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Analysis and Testing of Air-Cooled Turbine Rotor and Stator Blades

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Advancing turbine engine technology requires air-cooled turbines. Cooling mechanisms applied must be exploited in a practical manner to obtain maximum cooling effectiveness. Cooled turbine stator and rotor blade design requires rigorous analysis supplemented by verifying experimental data. Problem definition, analysis techniques, material application, cascade and engine testing, and correlation of data are presented for air-cooled turbines. Convection, impingement, film, transpiration, and combined cooling mechanisms are reviewed.

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By increasing turbine inlet temperatures, higher thrust to weight and thrust to volume ratios can be obtained in advanced gas-turbine engine designs. In addition, improved specific fuel consumption can be realized in some engine cycles including high bypass fan and turboprop configurations. These more powerful and, often, more efficient gas-turbine engines are required for advanced aircraft concepts including supersonic-hypersonic, vertical takeoff, lift-cruise, and long range, long endurance. The industry is being encouraged as never before to increase turbine inlet temperatures in new engines by an updating and exploitation of turbine cooling technology.

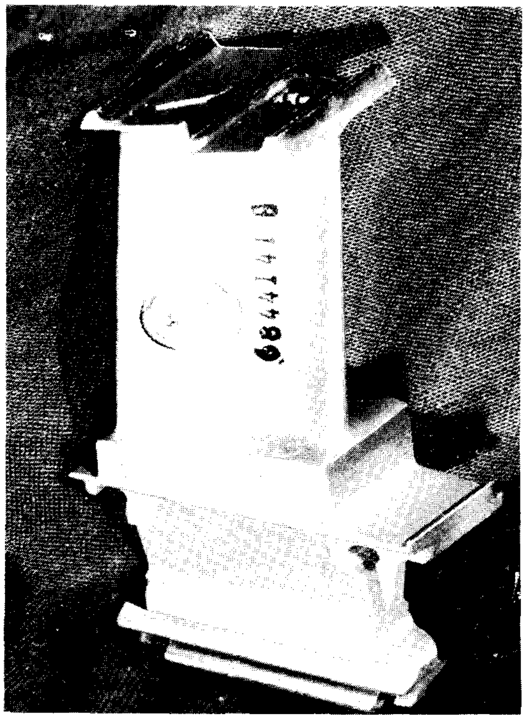
The use of air cooling in gas turbines dates back to the first practical engine configurations. Combustion liners were film cooled to prevent the high temperature products of combustion from overheating the combustion liner walls. During and after World War II the air cooling of turbine airfoils was introduced to permit the operation of gas-turbine engines at turbine inlet temperatures significantly above those established by allowable airfoil metal temperatures. The first attempt at air-cooled airfoil fabrication involved the use of sheet metal welded or brazed structures. Most of these efforts failed resulting from limitations inherent to the joining techniques. The most successful fabrication process employed to date has been investment casting. This development, which began in the mid-1950's has been exploited so that highly reliable airfoil castings are now manufactured on a production basis with complex internal geometries for convection cooling. A modified 4-stage turbine with cast convection-cooled first-stage airfoils was tested successfully in an engine on a 50 hr PFRT Schedule in 1960 at 2060F TIT. This temperature was approximately 300 deg F higher than production engine turbine inlet temperatures at that time. Continuing casting development and improvement of the cooling effectiveness has resulted in the development of the current technology. Reliable cast turbine blades, convection cooled, are now available for engine operation in the 2000-2300F turbine inlet temperature range. Such a current production air-cooled rotor blade is shown in Fig. 1. This blade is used in the T56-A-15 engine operating with long life at 1970F TIT.

In order to meet the requirements for new engine designs demanded by new airframe concepts, it is necessary that further improvement in turbine airfoil cooling be obtained. Casting technology alone cannot accomplish this advancement. Improved methods of blade analysis and fabrication using more efficient heat-transfer mechanisms are therefore under investigation. It is the purpose of this paper to examine the turbine airfoil cooling problem. Analytical methods will be discussed which aid in understanding and gaining solutions to the problem. The reduction of analytical methods to practical designs will be covered together with the test program used to evaluate empirically advanced designs. In conclusion, current trends will be enumerated and a few advance designs will be suggested.

THE BASIC COOLING PROBLEM

In a practical engine, the cooling problem for the rotor blade is greatly different from the problem for the vane. Because the rotor blade sweeps the combustor outlet pattern, the hot gases are averaged in the tangential direction thereby subjecting the rotor blade to only the radial combustor temperature variation. The cooling requirement is defined by a consideration of this averaged environment and by a given metal temperature established by stress, erosion, and oxidation criteria. Because of the various aerodynamic, heat transfer, stress and mechanical design criteria which the rotor blade must satisfy, the design of the internal blade geometry for cooling is somewhat restricted. To date, the most successful designs have incorporated radial passages through which cooling air passes exhausting at the tip. The delivery of cooling air to the rotating airfoil with minimum leakage presents some difficulty.

Because the stator vane is stationary, the cooling-air delivery problem is quite simple. With the vane in a low dynamic stress field, various fabrication methods can be considered safely for application. The vane is exposed to both radial and circumferential variations in the en-



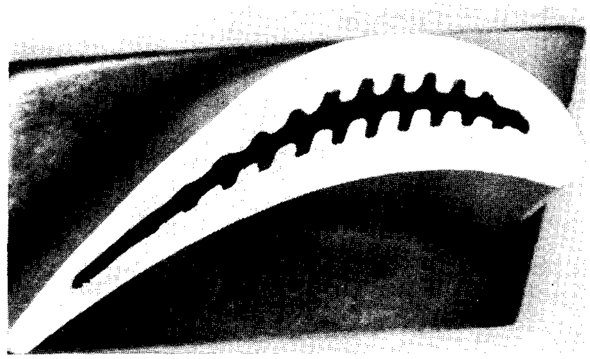


Fig. 1 Allison production T56-A-15 first-stage rotor blade

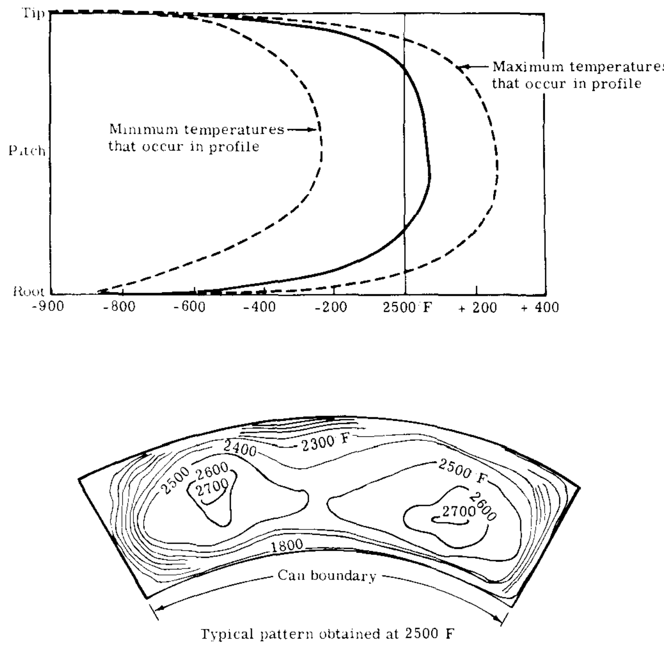


Fig. 2 Typical combustor outlet profile showing both radial and circumferential variation

gine combustor outlet temperature. Fig. 2 shows the typical variation in burner outlet temperature sensed by the stator vane. This temperature variation forces the designer to supply sufficient cooling to the vanes to protect all the hardware as if it were subjected to the most severe expected gas environment conditions. A waste of precious cooling air results. The loss in engine performance resulting from stator-blade cooling is minimized by exhausting the spent cooling air into the primary gas stream ahead of the nozzle throat.

