NASA TECHNICAL MEMORANDUM

NASA TM X-3005

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# EXPERIMENTAL TRANSIENT TURBINE VANE TEMPERATURES IN A CASCADE FOR GAS STREAM TEMPERATURE CYCLING BETWEEN 922 AND 1644 K (1200° AND 2500° F)

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • APRIL 1974

1. Report No.: NASA TM X-3005
2. Government Accession No.:
3. Recipient's Catalog No.:
4. Title and Subtitle: EXPERIMENTAL TRANSIENT TURBINE VANE TEMPERATURES IN A CASCADE FOR GAS STREAM TEMPERATURE CYCLING BETWEEN 922 AND 1644 K (1200° AND 2500° F)
5. Report Date: APRIL 1974
6. Performing Organization Code:


7. Author(s): Daniel J. Gauntner and Albert Kaufman


8. Performing Organization Report No.: E-7755


9. Performing Organization Name and Address: Lewis Research Center, National Aeronautics and Space Administration, Cleveland, Ohio 44135


10. Work Unit No.: 501-24
11. Contract or Grant No.:


12. Sponsoring Agency Name and Address: National Aeronautics and Space Administration, Washington, D. C. 20546


13. Type of Report and Period Covered: Technical Memorandum
14. Sponsoring Agency Code:
15. Supplementary Notes:


16. Abstract

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17. Key Words (Suggested by Author(s)): Transient temperatures; Cascade cycling; Turbine vane; High-speed data acquisition


18. Distribution Statement: Unclassified - unlimited

Cat. 33

| 19. Security Classif. (of this report) | 20. Security Classif. (of this page) | 21. No. of Pages | 22. Price* |
|---|---|---|---|
| Unclassified | Unclassified | 17 | $3.00 |

* For sale by the National Technical Information Service, Springfield, Virginia 22151

# EXPERIMENTAL TRANSIENT TURBINE VANE TEMPERATURES IN A CASCADE FOR GAS STREAM TEMPERATURE CYCLING BETWEEN 922 AND 1644 K ($1200^{\circ}$ and $2500^{\circ}$ F)

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## SUMMARY

Experimental transient turbine vane metal temperatures were obtained from tests conducted on air-cooled vanes installed in a four-vane cascade for a gas temperature cycled between 922 and 1644 K ($1200^{\circ}$ and $2500^{\circ}$ F). Transient data were recorded by a high-speed data acquisition system. Temperatures at the same phase of each transient cycle were repeatable between cycles to within 11 kelvins (20 deg F). Simulated cruise and idle steady-state readings were repeated by the cruise and idle readings taken from the ends of a transient half-cycle at low pressure to within 17 kelvins (30 deg F). The tests were conducted at pressure levels of 31 and 83 N/cm$^2$ (45 and 120 psia) with coolant temperatures of 811 and 589 K ($1000^{\circ}$ and $600^{\circ}$ F), respectively.

## INTRODUCTION

High-performance engines of the future are expected to operate at increased turbine inlet temperatures. The materials being used in today's engines for the fabrication of turbine vanes and blades are presently being pushed to the limit of their structural capabilities. Thus, much attention is being given to the problems of cooling turbine vanes and blades under conditions of transient and steady-state operation. A knowledge of their transient temperature response is important in evaluating thermal fatigue lives of blades and vanes. In previous studies at the NASA Lewis Research Center (refs. 1 to 4), the steady-state heat-transfer and life characteristics of some vane cooling configurations were investigated. References 1 and 2 describe experimental steady-state temperature distributions for air-cooled vanes tested in a static cascade and in a modified turbojet engine, respectively. References 3 and 4 describe the stress analysis of air-cooled turbine blades. However, little information is available on the transient heat-transfer characteristics of cooled vanes and blades.

The NASA Lewis Research Center is currently in a program to investigate the cooling performance of vanes and blades for turbojet engines at turbine inlet temperatures to 1644 K (2500° F). This program is expected eventually to utilize experimental transient temperature data in life studies for turbine vanes and blades. The use of such transient data will provide a solid base for the development of accurate life-predicting techniques.

The investigation reported herein was made to obtain an insight into the thermal response characteristics of a typical air-cooled vane installed in a static cascade. In addition, the reproducibility of test conditions, the vane thermal response, and the data acquisition systems during 6 minutes of cascade operation were observed.

In order to obtain the experimental data required for this investigation, transient tests were run on two identical test vanes installed in a static cascade. The gas stream temperature was cycled between 922 and 1644 K (1200° and 2500° F). The gas stream total pressures were set at values of 31 and 83 $N/cm^2$ (45 and 120 psia) for a simulated engine gas stream cruise condition. Cooling-air temperatures of 811 and 589 K (1000° and 600° F) were used at the low and high pressures, respectively. The coolant flow was set to limit the hot-spot vane temperature to 1283 K (1850° F).

Data were taken in U.S. customary units and converted to SI units for reporting purposes only.

## APPARATUS

### Facility Description

The cascade facility was designed for continuous operation at gas temperatures of 1644 K (2500° F) and pressures to 103.4 $N/cm^2$ (150 psia). The facility had five components: an inlet section, a burner section, a circular-to-annular transition section, a test section, and an exit section. The transition, test, and exit sections were water cooled to achieve structural durability during high-temperature operation. A more detailed description is contained in reference 5.

