products** | | | **Olean, NY** | |
| | Richards, Larry | 716.375.3293/3146 | | (Gas turbine packager) |
| | Ray, Elias (GE) | 513.552.6053 | | (oil & gas only) |
| **DRMO/DRMS** | | **616.961.7307** | | **Defense reutilization office** |
| | Bemus, John | 616.961.5630 | | |
| **Fluid Technology (subsidiary of Howden)** | | | **Salt Lake City, UT** | |
| | Woodward, Brent | 801.268.0600 | | |
| **GE Aircraft Engines** | | | **Cincinnati, OH** | |
| | Baird, Doug | 513.552.2000 | | Aircraft Engines |
| | Stowell, Tom | 513.552.2479 | | Engine Division |
| | Westerkamp, Doug | 513.552.5574 | | Marketing |
| | Millhelm, Bill | 513.552.5050 | | Marine |
| | Sailor, Ed | 513.552.5432 | | Marketing |
| | Oganowski, Greg | 513.552.5409 | | Manager, No. Am. Marketing |
| | Anthony, Rob | 513.552.5200 | | |
| **GE Motors and Industrial Systems** | | | **Denver, CO** | |
| | Brown, Lew | 303.753.2261 | | Motors & Drives |
| | Harris, Dave | 303.932.7891 | | |
| | Sperry, Howard | 303.753.2263 | | |
| | Marquez, Rigo | 219.439.2000 | | |
| **GE Power Systems** | | | **Salt Lake City, UT** | |
| | Long, Keith | 801.468.5720 | | |
| | Shide, Matt | 801.468.5712 | | |
| **GE Power Generation** | | | **New York, NY** | |
| | Smith, Stan | 518.385.4131 | | |
| **Idaho Power Company** | | | **Boise, ID** | |
| | McCarthy, Kent | 208.388.2565 | | Planning Dept. |
| | Shelburg, Ron | 208.388. | | Planning Dept. |
| **Kuznetsov** | | | **Samara, Russia** | |
| | Bourmistrov, Giennadi | 5462.256.253 | | General Director - Chief Designer |
| | Ovchinnikov, Valetin | 8462.293.795 | | Deputy Chief Designer |
| | Ermikov, Anry | 8462.251.263 | | Deputy Chief Designer |

| | | | | |
|---|---|---|---|---|
| **Lockheed Martin Aeronautical Systems** | | **Smyrna, GA** | | |
| Searle, Norm | 770.494.0938 | | Technical Engineer | |
| Kays, Steve | 770.494.7338 | | Procurement Manager | |
| Bangert, Lou | 770.793.0049 | | P&W engine for F22 Development | |
| Dupack, Joe | 770.494.8472 | | Recommended Dowty of U.K. | |
| Pounds, Gerald | 770.494.4158 | | Dept. Manager, Wind Tunnels & Aircraft Systems | |
| Perry, Mark | 770.494.5619 | | Lead Project Engineer, Wind Tunnel & Aircraft Systems | |
| **Lockheed Martin Astronautical Systems** | | **Denver, CO** | | |
| Giere, David | 303.977.1147 | | Experience with Kuznetsov rocket engines | |
| Parsons, Don | 303.971.7594 | | | |
| **New Philadelphia Fan Co. (subsidiary of Howden)** | | | | |
| Johnston, Dave | 330.339.1111 ext 233 | | | |
| **Philadelphia Gear Corp.** | 610.265.3000 | **King of Prussia, PA** | | |
| Clifton, Bill | ext 4553 | | | |
| **Pratt & Whitney** | | **East Hartford, CN** | | |
| Gissander, Joel | 860.565.6546 | | Technical Engineer | |
| Cavina, Mike | 404.714.3432 | | Technical Engineer | |
| **Stewart & Stevenson Services Inc.** | 713.868.7700 | **Houston, TX** | | |
| Axford, Mark H. | 713.868.7650 | | | |
| **NASA Ames Research Center** | | **Moffet Field, CA** | | |
| Kidwell, George | 415.604.5060 | | Deputy Director of Aeronautics | |
| Bufton, Dan | 415.604.4107 | | Unitary Wind Tunnel | |
| Nguyen, Nhan | 415.694.5876 | | Facility Engineer | |
| Ospring, Mike | 415.604.4077 | | Engineering Manager | |
| Presley, Roy | 415.604.5851 | | Aero Test & Simulation Division | |
| **Rolls-Royce (UK)** | 44.133.266.1461 | | | No Contact |
| **US Air Force** | | **San Antonio, TX** | | |
| Aker, Rick | 210.925.3687 | | Engine Management office | No Contact |
| **Sverdrup Technology, Inc.** | 615.455.6400 | **Tullahoma, TN** | | |
| Starr, Rogers | 615.393.6694 | | Vice President | |
| Jenke, Leroy | 615.393.6311 | | | |
| Johnson, Ward | 615.393.6674 | | | |
| **Westinghouse** | 407.281.2000 | | | |
| Rothos, Dan | 407.281.2140 | | | |
| Jones, Ken | 801.566.3600 | | Sales Engineer | |

