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Turbine Blade Tip Clearance Measurement Utilizing Borescope Photography

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In this paper, a technique is presented for the detrmination of turbine rotor bade tip-to-stationary shroud clearance requirements utilizing fiber optics. To accomplish these tip clearance determinations, special rub pins were installed in the turbine shrouds, or tip-shoes, of a 10,000-hp engine. A test procedure was created based upon a transient dimensional analysis, and a cooled borescope and camera were developed. The clearances are presented from a series of successive engine tests.

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Turbine Blade Tip Clearance Measurement Utilizing Borescope Photography

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INTRODUCTION

One of the many items that must be considered in determining the overall design-point efficiency of a turbine is the tip-clearance loss. The tips of the turbine rotor blades, in an unshrouded blade design, operate at some clearance from the stationary shroud. This induces losses due to the leakage flow across the tips. Analytical determination of the performance losses due to tip leakage is an arduous task. Usually empirical expressions are used for predicting the effects of tip clearance.[1]

A typical graphic representation of the effect of individual stage operating tip clearance on overall turbine performance for a two-stage turbine is illustrated in Fig. 1. The performance level is referenced to a condition of zero tip clearance for each stage. In this type of graph, the combined effect of the individual stage tip clearance on overall turbine efficiency can be determined. This clearance effect upon engine design point performance has been measured, and minimization of turbine rotor blade tip clearance has been shown to be an important consideration in obtaining optimum engine performance.[2]

The aerodynamic need for minimum turbine tip clearance to optimize engine performance is counteracted by the mechanical desirability for maximum tip clearance to avoid rubbing of the blade tips on the shrouds. If this mechanical freedom from rubbing can be achieved, then no restrictions on the engine transient and restart operating procedures would be required. As with most practical turbine engineering problems, the establishment of turbine blade tip clearances is a reasonable compromise between the aerodynamic and mechanical requirements.

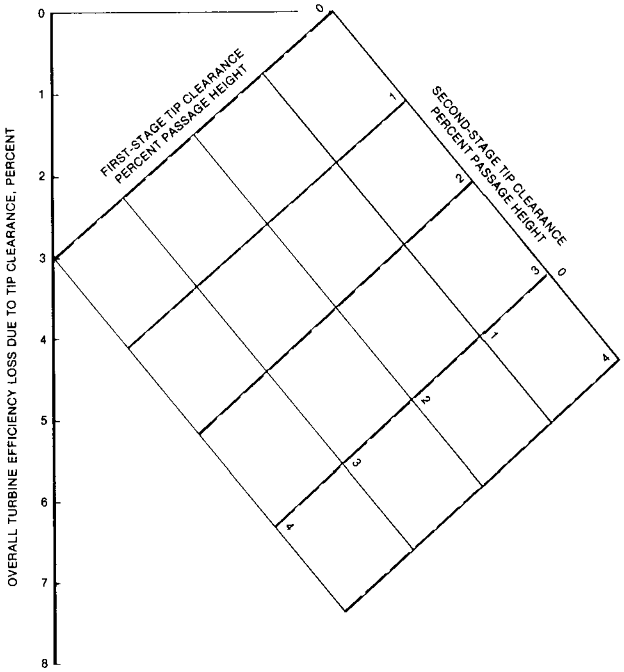

Fig. 1 The combined effect of operating turbine tip clearance on overall turbine efficiency

The factors that affect the engine operating clearances between the rotating turbine blade tips and the stationary shrouds are the changes in radial dimension and axial location of these components. These changes are caused by thermal, centrifugal, pressure, and rotor dynamics phenomena. The engine operating requirements that influence the tip clearance provisions are:

1 Starting Transients: The starting transients bring about the requirement for rapid full-load applications with attendant clearances prior to a condition of steady-state

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[1] Glassman, A. J., ed., "Turbine Design and Application," Vol. 2, NASA SP-290, Washington, D. C. 1973, pp. 125-131.

[2] Pichel, P. W., "A New 10,000-HP Gas Turbine Engine for Industrial Service," ASME Paper No. 77-GT-4, 1977.