The test section represented an annular sector of a vane row and contained four vanes and five flow channels. A top view of the test section with the access cover removed is shown in figure 1. A vane pack assembly is shown in place. Extending above the vane pack are the cooling-air inlet tubes for each vane. The central two vanes were connected to a common air-supply plenum, while the outer two vanes were connected to separate air-supply systems. Only the central vanes could also be supplied by a vitiated air heater capable of operation at temperatures to 922 K (1200° F). Figure 2 is a schematic top view of the test section. The four vane positions and five flow channels are numbered left to right. The central vanes (2 and 3) are referred to as test vanes, and the outer vanes (1 and 4) are referred to as slave vanes.

## Vane Description

The vane cooling configuration tested in this investigation is identical to the vane configuration of reference 1. The vane span was 9.78 centimeters (3.85 in.), and the midspan chord length was 6.28 centimeters (2.47 in.). Cooling air entered the vane from an air-supply tube located at the tip or outer diameter of the vane. A cutaway view of the vane is shown in figure 3. The leading edge was impingement cooled by air issuing from a row of slots. This spent flow then passed through chordwise passages having fins integral with the leading-edge suction- and pressure-surface vane walls. This cooling air then left the leading-edge region by flowing radially inward to the airfoil base, where it exited through the hub platform. The midchord region was impingement cooled by air flowing from a multiple array of circular jets in a formed insert adjacent to both the suction and pressure midchord surfaces. Some of the spent flow from the midchord region was ejected from slots to film cool the trailing-edge region of both vane surfaces. The remaining air was used for chordwise convective cooling through a pin-finned split trailing edge. Details of the vane cooling geometry are given in reference 1.

## Fuel Control System Description

The apparatus needed to cycle the cascade gas stream between simulated idle and cruise conditions was concentrated at the fuel supply line, as shown in figure 4. With solenoid valve A in the fuel bypass line closed, valve B in the fuel line was used to set the gas stream cruise conditions. Then, with valve A open, valve C was used to set the gas stream idle conditions by causing fuel to recirculate through the fuel bypass line. An automatic timer controlled the off-on operation of valve A at the appropriate times during the cyclic operation.

# INSTRUMENTATION

The cascade instrumentation can be separated into two categories: the general operational instrumentation and the research instrumentation. The operational instrumentation was used to set data points and to monitor the general condition of the cascade and the supporting systems. Most of this instrumentation was connected to visual readouts in the control room. The research instrumentation was designed to provide data for detailed analysis of the temperature distributions around the test vanes. These data were recorded by a central data recording system. Reference 5 contains a more detailed description of the cascade instrumentation and data recording system.

### Operational Instrumentation

The cascade was equipped with the general instrumentation required to monitor quantities such as combustion gas total inlet temperature and pressure; vane row exit static pressures; fuel flow rate, temperature, and pressure; cooling-water flow rate, temperature, and pressure; and the various cooling-air flow rates, temperatures, and pressures.

### Research Instrumentation

The purpose of the research instrumentation was to provide detailed information on the gas stream conditions, the cooling-air flow conditions, and the vane wall temperature distribution. One radially traversing total-temperature probe and one total-pressure probe were located upstream of the vane row (fig. 2). The total-temperature distribution was measured in front of channel 3, and the total-pressure distribution was measured in front of channel 4. Static pressure was measured at the hub platform immediately upstream of the vane leading edge and was assumed to be constant across the gas stream. Static pressures were also measured at the exit midchannel position at both the hub and tip platforms. These exit pressures were used to establish the midspan exit Mach number.

Each test vane was instrumented with an array of 13 thermocouples (fig. 3). The thermocouple dimensionless surface locations are given in table I. The thermocouple assemblies were constructed of Chromel-Alumel wire with magnesium oxide insulation in an Inconel-600 sheath. These assemblies were drawn to two sizes, 0.051- and 0.025-centimeter (20- and 10-mil) outside diameter, with a closed-end grounded thermocouple junction formed at one end. The two thermocouples nearest the leading edge were of 0.025-centimeter (10-mil) outside diameter, while the remaining thermocouples were of 0.051-centimeter (20-mil) outside diameter. The procedures used for thermocouple construction are described in detail in reference 6.

## EXPERIMENTAL PROCEDURE

An experimental investigation was conducted in a static cascade to obtain transient vane temperatures which occurred while the gas stream conditions were cycled between simulated engine idle and cruise conditions. The operating conditions selected were typical of those for a special research engine used at the Lewis Research Center for turbine cooling investigations (see ref. 5 for details of this engine). The design maximum gas temperature of this engine was 1644 K ($2500^{\circ}$ F) at a pressure of 31 $N/cm^2$ (45 psia). The vane trailing-edge, midspan, midchannel Mach number was about 0.85. The engine idle condition resulted in a turbine inlet temperature of about 922 K ($1200^{\circ}$ F). The gas conditions indicated previously were used in the cascade investigation herein to simulate an actual engine operating cycle representing typical cruise and idle gas stream conditions. Hereinafter, the high- and low-temperature gas stream conditions will be referred to as the "cruise" and "idle" conditions, respectively. The effect of pressure level on the transient characteristics was investigated by conducting additional cyclic tests with 83-$N/cm^2$ (120-psia) air.

