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ABSTRACT

NASA Lewis Research Center is presently constructing a new test facility for developing turbine-cooling and combustor technology for future generation aircraft gas turbine engines. Prototype engine hardware will be investigated in this new facility at gas stream conditions up to 2480 K average turbine inlet temperature and 4.14×10^6 N/m^2 turbine inlet pressure. The facility will have the unique features of fully-automated control and data acquisition through the use of an integrated system of mini-computers and programmable controllers which will result in more effective use of operating time and operators, and will provide a built-in self-protection safety system. The facility, turbine rig, and turbine cooling test program will be described.

INTRODUCTION

The majority of experimental data needed for flow and heat transfer correlations and analytical models for use in the design of cooled turbine parts has and will continue to be obtained from simplified, low pressure and temperature gas environment rigs such as flat plate tunnels, large model tunnels, and stator vane cascades. Rotating rigs, particularly large units with adequate instrumentation, operating at relatively low gas temperature (<811 K (1000° F)) can provide much needed basic information on the complex flows and heat transfer that occur in this environment. These rigs can form the basis for formulating improved analytical models and computer programs. The applicability and accuracy of these programs in predicting the actual flows and metal temperatures in real engine environments, however, will need to be known.

The ability to make detailed measurements in an engine is very limited, particularly on the rotating parts, because of the space limitation, complexity, and cost involved. Also, there are the potential risks of instrument probe failure,

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engine part failure as a consequence of the instrumentation installation, and additional damage to downstream turbine parts. A dedicated turbine component test facility is a more practical means of providing this capability. Space can be provided for the installation of large quantities and a variety of instrumentation, and the gas and coolant environments expected in future gas turbines can be duplicated. In addition, the facility can provide flexibility of operation over a wider range of conditions than in a given engine.

The NASA Lewis Research Center has designed and is building a new facility consisting of independent and parallel combustor and turbine component test sites with supporting service systems to duplicate the environments expected in future gas turbines (ref. 1). The facility will have capability for gas stream pressures to 40 atmospheres and average gas temperatures to 2480 K (4000° F). Because the uniqueness of this facility lies in its high pressure capabilities, it has been named the High Pressure Facility or HPF; it will be referred to by this abbreviation hereafter. A general description of the facility and turbine test rig is presented herein. A more detailed description of the facility and of the combustor test rig can be obtained from reference 2. Also discussed herein will be the turbine cooling test program.

HIGH PRESSURE FACILITY (HPF)

The predicted trend in engine compressor discharge temperature and compression ratio, as shown in figure 1, was used as a guide for establishing the operating levels of the new facility. The design point conditions chosen at the inlet to the combustors of the combustor and turbine test rigs were 40 atmospheres (4.14 MPa or 600 psia) and 894 K (1150° F). A survey of available gas turbine drivers to power the facility compressors indicated that the pressure increase should be obtained in two tandem steps and the airflow rate should be limited to 91 kg/sec (200 lb/sec). This is also about the flow rate expected in the core turbines of advanced turbofan engines.

A schematic diagram of the HPF is shown on figure 2. Air pressurized to slightly over 11 atmospheres in an existing NASA Lewis air system is heated in an existing preheater to 534 K (500° F). This air passes through the first facility compressor to emerge at almost 23 atmospheres pressure and 725 K (845° F). The air then passes through the second facility compressor and exits at almost 45 atmospheres pressure and 894 K (1150° F). To facilitate the startup of the air system, all or any portion of this airflow can be routed directly to an existing exhaust system. In normal facility operation, the airflow will be directed to either the turbine or the combustor test rigs. A common control valve, a common metering station, and a flanged swinging elbow are used in the combustion air piping ahead of the test rigs. A pressure control valve and an isolation valve are located downstream of each test rig. Cooling air for 10 separately-controlled cooling air systems for various parts of the turbine test rig is taken from the facility compressor discharge at a point ahead of the metering run for combustion air.

A physical layout of the facility showing the preheater, facility compressors and drivers, turbine and combustor rigs, control room, etc. is shown in a cut-away perspective view in figure 3. The facility will have the unique features of fully-automated control and data acquisition through the use of an integrated system of mini-computers and programmable controllers which will result in more effective use of operating time and operators, and will provide a built-in self-protection safety system. The operation and data acquisition for the test rigs will be accomplished by the use of an integrated digital mini-computer system called the Digital Control Center (DCC).