It is thus observed that the basic cooling problem is one of matching the cooling in both stator vanes and blades to the environment around the airfoils. Because of combustor outlet temperature variation, cooling must be concentrated near the pitch line of the airfoil with decreased cooling required to either side of this location. Many other considerations will become apparent in subsequent discussion.

TYPICAL AIRFOIL THERMAL ANALYSIS

Analyses obtained by use of the new high-speed digital computers have enabled the designer to now solve equations that were previously cumbersome and sometimes impossible to solve. Finite difference techniques using large nodal point patterns have been applied successfully in these problems. It is now commonplace to have up to 2000 nodal points in one, two or three-dimensional heat-conduction problems. Simultaneously, variable convection film coefficients with time and variable thermal properties with temperature are accounted for in these analyses. Recent advances in successfully achieving nodal point mesh generators, especially in the two-dimensional problem, have removed considerable drudgery from data entry for the users of these sophisticated programs.

The basic equation defining the heat input by convection of the hot gas to the turbine blade is given by

$$q = hA\Delta T + q'$$

In this equation q is the total heat input, h is the local film coefficient for heat transfer, A is the local area, ΔT is the temperature differ-

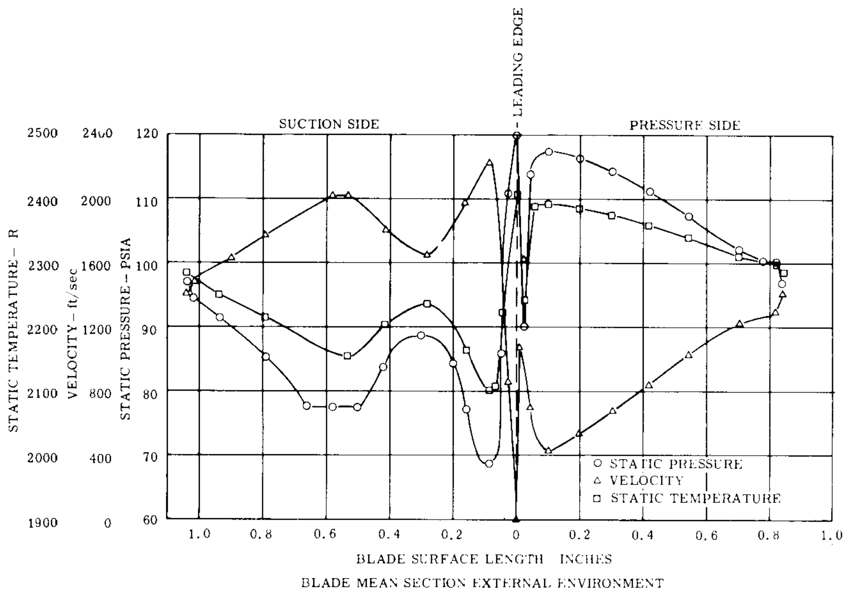


Fig. 3 Pressure, velocity, temperature variation shown on unfolded airfoil

ence between the free-stream gas temperature and the outside wall temperature, and q' is the heat input by radiation. The film coefficient is formed by an accurate knowledge of the physical dimensions of the airfoil and the pressure (P), velocity (V), temperature (T) relationship. A typical plot of PVT is shown in Fig. 3.

This diagram is caused to vary as the engine operational mode varies and will thus represent the basic parameters defining the environment surrounding the airfoil for transient conditions.

External heat-transfer film coefficients are defined from these P-V-T diagrams as shown in Fig. 4. An adiabatic wall temperature is also shown along with the film coefficients. Classical boundary equations are available in the literature for defining these film coefficients, References (1-5).[1] Modifications to the boundary conditions are made to accommodate cooling air ingested into the airfoil boundary layer by film and transpiration cooling mechanisms.

An analytical technique applied very successfully to convection-cooled airfoils is shown in Figs. 5, 6 and 7. In Fig. 5 it is noted that the airfoil is split along the trailing edge and unwrapped as shown in Fig. 6. A rigorous analysis yields the airfoil isotherms as shown in Fig. 7. The conduction analysis is controlled such that the two trailing edge surfaces at the split line must give equal temperatures along the surface sliced for unwrapping the airfoil. Geometry terms in the analysis accommodate the uneven areas generated by unwrapping this nonsymmetrical surface.

The isotherm pattern shown in Fig. 7 now becomes the basis for subsequent design analysis. Proper mechanical properties, such as modulus of elasticity, are selected for use in vibration analysis. Yield, creep or endurance strength at any given section is selected for thermal and mechanical stress analysis. Erosion and oxidation characteristics are known to be a function of metal temperature, gas velocity, and time. With the analytical metal temperatures known for various operation conditions, the predicted engine operating spectrum may be surveyed for expected life characteristics. When stress and environment analysis finds metal temperatures are too high, an iterative loop in the analysis procedure is pursued where the aerodynamicist, heat-transfer analyst, and the stress analyst tradeoff design parameters to arrive at metal temperatures yielding the required structural integrity of the airfoils.

Many analyses of various cooling concepts have suggested that four basic cooling mechanisms offer the greatest promise. These four are convection, transpiration, film and impingement cooling.

EXPERIMENTAL EVALUATION OF AIRFOIL COOLING

In order to test newly designed cooled airfoil geometries, the use of a stationary hot cascade rig has been found to be invaluable for the generation of data and obtaining correlation with