The cascade operating procedure was to first set the gas stream cruise condition. Coolant flow rates were then set to produce a maximum vane temperature of 1283 K ($1850^{\circ}$ F). The coolant temperatures were 811 and 589 K ($1000^{\circ}$ and $600^{\circ}$ F) at the low- and high-pressure gas stream cruise conditions, respectively. The vane coolant temperature for the high-gas-pressure tests was held to 589 K ($600^{\circ}$ F) to avoid excessive metal temperatures. After equilibrium was reached, a steady-state reading of all research instrumentation was made with the central data recording system.

The idle condition was then set solely by opening valve A in the fuel bypass line and adjusting valve C (fig. 4) until the turbine inlet temperature reached 922 K ($1200^{\circ}$ F). Thus, only the gas stream temperature was purposely adjusted (by means of the quantity of fuel supplied to the combustor). As a result of the gas temperature change, there were changes in gas stream flow rate and pressure and in coolant flow rate and pressure. No attempts or adjustments were made to maintain these gas coolant parameters at their cruise condition values. A steady-state reading of research instrumentation was again taken.

With the cascade system in equilibrium at the idle condition, an automatic timer-control mechanism was activated. The control closed valve A in the fuel bypass line, causing an acceleration from idle to cruise conditions in the gas stream. After 1 minute, the control opened valve A, causing a deceleration from cruise to idle conditions in the gas stream. The cycle was completed when, after 1 additional minute, the control closed valve A again. Transient data from the research instrumentation were recorded automatically during a continuous run of three cycles. The data recorded at the end of the acceleration half-cycle (60 sec into the acceleration) will be hereinafter referred to as the "cruise transient reading." The corresponding data at the end of the deceleration half-cycle will be referred to as the "idle transient reading."

## DATA ACQUISITION

During the three cycles of the gas stream conditions, the transient test data were taken by high-speed recorders capable of making as many as 30 000 samples per second. Data processing was performed on a commercial direct-couple system. The data selection, the amplifier gain settings, the recording rates, and the number of temperatures, pressures, and flow rates to be sampled were all programmed on the automatic high-speed recording system.

The transient data of this investigation were recorded at the rate of 4000 samples per second. Each temperature or pressure was sampled at intervals of 0.01 second of the transient. Five successive values (over a time of 0.05 sec) of a given temperature or pressure were processed to remove spurious electronic noise. Thus, a smoothed value of temperature or pressure was produced. The smoothed values of temperature are the ones reported herein.

## RESULTS AND DISCUSSION

Experimental transient turbine vane metal temperatures were obtained from tests conducted in a static cascade with the gas stream temperature cycling between 922 and 1644 K ($1200^{\circ}$ and $2500^{\circ}$ F). Local midspan vane temperatures were obtained during 1-minute accelerating and 1-minute decelerating portions of a 2-minute cycle which simulated the transition from idle to cruise and back to idle engine conditions.

The gas temperature response during acceleration and deceleration is shown in figure 5 for both gas stream pressure levels, 31 and 83 $N/cm^2$ (45 and 120 psia). The response was faster at 83 $N/cm^2$ (120 psia). Although not shown, the gas temperature for both pressure levels was essentially constant for at least the last 30 seconds of each half-cycle. The gas temperature transient repeated itself between cycles at points of the same phase to within 28 kelvins (50 deg F).

### Local Temperature Response

The change in local midspan vane temperature as a function of $x/L$ and time is shown in figure 6 (where $x$ is the local surface distance, measured from the leading edge, and $L$ is the surface length of the suction or pressure surface). The transient responses during the acceleration and deceleration portions of the cycle for 31 $N/cm^2$

(45 psia) are presented in figures 6(a) and (b). The corresponding responses at 83 $N/cm^2$ (120 psia) are presented in figures 6(c) and (d). The inlet cooling-air temperatures are 811 and 589 K ($1000^o$ and $600^o$ F) for the low- and high-pressure cases, respectively.

Low-pressure data. - The transient response of the vane at 31 $N/cm^2$ (45 psia) is fairly uniform over the entire surface, including those responses in the steady-state distributions that were taken to be the idle and cruise transient readings (0 and 60 sec). In the time domain, the temporal gradients show the vane temperature response for both acceleration and deceleration to be approximately 50 percent of the total response by the elapsed time of 4 seconds.

During acceleration from idle to cruise conditions (fig. 6(a)), the temperature distribution of the thin-walled (0.15 cm (0.060 in.)) leading-edge region transforms from concave upward to concave downward at 1 second and back to a concave upward distribution again at 60 seconds. The temperature distribution of the thick-walled (0.25 cm (0.10 in.)), high-thermal-capacity vane regions near thermocouples 3 and 12 (fig. 3) goes from concave downward to concave upward in 2 seconds and back to concave downward again at 60 seconds.

During deceleration, when the gas stream goes from cruise to idle conditions, figure 6(b) shows that the temperature distribution of the vane leading-edge region is always concave upward, and that the temperature at thermocouple 1 is the vane minimum temperature between 2 and 12 seconds. Again because of high thermal capacity, the temperature distributions of the vane regions near thermocouples 3 and 12 lag the leading-edge response, with the temperature distributions being concave downward and the temperature at thermocouple 3 being the vane maximum during the entire time of deceleration (except for 0 and 60 sec).