DIGITAL CONTROL CENTER

Four mini-computers plus peripheral equipment comprise the Digital Control Center (DCC). Figure 4 shows a simplified schematic of the DCC. The four computers are labeled according to their dedicated task as the Input, Control, Operation, and Research Computers. The number and types of inputs, outputs, and displays are shown for each computer. The Input Computer serves as data acquisition controller, data buffer, and intermachine communication buffer. The Control Computer directly controls the process variables on the turbine and combustor rigs, with update rates of 20 to 150 per second. The Operation Computer supervises overall control of the experiment, such as setpoint calculations during startup, test point conditions, and shutdown operations. This computer uses a real-time operating system. The Research Computer continuously displays the information needed by the test director, and selectively stores, collates, and transmits data to a Central Data Collector via telephone lines. Associated with each of the four computers is a magnetic core memory. All the computers, except the Input Computer, have associated printers for making hard-copy records of preliminary data.

Data Acquisition

The acquisition of research data will be performed by the DCC in a semi-automatic mode (i.e., automatic collection and manual control of data flow by the test director through the use of programmed push-button selector switches). On command from the Input Computer, the multiplexer-digitizer will scan all the various types of signal inputs, digitize them as required, and load them into the appropriate memory within the Control, the Operation, or the Research Computer. This process of loading raw fixed-point data into memory will run continuously at a rate commensurate with the requirements of the control and data acquisition/display systems.

Certain selected stored data in these memories will be used in calculations such as flow rates, averages, and ratios. The results of these calculations, as well as temperature and pressure data, will be displayed in engineering units on several cathode ray tube (CRT) displays in the control room. The test director, after viewing these CRT displays, will initiate the recording of data by push-button control, causing the most recent complete set of data in memory to be transferred to temporary storage on a magnetic disk associated with the Research Computer. These accumulations of data on the disk can be transferred to the Central Data Collector at the discretion of the test director.

The first category of inputs to the DCC are analog signals from various sources such as strain gages, pressure transducers, thermocouples, and position indicating devices. All these signals enter the DCC through the multiplexer/digitizer. Initially only 704 of over a thousand available channels are being used. The digitizer is an amplifier-per channel unit that can accommodate instrument-type signals in the range of 5 MV to 10 V full scale.

The second category of inputs to the DCC are digital signals in the form of discrete on-off type signals. These discrete signals go directly to the Control, Operation, and Research Computers. Both program-controlled and program-interrupting type signals are involved. The program-controlled signals are used by the user application program to check the status of switch contacts. For example, the computer may be programmed to detect the closing of a limit switch before advancing a probe actuator. The interrupting type signals are used for devices that, because of priority or short duration conditions, require fast service from the computer. All push button selector switches for controlling data flow, for example, will be associated with this type of signal.

The third category of inputs come from special instrumentation sources such as fluid flow and shaft speed transducers (interfaced through rate converters), pneumatic multiplexers, a turbine blade metal temperature mapping system, a rotary data package (for turbine blade temperature and pressure measurements) and a combustion gas analysis system. The turbine blade metal temperature mapping system is a customized photoelectric system that was developed by NASA Lewis for surface temperature measurements on rotating blades. (For detailed description of this system, see ref. 3.) The system is capable of resolving a spot diameter of 0.05 cm (0.02 in.) on a blade moving at tip speeds of the order of 300 to 400 m/sec (1000 to 1300 ft/sec). Approximate real time displays of blade temperature profiles at steady-state operating conditions can be generated for a single blade or for small groups of blades. To handle the data from this system, a fifth dedicated mini-computer will be interfaced with the Research Computer. This fifth computer will do limited calculations on the data and will drive its own CRT displays. Through the interface, the Research Computer will record these data and transmit them to the Central Data Collector.

Eight pneumatic multiplexers will scan gaspath and cooling air pressure signals. Each multiplexer has 48 channels for measuring steady-state pressure; six channels in each multiplexer are assigned to calibration pressures. The rotary data package (ref. 4) scans thermocouple and pressure signals from the turbine blades. There are 72 channels on this package; a maximum of 10 of these channels can be used for pressure signals. The outputs of each device will be amplified, digitized, and stored in a small memory resident within its interfacing hardware. Under program control, this information will be transferred into memory of the Research Computer.