# Appendix D

# Characteristics of Candidate Systems

**Table D-1.** Aircraft turbofan engine characteristics.

| | Fan Dia. | Rated Thrust | Fan Mass Flow Rate | Rated Bypass Ratio | Fuel Consump- tion | Average Exhaust Temp. | Ex-core Mass Flow Rate | Core mass Flow Rate | Average Exit Velocity | Power Output | Cost/ Status | Approximate Cost per MW of Power |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | (m) | (kN) | (kg/sec) | (BPR) | (mg/Ns) | (K) | (kg/sec) | (kg/sec) | (m/sec) | (MW) | ($ Millions) | ($/MW) |
| USA GE90-76B | 3.12 | 339.9 | 1,361.0 | 8.65 | - | 600 | 1,220.0 | 141.0 | 249.74 | 42.44 | $10 - 11 M | 247,386 |
| USA GE90-85B | 3.12 | 376.8 | 1,415.0 | 8.65 | - | 600 | 1,268.4 | 146.6 | 266.29 | 50.17 | $11 - 12 M | 229,225 |
| USA GE90-90B | 3.12 | 400.4 | 1,449.0 | 8.65 | - | 600 | 1,298.8 | 150.2 | 276.33 | 55.32 | $12 - 13 M | 225,954 |
| USA GE90-92B | 3.12 | 409.3 | 1,461.0 | 8.65 | - | 600 | 1,309.6 | 151.4 | 280.15 | 57.33 | $12 - 13 M | 218,025 |
| USA P&W JT3D-1 | 1.35 | 75.6 | 209.0 | 1.36 | 15.15 | 818 | 120.4 | 88.6 | 361.53 | 13.66 | Out of production | - |
| USA P&W JT3D-8B | 1.35 | 93.4 | 209.0 | 1.36 | 15.85 | 750 | 120.4 | 88.6 | 446.89 | 20.87 | Out of production | - |
| USA P&W JT9D-3A | 2.43 | 200.8 | 684.0 | 5.17 | 17.67 | 725 | 573.1 | 110.9 | 293.57 | 29.47 | Out of production | - |
| USA P&W JT9D-59A | 2.46 | 236.0 | 769.0 | 5.15 | 17.87 | 853 | 644.0 | 125.0 | 306.89 | 36.21 | Out of production | - |
| USA P&W JT9D-7R4 | 2.46 | 249.0 | 769.0 | 5.01 | 17.42 | 848 | 641.0 | 128.0 | 323.80 | 40.31 | Out of production | - |
| USA P&W 2037 | 1.99 | 170.1 | 608.0 | 6.00 | 9.35 | 733 | 521.1 | 86.9 | 279.77 | 23.79 | $6 - 7 M | 252,160 |
| USA P&W 2040 | 1.99 | 181.9 | 608.0 | 6.00 | 9.35 | 750 | 521.1 | 86.9 | 299.18 | 27.21 | $7 - 8 M | 257,256 |
| USA P&W 2043 | 1.99 | 191.2 | 608.0 | 6.00 | 9.35 | 750 | 521.1 | 86.9 | 314.47 | 30.06 | $8 - 9 M | 266,102 |
| USA P&W 4052 | 2.46 | 232.1 | 773.0 | 4.85 | 8.81 | 750 | 640.9 | 132.1 | 300.26 | 34.85 | $9 - 10 M | 272,636 |
| USA P&W 4168 | 2.54 | 302.5 | 773.0 | 4.85 | 9.35 | 750 | 640.9 | 132.1 | 391.33 | 59.19 | $10 - 12 M | 185,845 |
| USA TF39-GE-1 | 2.44 | 182.8 | 700.0 | 8.00 | 8.93 | 750 | 622.2 | 77.8 | 261.14 | 23.87 | Out of production | - |
| USA TF39-GE-1C | 2.44 | 191.3 | 700.0 | 8.00 | 8.93 | 750 | 622.2 | 77.8 | 273.29 | 26.14 | Out of production | - |
| USA CF6-50A | 2.20 | 218.0 | 653.0 | 4.40 | 10.90 | 750 | 532.1 | 120.9 | 333.84 | 36.39 | Out of production | - |
| USA CF6-50E | 2.20 | 233.5 | 673.0 | 4.40 | 10.65 | 750 | 548.4 | 124.6 | 346.95 | 40.51 | Out of production | - |
| USA CF6-80C2A1 | 2.69 | 257.4 | 802.0 | 5.03 | 9.46 | 750 | 669.0 | 133.0 | 320.95 | 41.31 | $12 - 13 M | 302,620 |
| USA CF6-80C2A5F | 2.69 | 267.3 | 805.0 | 5.06 | 9.63 | 750 | 672.2 | 132.8 | 332.05 | 44.38 | $12 - 13 M | 281,668 |
| GB Rolls-Trent 768 | 2.47 | 300.3 | 876.0 | 5.75 | 16.00 | 750 | 746.2 | 129.8 | 342.81 | 51.47 | $11 - 12 M | 223,420 |
| GB Rolls-Trent 772 | 2.47 | 316.3 | 897.0 | 5.75 | 16.00 | 750 | 764.1 | 132.9 | 352.62 | 55.77 | $11 - 12 M | 206,216 |
| GB Rolls-Trent 875 | 2.79 | 346.5 | 1,126.0 | 5.75 | 15.77 | 750 | 959.2 | 166.8 | 307.75 | 53.32 | $11 - 12 M | 215,667 |
| GB Rolls-Trent 877 | 2.79 | 356.2 | 1,169.0 | 5.75 | 15.77 | 750 | 995.8 | 173.2 | 304.73 | 54.28 | $11 - 12 M | 211,876 |
| GB Rolls-Trent 884 | 2.79 | 384.8 | 1,207.0 | 5.75 | 15.77 | 750 | 1,028.2 | 178.8 | 318.81 | 61.34 | $12 - 13 M | 203,787 |
| GB Rolls-Trent 890 | 2.79 | 406.1 | 1,234.0 | 5.75 | 15.77 | 750 | 1,051.2 | 182.8 | 329.12 | 66.84 | $12 - 13 M | 187,027 |
| Germany BR710 | 1.22 | 65.8 | 197.0 | 3.00 | 17.81 | 750 | 147.8 | 49.3 | 334.16 | 11.00 | - | - |
| INT. CFM 56-2 | 1.74 | 97.9 | 357.4 | 6.00 | 18.61 | 750 | 306.3 | 51.1 | 273.92 | 13.41 | $4 - 5M | 298,318 |
| INT. CFM 56-3 | 1.52 | 104.5 | 309.8 | 5.00 | 18.55 | 750 | 258.2 | 51.6 | 337.31 | 17.62 | $5 - 6M | 283,693 |
| INT. CFM 56-5 | 1.84 | 151.3 | 397.4 | 6.20 | 16.87 | 750 | 342.2 | 55.2 | 380.60 | 28.78 | $5 - 6M | 208,458 |
| INT. CFM 56-7 | 1.55 | 117.4 | 329.3 | 5.60 | 16.98 | 750 | 279.4 | 49.9 | 356.51 | 20.93 | $5 - 6M | 238,922 |
| INT. CFM 56-9(Lite) | 1.40 | 104.5 | 268.0 | 5.17 | 16.06 | 750 | 224.6 | 43.4 | 389.93 | 20.37 | $5 - 6M | 245,416 |