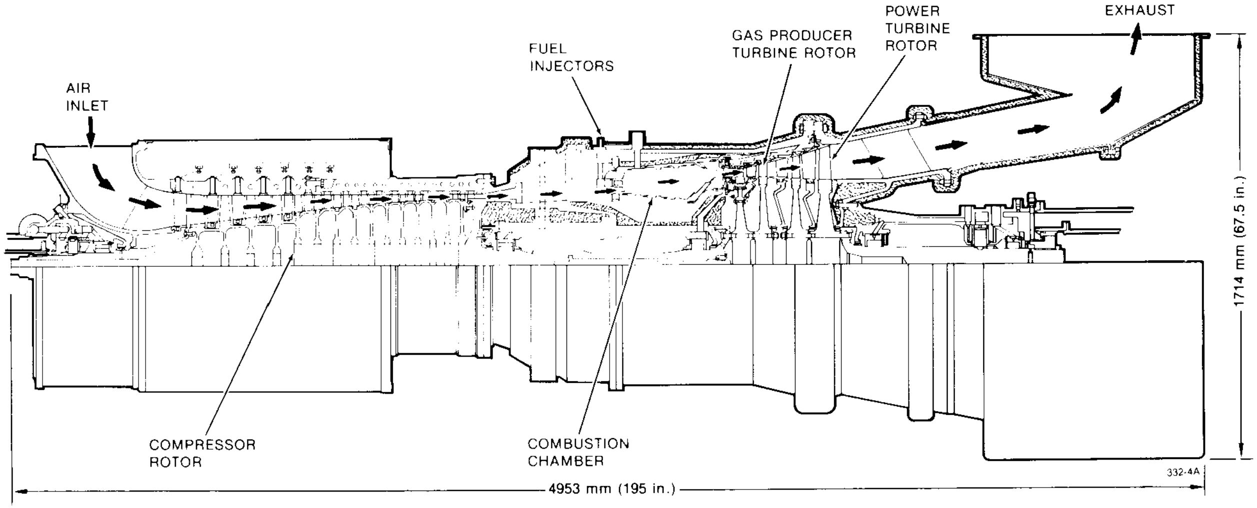

Fig. 2 Simplified cross-section of engine assembly

thermal equilibrium.

2 Maximum Steady-State Operation: At maximum steady-state operation with the engine in equilibrium with respect to temperature, speed, pressure and rotor dynamics, the clearances are usually designed to be minimized to result in optimum performance.

3 Operational Transients: The sudden removal or application of load causes large rapid gas temperature changes that result in varying thermal responses of the component parts.

4 Shutdown Transients: The shutdown procedure can bring about the requirement for a rapid transient from full-load, full-speed operation to rest. The period at rest results in tip clearance changes due to symmetrical and asymmetrical thermal gradients and rotor deflection due to shaft "bowing." Shutting down from lower temperature operation generally reduces the magnitude of the shutdown transient. Special drives are sometimes used to rotate the engine slowly after shutdown to minimize shaft bow.

5 Restart Conditions: Restart after shutdown is at tip clearances that are dependent upon the shutdown transients and the time after shutdown.

CLEARANCE DETERMINATION

Determination of clearances has generally been accomplished either by the predictive method of analysis or by the experimental technique of installing various types of sensors in the engine. Design calculations tempered by experience in thermal expansion, axial shifts and centrifugal growth of the various engine components were the basis of the dimensional analysis. The clearances during steady-state and various transient operating modes were predicted from this analysis. With the sensor method to determine clearances, probes were incorporated directly into the engine to obtain data under actual operating conditions. The inability of sensors to function adequately in the higher temperature ranges, and their relative expense, imposed limitations on this method when used in the hotter sections of the engine. Recent government contracted research and development have used Laser light focused upon blade tips to measure clearances while operating small turbine engines.[3] The use of X-rays to record a picture of the clearances during engine operation is also reported.[4]

OBJECTIVE

Simple, inexpensive "rub pins" installed into shrouds have been used in engine development. The difficulties with this existing technique is the requirement for turbine disassembly in order to measure the change in pin dimension after the test run, the inability to obtain soakback clearances, and the difficulty of performing successive tests on a particular

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[3] Ford, M. J., Hildebrand, J. R., and Prosser, J. C., "Design, Fabrication, and Demonstration of a Miniaturized Tip Clearance Measuring Device," AD-787318/SSL, USAAMRDL, Fort Eustis, Va.

[4] Stengel, R. F., "X-Rays Measure Clearance While Jet Engine Runs," Design News, Denver, Col., July 4, 1977, p. 34.

