NASA Technical Memorandum 79301

(NASA-TM-79301) IMPACT OF NEW INSTRUMENTATION ON ADVANCED TURBINE RESEARCH (NASA) 25 p HC A02/MF A01 CSCL 21E

N80-15133

Unclas G3/07 46630

IMPACT OF NEW INSTRUMENTATION ON ADVANCED TURBINE RESEARCH

Robert W. Graham
Lewis Research Center
Cleveland, Ohio

Prepared for the
1980 Spring Annual Meeting
sponsored by the American Society of Mechanical Engineers
New Orleans, Louisiana, March 5-13, 1980

E-251

IMPACT OF NEW INSTRUMENTATION ON ADVANCED TURBINE RESEARCH

by Robert W. Graham[1]
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio

ABSTRACT

The principal design objective for advanced aircraft gas turbines is to achieve improved fuel consumption through higher operating temperatures and pressures. The necessity of cooling the blades can introduce penalties in aerodynamic performance of the turbine and also can reduce the overall cycle efficiency of the engine. The optimization of the cooling design with minimum performance losses necessitates precision in the heat transfer and aerodynamic prediction techniques employed. Confidence in these prediction techniques comes about through verification procedures in research programs. Such research progresses from simple one and two dimensional stationary blade row tests and finally to three dimensional, rotating turbine blade row tests. Both low temperature and high temperature experiments are carried out in facilities of these types. In this paper a description of an orderly test program that progresses from the simplest stationary geometry to the more complex, three dimensional, rotating turbine stage will be discussed. The instrumentation requirements for this evolution of testing will be described. The emphasis will be on the heat transfer instrumentation. It will be apparent that recent progress made in devising new measurement techniques has greatly improved the development and confirmation of more accurate analytical methods for the prediction of turbine performance and heat transfer. However, there remain challenging requirements for novel measurement techniques that could advance the future research to be done in rotating blade rows of turbomachines.

[1]Fellow ASME.

INTRODUCTION

Among the improvements desired in advanced aircraft gas turbines are improved fuel efficiency and greater operational reliability. Unfortunately, higher efficiency and reliability do not go hand in hand. In fact, to the contrary, higher turbine inlet gas temperature and engine pressure ratios needed to improve specific fuel consumption tend to make components of the engine more susceptible to structural failure and thus incur more frequent maintenance. However, it is hoped that through the selection of appropriate materials, clever structural design and cooling techniques for critical hot components of the engine that both performance and reliability improvements can be realized in future generations of aircraft gas turbines.

The chief obstacles to this goal lie in the major uncertainty regarding the important details of flow and heat transfer in the principal components of a gas turbine jet engine. This fact has been apparent for some time but only rather recently has become a reality because of the possibilities for significant improvement of the basic information about flow and heat transfer. New instrumentation techniques and advances in analytical or numerical methods which describe fluid flow and heat transfer processes, present the exciting possibility of more comprehensive design criteria based upon experimental and analytical research. The experimental and analytical research complements one another. Of great importance to new design methods is the verification of analytical models of flow or heat transfer pertinent to turbomachinery.

In this paper the progression of experimental programs will be discussed from the simplest two dimensional stationary geometry to the highly complex three dimensional flow in a rotating blade row. The experimental methods and instrumentation techniques in this evolutionary process from the simplest to the most complex geometry will be described. Of particular appropriateness for this session are the available methods for rotating blade row measurements. Most of the examples or illustrations that I will cite in this paper will come from research programs performed at the Lewis Research Center or programs sponsored by the Center. Where possible, pertinent information derived from some of the papers to be presented at this session will also be referenced.

REVIEW OF INSTRUMENTATION AND MEASUREMENT TECHNIQUES

In this section I will review basic instrumentation types of importance to turbine research and comment on the limitations of each.

Temperature Measurement

Thermocouples. The thermocouple remains as the most popular and versatile temperature measuring device available. Thermocouple material combinations can be selected to cover a large range of temperatures.

Of the many thermocouple combinations to choose from reference 1, the most commonly used over for turbine experiments are: chromel-constantan (type E) for temperatures up to approximately 1000° C (1832° F), chromel-alumel (type K) for temperatures up to about 1300° C (2372° F) and platinum rhodium-platinum (types R&S) for temperatures up to about 1600° C (2912° F). For higher temperatures Pt 40 Rh-Pt 20 Rh thermocouples, are useful up to 1700° C (3092° F), the pairing of Ir 40 Rh/Pt 40 Rh described in reference 2 are applicable to temperatures up to 1800° C (3272° F). For temperatures as high as 2100° C (3812° F), the pulsed thermocouple technique (3) has been used successfully.

The accuracy of a thermocouple system depends to a large degree on the care taken in mounting the couple in the environment it is to measure. In general, one must ascertain the degree to which the thermocouple itself disturbs its immediate environment. How does it affect the local temperature distribution in a gas layer or influence the thermal conductance of a metal wall surroudning it? The lead wires of the thermocouple provides a conductance path that can influence the local condition at the junction. If a thermocouple is mounted in a probe, the entire probe can communicate with an external environment through radiation and conduction and alter the thermocouple junction reading.

If a thermocouple or a thermocouple probe is utilized in transient heat transfer measurements, the thermal capacitance of the couple or the probe can introduce a significant lag in the instantaneous measurement. It is well to keep in mind that thermocouples have a frequency response below 1 kHz which limits their use in transient studies. Each thermocouple application must be carefully analyzed to insure an acceptable level of accuracy.

Perhaps research engineers need to be reminded that particular care must be exercised in the connecting of thermocouples to recording instruments. Stray e.m.f.'s through dissimilar metal junctions or from intermediate temperature gradients can ruin a thermocouple reading. Most R&D organizations have personnel who are knowledgeable in the proper wiring of thermocouples. They ought to be consulted even when temporary hookups are made.

The platinum resistance thermometer is recognized as the standard measurement device for calibration purposes. Thus thermocouple systems can be checked with such a standard instrument. The inherent stability of the platinum resistance thermometer makes it an ideal calibration reference.

In gas turbine research, thermocouple probes are used to survey the gas stream to determine the enthalpy change across a blade row. Although reference 4 was published in 1952, much of the information it contains about thermocouples and probes is still current. Figure 1 taken from that reference shows several of the NACA bare wire thermocouples probes. The wedge geometry shown has remained a popular type of thermocouple which is still used in gas turbine research. Reference 5 updates some of the information in reference 4 particularly the characteristics of two standard probes over a range of sizes.

Metal sheathed thermocouples, which are commercially available, have been a versatile thermometer for turbine research. In miniature sizes (0.25 mm) they have been used to measure both blade wall and cooling air temperatures. In reference 6 the application of these sheathed thermocouples to turbine research is discussed and the attendant limitations of physical size and thermoelectric performance is evaluated. For wall temperatures the sheathed thermocouple suffers from size limitations in making strictly local measurements. Film thermocouples appear to be a more suitable form of temperature measurement for local surface temperatures. In some applications they are used to detect whether the boundary layer flowing over a wall is laminar or turbulent. An abrupt change in the surface temperature in the direction of flow is an indication of transition.

Optical Measurement

Interferometers. A number of optical arrangements offer the possibility of direct measurement of temperature or derived temperatures from density changes. In heat transfer research the interferometer has had extensive use. Such an instrument system has the obvious advantage of viewing the temperature field without disturbing it. As the name of the instrument implies, it operates on the principle of interference of light waves caused by phase shifting in paths of different optical length. By counting the interference fringes developed in superposing a reference beam on a test section beam, temperature gradients can be computed.

Schlieren/shadowgraph. Schlieren or shadowgraph systems reveal density changes through the phenomenon of light refraction changes with temperature. Rather extreme density changes as noted in thermal boundary layers or across shock waves are discernable with either-arrangement.

It is not easy to derive temperature values from the schlieren or shadowgraph intensity images: for shadowgraph two integrations of the basic intensity data are required. Shadowgraph or schlieren should be considered to be a qualitative source of density change information in a fluid flow. Primarily these instrument systems yield images of the flow patterns.

Infrared imagery. In a recent study of film cooling effectiveness (7) we found that an infrared scanning system was a highly suitable way of determining the isotherms of surface temperature. In this investigation room temperature air was used to simulate the hot gas and cooled air supplied by a Hilsch tube simulated the film coolant. A schematic of the apparatus and infrared detector is shown in figure 3. Employing the type of infrared equipment that is used clinically for body temperature scans, we were able to make images of the thermal footprint downstream of the film cooling hole. The particular infrared scanner was capable of operating in the temperature range of -30° to 200° C (-22° to 392° F) with a resolution of 0.2° C. Newer instruments are capable of much higher temperatures. Figure 4 is the thermal image downstream of a single film coolant hole. The scanning instrument enables recording of the surface isotherms. Through prior calibration, the temperature level of each isotherm can be known to high precision (0.2° C). In developing figure 4, instant photographs of the cathode display screen were processed with a computerized plotter. This made it possible to superpose a set of isotherms on one figure and to store the original data in digital form.

Infrared photographic recording of high temperatures in jet engine research has been utilized for approximately thirty years. A comprehensive discussion of a photographic IR system and the appropriate operating procedure is described in reference 8. The first author of that report is present at this session and will describe an updated system for applying IR detection to a rotating blade row.

Figure 5, taken from reference 8, is a schematic of the system for recording IR information on photographic film and converting the photographic image into temperature data. The elements of this system are:

(a) A heated metal target which is the surface of a turbine blade or vane in question and an independent temperature measurement.

(b) An optical system and a camera for recording the IR images of the heated surface.

(c) A film processor, for the uniform development of the thermal images on the film. A calibration procedure has to be carried out so that a known surface temperature can be compared to its photographic image. This procedure requires considerable skill and patience in establishing the relationship between temperature and the photographic film density. There are nonlinear effects which make calibration over a practical range of temperatures necessary. Fortunately, these nonlinear effects are not very great so that linear interpolation is possible.

(d) A densitometer, for measuring and recording the film density variation of a given thermal image. This instrument is integral to the calibration procedure and is the essential element in recording the contours of temperature for the test surface.

The physical principal for infrared photography is that surfaces emit radiation as a function of their absolute temperature. One can select arbitrarily a given radiation wave length and a strong dependence of radiant energy on temperature is evident. The IR bandwidth region seems particularly suited for turbine blade measurement because the emissivity of metals is more stable and higher than at other wave lengths. These advantages plus high sensitivity to temperature, make the IR region highly suitable to this application.

There are commercial instruments available that record infrared images in a digital form thus the camera and densitometer are not required in the system. The recording system for the infrared images of rotating blades to be described in this session records the information in digital form rather than as photographic film. Perhaps the digital format will replace the photographic way of recording the infrared emissions, and make the system a more automated operation in the future.

Pressure Measurement

Pressure probes. More for completeness than anything else, a quick review of the status of pressure probes needs to be included. Total pressure probes or rakes generally incorporate the simple square or chamfered-end tube as the pressure sensing element. The chamfered tube will sense total pressure accurately over an angle of attack range of ±20° (see ref. 9). For static pressure probes, the wedge configuration appears to be the least sensitive to misallignment. Flow angle measurements in a two-dimensional plane can be determined by a symmetrical arrangement of two pressure sensing tubes. In turbine research, difficult measurement problems are encountered if the flow is unsteady (due to passing wakes) or severe local pressure gradients are present.

If any of these pressure or flow direction probes are used in a thermally hostile environment, provision for forced convection cooling the probe support is mandatory and the sensing elements are either conduction cooled or constructed out of high temperature material.

