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RESEARCH MEMORANDUM

TEMPERATURES IN A J47-25 TURBOJET-ENGINE TURBINE SECTION DURING STEADY-STATE AND TRANSIENT OPERATION IN AN ALTITUDE TEST STAND

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NATIONAL ADVISORY COMMITTEE
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SUMMARY

In order to determine the operating temperatures at altitude in the turbine section of a turbojet engine, a J47-25 engine was instrumented with thermocouples and operated under steady-state and transient conditions in an altitude test stand. Runs were made at altitudes of 7000, 25,000, and 45,000 feet and inlet Mach numbers of 0.5 and 0.8.

Turbine disk temperatures and temperature differences responded most rapidly to gas temperature changes at an altitude of 7000 feet. At this altitude, the disk temperatures were within 25° F of stable conditions 8 minutes after ignition, compared with 13 minutes and 23 minutes for the 25,000- and 45,000-foot-altitude runs, respectively.

The temperature differences recorded for the nozzle guide vanes during transient runs were lower than during steady-state operation at rated speed. Nozzle-guide-vane temperatures and temperature differences were generally lower than in previous sea-level tests.

The turbine blade temperatures were lower at high altitudes except for the region beyond 75 percent span, where the temperature increased with altitude, indicating a trend of the maximum temperature zone to shift outward on the blade with increased altitude. Turbine blade temperature differences measured in transients at altitude were of the same order of magnitude during accelerations and considerably lower during starts compared with sea-level zero-ram operation.

INTRODUCTION

In computing thermal stresses and in evaluating materials or designs for use in the turbine section of a turbojet engine, knowledge of the

temperature distributions occurring in engine parts during the various types of engine operation is highly desirable. Measurement of temperatures during transient operation is necessary in order to discover the magnitude of temperature gradients that occur and the time intervals during which they take place. Some of these data are available for sea-level conditions (ref. 1). In order to extend the scope of these data to altitude conditions, an experimental investigation was made at the NACA Lewis laboratory using a J47-25 turbojet engine in an altitude test stand.

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This investigation included steady-state operation at 80 and 100 percent of rated speed (7950 rpm) with a fixed-area jet nozzle at three different altitude conditions and two inlet ram pressures. Temperatures measured included the (1) metal temperatures of nozzle guide vanes, (2) metal temperatures of turbine blades, and (3) metal temperatures of the turbine disk. During transient operation of the engine (starts, rapid accelerations, and decelerations) at the same altitudes and ram pressures as those of the steady-state runs, continuous records were made of the (1) metal temperatures of nozzle guide vanes, (2) metal temperatures of turbine blades, (3) tailpipe gas temperatures, (4) engine speed, and (5) throttle lever position.

At each of the three altitude conditions selected, a special run was made using thermocouples to read the turbine disk temperatures. These runs consisted of a start, acceleration to rated speed and tailpipe gas temperature, operation at rated conditions until disk temperatures stabilized, and a rapid shutdown or "stopcocking" of the engine.

APPARATUS

A J47-25 engine was instrumented to obtain nozzle-guide-vane and turbine blade metal temperatures. The configurations used to obtain these temperatures are described in the following paragraphs.

Thermocouples

Nozzle-diaphragm (station 2). - In order to determine temperature differences in the nozzle guide vanes in regions subjected to high thermal gradients (fig. 1), a nozzle guide vane in the center of the outlet of the number 1 combustor was instrumented with four thermocouples as shown in figure 2(a). The thermocouples were made of 24-gage (0.0201-in. diam.) chromel-alumel wire with the bead installed in the blade metal at midthickness of each particular station on the blade. Lead wires were routed through the hollow vane with the single exception of the trailing-edge installation, where the lead wires were enclosed in a 0.075-inch-diameter stainless-steel conduit which was faired into a recess cut in the trailing edge so that the original airfoil section was maintained.

The variation in operating temperatures of the nozzle guide vanes behind the eight combustors was measured by installing a thermocouple on the leading edge at midspan of each of the two guide vanes nearest the center of the outlet of each combustor (fig. 2(b)). The thermocouple beads were embedded in the metal at the center of the radius of the leading edge. The thermocouples were constructed of 24-gage (0.0201-in. diam.) chromel-alumel wire and the leads were carried through the hollow nozzle guide vanes.