**Table D-2.** Aircraft turboshaft engine characteristics.

| | T-O Power (MW) | T-O Power (shp) | Pressure Ratio | Mass Flow Rate (kg/sec) | Fuel Consumption (lb/h/shp) | Length (in) | Diameter of Power Section (in) | Dry Weight (lb) | Engine Cost ($M) | Specific Cost ($/MW) |
|---|---|---|---|---|---|---|---|---|---|---|
| Allison T56-A-425 | 3.42 | 4,591 | 9.6 | 14.7 | 0.501 | 146.3 | 27.0 | 1,899 | 0.8 | $233,645 |
| Allison T56-A-42 7 | 3.91 | 5,250 | 12.0 | 15.2 | 0.470 | 146.1 | 27.0 | 1,940 | 0.8 | $204,604 |
| Allison AE 2100A | 4.47 | 6,000 | - | - | 0.41 | - | 24.5 | 1,548 | 1.2 | $268,216 |
| Allison AE 2100C | 4.47 | 6,000 | - | - | 0.41 | - | 24.5 | 1,548 | 1.2 | $268,216 |
| Czech Walter M602 | 1.36 | 1,824 | 4.2 | 7.3 | 0.559 | 105.1 | 29.7 | 570 | - | - |
| Dvigatel NK-93 (propfan) | 22.40 | 30,000 | 37.0 | 1000 | 0.490 | 216.5 | 124.0 | 8,047 | - | - |
| France Turbomeca Astazou | 0.93 | 877 | - | - | 0.525 | 80.6 | 21.5 | 454 | - | - |
| Kuznetsov NK-12 | 8.95 | 11,995 | 13.0 | 62 | 0.501 | 188.4 | 46.9 | 6,393 | 0.9 | $100,615 |
| Kuznetsov NK-12M | 11.18 | 14,995 | 13.0 | 65 | 0.501 | 188.4 | 46.9 | 6,393 | 0.9 | $80,486 |
| Kuznetsov NK-12MV | 11.03 | 14,795 | 13.0 | 65 | 0.501 | 185.8 | 46.9 | 5,710 | 0.9 | $81,573 |
| Kuznetsov NK-12MA | 11.19 | 15,000 | 13.0 | 65 | 0.501 | 197.0 | 46.9 | 5,710 | 0.9 | $80,458 |
| Poland TWD-10B | 0.75 | 1,000 | 7.4 | 4.6 | 0.570 | 81.1 | 21.9 | 661 | - | - |
| P&WC PT6A-6 | 0.43 | 578 | 6.7 | 3.1 | 0.200 | 62.0 | 19.0 | 270 | - | - |
| P&WC PT6A-27 | 0.55 | 715 | 6.7 | 3.1 | 0.200 | 62.0 | 19.0 | 335 | - | - |
| P&WC PT6A-65 | 0.88 | 1174 | 10.0 | 4.3 | 0.200 | 74.0 | 19.0 | 481 | - | - |
| Russia TV7-117 | 1.84 | 2,467 | 16.0 | 8.0 | 0.397 | 84.4 | 34.9 | 1,146 | - | - |
| Russia TVD-20 | 1.04 | 1,400 | 9.0 | 5.4 | 0.506 | 69.7 | 33.5 | 628 | - | - |
| US GE CT7-6 | 1.49 | 2,000 | - | - | 0.476 | 79.0 | 26.0 | 720 | - | - |
| US GE T64 | 3.27 | 4,380 | 13.4 | - | 0.477 | 79.0 | 26.0 | 720 | - | - |
| Ukraine AI-20D | 3.86 | 5,180 | 9.2 | 20.7 | 0.529 | 121.9 | 33.2 | 2,293 | - | - |
| Ukraine AI-24 | 1.88 | 2,515 | 7.6 | 13.1 | 0.54 | 92.4 | 26.7 | 1,323 | - | - |
| Ukraine D-236 (propfan) | 8.09 | 10,850 | - | - | 0.359 | - | - | - | - | - |
| Ukraine D-27 (propfan) | 10.29 | 13,800 | - | - | 0.57 | 212.6 | 109.9 | 9,039 | - | - |
| UK Rolls-Royce Dart | 2.24 | 3,000 | 5.4 | 9.75 | 0.578 | 98.4 | 37.9 | 1,268 | - | - |
| UK Rolls-Royce Tyne+ | 4.92 | 6,600 | 14.0 | 21.1 | 0.485 | 108.7 | 55.0 | 2,177 | - | - |