Drag force anemometer. A novel method for measuring flow direction or dynamic pressure is a strain gage beam probe described in reference 10. The beam is constructed from a silicon wafer 2.5 millimeters long, 1.5 millimeters wide and only 0.25 mm thick. Pressure forces acting on the beam are indicated as strain and are measured by four strain gage units mounted at the base of the beam. When the wafer is oriented parallel to the flow direction, a null output results and this probe indicates flow direction. The instrument is technically known as a "minature drag-force anemometer" and a sketch appears on figure 6. The instrument has a very high natural frequency (40 kHz) so it is capable of detecting turbulence intensity as well as dynamic pressure. It can be used in both forward and reversed flow. The strain gage mounting at the base of the probe limits the local temperature to less than 120° C. The silicon beam is quite brittle so extreme care has to be exercised in handling it, particularly in installation.

Pressure scanner. The advances in electronics and computer technology have made major strides possible in all types of instrumentation. There is no better example than a scanning pressure recording system which is capable of reading several hundred pressures per second. Such a system is described in reference 11. In a large gas turbine facility where hundreds of steady state pressure measurements are required, this type of scanning is an economical answer to multimeasurement requirements. A microcomputer controls the system and stores the data in a memory that can be accessed by a master computer. The microcomputer controls the calibration function and also monitors the data sequence so that the researcher is assured of receiving an accurate, correctly ordered set of data. The pressure sensor is a centrally mounted transducer integrated with a rotary-type pressure switch. The stepped movements of the rotary switch are controlled electronically.

Unsteady pressure measurement. In reference 12 an experimental study was conducted on the ability to measure unsteady pressures on blades of turbomachines. Actual compressor blades or suitable replicas were instrumented with miniature semiconductor strain gage transducers that had natural frequencies above 100 kHz. The diaphram diameter of the gage sensor was only one millimeter. The oscillatory pressures varied from 1 to 310 kPa (0.145 to 45 psi). Both static and rotational tests were conducted. In the rotational tests, the centripetal acceleration reached 90 000 g's and the normal acceleration 650 g's. Errors in measurement of the blade mounted transducers were found to be about ±6%.

The strain in the blade was thought to be a major contributor to the uncertainty in the spin tests. Consequently, the manner of mounting the transducer and the position on the blade so as to minimize strain effects is an important consideration.

These transducers, which were intended primarily for measuring nonsteady pressures, were not recommended for measuring the steady state pressures and are restricted to temperatures below 120° C (248° F).

Flow Measurements

Hot wire anemometer. In turbulence research or any study of unsteady flow, the hot wire anemometer is an important instrument system because of its high frequency response capability. The hot wire operates on the principle of cooling the wire by convection. King's law states that the convective losses from a heated wire to the free stream are proportional to the square root of the product of density times velocity and the temperature difference between the wire and the air stream.

There are two hot wire instrument systems. In the constant current system, a compensator maintains the wire current constant and thus responds to the fluctuations in free stream velocity. A more popular hot wire circuit is constant temperature compensation by an amplifier. A negative-feedback voltage responds to the flow fluctuations and maintains the wire temperature at a constant value. The constant temperature hot wire system can measure large fluctuations, such as rotating stall in a compressor; the constant current system can deal with rather modest fluctuations (<15%, see ref. 13).

It is claimed that modern constant temperature hot wire systems can respond to frequencies exceeding 100 kHz. In practice this is difficult to achieve.

Hot wires are extremely fragile because of their hair-like dimensions and they cannot be operated in hot gases. Hot films which are thin metallic coatings mounted on quartz rods or tubes are more rugged and can be operated in warm gas flows, when cooled internally. Generally, they suffer from a severely reduced frequency response capability as compared to hot wires. Nevertheless they are capable of detecting turbulence intensity. Such a measurement is important because turbulence intensity variations can alter heat transfer and frictional losses in a given apparatus configuration. Whenever it is feasible, turbulence intensity measurements ought to be made in the inlet section of a turbomachine test rig.

The hot wire can have an important role in the measurement of unsteady components of flow that an ordinary pressure probe cannot distinguish because of response limitations.

Laser anemometer (LDV). The laser anemometer is an optical method for measuring fluid velocity. Sometimes it is called the Laser Doppler Velocimeter (LDV). The frequency of laser light scattered from a moving particle is shifted by the Doppler effect. This shifted, scattered radiation can be detected by comparing it with a reference beam of unshifted light from the same laser light source. A more popular geometric arrangement is the dual scatter system in which both beams form a set of interference fringes in the sample volume. In both arrangements the velocity can be computed from the precisely observed Doppler shift frequency. Reference 14 describes a laser anemometer system which was used to measure velocity and turbulence in water. Essentially the same system can be used for measurements of air velocities. The laser anemometer does have some limitations in application but it is a passive system that does not disturb the fluid flow being measured.

In a later section of the paper, mention will be made of a turbine cascade facility which used the laser anemometer to survey the flow passages between vanes. Although use of this instrument is still in the experimental, beginning stages, it is bound to become one of the more popular techniques for measuring flow velocities in turbomachinery. The absence of an interfering probe makes it very attractive.

Experimental Methods for Determining Heat Transfer

Miniature heat sensor. In the measurement of heat flux at a local region, miniaturized heat sensors are frequently used. Either a high response thermocouple or resistance thermometer is incorporated in the sensor. The heat transfer characteristics can be detected by imposing a step change in the heat flux and employing transient heat transfer conduction analysis to calculate the local heat flux. This approach has the important advantages of protecting the entire apparatus from high, steady state temperatures while making determinations of local heat flux. On the other hand the measurement of transient temperatures involves more complex and expensive recording equipment. The miniaturized gages and their associated thermometry are fragile and expensive. Also, they may introduce a discontinuity or disturbance on the surface to be measured. Heat sensors may not be likely candidates for measuring heat flux on turbine blades in full scale tests because of the aforementioned disadvantages. Heat sensors and the transient technique have been employed by researchers at the MIT Gas Turbine Laboratory for local heat flux measurements in turbine cascades. The MIT shock tunnel will be described in a later section.

Reference 15 contains a description of a novel sputtered heat sensor which is extremely small and durable. Thin film thermocouples are sputtered on to a thin surface oxide. The oxide and thermocouple layers are on the order of 2.5 μm (0.0001 in.) thick for each one. The thermocouples were made from platinum-rhodium. These particular gages were employed in measuring the local heat flux on a cylindrical surface in the cross flow of hot gases.

Finite element analysis technique. This technique for determining local heat transfer coefficients in turbine blades or stator vanes is based upon a method described in reference 16. Essentially the blade or vane is treated as though it were a heat gage and local values of heat flux are calculated at desired locations. This procedure is the inverse of the customary heat transfer design of a cooled blade or vane wherein the gas-side and coolant side heat transfer coefficients are estimated and made the boundary conditions of a conduction solution at selected cross sections along the blade span. In this procedure the blade element is treated as a heat gage, temperatures are the boundary conditions and the heat conduction equation is utilized to calculate the temperature field for the element. Numerical differentiation at the edges of the blade/vane yield temperature gradients which can be related directly to the local gas-side heat transfer coefficients.

This method is being used by Detroit Diesel Allison in analyzing experimental data of a cascade-end wall configuration. Strategically placed thermocouples in the blade and endwall region and a two-dimensional conduction analysis enable estimates of the local heat transfer coefficients. For very complex geometries it may be necessary to go to a three-dimensional conduction solution which will greatly complicate the finite element calculation.

In the next section of this paper the types of apparatus that can be employed in turbine research will be discussed and their advantages/disadvantages considered. The first will be the cascade geometry.

REVIEW OF EXPERIMENTAL EQUIPMENT

Two-dimensional Cascade

The simplest and most versatile geometry for a cascade arrangement is the flat plate two-dimensional cascade. Figure 7 is a photograph of a two dimensional cascade located at the Lewis Research Center used in measuring the aerodynamic loss characteristics of turbine blades or stators. The cascade is equipped with an adjustable floor and ceiling at the inlet. Boundary layer bleed removal is provided on the planar side walls. The parallel side walls are set approximately 10 cm apart and are constructed of transparent plastic so that flow visualization is possible. This cascade operates with atmospheric inlet air and discharges to the laboratory vacuum exhaust system.

The conventional instrumentation for such a cascade involves a total pressure and temperature measurement at the inlet and survey instrumentation downstream of the cascade blade row which indicates total pressure, static pressure and flow angle. A combination probe such as is shown in figure 8 can be utilized in radial and circumferential surveys of the downstream instrument station.

While the simplicity of the two-dimensional cascade is a significant advantage in conducting research, such a two-dimensional geometry is limited in its ability to represent the actual flow conditions found in turbomachinery. Three dimensional flow patterns are prevalent in turbomachines and annular cascades (described in the next section) are more capable of simulating aspects of these more complex flow patterns. Nevertheless the two-dimensional cascade provides the researcher with data which serves as a reference base for examining the magnitude of the three dimensional secondary flows.

As mentioned earlier, a cascade with transparent side walls can be used effectively in flow visualization. The two dimensional visual cascade located at Lewis Research Center and shown in figure 9 was designed expressly for that purpose. A visual study was carried out on the behavior of the secondary flow at the juncture between the end wall and the blade. These visual results contribute to the test program of the hot gas cascade described in the next paragraph.

Detroit Diesel Allison of General Motors has constructed a planar cascade to study the heat transfer at the endwall regions of a turbine cascade. This facility shown in figure 10 is capable of operating at system pressures up to 2.4 M pascals (350 psi) and gas temperatures up to approximately 426.7° C (800° F). Optical and thermocouple instrumentation is being used in the facility. Figure 11 shows a schematic of the probe survey and thermocouple instrumentation for the endwall and a test vane. Approximately sixty thermocouples are involved in the instrumented vane alone. The added complexity of thermometry on the endwall makes this a highly instrumented facility despite the relative simplicity of the cascade geometry.

Two-dimensional Tunnel

For the study of isolated factors that influence the local heat transfer in turbine blades, a simple two-dimensional flow facility (small tunnel) is a useful piece of apparatus. A facility of this type located at the Lewis Research Center is shown in figure 12. It consists of an atmospheric inlet bellmouth section, the test section channel and a transition piece for discharging to the vacuum exhaust system of the laboratory. This type of facility is quite versatile in that a variety of small heat transfer surface and flow geometries can be installed for testing. Associated with this heat transfer apparatus at the Lewis Research Center is an extensive instrumentation capability for both steady-state and transient recording. All measurements are converted to electrical signals and are fed into a mini computer for processing into parameters. A variety of measurement types are possible including pressures, temperatures, electrical joule heating loads and hot wire anemometer output. Electrical heating elements are mounted in the test models to simulate heat transfer conditions. For example, heated cylinders have been used to simulate leading edge heat transfer of a turbine vane or blade. For most testing the facility is operated in a steady-state mode although unsteady or transient phenomena are detectable by elements of the instrumentation system.

Two-dimensional Shock Tunnel

One of the two dimensional shock tunnel experimental methods for simulating heat transfer conditions in turbines is the use of a shock tube in conjunction with a two-dimensional cascade. A transient technique for calculating heat transfer rates from heat capacitance gauges is employed in determining the local heat transfer rates on the blades or vanes of the cascade. Turbine conditions are modeled by a relatively high shock tube gas temperature representing the main stream and a low temperature flow for the coolant. The short duration of the shock tube gases (approx. 10 ms) as they pass through the cascade prevents any extreme rise in the cascade wall temperatures. However, the transient is detectable from the temperature record of the heat gages and transient pressure recording.