System Control and Operation

The Control Computer performs the function of 20 separate process controllers for the turbine rig on a time-sharing basis. The demands on this computer are severe because of the large number of control loops involved and the high speed at which these loops must be serviced. The majority of the loops have a very fast response time, are highly interactive, and are required to perform accurately under dynamic conditions. The Control Computer, for example, reads fresh data, calculates the set point error, and computes the valve position using whatever compensation is needed for the loop. The control loops are serviced sequentially. As soon as each loop has been serviced and the position set point transmitted to the control valve, the computer proceeds to service the next loop.

The automated supervision of the overall test operation is accomplished by the Operation Computer. Before a given test run, a table of data point conditions is entered into this computer establishing the test conditions to be set and maintained by the computer. The major tasks that this computer performs include: pre-run functional check of control equipment, start sequence to get the rig to a designated idle condition, ramping to and from designated data point conditions, normal or emergency shutdown of the test rig, and updating of displays of test rig operating conditions. Although overall test site operation is handled by the Operation Computer, there are situations where unprogrammed action must be initiated; therefore, suitable controls have been provided to allow operator intervention without changing the computer software.

Prior to making any research runs, a hybrid simulation of the process controls systems for the test rig will be run using analog models of the rig systems on an independent computer. The Control Computer will then be interfaced temporarily to this analog computer and simulated test runs will be made to determine overall systems response times, the effects of the interactions between systems, etc. Figure 5 is a picture of the control room showing some of the equipment just described.

TURBINE TEST SITE AND RIG

The turbine test site was designed for turbine-cooling research on various prototype air-cooled configurations of turbine vanes, blades, and blade tip shrouds (endwalls). This test site, shown in figure 6, consists of a turbine test rig, a waterbrake to absorb the power output of the turbine, and the necessary piping, controls, instrumentation, etc.

The main features of the turbine test rig are:

1. A single-stage air-cooled turbine
2. Individually replaceable and interchangeable turbine blades and turbine vanes
3. Separate groups (cascades) of test blades and vanes which have their cooling air flows independently controlled from the cooling airflows to the remaining slave airfoils in the row
4. Replaceable air-cooled turbine blade tip shroud with independently controlled cooling-airflow system
5. Ready access to the turbine section for ease of servicing and/or replacement of turbine components (stator, rotor, and tip shroud assemblies)
6. Combustion-air inlet flow path and combustor casing internal geometry conforming to a specified NASA annular combustor design
7. Maximum conditions of 4.14 MPa (600 psia) pressure and 894 K (1150° F) temperature in the combustor and cooling air supplies
8. Maximum gas path temperature of 2480 K (4000° F)
9. Bearing and shaft designed for maximum operating speed of 23 000 rpm
10. Turbine power absorbed by a direct-drive waterbrake

A view of the turbine section of the turbine rig is shown on figure 7. A 10-vane test cascade occupies the upper portion of the stator assembly which consists of a total of 36 vanes. Test vane air for this cascade is routed to the individual test vanes as indicated on figure 7. The remaining 26 slave vanes are cooled by a separate air supply from the annular manifold which surrounds the outer periphery of the stator assembly. Two diametrically-opposed six-blade test cascades are located in the 64-blade turbine rotor. Air for both test blade cascades flows through the centerline supply tube and up the rear face of the turbine disk to enter the rear of the 12 test blade bases below the hub platforms. The remaining 52 slave blades on the rotor are cooled by a separate air supply that flows up the front face of the turbine disk and enters the front of the slave blade bases. A picture of the turbine rotor with a checkout blade configuration is shown in figure 8. The first cooled research blade and vane configurations are impingement and full-coverage film-cooled. The parameters for the turbine design are listed in Table I. The initial turbine tip shroud is made in eight equal circumferential segments and has a honeycomb gaspath surface backed up by porous woven wire cloth and a perforated structural support. The tip shroud air enters the annular manifold that surrounds the outer periphery of the shroud assembly as shown on figure 7.

Positions for mounting radially-actuated water-cooled temperature and pressure measuring probes are provided at Stations 4 and 6 (see fig. 7). Similar probe housings for optical borescopes or optical fiber bundles will be used at these same locations to make infrared surface temperature measurements on the blades and vanes. Thermocouples and pressure sensing tubes are mounted on the blades and vanes to measure metal temperatures and gas and cooling-airflow path temperatures and pressures. The instrumentation leads from these measurements on the vanes are routed through the outer pressure shell of the rig to appropriate terminals; the leads from the blades are routed down the front face of the turbine disk and through the center of the turbine and waterbrake shafts to the rotary data package located at the outboard end of the waterbrake (see fig. 3).