**Table D-3.** Gas turbine engine prices from Gas Turbine Engineering, Inc. (http://www.gas-turbines.com) as of July 6, 1996.

| Manufacturer | Model | Rpm | Output (kW) | Heat Rate | Cost ($M) | $ / KW |
|---|---|---|---|---|---|---|
| ABB | GT35 | 3600 | 16,360 | 10,600 | 8 | $489.00 |
| ABB | GT10 | 7700 | 21,800 | 10,405 | 9.5 | $435.78 |
| ABB | GT10 | 7700 | 24,630 | 9,965 | 10.1 | $410.07 |
| ABB | GT8 | 6300 | 48,500 | 10,750 | 15.6 | $321.65 |
| ABB | GT8C | 6200 | 52,600 | 9,980 | 16 | $304.18 |
| ABB | GT11N | 3600 | 81,600 | 10,700 | 20.5 | $251.23 |
| ABB | GT11N | 3600 | 83,880 | 10,370 | 20.5 | $244.40 |
| ABB | GT11N2 | 3600 | 109,200 | 10,030 | 24.5 | $224.36 |
| ABB | GT13D2 | 3000 | 100,500 | 10,600 | 22.5 | $223.88 |
| ABB | GT13E | 3000 | 148,000 | 9,855 | 31 | $209.46 |
| ABB | GT13E2 | 3000 | 164,300 | 9,560 | 36 | $219.11 |
| ALLISON | 501KB5 | 14250 | 3,725 | 12,317 | 1.8 | $483.22 |
| ALLISON | 501KH | 14600 | 3,740 | 12,363 | 2.1 | $561.50 |
| ALLISON | 570KA | 11500 | 4,610 | 12,225 | 2.6 | $563.99 |
| ALLISON | 571KA | 11500 | 5,590 | 10,650 | 2.8 | $500.89 |
| DRESSER | DC990 | 7200 | 4,200 | 11,820 | 2 | $476.19 |
| GE | 5271RA | 5100 | 20,260 | 12,800 | 5.7 | $281.34 |
| GE | 5371PA | 5100 | 26,785 | 11,730 | 7.5 | $280.01 |
| GE | M5382C | 4670 | 28,337 | 11,667 | 7.7 | $271.73 |
| GE | 6541B | 5100 | 39,325 | 10,560 | 10.5 | $267.01 |
| GE | 6101FA | 5100 | 71,750 | 9,740 | 18.5 | $257.84 |
| GE | 7111EA | 3600 | 84,920 | 10,212 | 19.3 | $227.27 |
| GE | 7171EF | 3600 | 126,200 | 9,990 | 28.8 | $228.21 |
| GE | 7191F | 3600 | 151,300 | 9,625 | 30.4 | $200.93 |
| GE | 7221FA | 3600 | 161,650 | 9,243 | 34 | $210.33 |
| GE | 9161E | 3000 | 119,355 | 10,105 | 23.8 | $199.41 |
| GE | 9171E | 3000 | 125,940 | 9,890 | 24.5 | $194.54 |
| GE | 9231EC | 3000 | 173,680 | 9,435 | 32.2 | $185.40 |
| GE | 9281F | 3000 | 217,870 | 9,625 | 39.9 | $183.14 |
| GE | 9301F | 3000 | 214,000 | 9,700 | 42 | $196.26 |
| GE | 9311FA | 3000 | 228,195 | 9,360 | 45 | $197.20 |
| GE | LM500 | 7000 | 3,880 | 11,430 | 1.9 | $489.69 |
| GE | LM1600 | 7000 | 13,430 | 9,560 | 6.9 | $513.78 |
| GE | LM2500 | 3600 | 22,216 | 9,404 | 9.5 | $427.62 |
| GE | LM2500PH | 3600 | 19,700 | 9,630 | 10.3 | $522.84 |
| GE | LM5000PD | 3600 | 33,350 | 9,390 | 13.6 | $407.80 |
| GE | LM5-ST80 | 3600 | 46,300 | 8,170 | 14.7 | $317.49 |
| GE | LM5-ST120 | 3600 | 51,500 | 7,885 | 15.3 | $297.09 |
| GE | LM5000PC | 3600 | 33,700 | 9,350 | 13.8 | $409.50 |
| GE | LM6000PA | 3600 | 41,020 | 8,720 | 12.1 | $294.98 |
| GE | LM6 50HZ | 3600 | 40,410 | 8,850 | 12.6 | $311.80 |
| KWU | V64.3 | 5400 | 60,650 | 9,705 | 18.5 | $305.03 |
| KWU | V84.2 | 3600 | 103,200 | 10,220 | 23.5 | $227.71 |
| KWU | V84.2 | 3600 | 106,200 | 10,124 | 23.3 | $219.40 |
| KWU | V84.3 | 3600 | 139,000 | 9,560 | 33 | $237.41 |
| KWU | V84.3 | 3600 | 152,700 | 9,450 | 34.5 | $225.93 |
| KWU | V94.2 | 3000 | 148,800 | 10,210 | 30.2 | $202.96 |
| KWU | V94.2 | 3000 | 154,000 | 10,065 | 30.2 | $196.10 |
| KWU | V94.3 | 3000 | 200,360 | 9,550 | 41 | $204.63 |