Turbine blades (station 3). - In order to determine the spanwise temperature profile of the airfoil section, a set of three turbine blades was instrumented with two thermocouples per blade located at two of the six positions along the span at midchord (fig. 2(c)). A photograph of a typical instrumented blade installation is shown in figure 2(d). The thermocouples were made of 28-gage (0.0126-in. diam.) chromel-alumel wire and in each case were installed at midthickness (fig. 2(c)) of the particular location on the blade. Installation of the thermocouples was accomplished by drilling a small hole at the desired location, locating the thermocouple bead at midthickness, and filling the hole with Number 100 Colmonoy high-temperature solder. Lead wires from the thermocouples were incased in ceramic tubing which was protected by a stainless-steel conduit of 0.075-inch outside diameter and 0.005-inch wall. The enclosing conduit was secured to the convex face of the blade by straps of 0.005-inch-thick Nichrome spot-welded to the blade material. At the blade base, the conduit was led through an angularly drilled passage which opened to the aft end of the blade-root section. The conduit was led radially inward to the center of the turbine disk and attached to the disk by closely overlaying it with a ribbon of Nichrome 0.25 inch wide and 0.005 inch thick which was spot-welded to the rear face of the turbine disk. The lead wires were led to a slip-ring assembly on the engine accessory case through a 3/8-inch-diameter drilled hole in the turbine bolt and compressor shaft. The turbine blades were made of standard S-816 material.

Following the determination of the highest temperature location on the span of the blade, two turbine blades were instrumented to obtain the chordwise temperature profile of the airfoil at this location by installation of thermocouples at three positions along the chord (fig. 2(c)). The thermocouples were installed on one blade at the leading edge and midchord, and on the other blade at the trailing edge and midchord.

The thermocouple installation technique at midchord and midthickness was the same as the procedure described for the spanwise survey installation. The beads of the leading- and trailing-edge thermocouples were welded by electrical resistance into a notch ground in the blade edge, which was then faired into the original airfoil shape with the Number 100 Colmonoy high-temperature solder. These edge thermocouples were located in the center of the radii defining the leading and trailing edges.

Turbine disk (station 3). - Thermocouples were installed (fig. 1) in the bottoms of holes drilled from the rear face of the turbine disk (fig. 2(e)) in order to measure turbine disk temperatures in the rim and weld sections. The lead wires from these thermocouples were protected and fastened to the rear face of the turbine disk as shown in figure 2(f) and were run to the slip rings by a technique identical to that described for the turbine blade thermocouples.

Tailpipe (station 4). - The tailpipe gas temperature during steady-state operation was measured by averaging the readings of 10 bare-wire chromel-alumel thermocouples equally spaced around the tailpipe at station 4 (fig. 1) immediately downstream of the engine tailcone. The thermocouple beads were located 2 inches radially inward from the wall of the tailpipe.

During the transient runs, four high-response-rate thermocouples were installed approximately 90° apart at station 4. The bead and the first 3/32 inch of lead wire for these thermocouples was made of 30-gage (0.010-in. diam.) chromel-alumel wire, which was, in turn, welded to 16-gage (0.051-in. diam.) alloy lead wire. These thermocouples were installed with the beads 2 inches radially inward from the wall of the tailpipe.

The calculated temperature-time constant of the high-response thermocouples with the engine operating at rated take-off conditions at sea level was 0.07 second, signifying that the thermocouples would indicate 62 percent of the actual surrounding gas temperature in 0.07 second (ref. 2).

Temperature-Indicating Instruments

Steady-state turbine blade, turbine wheel, nozzle-guide-vane, and tailpipe gas temperatures were recorded on a strip-chart recording electronic potentiometer. Transient data were recorded on a multichannel oscillograph.