The cooling airflow to each of the cooled components in the turbine rig is controlled by the Control Computer, based on measurements from venturis in the supply lines. Cooling-air temperatures and pressures are measured in internal manifolds in each of the separate cooling systems. The exhaust gas leaving the turbine is spray-cooled in the exhaust collector to a 589 K (600° F) temperature level prior to discharge into the exhaust system.

TURBINE COOLING TEST PROGRAM

The test program for the turbine rig will cover a variety of cooling configurations for the vanes, blade, and tip shroud. The airfoil configurations in the test cascades only will be replaced; the slave airfoils remain as permanent parts of the rig. The entire tip shroud assembly will be replaced with changes in tip shroud cooling configuration; uniform thermal growth in all segments of the tip shroud could not be assured otherwise. The ranges of gaspath and cooling-air conditions that will be covered by these tests are:

	Pressure		Temperature	
	MPa	psia	K	^{o}F
Gaspath - combustor inlet	0.52 - 4.14	75 - 600	311 - 894	100 - 1150
Gaspath - combustor exit	0.48 - 4.0	70 - 580	1090 - 2480	1500 - 4000
Cooling air	0.52 - 4.14	75 - 600	311 - 894	100 - 1150

Test runs will be made at several fixed levels of gaspath temperatures and pressures within the ranges listed above while varying cooling-air temperature and cooling-airflow rate. During these test runs, temperature, pressure, and weight-flow measurements will be made in the gaspath and in each of the cooling-air supply lines. Metal temperature measurements will be made on the combustor, the vanes, the blades, the turbine disk, and the tip shroud, and on the gaspath walls downstream of the turbine.

The cooling effectiveness of the various configurations of air-cooled vanes, blades, and tip shrouds will be evaluated on the basis of these measurements. Comparisons will be made between predicted and measured values of metal temperatures and cooling-airflows; and, based on these comparisons, corrections and improvements will be made to the analytical methods of prediction.

CONCLUDING REMARKS

This test facility will provide proper simulation of the gaspath conditions in advanced aircraft gas turbines for the evaluation of prototype combustor and air-cooled turbine designs. Automated control and data handling will permit the most efficient use of operating personnel and operating time. The flexible designs of the turbine rig will allow frequent changes in the prototype test hardware as the test program progresses. As a research tool, the HPF is unique and promises to have a very productive life.

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TABLE I. - INITIAL TURBINE DESIGN PARAMETERS

[Inlet temperature, 2200 K (3500° F); inlet pressure, 4.0×10^{6} Pa (580 psia).]

	Vane	Blade
Airfoils:		
Number	36	64
Tip diameter	0.51 m (20 in.)	0.51 m (20 in.)
Hub diameter	0.43 m (17 in.)	0.43 m (17 in.)
Span	0.038 m (1.5 in.)	0.038 m (1.5 in.)
Axial chord	0.038 m (1.5 in.)	0.036 m (1.4 in.)
Aero. profile	Constant section, untwisted	
Cooling configuration	Combination of impingement and full-coverage film cooling	
Fabrication	Cast shell, sheetmetal insert	

Maximum coolant/gas flow ratios:
- Vane, 0.20
- Blade, 0.15
- Tip shroud, 0.05

FIGURE LEGENDS

Figure 1. - Turbofan engine compressor characteristics.

Figure 2. - Schematic diagram of HPF.

Figure 3. - Perspective view of HPF.

Figure 4. - Schematic of Digital Control Center (DCC).

Figure 5. - High pressure facility control room.

Figure 6. - Turbine rig, high pressure facility.

Figure 7. - Test section of turbine rig.

Figure 8. - Turbine wheel and blades for check-out tests in high pressure facility.