**Table D-3.** (continued).

| | | | | | | |
|---|---|---|---|---|---|---|
| KWU | V94.3 | 3000 | 219,000 | 9,450 | 45 | $205.48 |
| MITSUBISHI | MF111A | 9660 | 12,835 | 11,175 | 5.8 | $451.89 |
| MITSUBISHI | MF111B | 9660 | 14,845 | 10,895 | 6.2 | $417.65 |
| MITSUI | SB60 | 5680 | 12,650 | 11,460 | 5.9 | $466.40 |
| NUOVO PIGNONE | PGT10 | 7900 | 9,980 | 10,500 | 5.2 | $521.04 |
| RR | SPEY SK15 | 5220 | 11,630 | 10,510 | 5.7 | $490.11 |
| RR | AVON | 5500 | 14,610 | 11,885 | 4.8 | $328.54 |
| RR | RB211 | 4800 | 25,250 | 9,550 | 11.1 | $439.60 |
| RR | RB211 | 4800 | 27,240 | 9,575 | 11.5 | $422.17 |
| RUSTON | TB5000 | 7950 | 3,830 | 13,450 | 1.7 | $443.86 |
| RUSTON | TORNADO | 11085 | 6,215 | 11,340 | 2.9 | $466.61 |
| RUSTON | TYPHOON | 16570 | 3,945 | 11,360 | 2 | $506.97 |
| RUSTON | TYPHOON | 17380 | 4,550 | 11,350 | 2.1 | $461.54 |
| RUSTON | HURRICANE | 27245 | 1,575 | 13,820 | 1.1 | $698.41 |
| SOLAR | SATURN | 22120 | 1,080 | 14,685 | 0.8 | $740.74 |
| SOLAR | CENTAUR | 14950 | 3,880 | 12,250 | 1.7 | $438.14 |
| SOLAR | TAURUS | 14950 | 4,370 | 12,250 | 1.9 | $434.78 |
| SOLAR | MARS | 8568 | 8,840 | 10,975 | 4.3 | $486.43 |
| SOLAR | MARS | 9000 | 10,000 | 10,550 | 4.6 | $460.00 |
| TURBOMECA | M | 22000 | 1,086 | 13,125 | 0.9 | $828.73 |
| TP&M | FT4C-3F | 3600 | 29,810 | 10,875 | 5.7 | $191.21 |
| TP&M | FT8 | 3600 | 25,600 | 8,875 | 11 | $429.69 |
| WESTINGHOUSE | 251 B10A | 5420 | 42,300 | 10,600 | 11 | $260.05 |
| WESTINGHOUSE | 251 B12 | 5400 | 47,660 | 10,420 | 13 | $272.77 |
| WESTINGHOUSE | 251 B12A | 5400 | 49,200 | 10,440 | 14 | $284.55 |
| WESTINGHOUSE | 501 D5 | 3600 | 106,800 | 10,100 | 22.1 | $206.93 |
| WESTINGHOUSE | 501 D5 | 3600 | 109,350 | 10,010 | 23 | $210.33 |
| WESTINGHOUSE | 501 D5 | 3600 | 121,300 | 9,890 | 25 | $206.10 |
| WESTINGHOUSE | 501F | 3600 | 163,530 | 9,470 | 34.5 | $210.97 |
| WESTINGHOUSE | 701D5 | 3000 | 133,750 | 9,960 | 26.5 | $198.13 |
| WESTINGHOUSE | 701DA | 3000 | 138,520 | 10,040 | 27.5 | $198.53 |
| WESTINGHOUSE | 701F | 3000 | 235,720 | 9,280 | 47 | $199.39 |

**Table D-4.** Gas turbine engines listed by supplier.

| MANUFACTURER | MODEL | OUTPUT MW | HEAT RATE BTU / KW |
|---|---|---|---|
| Allied Signal Engines | AS 4055 | 4 | 8960 |
| Allison Engine Company | 501-KH (STEAM INJ | 6.75 | 8560 |
| Allison Engine Company | 571-K | 5.91 | 10074 |
| Allison Engine Company | 501-KB7 | 5.22 | 10826 |
| Allison Engine Company | 501-KB5S | 4.1 | 11570 |
| Allison Engine Company | 501-KB4 (STANDBY | 4.33 | 11697 |
| Allison Engine Company | 501-KB3 | 2.84 | 13136 |
| Ansaldo Energia | V84.3 | 154 | 9426 |
| Ansaldo Energia | V94.3 | 222 | 9426 |
| Ansaldo Energia | V64.3 | 63 | 9640 |
| Ansaldo Energia | V94.2 | 159 | 9977 |
| Ansaldo Energia | V84.2 | 109 | 10126 |
| Centrax Gas Turbine | CX501-KH | 6 | 9115 |
| Centrax Gas Turbine | CX501-KN7 | 5.6 | 10992 |
| Centrax Gas Turbine | CX571 | 5.4 | 11260 |
| Centrax Gas Turbine | CX501-KN5 | 4.5 | 11394 |
| Centrax Gas Turbine | CX501-KB7 | 5 | 11662 |
| Centrax Gas Turbine | CX501-KB5 | 3.8 | 12332 |
| Centrax Gas Turbine | CX501-KN3 | 3.1 | 12601 |
| Centrax Gas Turbine | CX501-KB3 | 2.7 | 13673 |
| Cooper Rolls, Inc. | Coberra 6000 | 27.21 | 9534 |
| Cooper Rolls, Inc. | Coberra 2000 | 14.58 | 12097 |
| Dresser Rand | DR63G | 41.95 | 8425 |
| Dresser Rand | DR61 PLUS | 28.5 | 8916 |
| Dresser Rand | DR61G | 23.28 | 9084 |
| Dresser Rand | DR61 | 22.98 | 9115 |
| Dresser Rand | DR61G PLUS | 27.6 | 9141 |
| Dresser Rand | DR60G | 14.07 | 9169 |
| Dresser Rand | DR990 | 4.4 | 11193 |
| Dresser-Rand | DR-63G | 40.67 | 8694 |
| Dresser-Rand | DR-61 PLUS | 27.63 | 9130 |
| Dresser-Rand | DR-61G | 22.8 | 9273 |
| Dresser-Rand | DR-61G PLUS | 27.04 | 9330 |
| Dresser-Rand | DR-61 | 22.06 | 9450 |
| Dresser-Rand | DR-60G | 13.58 | 9505 |
| Dresser-Rand | KG2-3E (STANDBY) | 2.14 | 20249 |
| Dresser-Rand | KG2-3E | 1.85 | 20652 |
| Dresser-Rand | KG2-3C (STANDBY) | 1.8 | 21278 |
| Dresser-Rand | KG2-3C | 1.45 | 21620 |