Engine Instrumentation

Engine speed was measured by an electronic counter. Engine thrust and fuel-flow measurements were not made. The engine was equipped with a fixed-area jet nozzle, the area of which gave a tailpipe gas temperature of 1250° F at 100 percent of rated rotor speed at sea-level conditions. All engine operation was performed with a standard engine fuel regulator installed and in normal operating condition.

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PROCEDURE

Steady-State Operation

The steady-state operation was performed at three simulated altitudes of 7000, 25,000, and 45,000 feet (the maximum service altitude of this engine). The lowest altitude at which it was possible to run the altitude test facility at the time of these tests was 7000 feet.

At each altitude three runs were made at the following conditions: 80 percent of rated speed and a Mach number of 0.5, 80 percent of rated speed and a Mach number of 0.8, and 100 percent of rated speed and a Mach number of 0.8. The Mach numbers indicate inlet ram conditions of the test engine. The altitude static pressure was indicated by static-pressure taps at the lip of the fixed-area jet nozzle. The inlet total pressure and temperature were measured at 20 points on the inlet rakes (station 1, fig. 1). For each altitude, the ram conditions were obtained from tables in reference 3. Inlet duct and jet-nozzle static pressures for the altitude conditions of this investigation are tabulated as follows:

Altitude, ft	Mach number	Inlet total pressure, $\frac{lb}{sq\ ft}$	Inlet stagnation temperature, ^{o}F	Jet-nozzle static pressure, $\frac{lb}{sq\ ft}$
7,000	0.5	1937	59	1633
7,000	.8	2489	97	1633
25,000	.5	932	-9	785.3
25,000	.8	1197	25	785.3
45,000	.8	470	-17	308

All temperatures measured were allowed to stabilize before any data points were read.

Temperature Measurements

Nozzle guide vane. - The nozzle-guide-vane temperatures were read on the electronic potentiometer when the temperatures reached a stable condition.

Turbine blades. - For the steady-state runs, the set of turbine blades having thermocouples at midchord and various distances from the blade base were installed, and the engine was operated at the conditions described previously. When equilibrium temperature was reached, the blade temperatures were recorded on a strip-chart recording potentiometer.

Turbine disk. - For turbine disk temperature measurements, a disk that had been instrumented with thermocouples was installed in the engine. A run consisting of a windmilling start and a rapid acceleration of the rotor to rated speed was made at each of the three altitudes previously mentioned at an inlet Mach number of 0.8. Disk temperature readings were made at suitable intervals on a strip-chart recording potentiometer. Rated speed was maintained until the temperatures reached a stable condition, then the engine was rapidly shut off and the rotor speed returned to the previous windmilling condition. The disk temperature recording was continued until all readings had fallen to about 300° F.

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For the 45,000-foot-altitude run, it was necessary to ignite the engine at an altitude of 40,000 feet, after which the inlet and exhaust pressures were stabilized at the 45,000-foot-altitude condition within 1 minute after ignition.

Transient operation. - Transient temperature measurements were made during starts, accelerations, and decelerations at 7000 and 25,000 feet at inlet Mach numbers of 0.5 and 0.8. At an altitude of 45,000 feet and a Mach number of 0.8, acceleration and deceleration runs were made. A start was recorded at an altitude of 40,000 feet and a Mach number of 0.8. Steady-state temperatures were recorded for all thermocouples after a stabilizing period preceding, and at the conditions immediately following, a transient run. During the transient operation, the thermocouple voltages were fed to individual channels of a multichannel oscillograph. Suitable balancing circuits, oscillograph elements, and amplifier-gain settings were selected to provide for the temperature ranges to be encountered.

Engine speed was recorded by an oscillograph element driven by suitable voltage tapped from the electronic counter, which was driven by the output of a tachometer generator on one of the engine accessory pads.

Engine throttle-arm position was recorded by an oscillograph element actuated by the voltage derived from a potentiometer circuit. The potentiometer was directly linked to the throttle arm.

Starts

The starts made for this investigation were begun under the conditions attendant to the particular altitude and ram condition with the

engine windmilling at the resulting speed. The ignition system was energized, fuel was supplied until ignition occurred, and the engine was accelerated to the proper idling speed for the existing ram and altitude conditions. With the ignition system used, the highest altitude conditio under which the engine could be started was 40,000 feet.