Figure 13 is a diagram of the MIT Gas Turbine Laboratory shock tube cascade. A blade geometry can be inserted in the test section. The operators of this facility claim that Reynolds number, Mach number and Prandtl number conditions for a real turbine can be matched in the test section. Through temperature scaling techniques, it is claimed possible to calculate heat transfer coefficients from experimental data which are representative of actual turbine conditions.

Single Vane High Enthalpy Tunnel

Another approach to operating at high enthalpy levels is a single cooled-vane tunnel facility which operates at steady state conditions for long periods. This facility is located at Lewis Research Center.

The testing of a cooled vane at operating conditions representative of advanced commercial or military engines can be accomplished in a high pressure, high temperature tunnel facility shown in figure 14. The operating range of the facility goes as high as 2200 K (4000° F) and 27.2 atm (400 psia). The principal components of the facility are a combustor, a bluff body section, a test section and water quench exhaust section. The bluff body serves as a mixer to make the thermal profile more uniform and shields the test vane from direct thermal radiation of the combustor.

The test section is designed to accommodate a full scale replica of a cooled vane for advanced engine application. The instrumentation at the test section is directed toward determining the gas conditions, coolant conditions and the test vane wall temperatures. A cooled traversing pressure and temperature probe is installed upstream of the vane. Two infrared bore sights are positioned to view the leading edge and pressure surface of the test vane. Cameras record the thermal images for eventual reduction into surface temperature data.

The cooling system is designed to give independent control to the test vane and the endwall cooling supply. Flowrate, temperature and pressure are monitored on independent instrumentation.

Annular Cascades

The annular cascade offers a more accurate simulation of the three dimensional flow effects of turbomachinery than can be obtained in the simpler flat plate two dimensional cascade.

Annular cascades are made in two gemetric types. One is an annular sector in which, as the name implies, only a limited sector of the total annular area constitutes the test section. This configuration offers the advantages of moderate initial cost and the sector flow area can be enlarged to accommodate larger than full scale stator vanes. On the other hand, the sector geometry necessitates fairly complex guide vane arrangements upstream and downstream of the test section. Circumferential gradients in flow are difficult to avoid even with carefully placed guide vanes. Also the two ends of the sector pose difficult boundary conditions. The full annular cascade avoids these circumferential limitations of the annular sector cascade. It is a more expensive piece of apparatus and generally requires a large flow capacity for its operation.

An annular cascade located at the Lewis Research Center is shown in figure 15. The cascade is mounted vertically with a bell mouth and straight section upstream of the test section. Atmospheric room air is admitted to the inlet and is discharged from the test section into the laboratory vacuum exhaust system. At the test section, the inner diameter of the annulus is 43.2 cm (17 in.) and the outer diameter is 50.8 cm (20 in.). Total pressure and temperature are measured upstream of the vanes. Static taps on the annulus walls and on the vane surfaces provide information about the flow characteristics of the vane channels. Radial and circumferential surveys at the discharge plane of the stator row enable measurements of the losses and the general flow characteristics of the stator row. A combination probe which measures total pressure, static pressure, total temperature and flow angle has been employed in the surveys.

Figure 16 taken from reference 17 shows some aftermixed efficiency and total pressure loss coefficient data. The aftermixed efficiency is based upon radial and circumferential surveys of the kinetic energy as compared to the idealized kinetic energy.

The annular cascade facility at the Lewis Research Center has been equipped with a Laser-Doppler flow Velocimeter. This modern instrumentation installation shown in figure 17 makes possible detailed measurements of the flow angle and velocity at the stator row exit. As described in reference 18 two modes of LDV operation were investigated. One was a discrete point mode in which a fixed number of locations in the flow field were examined. The other was a continuous scan mode in which continuous traverses of the flow field were made at fixed radial position. No appreciable differences between the data for the two modes were observed. Comparisons between laser anomometer and probe measurements showed less than 1% disparity in velocity measurements. However, larger differences were observed in flow angle indications near the end walls. The comparative precision between a laser anemometer and probe measurement is difficult to make because the probe always offers some blockage or flow disturbance. Perhaps it is this factor that has introduced the discrepancy in the angle measurements for the two methods.

The annular cascade mentioned herein operates at ambient inlet conditions. Its primary use is measurement of aerodynamic losses. Figure 18 is a picture of a full annular cascade that operates at approximately 2 atmospheres inlet pressure and temperatures up to 1000° F. A natural gas fueled burner system supplies the cascade with warm combustion products. A bellmouth and a plenum mixer assure that the warm gases enter the cascade test section with uniform temperature and velocity profile. The OD and ID of this annular cascade are 50.8 cm (20 in.) and 47 cm (18.5 in.), respectively. Separate cooling circuits are available for cooling the walls and the vanes.

The instrumentation for measuring the inlet and outlet air conditions comprises the conventional subsonic temperature and pressure probes. The cascade is equipped with remote controlled instrument actuation equipment to enable both radial and circumferential surveys.

The vanes in such an installation can be instrumented to measure heat fluxes so that local heat transfer rates can be determined. This type of facility is an ideal place to check out the performance of a new cooling design for the vanes of a gas turbine.

The use of a LDV system for this facility does not seem very likely because it is difficult to incorporate the optical paths needed. As of this writing there has been no experience in operating LDV systems at elevated gas temperatures. It is not likely that such an LDV system will ever be integrated into this warm cascade facility.

Warm Core Turbine Facility

An apparatus which is one step closer to actual turbine conditions is a warm core turbine facility. A photograph of the Lewis Warm Core Turbine is shown in figure 19. In many ways it resembles the warm core cascade but rotation of the blade row distinguishes it as a significantly different type of facility. The rotational capability makes it a more complex facility. This warm turbine facility operates at temperature and pressure levels appreciably below that of an aviation-type turbine. Comparison of both flow and heat transfer data from the annular cascade and warm turbine rig will yield information about the effects of rotation on the aerodynamic performance and heat transfer.

Like the Lewis annular cascade, the main flow temperature range is from 121° to 538° C (250° to 1000° F) at an inlet pressure of approximately 3 atmospheres. The triple array of aircraft-type combustor cans which supply the warm gases, burn natural gas. The test turbine shown in figure 19 is a single stage 51 cm (20 in.) diameter turbine with 3.8 cm (1.5 in.) blade and vane spans. Five independently controlled circuits supply cooling air to the vanes, blades, rotor disc, and endwalls. With appropriate instrumentation it is possible to make heat transfer measurements in the stator or rotor blade rows.

The nonrotating instrumentation upstream and downstream of the turbine stage consists of temperature and pressure probes and rakes and wall static taps. Flow angles are measured with self-aligning probes. Hot-wire anomometry can be used to determine the turbulence level of the flow entering the stage.

The power of the turbine is measured from torque and speed indications. A water cooled eddy current dynamometer absorbs the power generated by the turbine.

A rotating data package similar to that described in reference 19 is being planned for this facility. It will scan thermocouple and pressure signals from the rotating blade row. The capacity of such a rotating scanner is 72 channels with a maximum of 10 for pressure signals. More will be said about this type of instrumentation in the next section.

Other facilities exist that are similar to the NASA Warm Turbine but are larger in scale. They run at lower rotational speeds and because of their size can accommodate detailed instrumentation in the rotor and stator blade rows. Such facilities yield information about the contribution of the rotational velocity components to the flow patterns within the blade rows.

Measurement in the Rotor

This session at the 1980 Joint ASME Fluids Engineering/International Gas Turbine Conference and Products Show is devoted to Measurement Methods in Rotating Components of Turbomachinery. Several papers will be presented that address instrumentation methods for transmitting pressure, temperature and blade stress readings from a rotor to a data recording system. Interest in data acquisition from rotating parts has been strong ever since the development of the jet engine in the 1940's. Early systems for transferring measurements across a rotating-stationary interface have included: (a) pneumatic tubulation for the transfer of pressure through a seal, and (b) slip rings and brushes for the transmission of electrical signals including thermocouple emf. Both of these techniques have many inherent mechanical and electrical deficiencies that degrade measurement accuracy and contribute to severe maintenance problems. More recently, the advances in small electronic components have made possible radically new designs that obviate the main deficiencies of transmission across seals or slip rings.

One of the electronic systems developed in the late 60's is reported in reference 19. Transmission of power to the instrumentation mounted on the rotor and reception of the digitized data from the rotor occurred across a rotating transformer that operated in the 10 kHz frequency range. On-the-shelf microelectronics components were assembled to effect the power conditioning, multiplexing, amplification and analog-to-digital conversion necessary in the system. Initially this system was tested at rotational speeds up to 15 000 rpm. The measured system error was less than ±0.5% of full scale.

Over the past decade there have been efforts to develop shaft-mounted radio telemetry systems for application to turbomachinery testing. A survey article describing the progress in developing this type of instrumentation appeared in the March 1979 issue of Mechanical Engineering. The development of this type of instrumentation was greatly motivated by the testing needs of the multispool engine where slip ring mountings at the end of a shaft were impossible. The telemetry system does require space allocation within the engine. Transmitters and antennas and their mountings have to be planned for and rigid cooling specifications must be followed. The temperature-operation restriction of 150° C (300° F) limits the application of this method to the compressor components of an actual engine or to a low temperature research turbine. Despite this limitation, telemetry offers some important advantages in the measurement of rotor performance in many research applications.

During this session we will hear several papers on recent developments on methods of recording data from rotating elements. This update should acquaint us with the latest techniques and instrumentation components. One of the papers will describe an optical method of scanning turbine blades with a pyrometer to yield temperature distributions over an entire surface.

NASA High Pressure Facility

In this review of facilities I have attempted to present them in the order of their complexity starting with two dimensional cascades and progressing to rotating machinery. The last one to be presented is the Lewis Research Center High Pressure Facility.

There is a need for a turbine test facility that reproduces all the real thermal and pressure effects found in turbines of advanced turbojet engines but also allows the instrumentation necessary to evaluate the thermodynamic performance and cooling effectiveness. It is not possible to take a full scale prototype engine and instrument it adequately so that detailed performance is measured. The real engine configuration is not readily amenable to the insertion of instrument probes or other recording devices.

An analysis of the uncertainties encountered in gas turbine thermal research has revealed that present-day prediction schemes for blade temperatures are in error by approximately 8-1/2% (21). It is claimed in this same reference that the information derived from an advanced turbine research rig will reduce the prediction error to approximately 6%. Reducing the uncertainty by over 2.5% will improve the estimate of the fatigue life-cycle of the blades or vanes by an appreciable amount.

An underestimation of blade temperature of 55.5° C (100° F) can mean an order of magnitude reduction in fatigue life cycle (22). Consequently, research facilities that are capable of gathering more reliable heat transfer data are essential.

The Lewis Research Center is in process of building a test facility complex that can operate at the enthalpy and pressure levels anticipated in jet engines of the future but with great instrumentation capabilities for the turbine performance. This facility known as the High Pressure Facility (HPF) consists of independent combustion and turbine components. Figure 20 is an artists drawing of the facility. It is designed to be capable of operating at 40 atmospheres pressure and gas temperature up to 2200° C (4000° F). The HPF will be mentioned in this session as the facility for which the scanning pyrometer of a rotating blade row is being built. A description of the facility along with its testing capabilities appear in reference 23. Not only will this facility be valuable for its contribution to advanced turbine and combustion technology, it will serve as a test bed for new instrument advancements in these areas.