**Table D-4.** (continued).

| | | | |
|---|---|---|---|
| Ebara | PW7M | 0.78 | 14538 |
| Ebara | PW14M | 1.56 | 14538 |
| Ebara | PW6M | 0.64 | 15168 |
| Ebara | PW12M | 1.28 | 15168 |
| Ebara Corporation | FT 8 Twin | 51.1 | 8905 |
| Ebara Corporation | FT 8 | 25.42 | 8950 |
| Ebara Corporation | PW 7E | 0.7 | 15535 |
| Ebara Corporation | PW 6E | 0.57 | 16300 |
| European Gas Turbines | RLM6000 | 40.6 | 8632 |
| European Gas Turbines | RLM5000 | 35.05 | 9019 |
| European Gas Turbines | RLM2500 | 23.3 | 9080 |
| European Gas Turbines | RLM2500+ | 27.6 | 9139 |
| European Gas Turbines | RLM1600 | 13.98 | 9189 |
| European Gas Turbines | RLM2500-PE | 22.8 | 9270 |
| European Gas Turbines | RLM5000-PC | 34.3 | 9270 |
| European Gas Turbines | RLM2500+ | 27 | 9335 |
| European Gas Turbines | RLM5000-PC | 34.3 | 9355 |
| European Gas Turbines | M5352 | 26.56 | 9370 |
| European Gas Turbines | M5322R | 23.87 | 9477 |
| European Gas Turbines | PG 9331 FA | 226.5 | 9570 |
| European Gas Turbines | RLM2500-PE | 21.9 | 9597 |
| European Gas Turbines | RLM1600 | 13.4 | 9633 |
| European Gas Turbines | M3142R | 10.44 | 9933 |
| European Gas Turbines | PG 9171 E | 123.4 | 10100 |
| European Gas Turbines | G3142R(J) | 10 | 10370 |
| European Gas Turbines | TORNADO | 6.64 | 10760 |
| European Gas Turbines | PG 6541 B | 38.3 | 10860 |
| European Gas Turbines | Typhoon | 4.9 | 11145 |
| European Gas Turbines | Tornado | 6.2 | 11265 |
| European Gas Turbines | Typhoon | 4.2 | 11405 |
| European Gas Turbines | M5382 | 28.35 | 11662 |
| European Gas Turbines | PG 5371 PA | 26.3 | 11990 |
| European Gas Turbines | TB5000 | 4.03 | 12586 |
| European Gas Turbines | M3142 | 10.89 | 12775 |
| European Gas Turbines | TB5000 | 3.8 | 13240 |
| European Gas Turbines | G3142(J) | 10.4 | 13320 |
| European Gas Turbines | Hurricane | 1.6 | 13920 |
| Fiat Avio Power Division | LM6000 (60 Hz) | 41.09 | 8607 |
| Fiat Avio Power Division | LM6000 (50 Hz) | 40.48 | 8738 |
| Fiat Avio Power Division | LM2500 (60 Hz) | 22.82 | 9273 |
| Fiat Avio Power Division | 701 F | 233.95 | 9290 |
| Fiat Avio Power Division | LM2500 (50 Hz) | 21.87 | 9600 |
| Fiat Avio Power Division | TG50D5S | 147.75 | 9880 |
| Fiat Avio Power Division | TG50D5 | 140.77 | 9890 |
| Fiat Avio Power Division | TG20B11/12 | 47.8 | 10200 |
| Fiat Avio Power Division | TG20B7/8U | 39.36 | 11430 |