1 Numbers in parentheses designate References at the end of the paper.

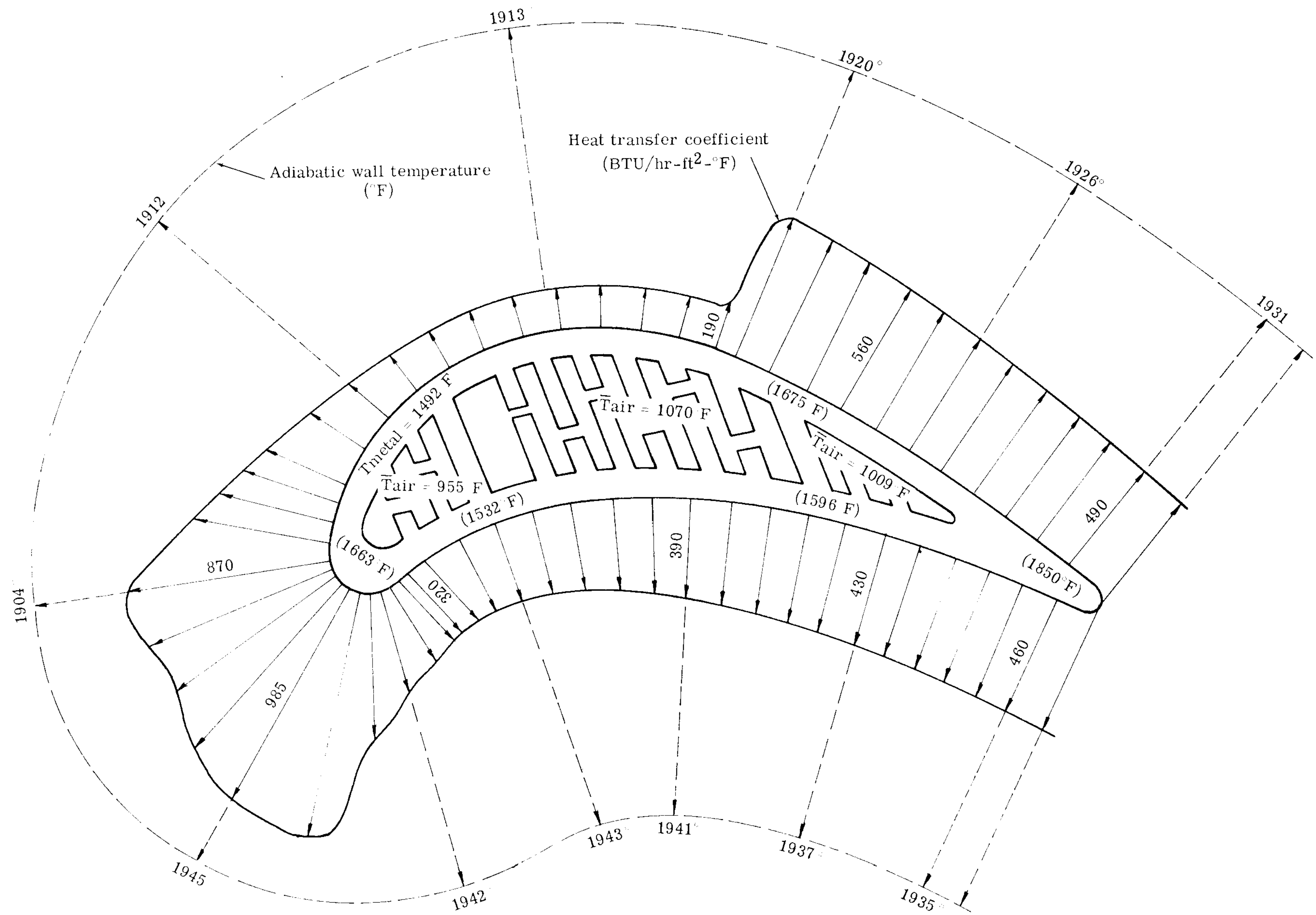


Fig. 4 Film-coefficient distribution around typical turbine blade

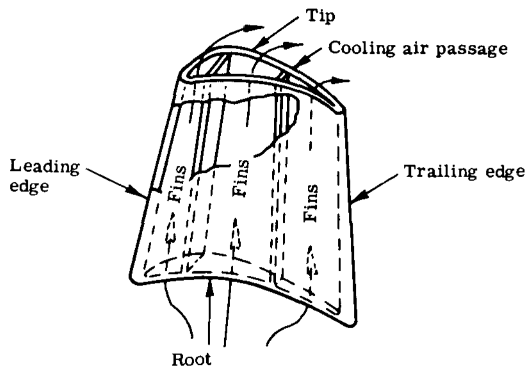


Fig. 5 Schematic of three-compartment, single-pass blade for analysis

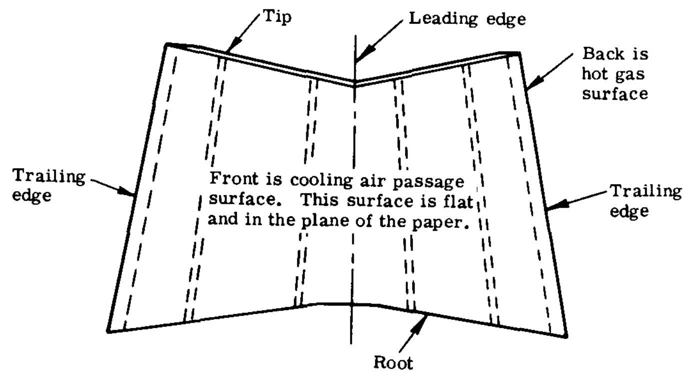


Fig. 6 Three-passage blade unfolded

analysis. The typical hot cascade rig consists of a duct through which high pressure air is forced and heated to the desired conditions by direct combustion. This hot gas then passes through a transition duct and flows through a suitable cascade section. This cascade typically contains the test blade in the center of the flow path. Other blades are added to guide the flow around the test blade in a manner duplicating true engine airfoil cascades. One of the available high temperature, stationary cascade rigs is shown in Fig. 8. The airflow is from left to right. Notice the "tower" in the center of the picture. This structure permits the extraction of the test blade from the gas path while test conditions are being established. The view port in the side of the duct provides access for optical temperature measurement.

Blade temperature measurement has posed a difficult problem at the elevated temperatures presently being investigated. Experience has indicated that thermocouples mounted on airfoils have the following shortcomings:

- Data restricted to a limited number of point locations
- Short life at gas temperatures above 2100F
- Expensive and time consuming to install
- Introduce flow disturbances with attendant variation in local heat-transfer coefficient

Other methods of temperature measurement were developed to remotely obtain data. This is particularly necessary when the blade metal surface is cooled by the passage of cooling air through the wall itself as with film or transpiration cooling.

Optical pyrometers have been used with success; however, they are limited to metal temperatures above 1400F. A method utilizing infrared photography has been developed and used in cascade testing. To investigate the use of this technique, a calibration tube was fabricated to produce a smooth temperature gradient from 1000 to 2000F over 7 in. of tube length.

Successive photographs of the tube were taken at various camera settings to determine the speed and latitude of the infrared film. A calibration was thus obtained and the technique has been applied successfully to the hot cascade rig. In this rig, the film is exposed to a selected narrow wave length of radiant energy. The result is film exposed in proportion to the incident radiant energy. Fig. 9 shows a typical blade photographed using this infrared film.

Interpretation of the film is obtained by the use of a film projector in conjunction with a very sensitive miniature light cell wired in series with a fixed resistor and a battery. With this method, data are read out very quickly and plotted as isotherms along the blade surface. A typical blade thermograph plotted from infrared film is shown in Fig. 10. The film can be read to the nearest 5F. For convenience, isotherms are plotted on 25F intervals. The particular blade shown is transpiration cooled and made of Lamilloy. Notice the uniformity of the chordwise thermal gradient. The absolute level of the temperatures indicated is accurate within ±25F.