CONCLUDING REMARKS

From research that is directed at improving the prediction capability of optimum cooling for advanced gas turbines, there is optimism that new instrumentation, more powerful computational methods and versatile research facilities will pay significant dividends in such an endeavor. The breakthrough in data acquisition and processing over the last decade alone make areas of experimental research possible that could not be done with former data recording systems. The emergence of the laser anomometer as a practical research tool, and improvements in hot wire circuits and controls have expanded the researchers capability to delineate intricate flow patterns and time-unsteadiness.

Electronic components are available that enable accurate transfer of data from a rotating element to a stationary one.

The control features on experimental equipment have advanced along with the controls industry. More sensitive response and quicker response times have made control of experiments more sure and more adaptable to a range of predetermined conditions. It is now possible to cover an extensive range of operating conditions and to store and process the data in an expeditious manner.

The increased capabilities of the computer for dealing with flow situations makes it possible to represent real flows encountered in turbomachines. Experiments will be designed to verify the computational prediction.

Likewise in the heat transfer area, miniaturization of thermometry and heat meters and new infrared detection methods have improved measurement capabilities. Coupled with the high speed data acquisition and computerized data analysis, these advances in instrumentation make detailed heat transfer measurements quite feasible.

Progress generally breeds the desire for more progress. While the advancements made are satisfying and encouraging, the demand continues for more sophisticated methods in measurement and computation. Such progress will erode the band of uncertainty that limits our current capability in turbomachinery design. The next decade should bring major improvements in this capability and make turbomachine design more of a science than an empirical art.

REFERENCES

1 Powell, R. L., et. al., "Thermocouple Reference Tables Based on the IPTS-68," NBS-MONOGRAPH-125, National Bureau of Standards, Washington, D.C., Mar. 1974.

2 Glawe, G. E., "New High-Temperature Noble-Metal Thermocouple Pairing," Review of Scientific Instruments, Vol. 46, No. 8, Aug. 1975, pp. 1107-1108.

3 Glawe, G. E., Will, H. A., and Krause, L. N., "A New Approach to the Pulsed Thermocouple for High Gas Temperature Measurements," NASA TM X-71883, 1976.

4 Scadron, M. D., Warshwasky, I., and Gettleman, C. C., "Thermocouples for Jet Engine Gas Temperature Measurement," Proceedings of the Instrument Society of America, Vol. 7, Sep. 1952, Paper No. 52-12-3.

5 Glawe, G. E., Holanda, R., and Krause, L. N., "Recovery and Radiation Corrections and Time Constants of Several Sizes of Shielded and Unshielded Thermocouple Probes for Measuring Gas Temperature," NASA TP-1099, 1978.

6 Holanda, R., "Evaluation of Miniature Single-Wire Sheathed Thermocouples for Turbine Blade Temperature Measurement," NASA TM-79173, 1979.

7 Papell, S. S., and Graham, R. W., "Coolant Tube Curvature Effects on Film Cooling Using Infrared Detection," ASME Paper No. 79WA/GT-7, To be Presented at the ASME Winter Annual Meeting, New York, Dec. 2-7, 1979.

8 Pollack, F. G. and Hickel, R. O., "Surface Temperature Mapping with Infrared Photographic Pyrometry for Turbine Cooling Investigations," NASA TN D-5179, 1969.

9 Dudzinski, T. J. and Krause, L. N., "Effect of Inlet Geometry on Flow-Angle Characteristics of Miniature Total-Pressure Tubes," NASA TN D-6406, 1971.

10 Krause, L. N. and Fralick, G. C., "Miniature Drag-Force Anemometer," NASA TM X-3507, 1977.

11 Anderson, R. C., "A Microprocessor Controlled Pressure Scanning System," NASA TM X-71886, 1976.

12 Englund, D. R., Grant, H. P., and Lanati, G. A., "Measuring Unsteady Pressure on Rotating Compressor Blades," NASA TM-79159, 1979.

13 Laurence, J. C. and Landes, L. G., "Application of the Constant Temperature Hot Wire Anemometer to the Study of Transient Air Flow Phenomena," Proceedings of the Instrument Society of America, Vol. 7, Sep. 1952, Paper No. 52-12-5.

14 Dunning, J. W., Jr., Angus, J. C., and Edwards, R., "Application of the Laser Doppler Flowmeter to Fluid Flow Measurements," TM X-52560, 1969.

15 Dils, R. R. and Follansbee, P. S., "High Temperature Sputtered Surface Sensors," Proceedings of 21st International Instrumentation Symposium, Instrumentation in the Aerospace Industry, Vol. 21, Instrument Society of America, New York, 1975, pp. 127-132.

16 Turner, A. B., "Local Heat Transfer Measurements on a Gas Turbine Blade," Journal of Mechanical Engineering Science, Vol. 13, No. 1, Feb. 1971, pp. 1-12.

17 Goldman, L. J. and McLallin, K. L., "Cold-Air Annular Cascade Investigation of Aerodynamic Performance of Cooled Turbine Vanes. I - Facility Description and Base (Solid) Vane Performance," TM X-3006, 1974.

18 Goldman, L. J., Seasholtz, R. G., and McLallin, K. L., "Velocity Surveys in a Turbine Stator Annular Cascade Facility Using Laser Doppler Techniques," NASA TN D-8269, 1976.

19 Lesco, D. J., Sturman, J. C., and Nieberding, W. C., "Rotating Shaft-Mounted Microelectronic Data System," NASA TN D-5678, 1970.

20 Adler, A., "Telemetry for Turbomachinery," Mechanical Engineering, Vol. 101, No. 3, Mar. 1979, pp. 30-35.

21 Stepka, F. S., "Analysis of the Uncertainties in Turbine Metal Temperature Predictions," NASA TP-1593, 1980.

22 Graham, R. W., "Fundamental Mechanisms that Influence the Estimate of Heat Transfer to Gas Turbine Blades," ASME Paper No. 79HT-43, Aug. 1979.

23 Cochran, R. P., Norris, J. W., and Jones, R. E., "A High-Pressure, High Temperature Combustor and Turbine-Cooling Test Facility," TM X-73445, 1973.

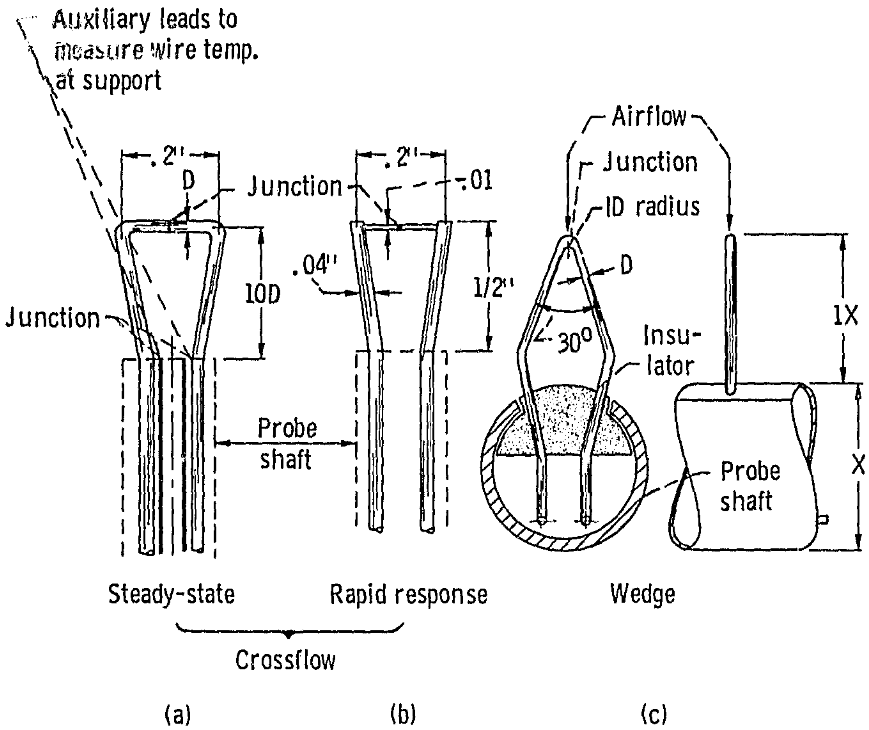


Figure 1. - NACA bare-wire thermocouple probes.

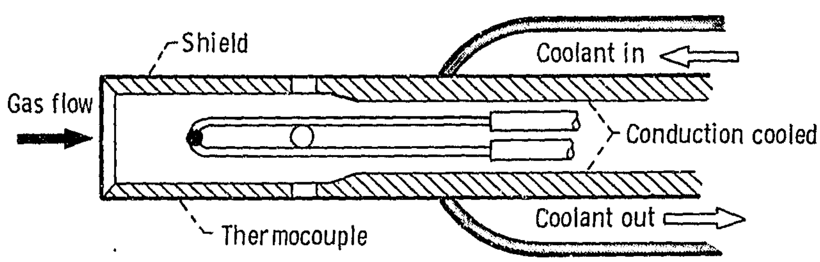


Figure 2. - Cooled thermocouple rake for gas turbine environment.

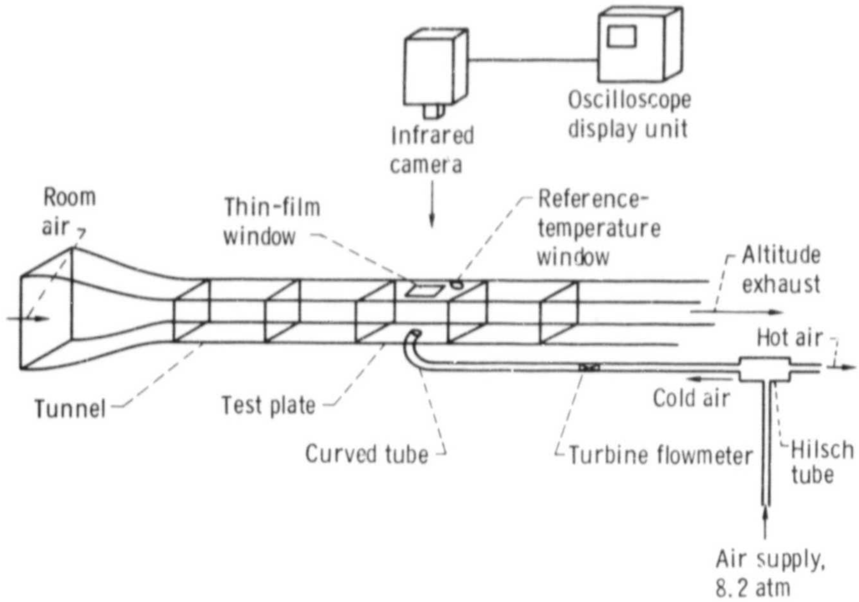


Figure 3. - Schematic of film-cooling rig.

$$\eta = \frac{T_\infty - T_{aw}}{T_\infty - T_c} \quad \text{FILM COOLING EFFECTIVENESS}$$

T_∞ FREE STREAM TEMPERATURE

T_{aw} ADIABATIC WALL TEMPERATURE

T_c COOLANT TEMPERATURE

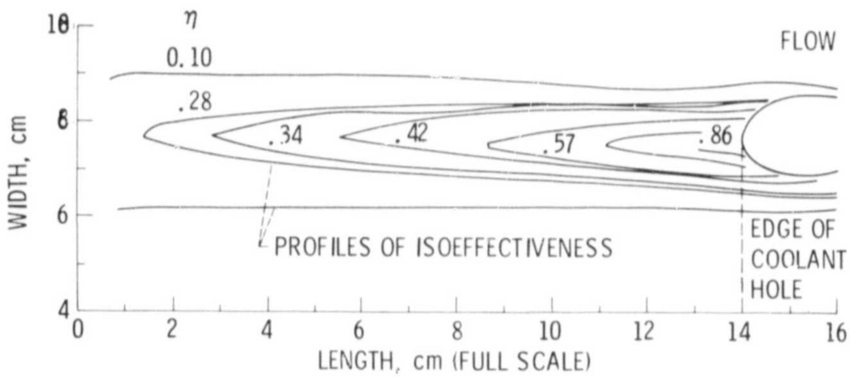


Figure 4. - Footprint of film cooling effectiveness.