**Table D-4.** (continued).

| | | | |
|---|---|---|---|
| FIAT TTG | TG7 | 8.6 | 14110 |
| FIAT TTG | TG16 | 18.4 | 12720 |
| FIAT TTG | TG20 | 38.43 | 11130 |
| FIAT TTG | TG50 | 92.65 | 10930 |
| Greenwich Turbine, Inc. | FT4A-9 | 19.8 | 12150 |
| Greenwich Turbine, Inc. | FT4C-3F | 28.1 | 11100 |
| Greenwich Turbine, Inc. | LM2500 | 22.8 | 9273 |
| Greenwich Turbine, Inc. | LM6000 | 39.9 | 8790 |
| Greenwich Turbine, Inc. | PG6541B | 38.3 | 10880 |
| John Brown Engineering | PG5371 | 26.3 | 11990 |
| John Brown Engineering | PG6541 | 38.34 | 10880 |
| John Brown Engineering | PG6101 | 70.14 | 9980 |
| John Brown Engineering | PG7111 | 83.5 | 10480 |
| John Brown Engineering | PG7231 | 167.8 | 9420 |
| John Brown Engineering | PG9171 | 123.4 | 10110 |
| John Brown Engineering | PG9331 | 226.5 | 9570 |
| John Brown Engineering | LM6000 | 39.97 | 8790 |
| KAWASAKI H.I. LTD. | S1A-02 | 0.21 | 20740 |
| KAWASAKI H.I. LTD. | S1T-02 | 0.42 | 21100 |
| KAWASAKI H.I. LTD. | S2A-01 | 0.7 | 15610 |
| KAWASAKI H.I. LTD. | M1A-01 | 1.17 | 16310 |
| KAWASAKI H.I. LTD. | M1A-03 | 1.47 | 15610 |
| KAWASAKI H.I. LTD. | M1T-01 | 2.26 | 16710 |
| KAWASAKI H.I. LTD. | M1T-03 | 2.82 | 15970 |
| KAWASAKI H.I. LTD. | M1A-11 | 1.3 | 13900 |
| KAWASAKI H.I. LTD. | M1A-13 | 1.55 | 13400 |
| KAWASAKI H.I. LTD. | M1A-23 | 2.15 | 13000 |
| KAWASAKI H.I. LTD. | M1T-13 | 3.06 | 13590 |
| KAWASAKI H.I. LTD. | M1T-23 | 4.19 | 13140 |
| KAWASAKI H.I. LTD. | M1A-13CC | 1.37 | 15330 |
| KAWASAKI H.I. LTD. | M1A-13CC STM. IN | 2.42 | 10140 |
| KAWASAKI H.I. LTD. | M7A-01 | 5.96 | 11200 |
| KVAERNER ENERGY AS | LM1600 PA | 13.4 | 9565 |
| KVAERNER ENERGY AS | LM2500 PE | 22.2 | 9404 |
| KVAERNER ENERGY AS | LM6000 PA | 39.56 | 8593 |
| KVAERNER ENERGY AS | PG5371 PA | 26.3 | 11990 |
| KVAERNER ENERGY AS | PG6541 B | 38.34 | 10880 |
| KVAERNER ENERGY AS | PG6101 FA | 70.14 | 9980 |
| KVAERNER ENERGY AS | PG7111 EA | 83.5 | 10480 |
| KVAERNER ENERGY AS | PG7221 FA | 159 | 9500 |
| KVAERNER ENERGY AS | PG9171 E | 123.4 | 10100 |
| KVAERNER ENERGY AS | PG9331 FA | 226.5 | 9570 |

**Table D-4.** (continued).

| | | | |
|---|---|---|---|
| MITSUBISHI H.I. LTD. | MF-61 | 5.92 | 11915 |
| MITSUBISHI H.I. LTD. | MF-111A | 12.61 | 11250 |
| MITSUBISHI H.I. LTD. | MF-111B | 14.57 | 11020 |
| MITSUBISHI H.I. LTD. | MF-221 | 30 | 10655 |
| MITSUBISHI H.I. LTD. | MW-251 | 36.8 | 11790 |
| MITSUBISHI H.I. LTD. | MW-501 | 104.5 | 10255 |
| MITSUBISHI H.I. LTD. | MW-701 | 130.5 | 10070 |
| MITSUBISHI H.I. LTD. | MW-701DA | 136.9 | 10040 |
| MITSUBISHI H.I. LTD. | 501F | 158.6 | 9475 |
| MITSUBISHI H.I. LTD. | 701F | 234.2 | 9330 |
| MITSUBISHI H.I. LTD. | 501G | 230 | 8859 |
| MITSUBISHI H.I. LTD. | MFT-8 | 26.78 | 8825 |
| MITSUI ENG.& S.B.CO. | SB5 | 1.08 | 13390 |
| MITSUI ENG.& S.B.CO. | SB15 | 2.72 | 13330 |
| MITSUI ENG.& S.B.CO. | SB30 | 5.41 | 13140 |
| MITSUI ENG.& S.B.CO. | SB60 | 12.49 | 11530 |
| MITSUI ENG.& S.B.CO. | SB60 | 13.57 | 11490 |
| MITSUI ENG.& S.B.CO. | SB120 | 23 | 11190 |
| Nuovo Pignone | PGT 2 | 2 | 13642 |
| Nuovo Pignone | PGT 5 | 5.22 | 12676 |
| Nuovo Pignone | PGT 10 | 10.14 | 11046 |
| Nuovo Pignone | PGT 16 | 13.39 | 9692 |
| Nuovo Pignone | PGT 25 | 21.91 | 9621 |
| Nuovo Pignone | LM2500 | 22.33 | 9445 |
| Nuovo Pignone | MS5001 | 26.3 | 11984 |
| Nuovo Pignone | MS6001 | 38.34 | 10858 |
| Nuovo Pignone | LM6000 | 40 | 8764 |
| Nuovo Pignone | MS6001FA | 70.14 | 9976 |
| Nuovo Pignone | MS7001E | 83.5 | 10469 |
| Nuovo Pignone | MS9001E | 123.4 | 10090 |
| Nuovo Pignone | MS9001EC | 169.2 | 9759 |
| Nuovo Pignone | MS9001FA | 226.5 | 9559 |
| Parsons Power Generatio | RB211 | 27.21 | 9534 |
| Parsons Power Generatio | TRENT | 51.19 | 8210 |
| Parsons Power Generatio | 251B11 | 49.2 | 10440 |
| Parsons Power Generatio | 701DA | 138.3 | 9990 |
| Parsons Power Generatio | 701F | 236.7 | 9280 |
| Solar | Mars 100 & 100s | 10.69 | 10505 |
| Solar | Mars 90 & 90s | 9.29 | 10765 |
| Solar | Taurus 70 & 70s | 6.3 | 10900 |
| Solar | Taurus 60 & 60s | 5 | 11250 |
| Solar | Centaur 50 & 50s | 4.35 | 11865 |
| Solar | Centaur 40 & 40s | 3.52 | 12240 |
| Solar | Saturn 20 | 1.14 | 14075 |