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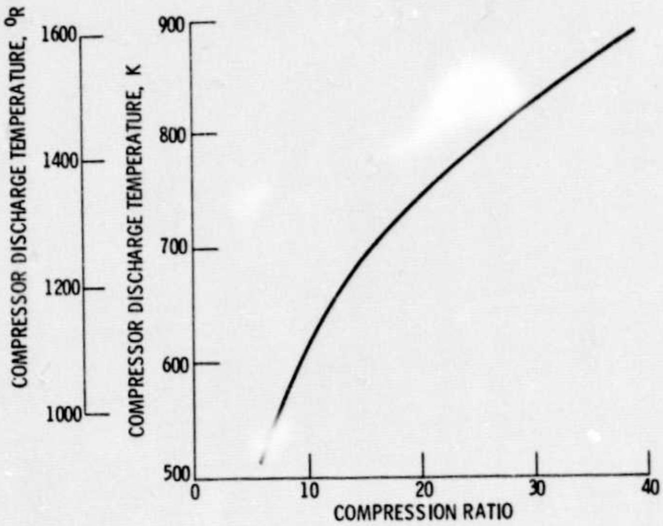

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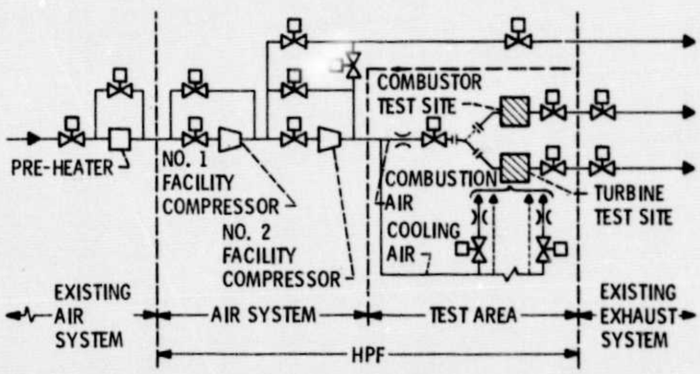

Figure 2. - Schematic diagram of HPF.

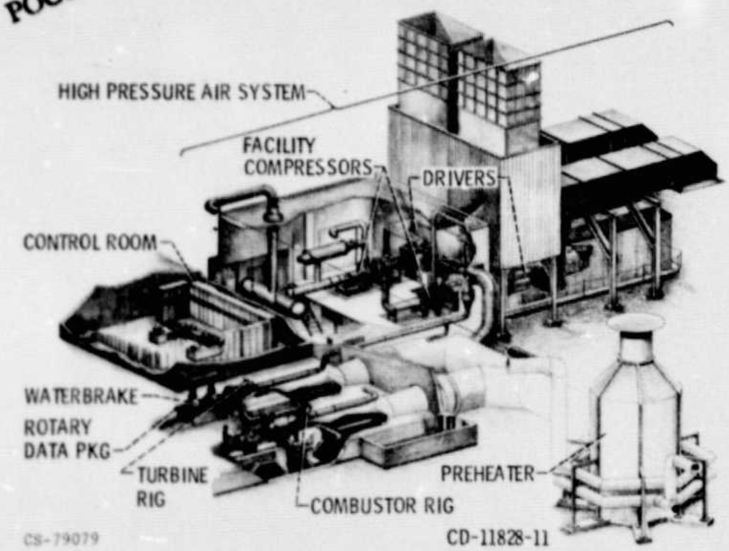

Figure 3. - Perspective view of HPF.