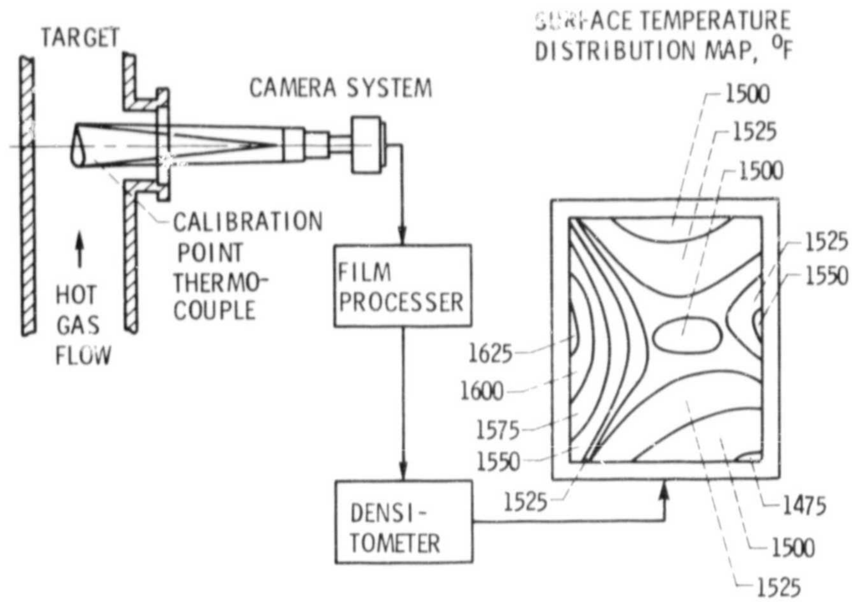
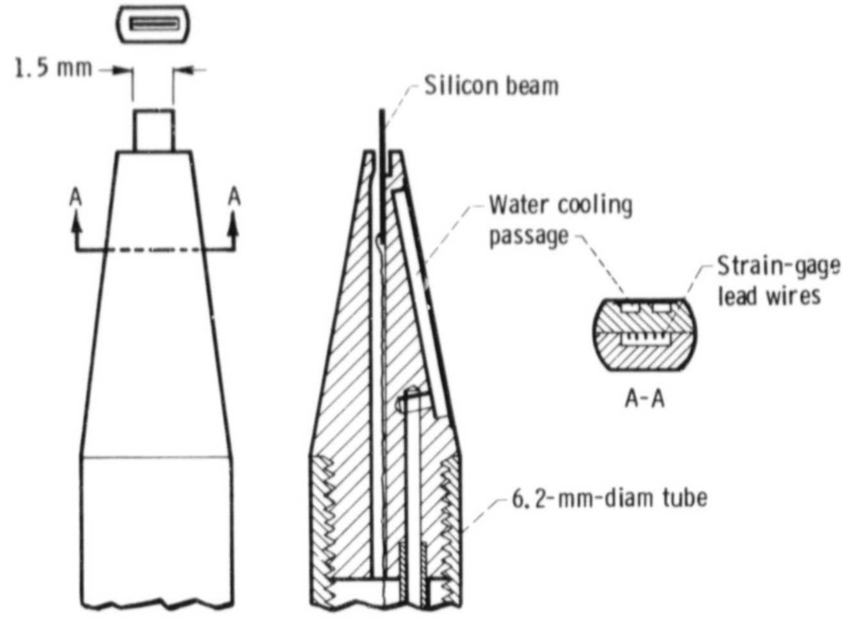
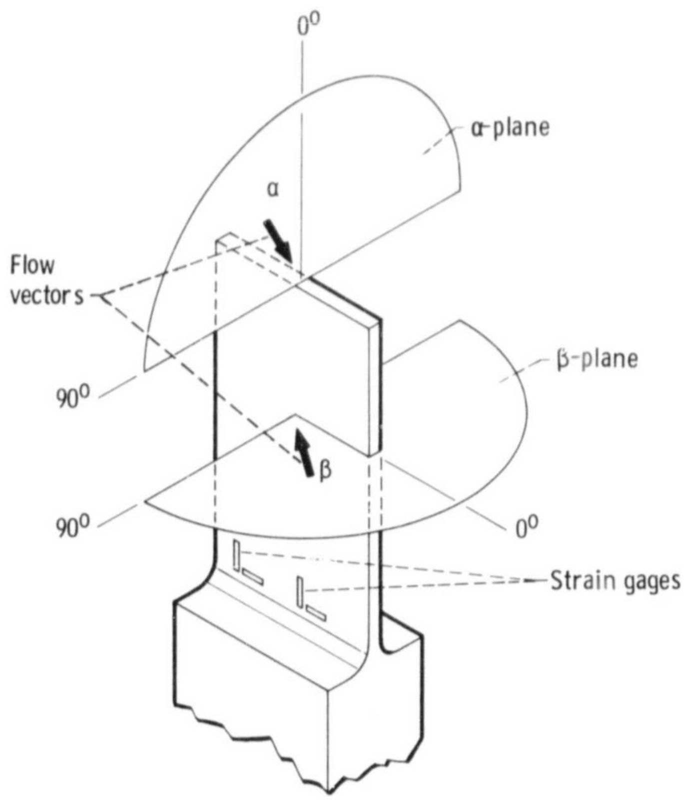


Figure 5. - General diagram of typical photographic pyrometry system.



(a) Detail of drag-force anemometer.



(b) Flow-direction nomenclature. For flow normal to beam, α and $\beta = 90^{\circ}$.

Figure 6. - Drag-force anemometer.

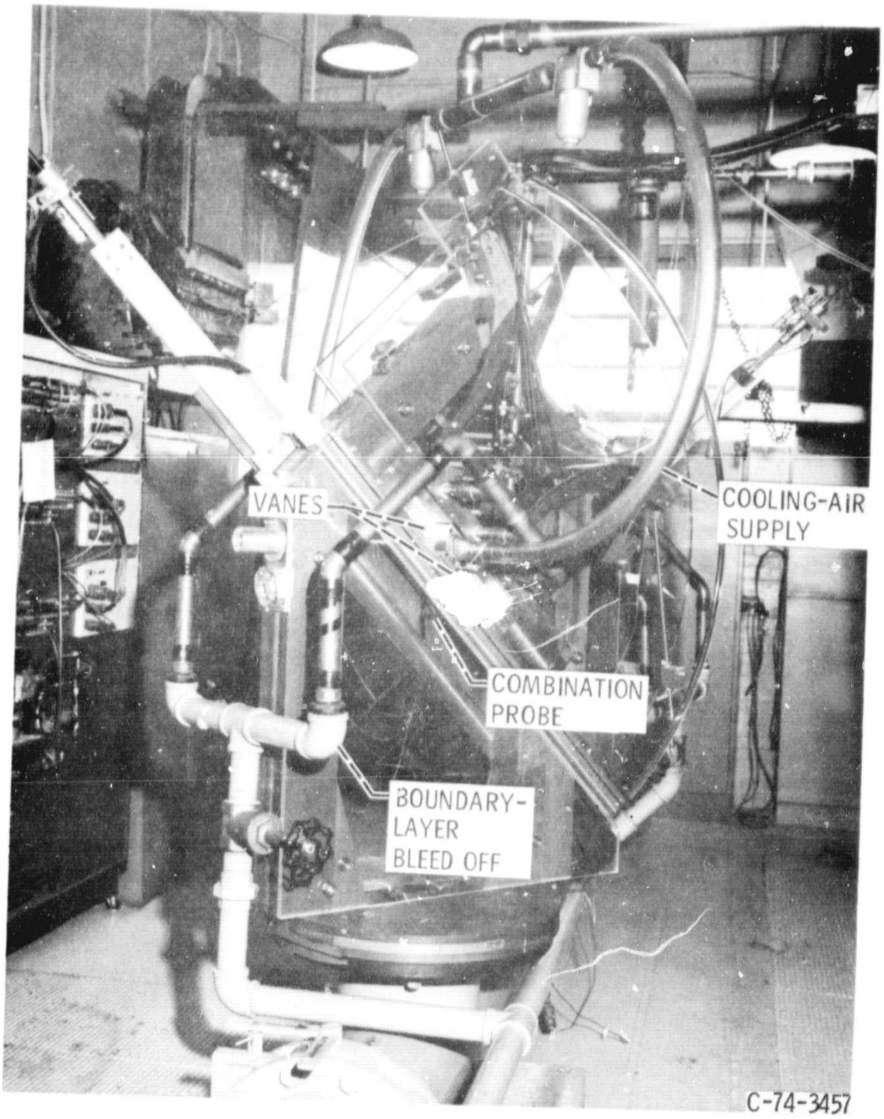


Figure 7. - Two-dimensional cascade tunnel.