**Table D-4.** (continued).

| | | | |
|---|---|---|---|
| Stewart and Stevenson | TG 5000 / STIG 120 | 51.62 | 7790 |
| Stewart and Stevenson | TG 5000 / STIG 80 | 48.1 | 8070 |
| Stewart and Stevenson | TG 2500 / STIG 50 | 28.05 | 8325 |
| Stewart and Stevenson | TG 6000 | 40.76 | 8590 |
| Stewart and Stevenson | TG 1600 / STIG 30 | 16.5 | 8641 |
| Stewart and Stevenson | TG 5000 | 34.4 | 9180 |
| Stewart and Stevenson | TG 2500 | 22.8 | 9280 |
| Stewart and Stevenson | TG 2500 + | 27.05 | 9330 |
| Stewart and Stevenson | TG 1600 | 13.44 | 9545 |
| Stewart and Stevenson | Tempest | 7.5 | 10876 |
| Stewart and Stevenson | Typhoon | 4.91 | 11142 |
| Stewart and Stevenson | Tornado | 6.25 | 11265 |
| | | | |
| Thomassen International | G3142 | 10.45 | 13337 |
| Thomassen International | G3142R | 10 | 10378 |
| Thomassen International | PG5271 | 20.26 | 12835 |
| Thomassen International | PG5371 | 26.3 | 12000 |
| Thomassen International | PG6541 | 38.34 | 10871 |
| Thomassen International | PG9171 | 123.4 | 10112 |
| Thomassen International | PG9331 | 226.5 | 9581 |
| Thomassen International | PG6101 | 70.14 | 9960 |
| Thomassen International | PG9231 | 168.9 | 9790 |
| | | | |
| Tuma Turbomach | TGC105CS | 1.1 | 14102 |
| Tuma Turbomach | TGC308CC | 3.5 | 12233 |
| Tuma Turbomach | TGC378CH | 4.1 | 12170 |
| Tuma Turbomach | TGC435CT | 4.8 | 11271 |
| Tuma Turbomach | TGC880CM | 9.3 | 10741 |
| Tuma Turbomach | TGC100CM | 10.7 | 10534 |
| Tuma Turbomach | TGC111MF | 14.3 | 10351 |

# Appendix E

# Kuznetsov NK12-MV Properties

# Appendix E

# Kuznetsov NK12-MV Properties

**Table E-1.** General dimensions.

| | | |
|---|---|---|
| Mass | (engine) | < 3,300 kg |
| Mass | (engine + packing crate) | 5,500 kg |
| Length | engine | 4.72 m |
| Diameter | engine | 1.20 m |
| Diameter | Engine mount points | 1.37 m |
| Diameter | Propeller AB-60K | 5.3 m |

**Table E-2.** Reliability information for ground-based operation with AB-60k propeller.

| | |
|---|---|
| Mean time between failure (with gearbox & propellers in ground application) | 23,500 hours |
| Time between overhaul (gearbox only) | 4000 hours |
| Time between overhaul (engine) | 12 years[a] |
| Mean time to repair | 10,000 hours |
| Mean recovery time | 5 hours |
| Probablility of failure free operation per 1,000 hours | 0.819 |

[a] Vendor language

**Table E-3.** Particle ingestion limits for normal service life.

| | |
|---|---|
| Atmospheric Dust Content Limits for Normal Service Life | |
| Average dust content | 0.3 mg /m3 |
| Diameter >20 mm | 0.03 mg/m3 |
| Short Term Conditions ( not to exceed 5% of Service Life) | |
| Dust content | 5 mg/m3 |
| Maximum particle size | 30 mm |

Ingress of foreign objects is not allowed

**Table E-4.** Combustion products at standard atmospheric conditions.

| Combustion Product | Level (mg/m3) |
|---|---|
| Nox | 142 |
| CO | 114 |
| CxHy | 132 |
| Benzopyrene | 0,000021 |

**Table E-5.** Sound pressures for NK12-MV on indoor test stand.

| Source | Level (dB) | Range (kHz) |
|---|---|---|
| Engine Inlet | 140 | 1 - 10 |
| Engine Outlet | 143 | 1 - 10 |
| Engine Casing Vibration (near air intake) | 113 | 0.8 - 16 |
| Engine Casing Vibration (near exhaust nozzle) | 120 | 0.8 - 16 |

Note: Sound pressure level drops 2 - 5 % in outdoor environment

**Table E-6.** NK12-MV engine operation parameters.

| | |
|---|---|
| Engine Core Air Flow | |
| Maximum | 56 kg/s |
| Maximum Continuous | 56 kg/s |
| Propeller Air Flow (no power given) | |
| AB-60K (5.3 m) | 930 kg/sec |
| AB-90 (6.2 m)[a] | 1,950 kg/sec |
| Fuel Consumption | |
| Maximum | 0.847 kg/s |
| Maximum Continuous | 0.740 kg/s |
| Exhaust Gas Temperature[b] | |
| Start-up (up to 15 sec) | 600 C |
| Maximum Power at 25 C ambient | 550 C |
| Maximum Power at 60 C ambient | 580 C |
| Starting & Control System | |
| Voltage | 24 - 27 VDC |
| Engine Start Current (4 - 8 sec) | < 3 kW |
| Engine Start Current ( 2 min) | < 1 kW |
| Fuel pump rate | 80 l/min |
| Oil pump rate | 40 l/min |
| DC generator (for starting other engines) | 18 kW |

---

a. AB-90 prop produces high vibration in ground application, shortening service life by 1.7 times

b. INEEL observed max EGT of 410 C at Maximum power (ambient 0 C).