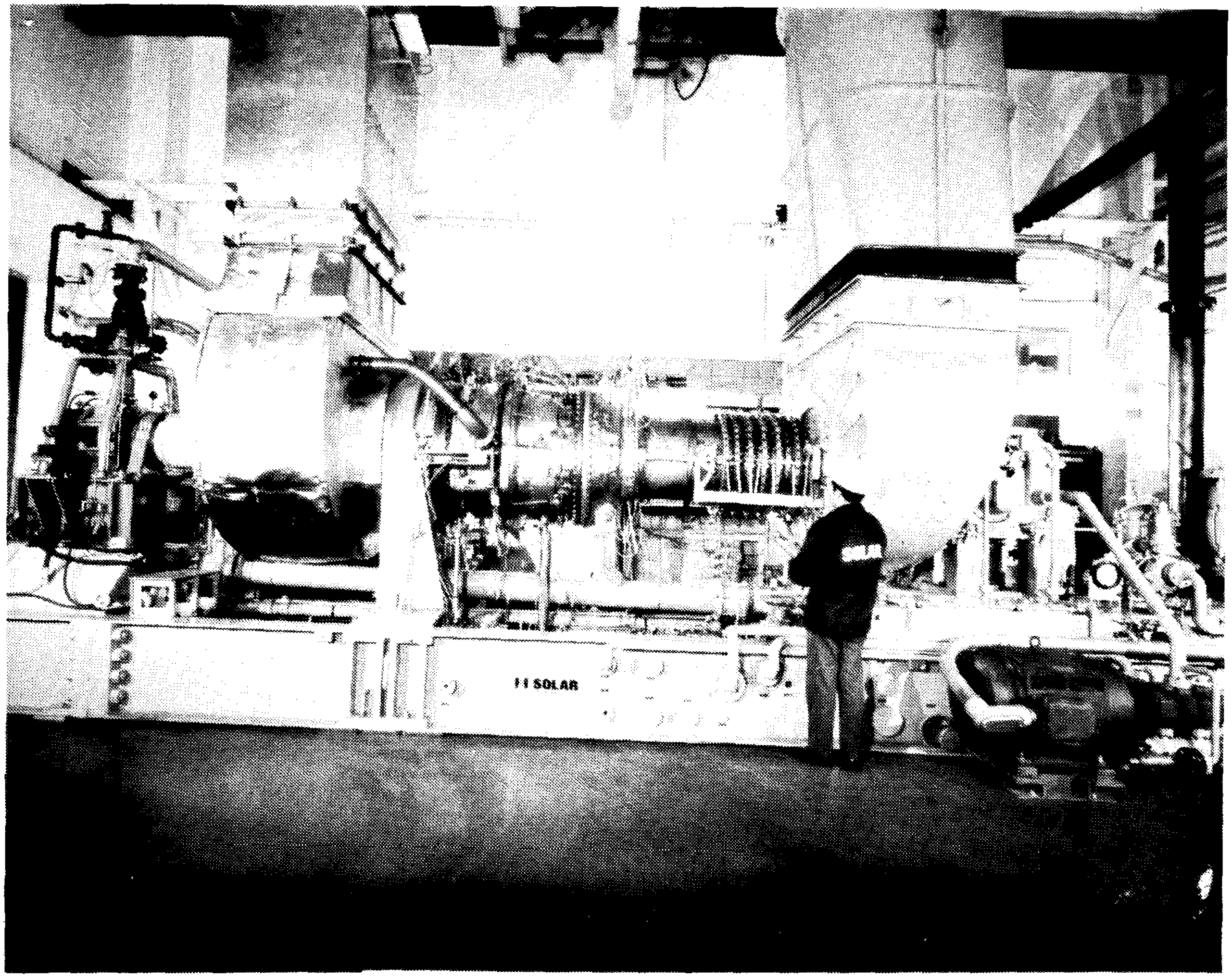

Fig. 3 Engine test installation

design and assembly.

To overcome the expense and high temperature life limitations of probe type sensors, and to improve upon the rub pin method, a new technique has been developed. This technique combines the latest borescope technology with improved rub pins in order to determine blade tip clearances in an actual engine turbine section.

It is the purpose of this paper to explain the experimental technique, show the initial test results, and present the improvements to be tested in the future.

ENGINE DESCRIPTION

The 10,000-hp Mars engine consists of a two-stage axial flow gas producer turbine and a separately supported two-stage axial flow power turbine with the simplified cross section shown in Fig. 2. Fig. 3 shows the exterior of the engine in a test cell installation with a direct-drive water-brake dynamometer.

The gas producer turbine incorporates an air-cooled first-stage stator, first-stage rotor, and second-stage stator. The stationary shrouds, or tip shoes, are a segmented brazed assembly faced with honeycomb material. The power turbine is of similar construction without air-cooled blades or vanes, and with a one-piece, fourth-stage shroud. The turbine section is shown in Fig. 4. All turbine stages are of a 50 percent reaction design. The turbine-section of the engine was designed with ports providing easy access for borescope visual inspection.

GENERAL EXPERIMENTAL TECHNIQUE

The combined rub pin and borescope technique was developed to determine the turbine blade tip clearances. During an assembly of a Mars test engine, rub pins were strategically incorporated in each of the four stationary