High-pressure data. - At 83 $N/cm^2$ (120 psia) (figs. 6(c) and (d)), the spatial and temporal temperature gradients which occur over the vane surface, in general, become steeper than the gradients occurring at 31$N/cm^2$ (45 psia) (figs. 6(a) and (b)). In the time domain, the vane thermal response reaches approximately 50 percent of total thermal response after 2 seconds into either the acceleration or deceleration portions of the cycle, half the time needed at the low-gas-pressure condition.

Besides the faster response of the vanes, some other effects of higher heat flux at this higher pressure are shown in figures 6(c) and (d). During acceleration, the leading-edge-region temperature distribution does not turn concave downward since the higher heat flux causes the thick-walled vane regions to respond more rapidly than they did at 31 $N/cm^2$ (45 psia). And during deceleration at high pressure, the greater reduction in heat flux when the gas stream temperature decreases causes the vane leading-edge-region temperature to decrease 122 kelvins (220 deg F) after 0.5 second. The decrease was 55 kelvins (100 deg F) in the same time period at 31 $N/cm^2$ (45 psia).

For cruise conditions at high pressure, the vane temperature at thermocouple 10 on the pressure surface is higher than that at thermocouple 9 (see 0-sec temperature distribution of fig. 6(d)). This is an unexpected result, if one assumes that the film effectiveness at thermocouple 10 is greater than or equal to the film effectiveness at thermocouple 9. Reference 7 discusses experimental flow distributions for this vane. It concluded that, under certain experimental gas stream and coolant conditions, the film-cooling flow out the pressure-surface slot can be sharply reduced, and, possibly, even hot combustion gas can be drawn into the vane. Thus, with no film-cooling flow over thermocouples 9 or 10 and with the assumption that the heat flux and inside wall temperature at both thermocouple positions are the same, the outside wall temperature will be lower at the thermocouple position where the vane wall is thinner. Thus, even though thermocouples 10 and 9 are both within 10 slot widths of the pressure-surface film-cooling slot, the temperature at thermocouple 10 can be higher than the temperature at thermocouple 9.

## Cyclic Temperature Repeatability

As stated in the section EXPERIMENTAL PROCEDURE, transient data were recorded during three complete cycles. Figure 7 compares vane local midspan wall temperatures between the first two gas stream cycles (since comparison of these two cycles showed the greatest error) for an acceleration between idle and cruise conditions at 83 $N/cm^2$ (120 psia). The two temperature distributions are compared at 0, 2, and 60 seconds. The data show a repeatability of temperatures within 11 kelvins (20 deg F). This repeatability held for both pressure levels, for all cases. This repeatability indicates that at least idle steady-state equilibrium is attained in the vane during each cycle. Otherwise, 0-second comparisons would not agree between the first cycle (which started at steady-state) and the second (or third) cycle.

## Comparison of Steady-State and Transient Cruise and Idle Vane Temperature Readings

An additional check on the cascade cyclic operation is a comparison between the vane temperatures at the cruise and idle steady-state readings and those temperatures at the cruise and idle transient readings of a given half-cycle. Figure 8(a) and (b) show such a comparison at 0 and 60 seconds for gas stream pressures of 31 and 83 $N/cm^2$ (45 and 120 psia), respectively. These steady-state and transient temperatures agree to within 17 kelvins (30 deg F) at both 0 and 60 seconds of the acceleration portion of the low-pressure cycle. Thus, the gas stream conditions produced while manually setting valves B and C in the fuel control system (fig. 4) can be maintained and reproduced during automatic cycling of the cascade, at least for the low-pressure case.

For the high-pressure comparison, however, agreement is not good. The cruise transient reading temperature distribution overshoots the cruise steady-state reading temperature distribution by as much as 111 kelvins (200 deg F). Inspection of the data and idle steady-state readings (fig. 8(b)) taken before and after the three recorded cycles of transient data revealed that the vane coolant flow decreased and the coolant inlet temperature increased between the two idle condition steady-state readings. Figure 7 shows that very little if any change occurred in the vane temperature distributions during the running of the three cycles, indicating that very little if any change occurred in the gas stream conditions during the automatic cycling of the cascade. We believe that between the setting of the cruise and idle gas stream conditions (which was accomplished solely by adjusting valve C in the fuel control system) the coolant supply flow rate dropped, with a corresponding increase in the inlet coolant temperature. The resulting decrease in heat-sink capacity of the coolant flow caused the temperature distribution at the cruise-condition transient reading to reach a higher level than that reached during the steady-state setting of the cruise condition.

## SUMMARY OF RESULTS

Experimental transient vane metal temperatures were obtained from tests conducted in a static cascade as the gas stream temperature cycled three times between 922 and 1644 K ($1200^{\circ}$ and $2500^{\circ}$ F). The operating conditions selected were simulated engine idle and cruise conditions typical of a special research engine used in turbine cooling research at the Lewis Research Center.