Continued development of infrared photography is in progress as it applies to turbine airfoil metal temperature measurement. The effort is concentrated on an application of the technique to operating turbine engines.

Even though hot cascade testing can be used successfully for design parameter investigation and for the comparison of similar cooled blade designs, the final turbine airfoil evaluation must be done in an actual operating gas-turbine engine.

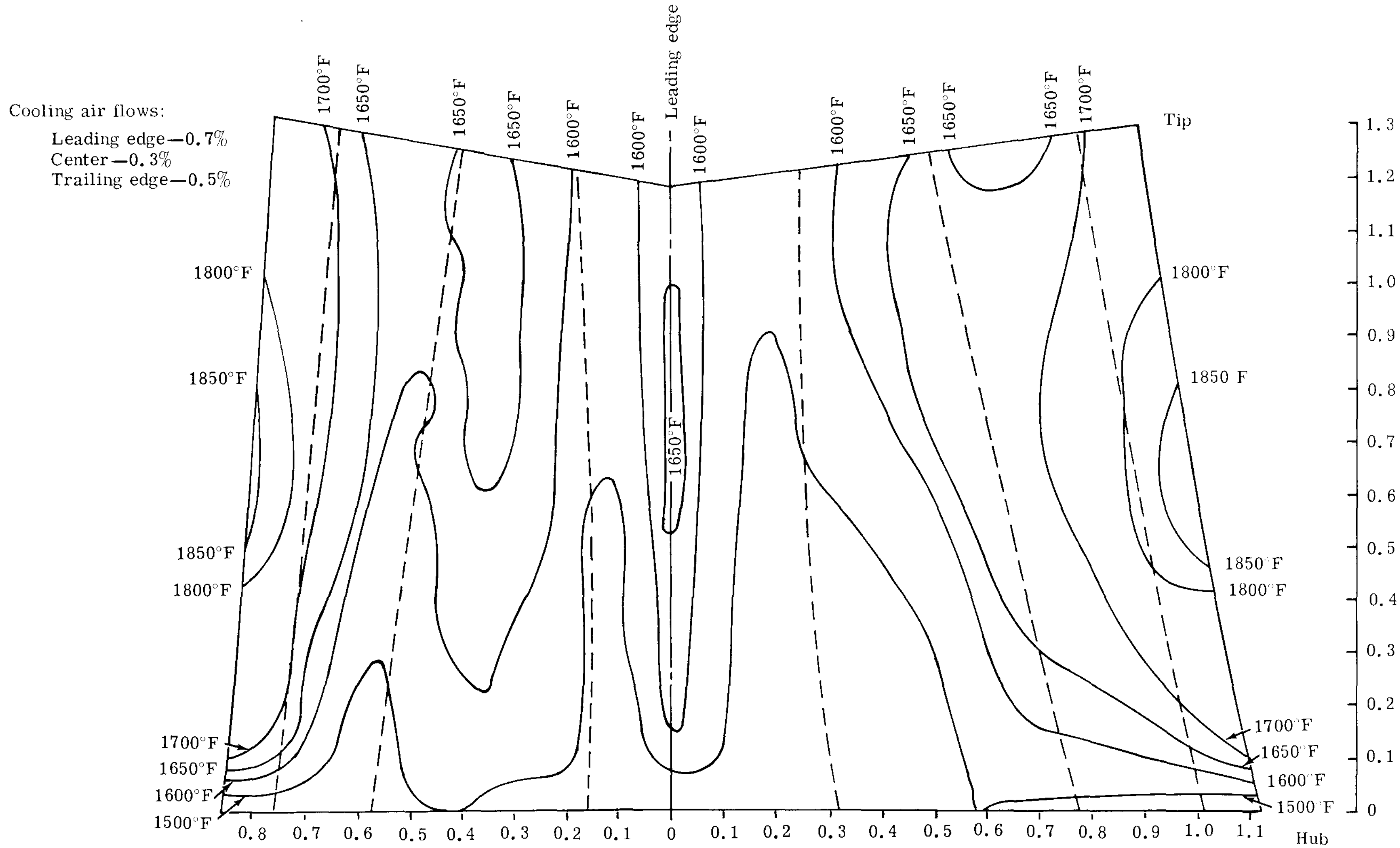


Fig. 7 Isotherm plot made from analysis for three-passage blade

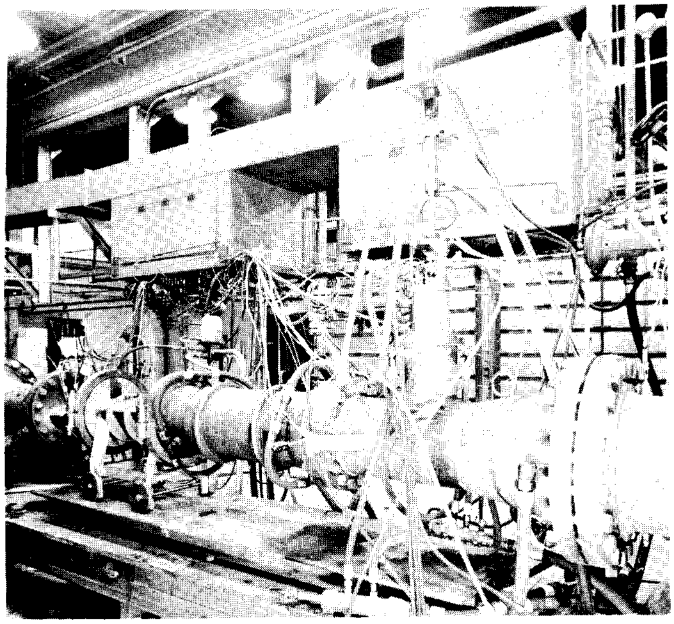


Fig. 8 Hot cascade test rig

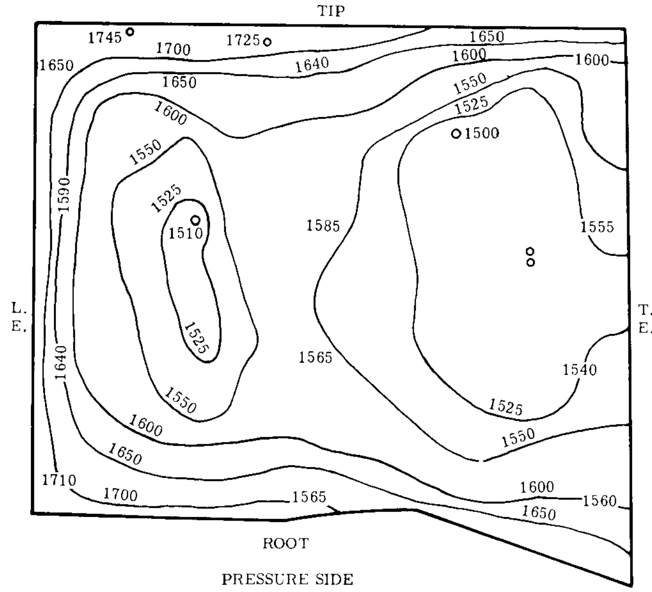


Fig. 10 Thermograph of isotherms plotted for transpiration-cooled blade from infrared film. Gas temperature is 2600 F