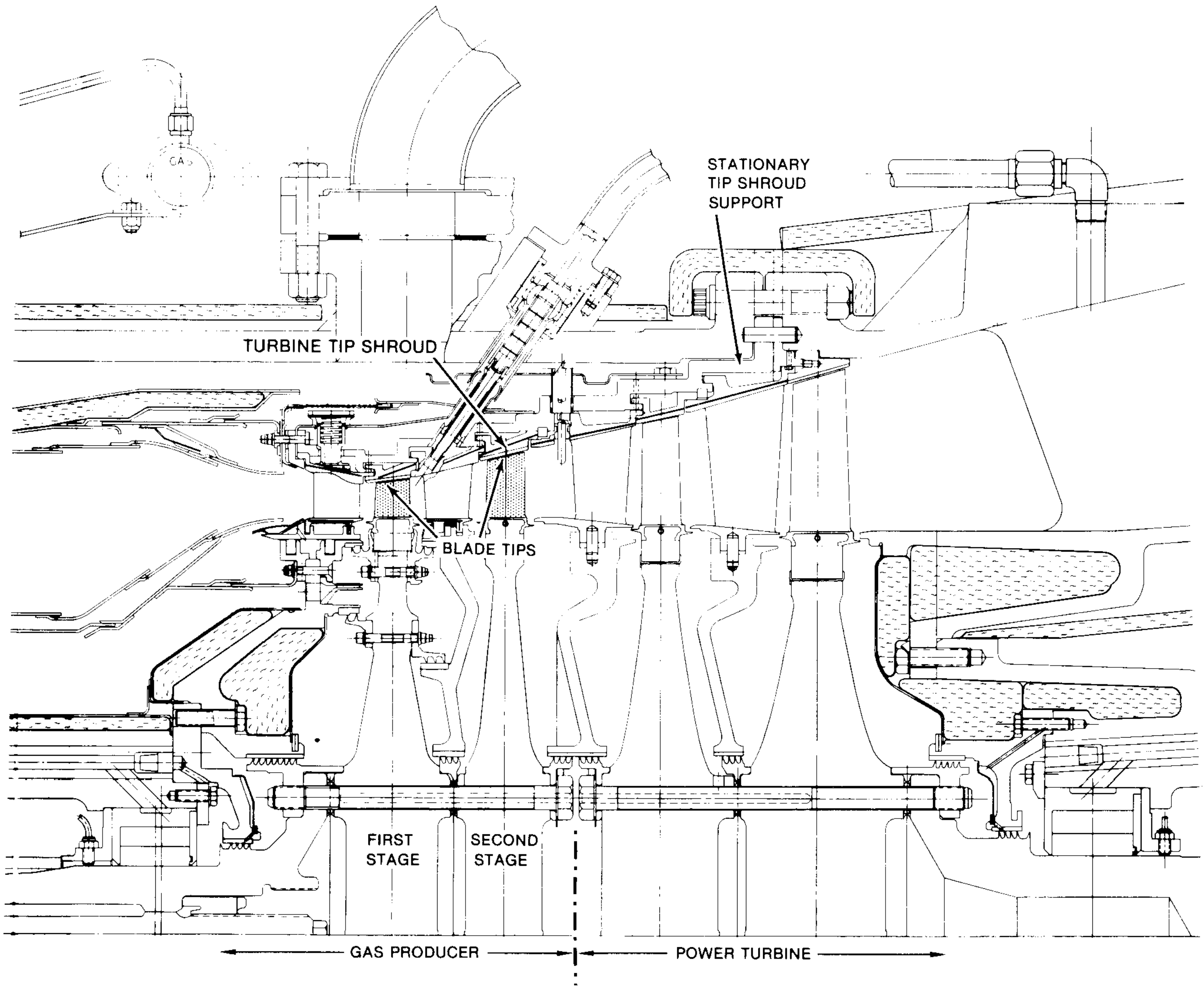

Fig. 4 Mars engine turbine section

turbine shrouds. A series of tests involving various transient engine operations (acceleration, deceleration, soakback, and restart) were conducted. Following engine shutdown from each of the tests, photographs of the rub pins were taken through a cooled fiberoptic borescope. The photographs were interpreted to assess the reduction in rub pin height. This reduction was due to the abrading effect of the turbine blade tips during engine operation. It directly corresponded with the minimum tip clearance. The turbine blade tip clearance data was obtained without disassembling the engine. An analysis of the clearance data generated from the series of transient tests permitted selection of optimum turbine clearances and test procedures for subsequent engine development.

RUB PIN DESIGN AND CONSTRUCTION

The rub pins were designed to be abradable, ensuring that they would not damage the turbine blade tips during engine operations. They were also designed to withstand erosion resulting from the flow of hot gases. As shown in Fig. 5, a cylindrical form was selected for the shape of the rub pins. The outside of the 0.250-in. (6.35-mm) dia cylinder was made from a 0.005-in. (0.127-mm) Hastelloy X material. The inside core of the cylinder was formed from 0.032-in. (0.80-mm) cell honeycomb and 0.002-in. (0.051-mm) Hastelloy X material. The honeycomb core was brazed inside the cylinder.

The completed rub pins were then welded in selected segments of the stationary turbine blade tip shroud as shown in Fig. 6. They were installed so that approximately 0.050-in.

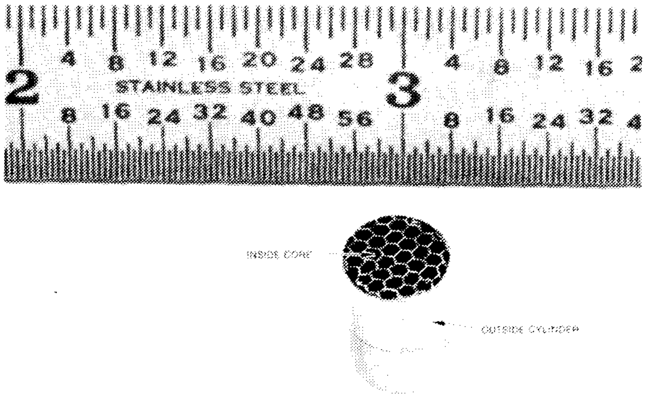

Fig. 5 Typical rub pin

(1.27 mm) of the pin protruded above the surface of the shroud. Following installation of the pin, the height above the shroud was accurately measured and recorded for use as a baseline measurement for subsequent testing.