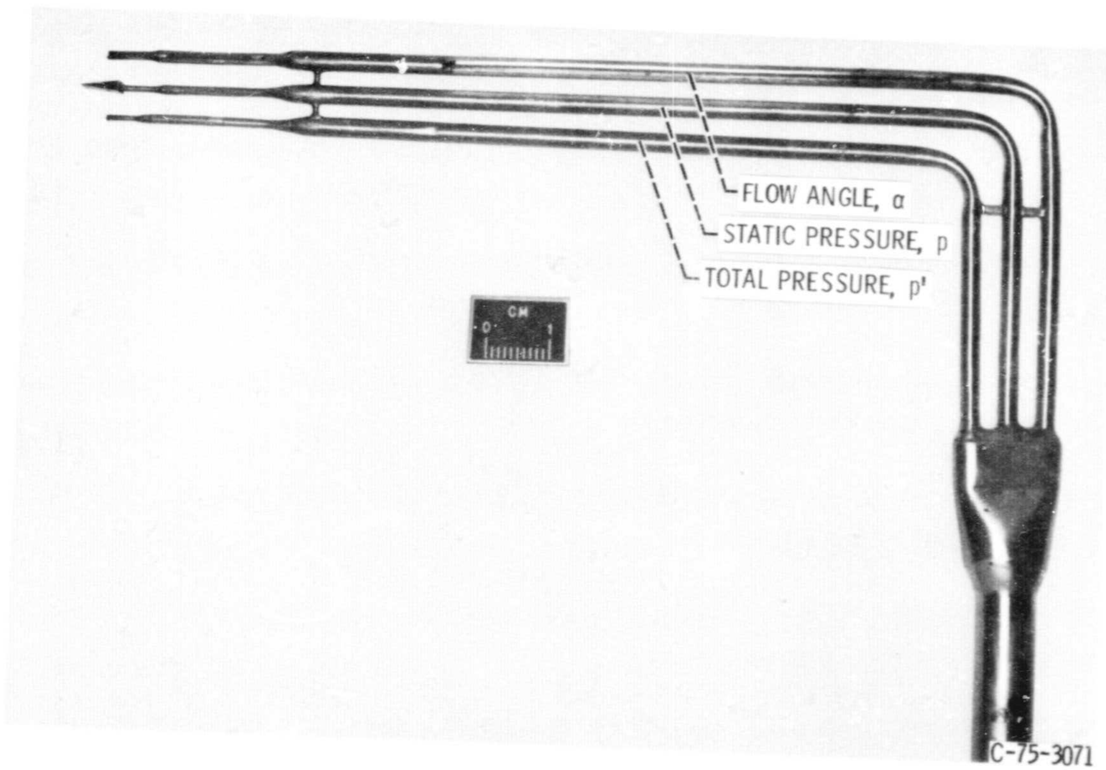
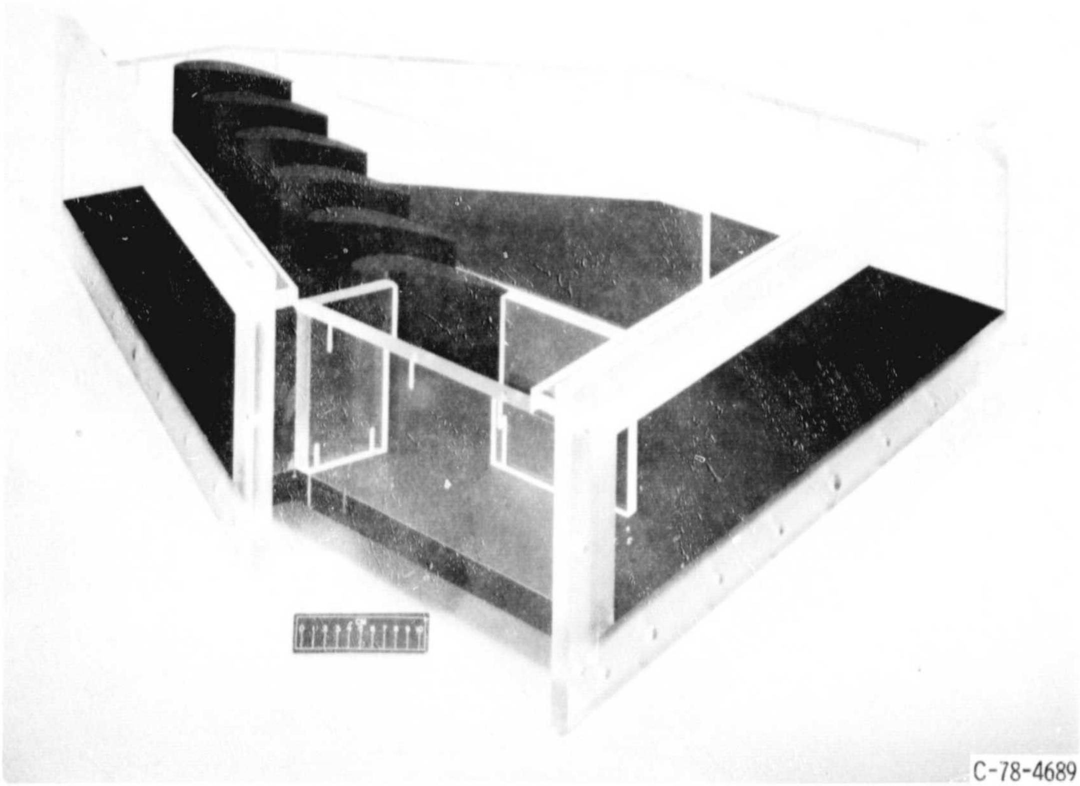


Figure 8. - Combination survey probe.



C-78-4689

Figure 9. - Two-dimensional visual cascade test section.

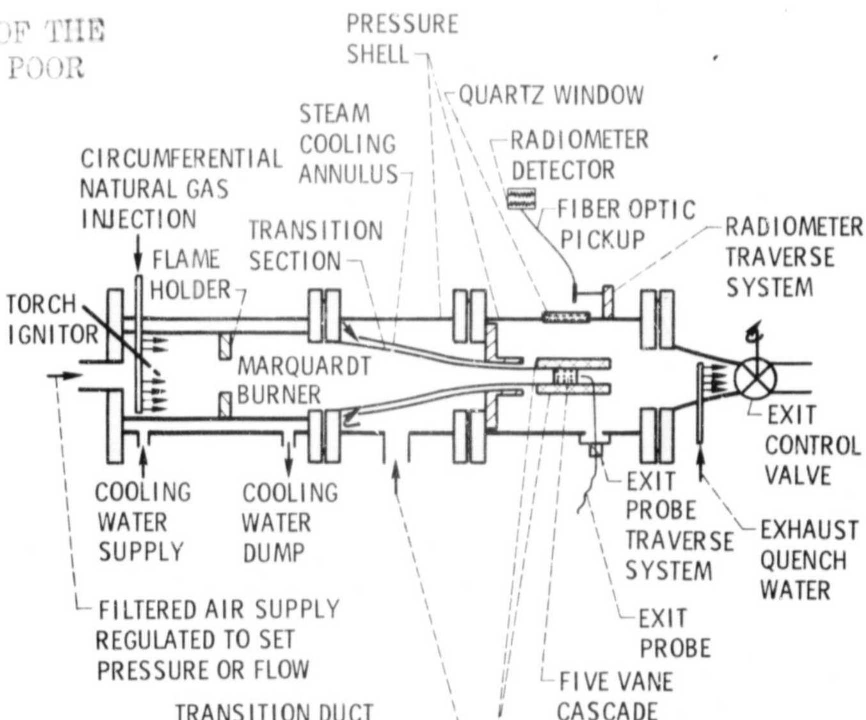
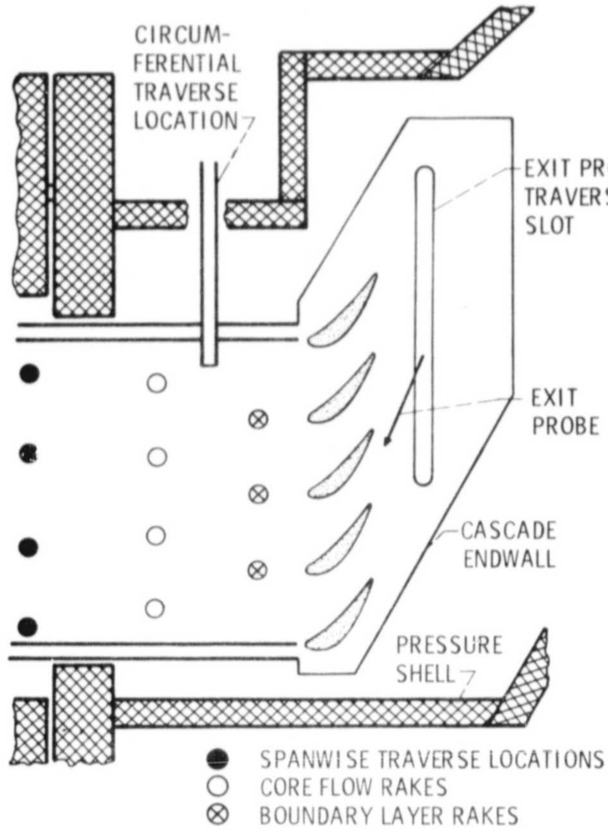
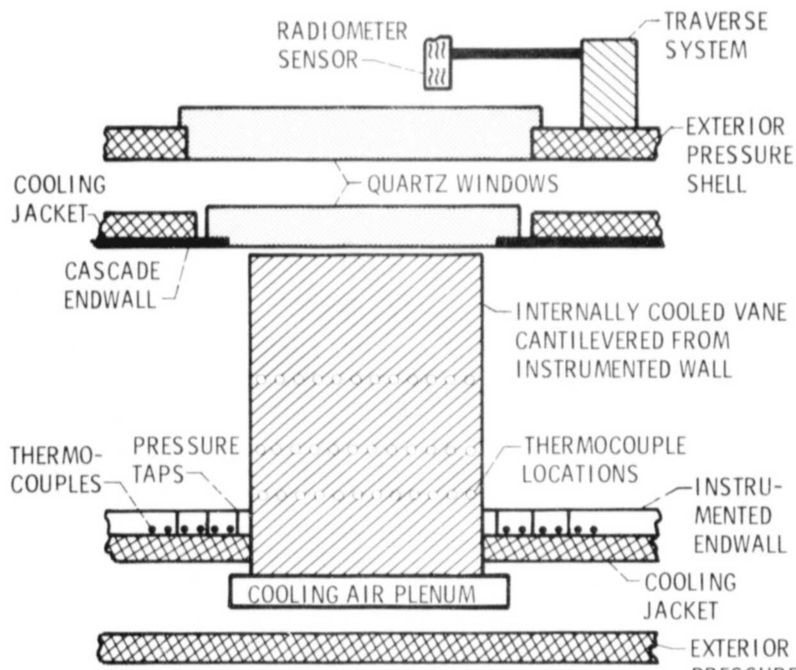


Figure 10. - Schematic of Detroit-Diesel-Allison aerothermodynamic cascade facility. Courtesy of Detroit Diesel-Allison.



(a) Principal aerodynamic instrumentation.



(b) Cascade schematic showing thermal instrumentation.

Figure 11. - DDA Cascade. Courtesy of Detroit Diesel-Allison.

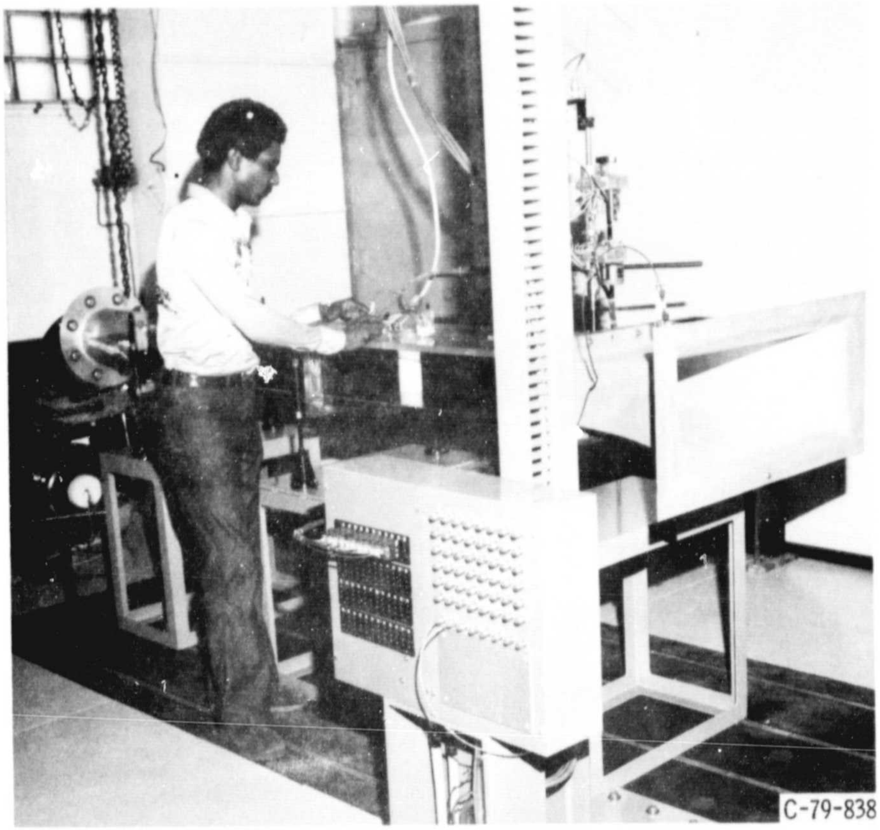


Figure 12. - Two-dimensional tunnel.