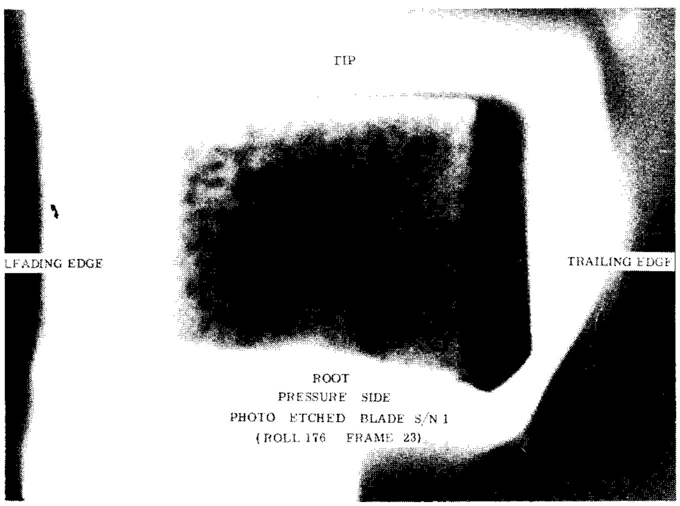


Fig. 9 Infrared photograph of Lamilloy blade being tested in hot cascade rig

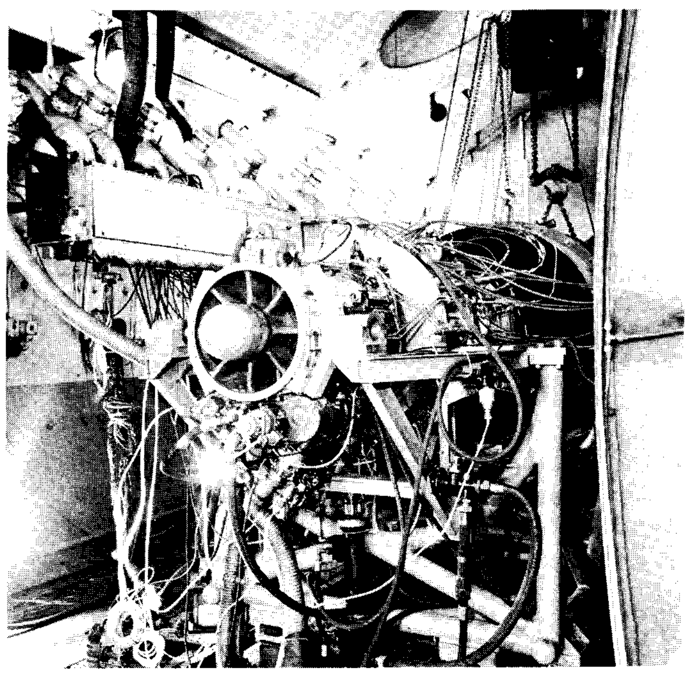


Fig. 11 Heat-transfer jet engine installed on test stand

This testing accomplishes two objectives. The airfoils are subjected to the variations in heat input caused by combustor pattern at various engine operating conditions and the blade is operated in a realistic centrifugal stress field.

A thrust producing turbine engine has been designed and constructed specifically for the developmental testing of advanced turbine airfoils. This engine, shown in Fig. 11, has the following design features:

- Compression ratio = 4 to 1
- Maximum TIT = 3000F
- Engine speed = 10,500 to 13,800 rpm
- Airflow = 30 lb_m/sec
- Single-stage turbine
- Turbine cooling air bleed to 12 percent
- Cooled exhaust-nozzle walls
- Variable exhaust nozzle
- Turbine cooling modulation capability
- Constant compression ratio, engine

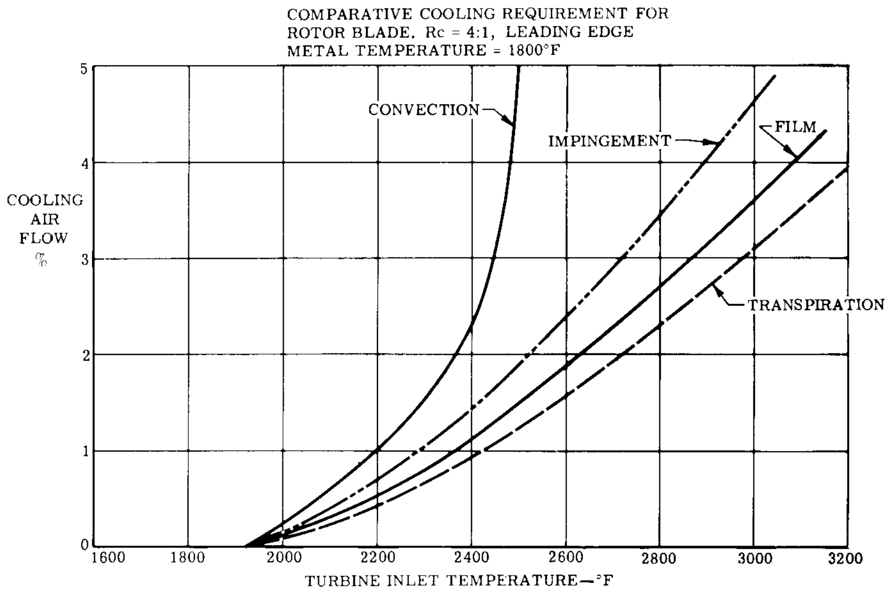


Fig. 12 Comparative cooling requirement for rotor blade. R_C = 4:1, leading edge metal temperature is 1800 F, cooling air temperature is 500 F

speed, and airflow over a wide range of TIT from 2000 to 3000F

The heat-transfer evaluation of turbine airfoils in the engine requires that cooling airflows, cooling air temperatures, metal temperatures, and cooling air system pressures be measured accurately. The cooling airflows are bled externally from the compressor, modulated and measured to each of three separate systems - the blades, vanes, and structure. Cooling air temperatures and inlet pressures are indicated by standard instrumentation at the inlet to the airfoil. The measurement of the turbine blade metal temperatures is obtained from rotating thermocouple instrumentation and thermally sensitive paint. The engine data obtained complimented by the hot cascade data and analysis lead to design information which may be applied to new and improved engines.