During assembly of the engine, four of the shroud segments containing the rub pins were incorporated in each of the four turbine stages. They were located approximately 90 deg from each other and positioned on the vertical and horizontal axes of the engine. These locations closely corresponded to existing engine borescope ports and other openings through which a borescope could be inserted and positioned to within 1 in. of the rub pins. Also during engine assembly, sufficient clearances between the turbine blade tips and the shrouds were provided so that only the rub pins would be contacted during engine operation. This ensured that the shroud surfaces were preserved as reference points from which pin height measurement could be taken.

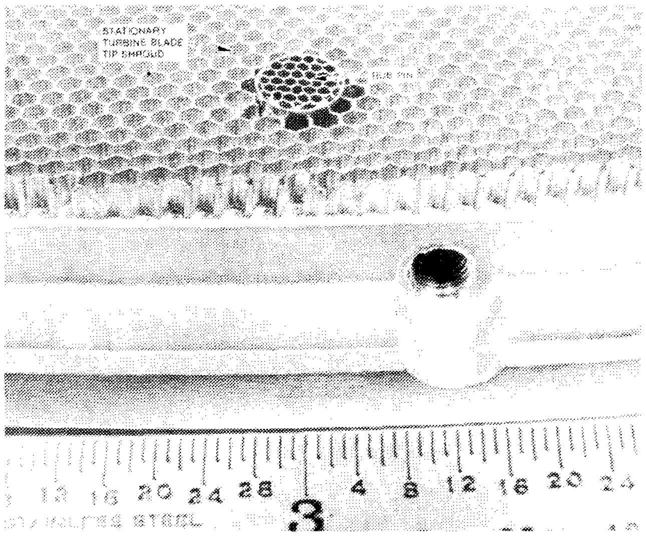

Fig. 6 Typical installation of rub pin in stationary turbine blade tip shroud

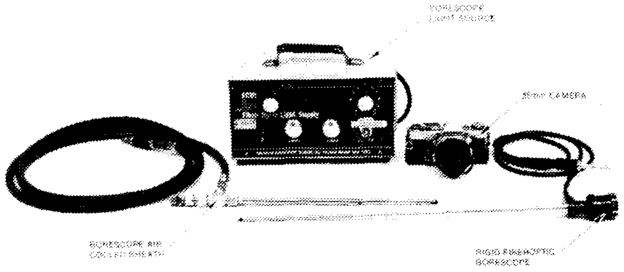

Fig. 7 Cooled borescope and camera equipment

BORESCOPE EQUIPMENT

As shown in Fig. 7, the primary visual tool used during the tests was a rigid, 6-mm-dia, right angle view, fiberoptic borescope. Illumination was provided by a 117-w light source. A 35-mm camera adaption was used to take clear photographs of the rub pins through the borescope with the engine at rest. Interpretation of these photographs was instrumental in assessing wear of the pins during the previous running.

Because the borescope had to be inserted into the engine for inspection of the rub pins

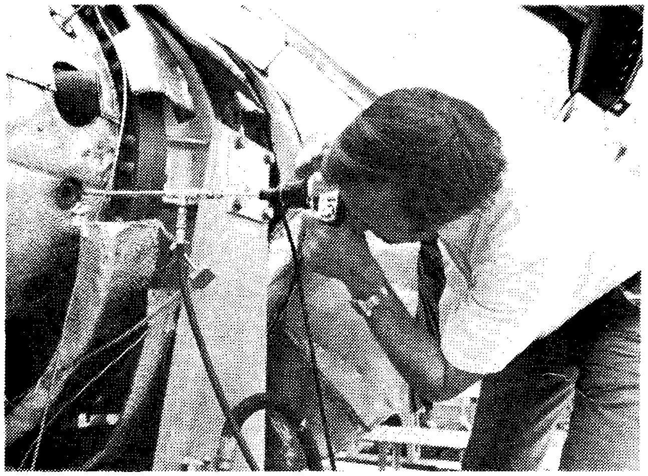

Fig. 8 Second-stage turbine rub pin being taken through the air-cooled fiberoptic borescope

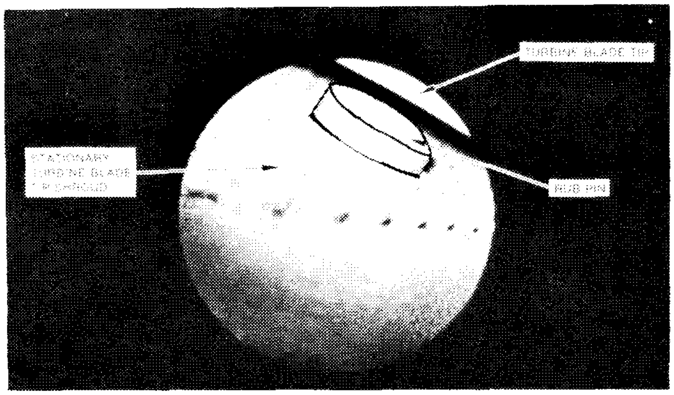

Fig. 9 Typical rub pin prior to transient tests at a height of 0.056 in. (1.42 mm)