The effects of pressure level were investigated by taking data at 31 and 83 $N/cm^2$ (45 and 120 psia). Several results from these tests follow:

1. The vane reached 50 percent of its temperature response after approximately 4 seconds into the gas stream transient at 31 $N/cm^2$ (45 psia), and after approximately 2 seconds into the gas stream transient at 83 $N/cm^2$ (120 psia).

2. Temperatures at the same phase of each cycle repeated within 11 kelvins (20 deg F) between cycles, showing the ability of the test apparatus to maintain the simulated cruise and idle operating conditions during automatic operation of the cascade.

3. When the simulated cruise and idle conditions were manually set on the cascade controls, these steady-state readings could then be repeated to within 17 kelvins.

(30 deg F) by the cruise and idle transient readings produced during each cycle of the automatic operation of the cascade, at least for the low-pressure condition.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, November 27, 1973,
501-24.

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TABLE I. - DIMENSIONLESS SURFACE

LOCATIONS OF VANE THERMOCOUPLES

| Thermocouple | Suction surface, L = 7.27 cm (2.86 in.) | Pressure surface, L = 6.53 cm (2.57 in.) |
| --- | --- | --- |
| | Dimensionless surface location | |
| 1 | 0 | |
| 2 | .025 | |
| 3 | .23 | |
| 4 | .42 | |
| 5 | .53 | |
| 6 | .735 | |
| 7 | .895 | |
| 8 | | 0.815 |
| 9 | | .685 |
| 10 | | .645 |
| 11 | | .325 |
| 12 | | .185 |
| 13 | | .068 |

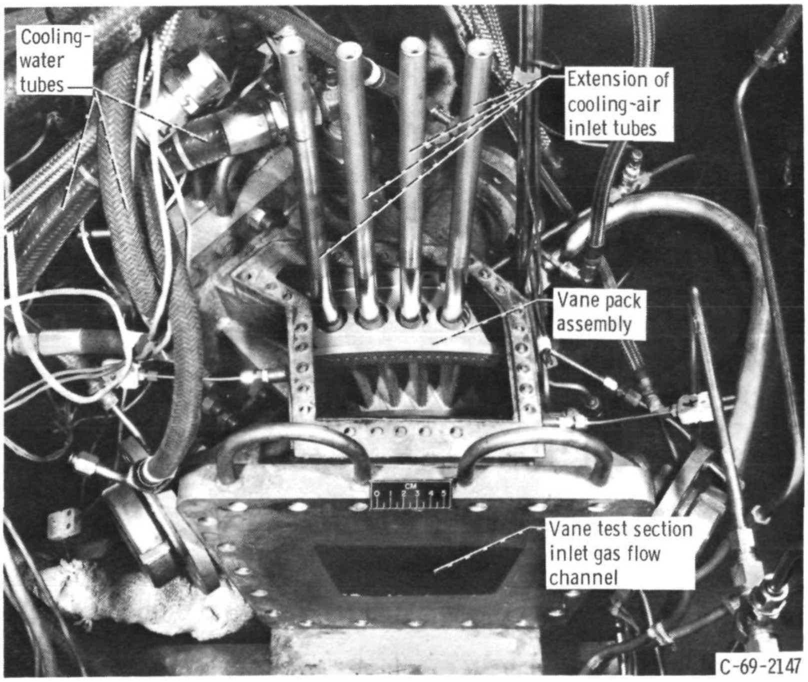



Figure 1. - Top view of cascade test section with access cover removed.

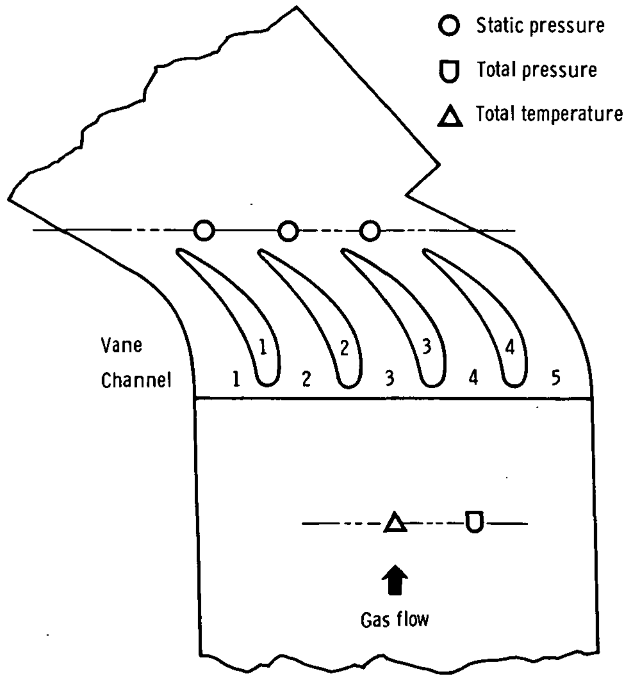



Figure 2. - Schematic top view of test section of 1644 K (2500° F) cascade.