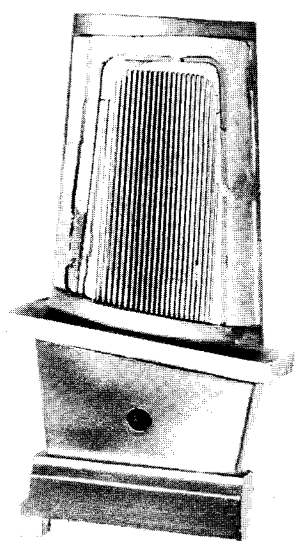


Fig. 13 Advanced convection-cooled blade design

TEST RESULTS

Hot cascade testing has been accomplished with a wide range of cooling mechanisms, blade shapes, and test conditions. Useful data for comparison have been generated from testing of one basic airfoil shape over a range of gas temperatures from 2000 to 3000F. Many different convection, film, impingement, and transpiration cooled configurations have been tested using this single basic airfoil shape. A wide variation in heat-transfer efficiency is observed with each heat-transfer mechanism depending on design geometry. This consideration dictates that practical application of cooling mechanisms be done carefully to achieve maximum cooling efficiency. A comparative plot of cooling effectiveness representing extensive test data is presented in Fig. 12. The convection cooling is for single-pass airflow with compartmented internal passages. The film, transpiration, and impingement cooling is for the most efficient geometries tested to date. Further testing is in progress and more efficient means of applying convection, impingement, film and transpiration cooling are being developed.

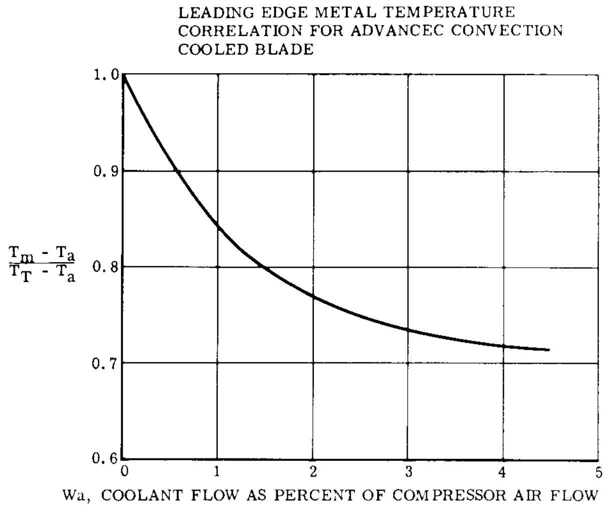


Fig. 14 Leading edge metal temperature correlation from experimental data for convection-cooled blade

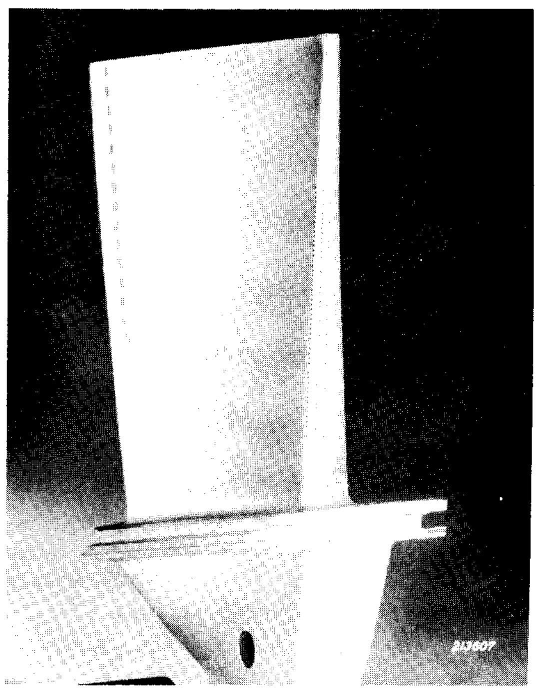


Fig. 15 Film-convection blade design with EDM holes in casting

From hot cascade testing, the convection-cooled blade design shown in Fig. 13 was produced. This blade has been undergoing extensive engine testing for several months. Engine testing in excess of 2700F turbine inlet temperature has been accomplished. A rotor blade leading edge cooling correlation for the blade tested is presented in Fig. 14. This correlation is based primarily on stationary cascade data as substantiated by engine operation. Analysis of this blade has

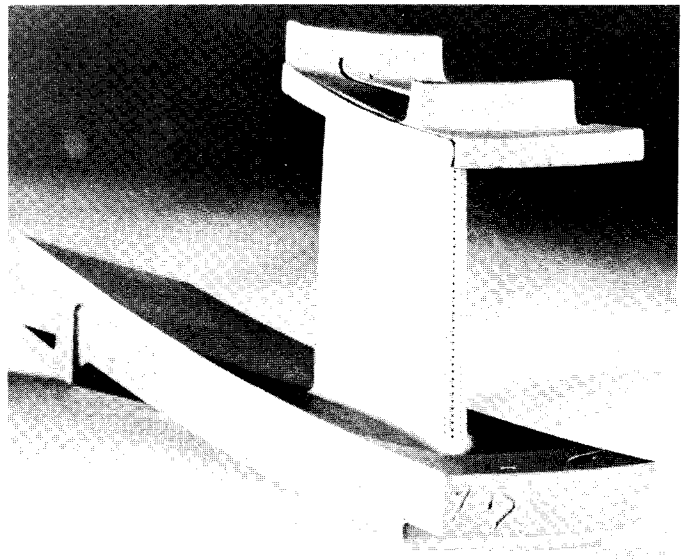


Fig. 16 First-stage turbine vane showing film-cooled leading edge

checked this correlation within 50F of indicated metal temperature. Data indicate that incorporating the latest advances in convection cooling, and using the new higher temperature alloys, this type of rotor blade could be operated successfully at turbine inlet temperatures 100 to 150F higher than the testing to date, for short periods of time. Also, both film and transpiration-cooled hardware have been fabricated and are under engine evaluation.

CURRENT PROGRESS IN ADVANCED COOLING APPLICATION

In order to extend the range of application of the existing art surrounding cast airfoils, precision castings have been reworked by the process of electrical discharge machining (EDM) and drilling to apply film cooling to local areas. Film cooling incorporated in this way has been shown to be highly successful by stationary cascade and engine testing. The EDM process removes the blade material by multiple spark discharge action at the end of a special electrode. By controlling the processing parameters, very accurate, smooth, low-residual stress holes can be produced down to 0.006 in. dia. High temperature materials such as INCO 713C and IN 100 have been reworked successfully by this method. By changing the shape of the electrode, many shapes of holes may be obtained. One experimental blade is shown in Fig. 15. This blade is a precision casting produced in the INCO 713 material. The leading and trailing edge areas have been reworked by EDM. Three rows of 0.008-in-dia holes were produced in the leading edge area while a row of slots 0.010