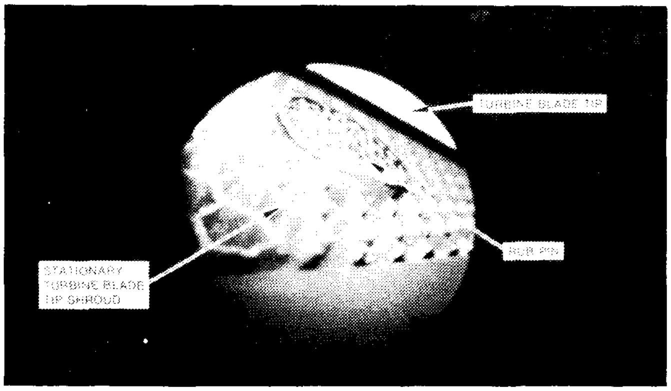

Fig. 10 Rub pin after test

during the thermal soakback period after shutdown, an air-cooled sheath was developed to protect the borescope from thermal damage. This air-cooled sheath comprised an aluminum tube, through which the borescope was inserted. Cooling air was forced into the area between the borescope and the tube and exited at the sheath viewing hole, providing an air film over the face of the borescope lens.

Special borescope ports are incorporated at critical locations in the Mars engine, allowing inspection of components in the turbine gas path. This design feature greatly facilitated borescope photography of the rub pins. Fig. 8 shows a second-stage rub pin being photographed through the borescope shortly after engine shutdown. Figs. 9 and 10 depict rub pins before and after engine transient tests. The key feature is the rub which has occurred following the tests.