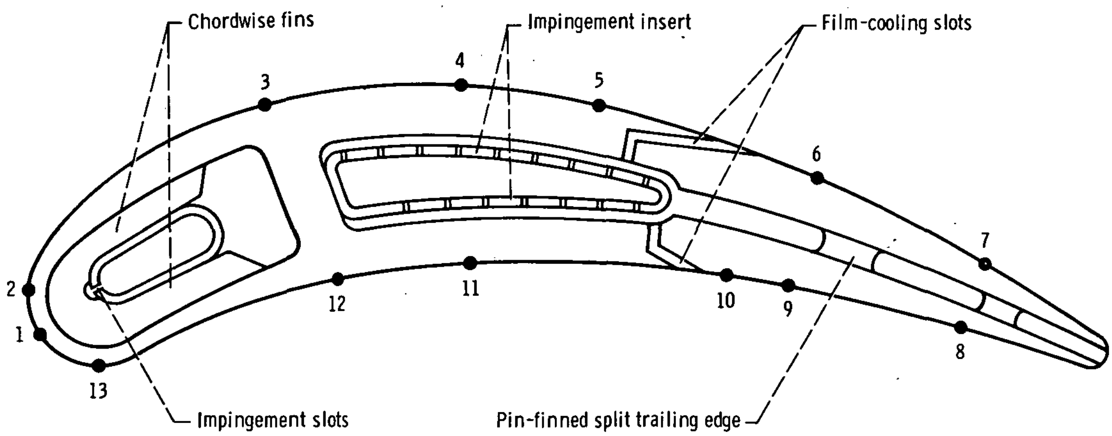



Figure 3. - Schematic of test vane showing thermocouple locations at airfoil midspan.

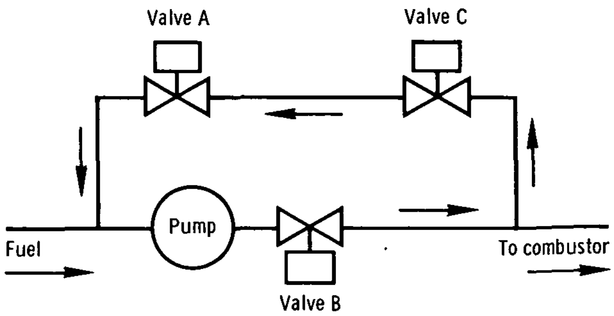



Figure 4. - Schematic diagram of fuel control system.

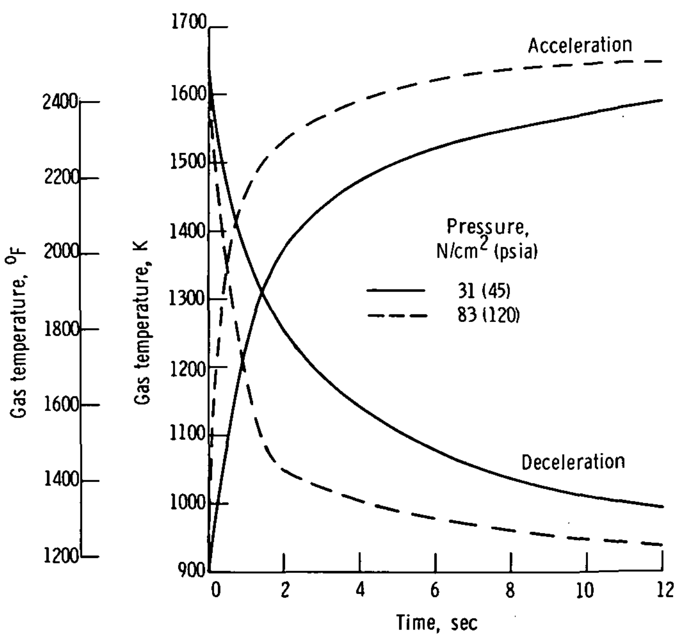
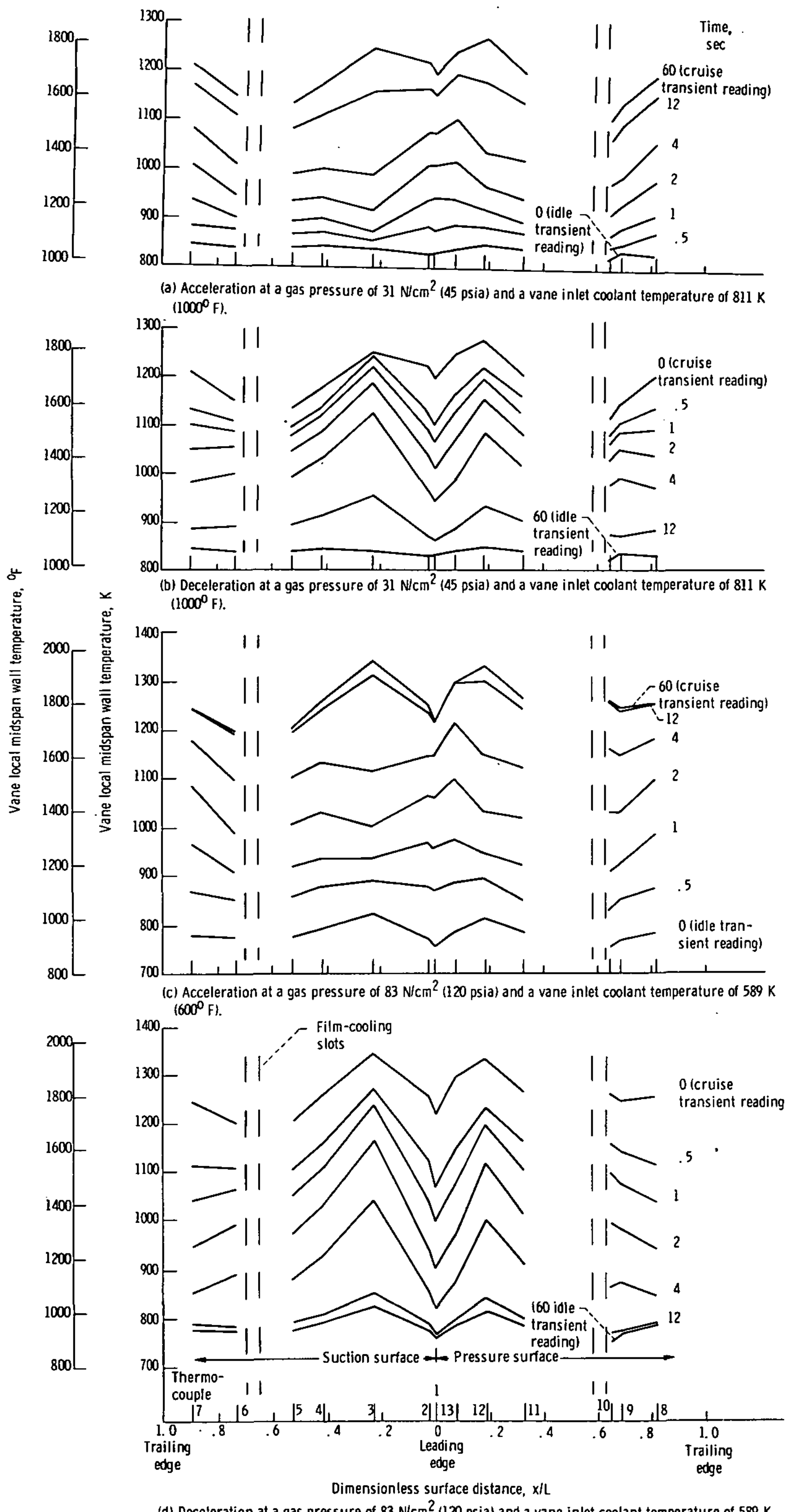