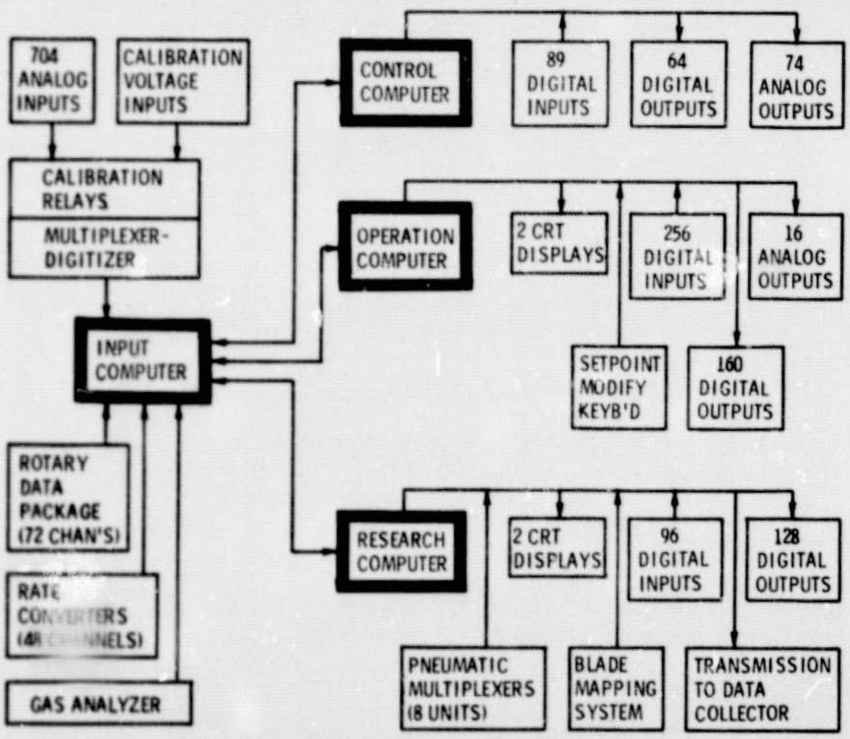

Figure 4. - Schematic of Digital Control Center (DCC).

Figure 5. - High pressure facility control room.

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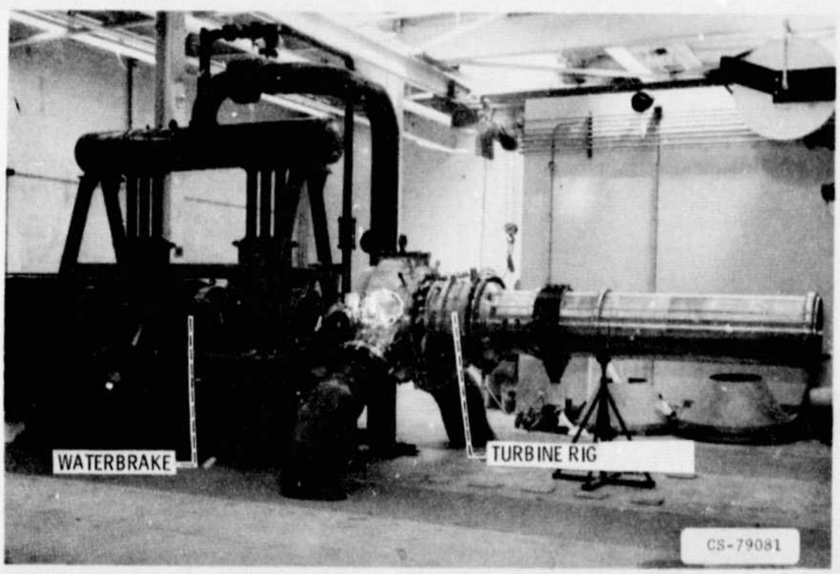

Figure 6. - Turbine rig, high pressure facility.

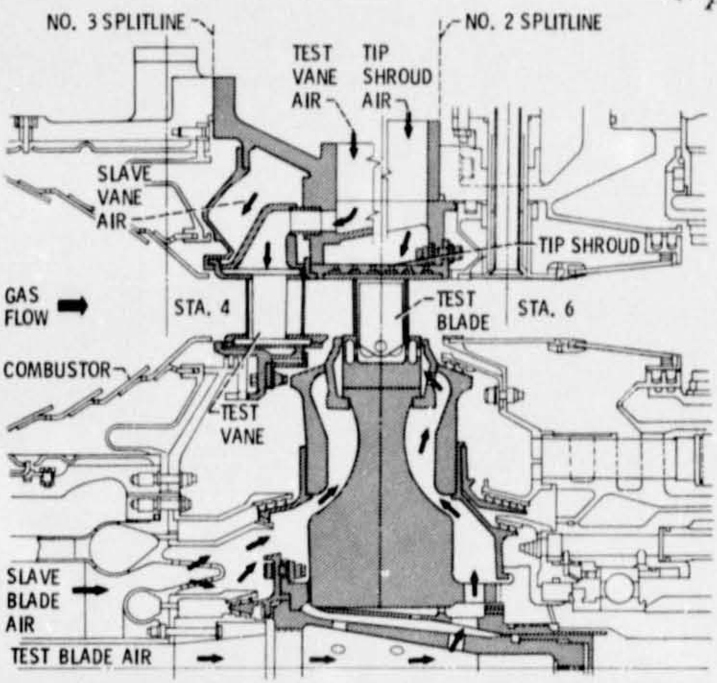

Figure 7. - Test section of turbine rig.

Figure 8. - Turbine wheel and blades for check-out tests in high pressure facility.