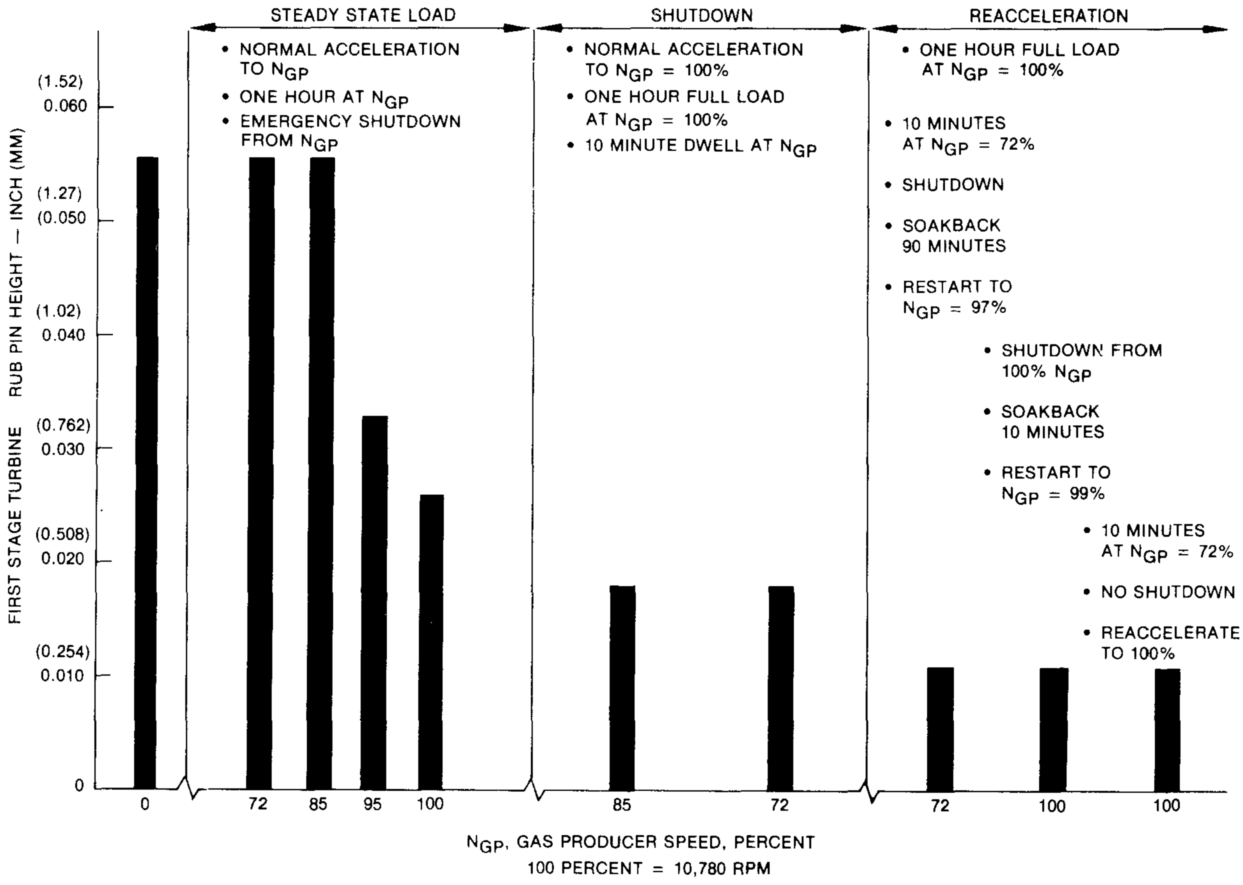

Fig. 11 Rub pin height changes during transient tests

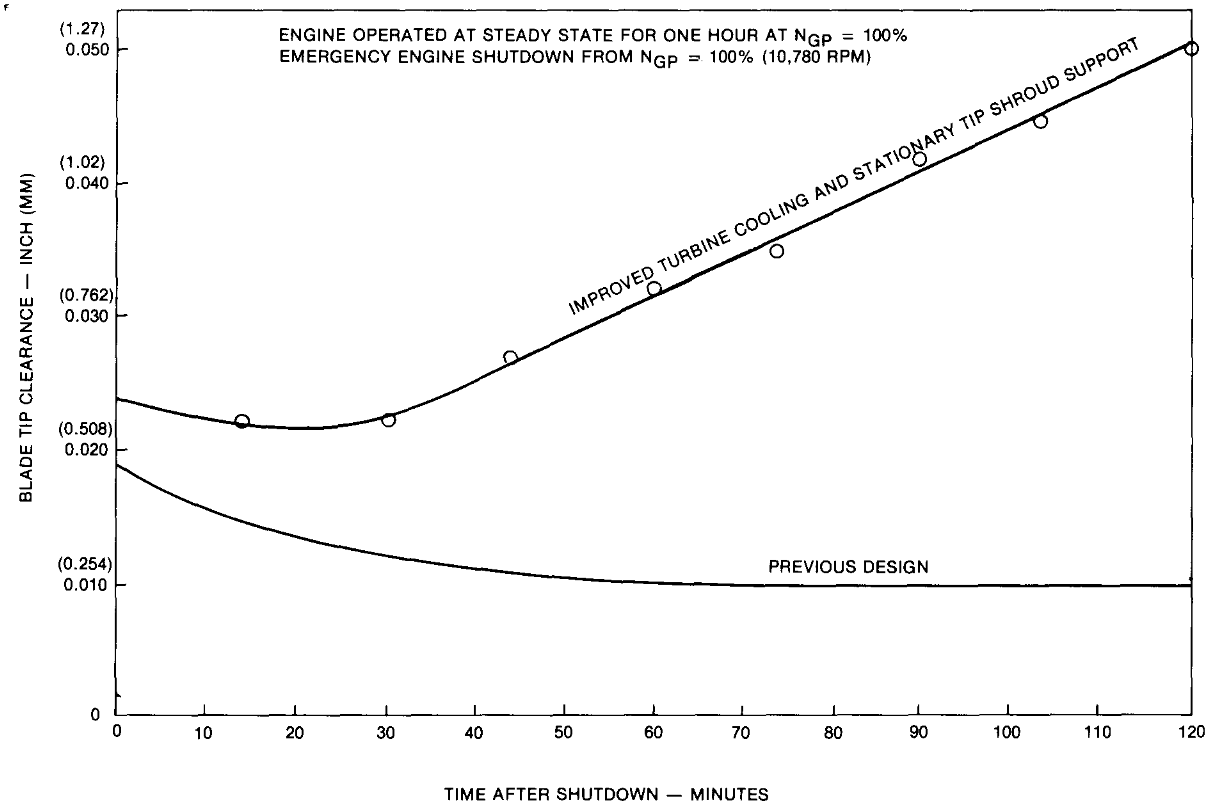

Fig. 12 Comparison of first-stage turbine blade tip clearances following engine shutdown

PHOTOGRAPH DIMENSIONAL INTERPRETATION

Interpreting the photographs to determine the reduction in rub pin height is accomplished by proportions. The rub pin diameter is 0.250 in. (6.35 mm) and held within tight tolerance during fabrication. When interpreting the photographs to determine the reduced rub pin height, the diameter of the pin is measured and the reduced height is measured. The computation is then expressed as:

$$\frac{\text{Photograph pin diameter}}{\text{Photograph reduced pin height}} = \frac{0.250 \text{ in. } (6.35 \text{ mm})}{\text{Actual reduced pin height (in.)(mm)}}$$

The reduced pin height is the minimum operating blade tip to shroud clearance encountered during the previous test run.