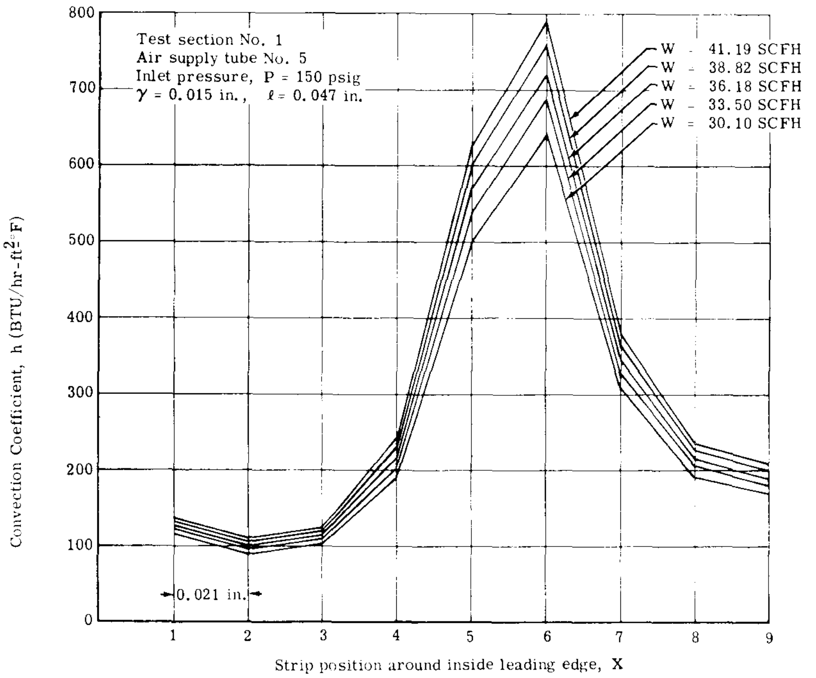


Fig. 17 Variation in film coefficient inside leading edge radius shown as as a function of displacement from jet direction

X. 100 in. provide cooling air discharge near the trailing edge on the pressure side of the blade. From analysis and subsequent stationary cascade testing of various configurations, castings have been reworked and tested in the heat-transfer test engine. One such vane is shown in Fig. 16. Three separate, radial rows of 0.017-in-dia holes were added in the leading edge area for film cooling. Other film cooled configurations have been and are now being evaluated.

Another method which has been incorporated recently for stator vane cooling is the impingement of cooling air in the inner surface of the leading edge radius. Initially, data for local film coefficients were found to be lacking for the size radius that is found on the inside of practical airfoils. Testing on special test sections has led to typical data presented in Figs. 17 and 18. Internal cooling film coefficients for different inside radii have been found to vary as shown with tangential distance from the impingement point, and with distance of the impingement nozzle from the cooled surface. The local internal film coefficient is also found to vary with hole or slot size, hole or slot spacing, and airflow. Exact film coefficient data obtained will be published in future papers. Fig. 19 shows a production impingement cooled vane which has benefited from data acquired by the previously outlined method of generating design data.

Because transpiration cooling apparently of-

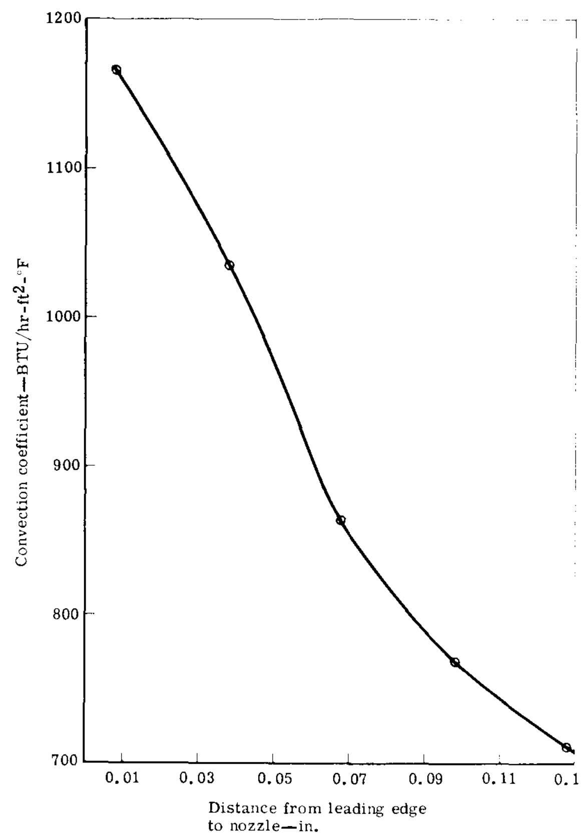
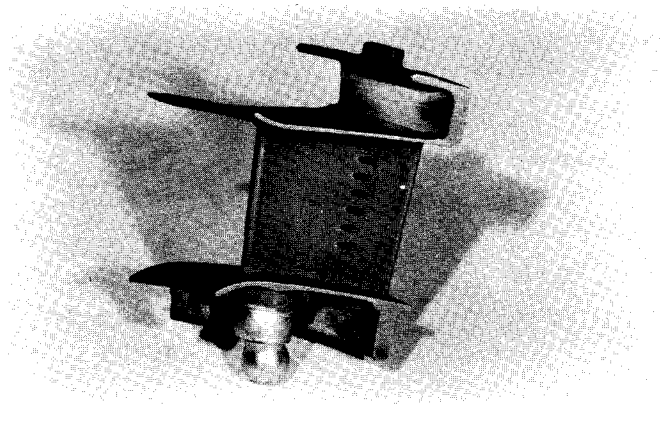


Fig. 18 Degradation in stagnation-point film coefficient with nozzle position from internal leading edge surface



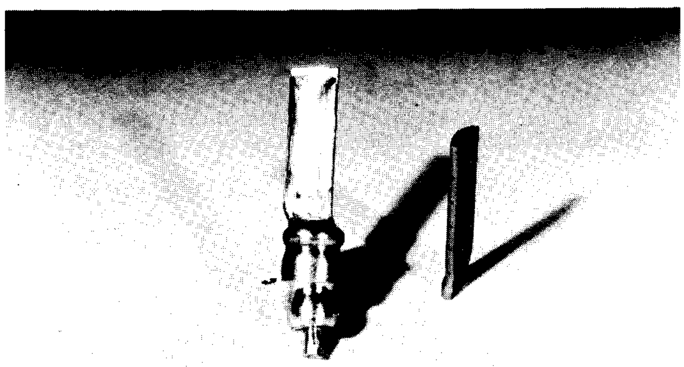


Fig. 19 Allison T78-A-2 impingement-cooled first-stage stator vane

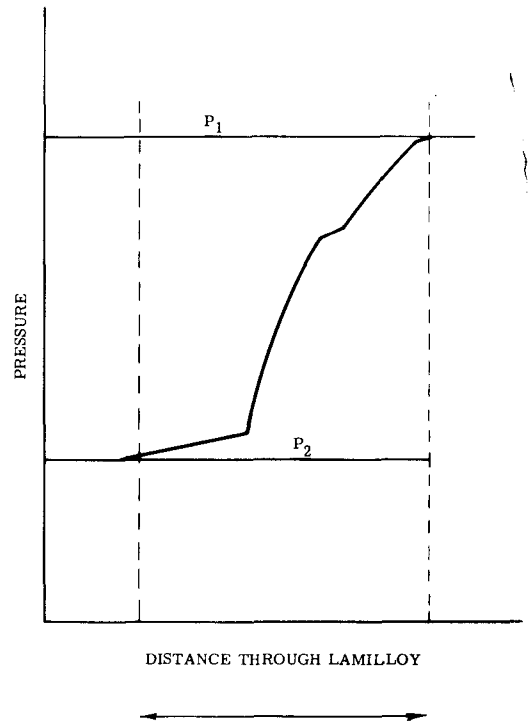


Fig. 20 Pressure drop through typical Lamilloy material

fers the most effective means of heat transfer, considerable effort has been extended to apply this form of cooling to gas-turbine airfoils. A limited amount of success has been realized owing to the difficulty of obtaining suitable transpiration materials and the lack of techniques for reliable fabrication of existing materials into workable hardware. Sintered wire composites are the most widely used of the available transpiring materials. Low strength at temperature, low modulus of elasticity, very small pore size, and poor oxidation resistance are problems encountered in the practical application of these materials.