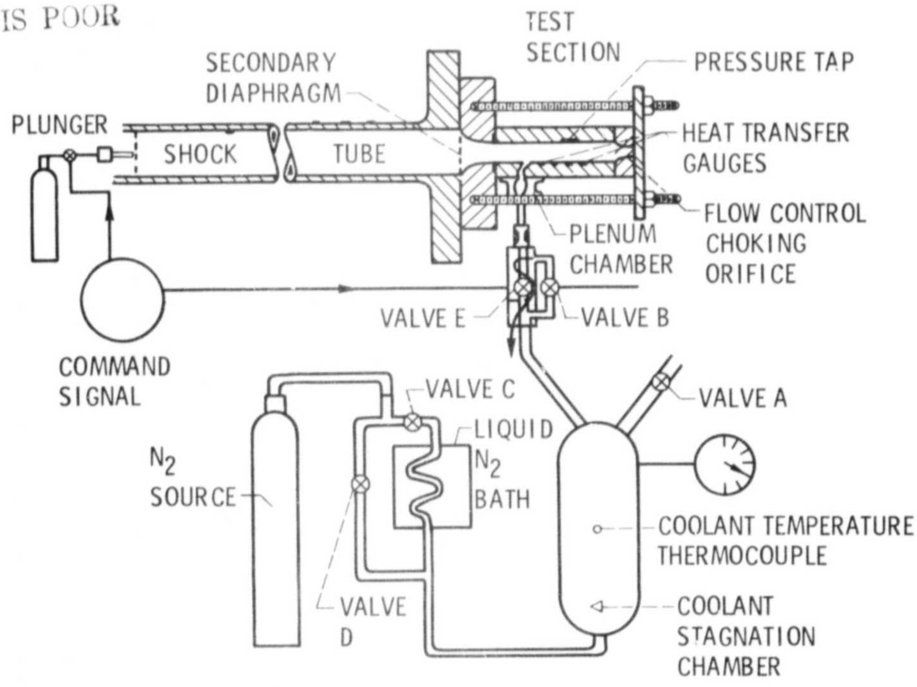


Figure 13. - Shock tunnel apparatus, MIT Gas Turbine Laboratory. Courtesy of MIT Gas Turbine Lab.

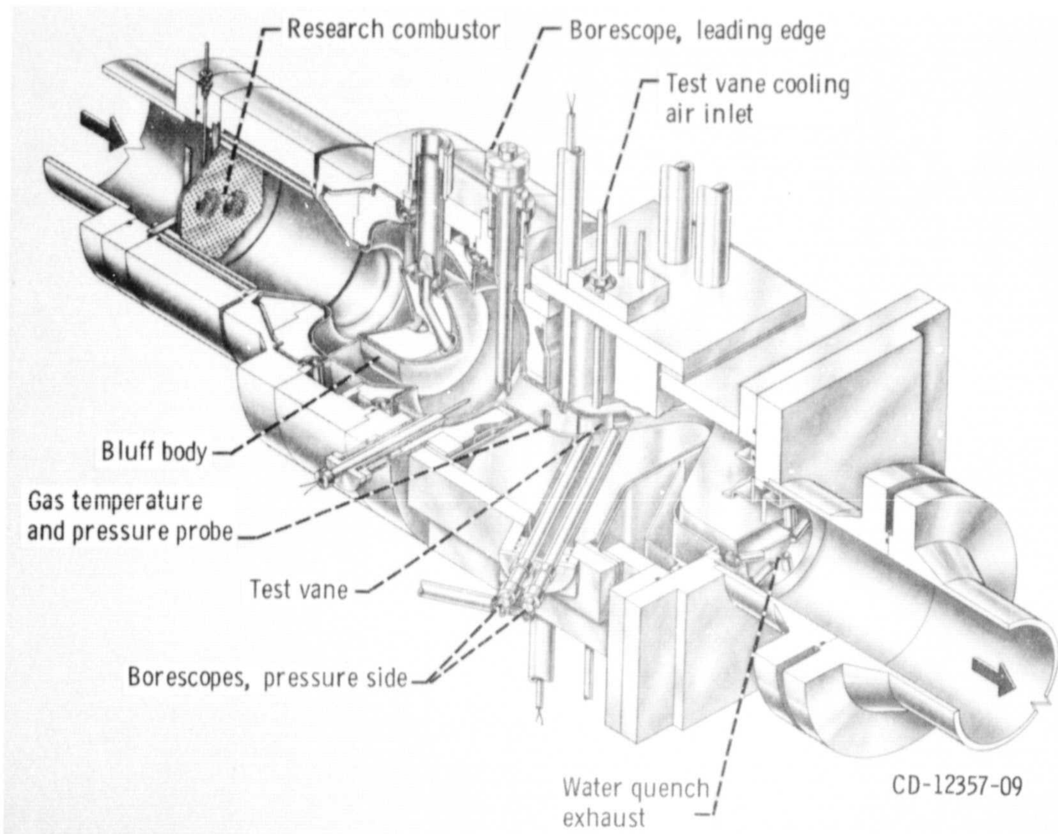


Figure 14. - One vane tunnel heat transfer test facility.

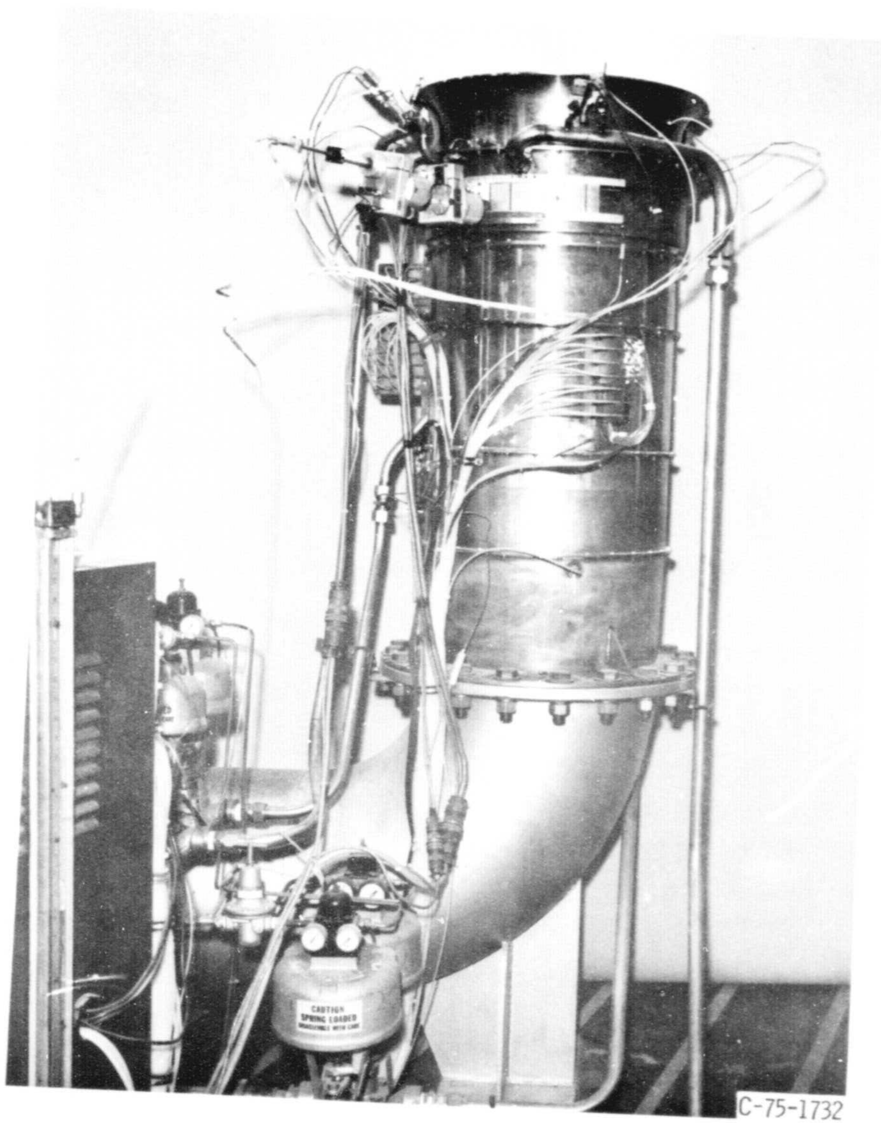
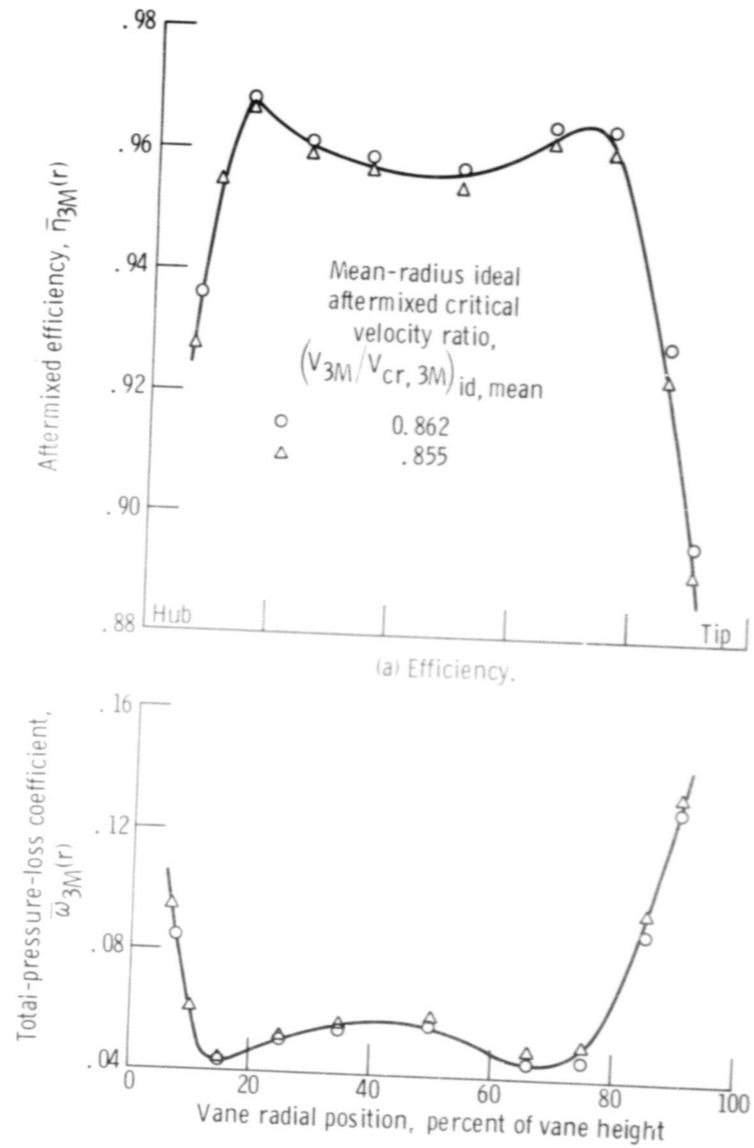


Figure 15. - Fifty-one centimeter (20-inch) annular cascade.



(b) Total-pressure-loss coefficient.

Figure 16. - Radial variation of efficiency and total-pressure-loss coefficient.