DEVELOPMENT PROGRAM

The engine test phase of the Mars development program started in April 1976. During the first year, four engines were assembled and tested. The initial sizing of the turbine blade tip clearance, based upon calculation, was planned to produce blade tip rubbing of the honeycomb, rub tolerant, shroud at steady-state full-power conditions. In this manner, the first engine tests were used to determine the maximum turbine performance with the turbine operating at essentially zero turbine blade tip-to-shroud clearance. Measurements of gas and cooling air temperatures were made during the initial engine tests. Thermocouples were installed on the stationary parts of the turbine that affect tip clearance in order to determine the actual metal temperatures. These values of temperature were used to improve upon the analytical heat transfer model of the turbine system. The next step in the program was to investigate the effect of the engine operational requirements upon turbine blade tip clearances. It is this phase of the engine development program that is reported in detail in this paper.

The operational variations that were to be tested were analytically investigated to determine the theoretical effect upon tip clearance. By investigating starts, acceleration to steady state at various dynamometer load levels from idle to full load, shutdown

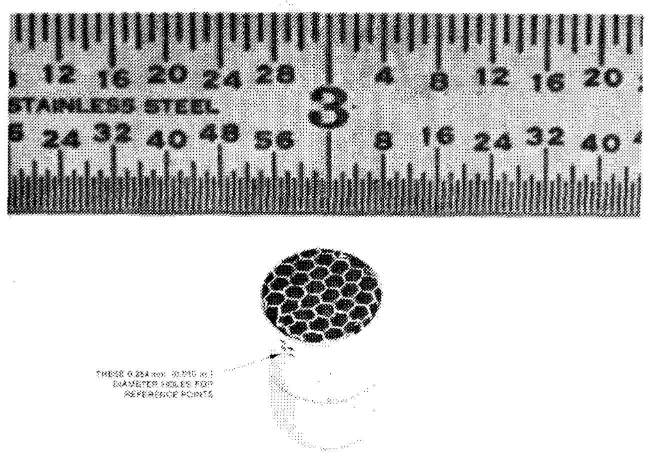

Fig. 13 Improved rub pin

procedures from load, load transients, and restarts, these events could be ranked according to tip clearance effect. On the basis of this analysis, the cold blade tip clearance with respect to the basic shroud was determined for each stage to provide approximately 0.010 in. (0.25 mm) under the most severe operational conditions. In this manner, the basic shroud for each stage would not be rubbed. A consistent base would be available for measuring the height of the rub pins. The rub pin heights for each stage were set to provide contact after a simple engine acceleration to approximately 85 percent gas producer speed providing 2500 hp.

The test sequence was scheduled based upon the analytical model clearance ranking. The first four tests consisted of normal accelerations to power levels from 2500 to 10,500 hp (full load), followed by an emergency shutdown. The emergency shutdown reduced the rotor speed to zero before significant thermal changes could occur. Any pin material removal would, therefore, have occurred at maximum steady-state conditions. The pin height measured with borescope photography directly provides the operational clearance at the steady-state condition. Also, the shutdown soakback transient clearances could be measured under maximum initial temperature conditions.

The next group of tests were concerned with the shutdown procedure from full load. By spending a dwell period at reduced load and speed conditions prior to shutdown, this transient could be evaluated for overall clearance reduction. The technique would provide the measurement of minimum clearance, but the particular information as to when in the load-reducing transient this clearance occurred, cannot be obtained in this manner. The final tests concerned reacceleration. Two different shutdown procedures were employed. Also, reacceleration was tested without shutdown from steady state, full load, to 10 min. idle, and return to full load.

TEST RESULTS

The results of the rub-pin borescope portion of the test show that the restart requirement determines the minimum turbine tip clearance for the Mars engine (Fig. 11). The tip clearance at steady state full load must be approximately one percent of the passage height for the first- and second-stage turbines. This is due to the operational requirement for restarting the engine after a shutdown in the time period where the turbine soakback temperatures are transient. This tip clearance results in an overall gas producer turbine efficiency that is two percent below the zero clearance value.

The borescope investigation of tip clearances during the transient shutdown soakback period showed the effect of a combined change in turbine disk cooling, and a change in supporting structure material. The tip clearance required for restarts was reduced by lowering the turbine disk metal temperatures through the use of lower temperature cooling air, and by reducing the coefficient of thermal expansion of the stationary tip shroud supporting structure. This is demonstrated in Fig. 12.

CONCLUSIONS

The techniques employed and reported in this paper for determining operational tip clearances provide a useful inexpensive tool for the development of turbine engines. The procedures can be adjusted to provide minimum turbine tip clearance by evaluating the effect upon tip clearances of various operational procedures, or, at least, the critical event that dictates clearance will be known.

FUTURE TESTING

During future testing of the Mars engine, improved rub pins will be used in the engine turbine sections as part of an on-going program to obtain clearance data. These improved rub pins incorporate small holes approximately 0.010 in. (0.25 mm) in diameter in the outside pin wall. This is shown in Fig. 13. Spacing between the holes is 0.010 in. (0.25 mm). These holes will be used as reference points from which more accurate assessments of rub pin wear can be made.

With increased accuracy, it will be possible to determine small gap differences in circumferential locations between the pin and the blade tip after shutdown as a function of time. Thus, we will be able to evaluate the shaft bow effect.

ACKNOWLEDGMENTS

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