A new "simulated transpiring" material made by a unique combination of fabrication techniques has been developed. The material known as "Lamilloy" is a sheet almost perfectly suited to gas-turbine engine application. "Simulated" transpiration cooling is accomplished by the ejection of cooling air at a discrete number of points. Since the material is produced by an accurately controlled process prior to assembly, the airflow characteristics of the resulting sheet can be tailored to the unique requirements of a specific design. Lamilloy has been made successfully from many high strength, high temperature materials.

The high temperature strength characteristics of the sheet are essentially those of the parent material on an equivalent area basis. By proper heat treatment, the material is given excellent forming characteristics.

The pressure drop characteristics of a typical Lamilloy material geometry is illustrated in Fig. 20. This graph shows the pressure drop through the sheet. By proper control of processing parameters, it is possible to produce accurately controlled variable pressure drop characteristics in the sheet.

A formed Lamilloy sheet-metal outer sheet and cast support strut are shown in Fig. 21. These details were used to produce a transpiration-cooled blade of the type shown in Fig. 22. Blades such as this have been used as part of the air-cooled blade development program. Testing has been accomplished in a stationary cascade rig at 2850F equivalent turbine inlet temperature. Complete engine sets of both turbine inlet guide vanes and rotor blades of a more advanced design have been fabricated.

DESIGN TRENDS

For the turbine inlet temperatures in the range from 2500 to 3500F being considered for future engine designs, the most promising cooling mechanisms are film, transpiration, and local

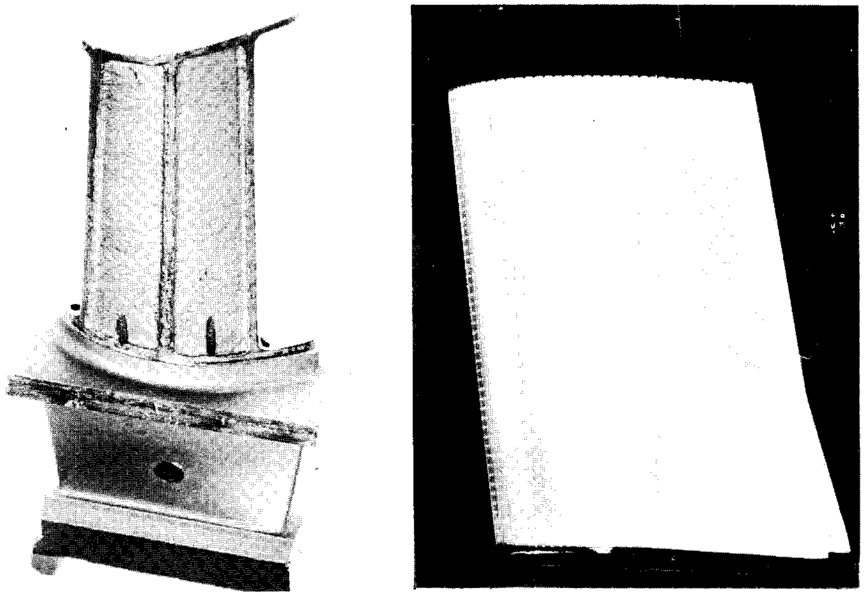


Fig. 21 Cast support strut and Lamilloy shell prior to joining

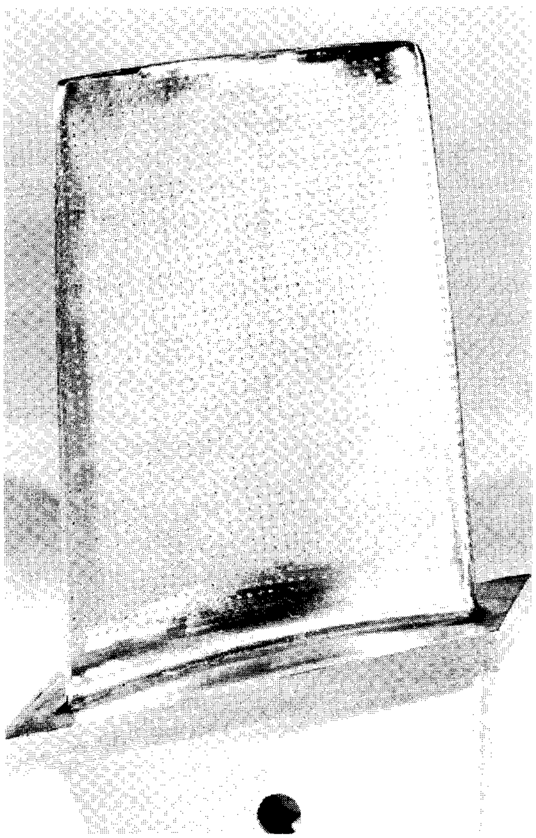


Fig. 22 Transpiration-cooled turbine blade incorporating Lamilloy airfoil

area impingement or possibly combinations of these. Increasing restrictions upon engine size and weight indicate that future engines must not only be high in temperature, but must be light in weight. Because of the unique combination of heat transfer and structural properties found in Lamilloy, blades made of this material will undoubtedly find increasing application.

CONCLUSIONS

Considerable progress has been made in applying air cooling to gas-turbine rotor and stator airfoils. Convection cooling has been demonstrated in low compression ratio engines to turbine inlet temperatures in excess of 2700F. Improvements in materials, casting technology and analysis will push convection-cooled airfoil capabilities to even higher values. Considerable effort should continue with convection cooling to evaluate many unique geometries such as multiple-pass cooling, double-walled airfoils and cooling air internal passageway surface preparation which will maximize cooling effectiveness. The inherent reliability, low cost and ease of fabrication of convection-cooled airfoils stimulate this extended effort.

Impingement is a very effective cooling mechanism in local areas and is easily adapted to stator vanes. Rotor blades can be made with this type cooling if proper room is available for making the required holes and for proper exhausting of the cooling air.

Film cooling has been demonstrated to be effective in both hot cascade and heat-transfer test engine environments. Proper hole and slot preparation and application demands additional evaluation before fully optimized geometries are useful for each potential application of film cooling.

Transpiration cooling has already been demonstrated in engine testing using two currently available sintered and pressed wire type transpiring materials. It is believed that improved fabrication techniques and materials such as Lamilloy will further improve transpiration cooling concepts and make feasible production engines using this very efficient cooling mechanism.

Supplementary testing of film and transpiration type surfaces is required to fill the gaps in basic data on cooling behavior with variable airfoil environment arising from basic parameter variations. Airfoils combining two of the preceding cooling mechanisms appear to offer considerable promise.

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