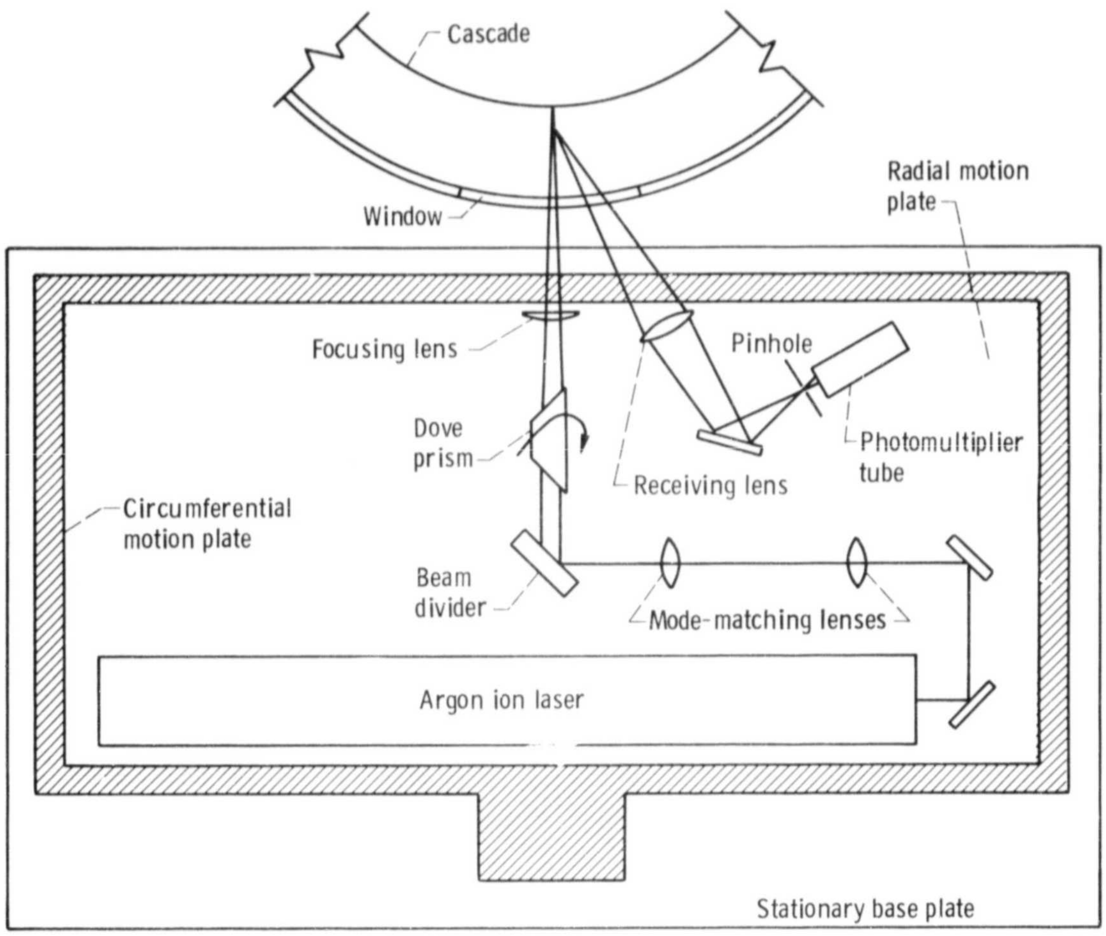


Figure 17. - Schematic of laser Doppler velocimeter and traversing mechanism.

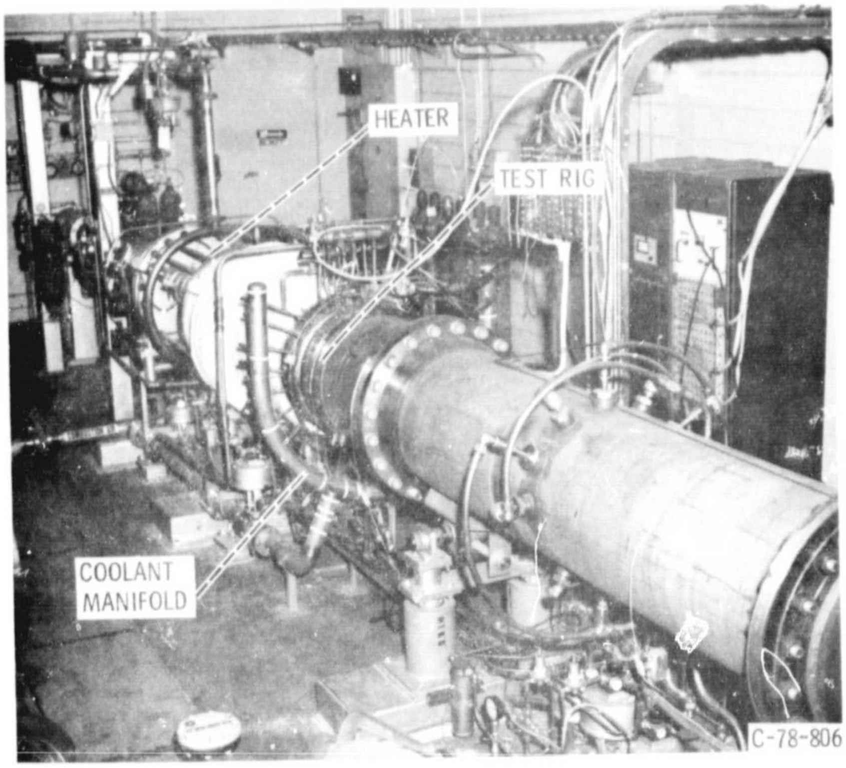


Figure 18. - Warm core annular cascade facility.

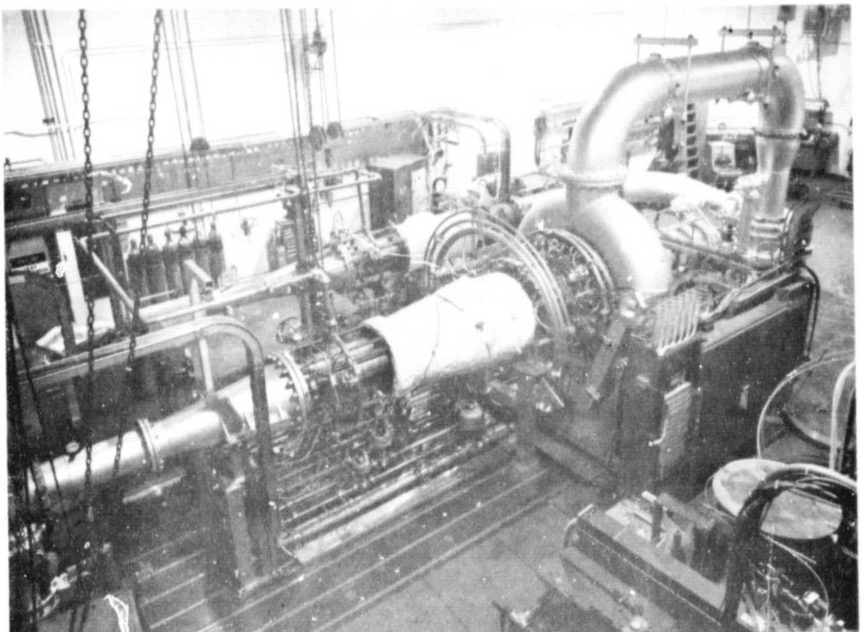


Figure 19. - Warm core turbine facility.

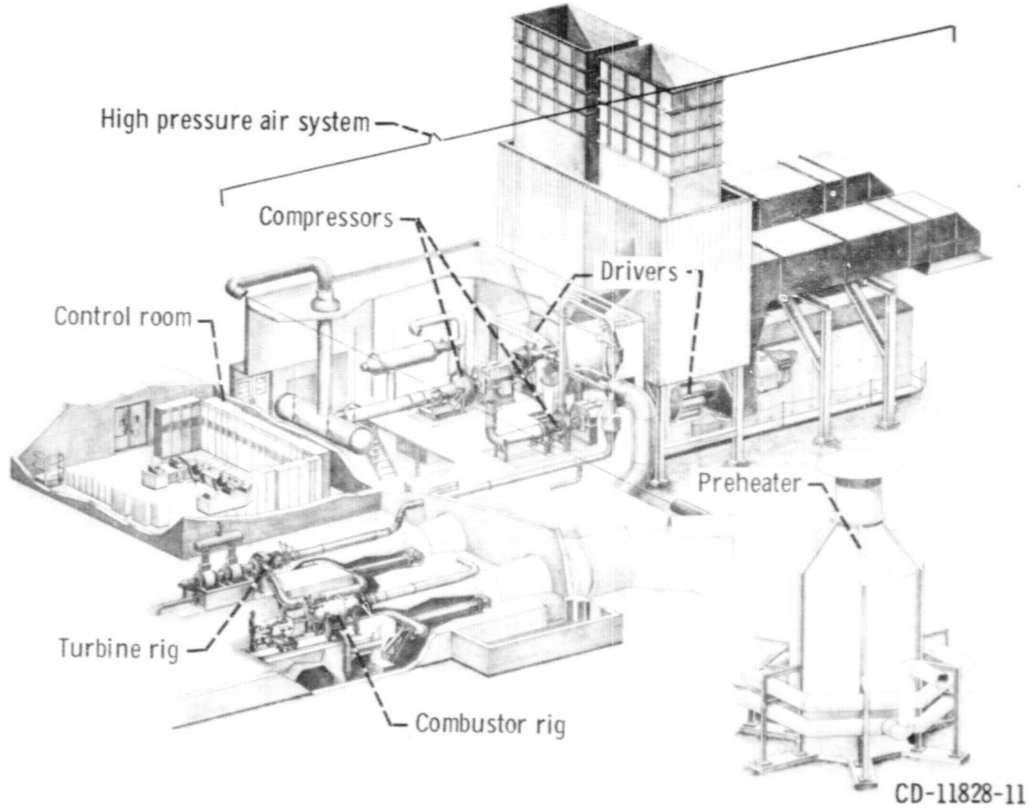


Figure 20. - High pressure facility.

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TM-79301		

4. Title and Subtitle	5. Report Date
IMPACT OF NEW INSTRUMENTATION ON ADVANCED TURBINE RESEARCH	
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
Robert W. Graham	E-251
	10. Work Unit No.
9. Performing Organization Name and Address	
National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135	11. Contract or Grant No.
	13. Type of Report and Period Covered
12. Sponsoring Agency Name and Address	Technical Memorandum
National Aeronautics and Space Administration Washington, D.C. 20546	14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

The principal design objective for advanced aircraft gas turbines is to achieve improved fuel consumption through higher operating temperatures and pressures. The necessity of cooling the blades can introduce penalties in aerodynamic performance of the turbine and also can reduce the overall cycle efficiency of the engine. The optimization of the cooling design with minimum performance losses necessitates precision in the heat transfer and aerodynamic prediction techniques employed. Confidence in these prediction techniques comes about through verification procedures in research programs. Such research progresses from simple one and two dimensional stationary blade row tests and finally to three dimensional, rotating turbine blade row tests. Both low temperature and high temperature experiments are carried out in facilities of these types. In this paper a description of an orderly test program that progresses from the simplest stationary geometry to the more complex, three dimensional, rotating turbine stage will be discussed. The instrumentation requirements for this evolution of testing will be described. The emphasis will be on the heat transfer instrumentation. It will be apparent that recent progress made in devising new measurement techniques has greatly improved the development and confirmation of more accurate analytical methods for the prediction of turbine performance and heat transfer. However, there remain challenging requirements for novel measurement techniques that could advance the future research to be done in rotating blade rows of turbomachines.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Gas turbines Heat transfer Instrumentation	Unclassified - unlimited STAR Category 07

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified		

* For sale by the National Technical Information Service, Springfield, Virginia 22161