Figure 5. - Effect of pressure level on gas temperature transients.




(a) Acceleration at a gas pressure of 31 N/cm$^2$ (45 psia) and a vane inlet coolant temperature of 811 K (1000° F).

(b) Deceleration at a gas pressure of 31 N/cm$^2$ (45 psia) and a vane inlet coolant temperature of 811 K (1000° F).

(c) Acceleration at a gas pressure of 83 N/cm$^2$ (120 psia) and a vane inlet coolant temperature of 589 K (600° F).

(d) Deceleration at a gas pressure of 83 N/cm$^2$ (120 psia) and a vane inlet coolant temperature of 589 K (600° F).

Figure 6. - Vane local midspan wall temperature response for gas stream temperature cycling between 922 and 1644 K (1200° and 2500° F).

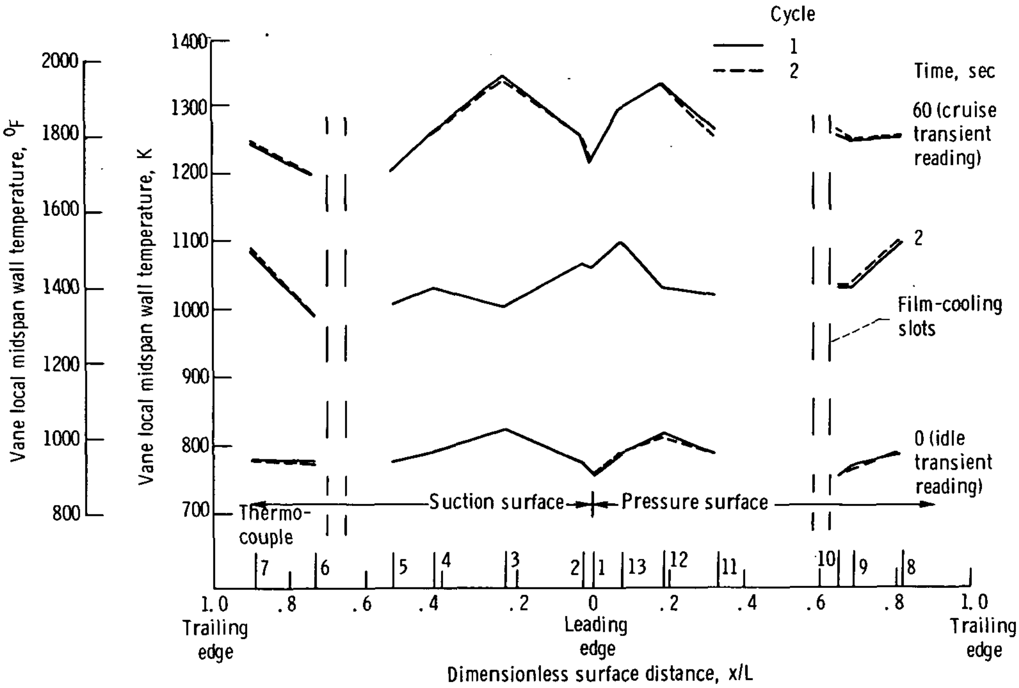
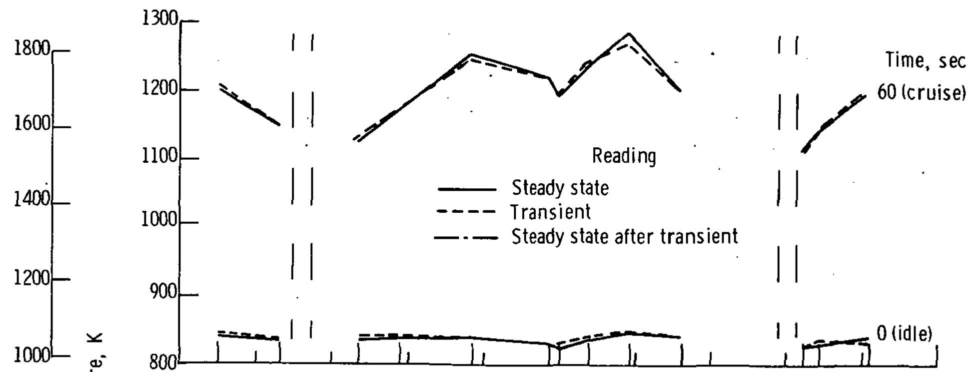
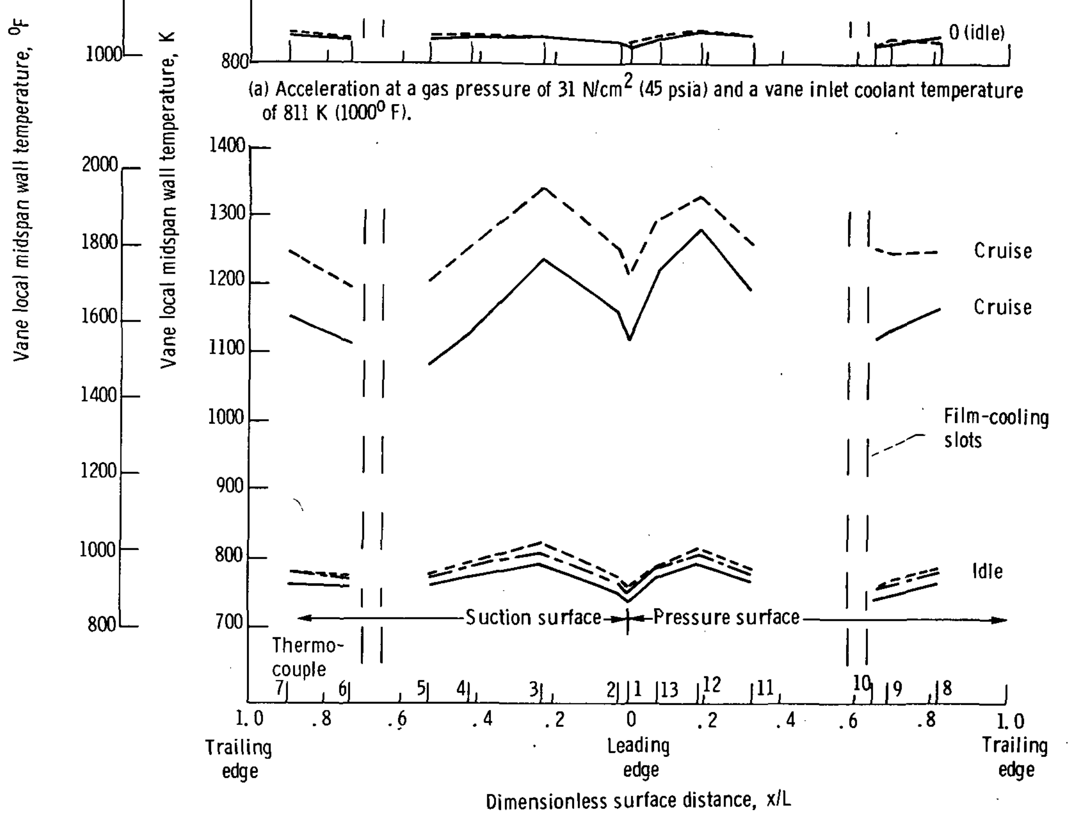



Figure 7. - Comparison of vane local midspan temperature between two gas stream temperature acceleration cycles for a gas pressure of 83 $N/cm^2$ (120 psia) and a vane inlet coolant temperature of 589 K ($600^\circ$ F).




(a) Acceleration at a gas pressure of 31 N/cm$^2$ (45 psia) and a vane inlet coolant temperature of 811 K (1000$^0$ F).




(b) Acceleration at a gas pressure of 83 N/cm$^2$ (120 psia) and a vane inlet coolant temperature of 589 K (600$^0$ F).

Figure 8. - Comparison of vane local midspan temperature at steady-state simulated cruise and idle conditions with temperatures produced at these conditions during automatic transient cycling of gas stream temperature from 922 and 1644 K (1200$^0$ to 2500$^0$ F).



NASA-Langley, 1974 E-7755

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—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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