Acceleration and Deceleration

Preceding each acceleration or deceleration run, the engine was operated at the level from which the transient was to take place until all temperatures concerned were stabilized. The run was accomplished by rapidly moving the throttle control lever to a previously set stop, allowing the engine fuel regulator to automatically control engine conditions through the transient period.

RESULTS AND DISCUSSION

Temperature Effects

In the following discussion of steady-state operation, only data obtained from 100 percent speed conditions are included. The temperatures measured during the 80 percent speed runs were so low as to be considered of no interest.

Nozzle guide vane. - In figure 3 are shown the average temperatures obtained at rated speed and a Mach number of 0.8 from the two thermocouples installed in the leading edges of the two nozzle guide vanes in the center of the outlets of each of the eight combustors. The temperatures were corrected to a tailpipe gas temperature of 1230° F, and the following averages were obtained:

Altitude, ft	Average temperature of nozzle-guide-vane leading edge, °F
7,000	1580
25,000	1610
45,000	1570

Since the average temperatures in the preceding table vary considerably less than the temperature of the guide vanes in the outlet of

the various combustors in any given run, it is apparent that altitude has very little effect on the temperature patterns in this region.

Turbine blades. - The turbine blade temperature distributions measured spanwise for the three altitude conditions at rated speed and a Mach number of 0.8 are shown in figure 4(a). The blade temperature for an altitude of 7000 feet is higher for locations below midspan, but the higher altitudes show high temperatures beyond 75 percent span. The 86-percent-span point at the 45,000-foot altitude rises to within 10° F of the maximum spanwise temperature recorded during this series of runs. The 25,000-foot-altitude curve is below the other curves for all points except the 86-percent-span location, where it is 55° F higher than the 7000-foot-altitude curve.

In general, the effect of altitude, when using a fixed-area jet nozzle, is to increase the blade tip temperature; whereas, in the region below midspan, a drooping characteristic is apparent with temperatures reaching their minimum value during the 25,000-foot-altitude run.

In order to show the variation in spanwise temperature distribution in turbine blades at the altitudes at which these data were obtained, the 7000- and 25,000-foot-altitude data were corrected to the tailpipe gas temperature of 1230° F of the 45,000-foot-altitude run (fig. 4(b)). In this plot, the two higher-altitude curves agree within 30° F at all spanwise locations, but the 7000-foot-altitude curve is 60° to 85° F higher than the higher-altitude curves in the region below 50 percent span and lower only in the region above 80 percent span.

If these corrected data are considered similar to those for fixed-tailpipe-gas-temperature operation with a variable-area jet nozzle, the effect of altitude on the blade spanwise temperature distribution is to reduce temperature in the region under 80 percent span while increasing tip temperatures slightly.

Since the centrifugal stress in the blade airfoil increases from tip to base, the lowering of temperatures below midspan with altitude indicates that near-sea-level operation imposes the most severe conditions of temperature and stress on the blades.

From data obtained with this engine, apparently a tailpipe gas temperature limit that is safe, with regard to blade temperature under sea-level conditions, will be allowable at higher altitudes.

Turbine disk. - The results of the three turbine-disk-temperature runs at a Mach number of 0.8 are shown in figure 5. The time to rated speed from ignition for these runs is shown in the following table:

Altitude, ft	Time to rated speed, min	Windmilling, percent rated	Mach number
7,000	1.2	40	0.8
25,000	.75	36	.8
45,000	1.7	25	.8

In general, the temperature changes in the turbine disk are more rapid at the lower altitudes during both acceleration and deceleration. The temperature readings of the disk thermocouples for the 7000-foot-altitude run are within 25° F of the stabilized state 8 minutes after ignition; for the 25,000-foot-altitude run, this took approximately 13 minutes; and for the 45,000-foot-altitude run, about 23 minutes. In order to facilitate comparison of the altitude effects on the rate of temperature change in the turbine disk, the temperature data are listed in the following table:

Altitude, ft	Radius, in.			
	10.5 (weld)		13.10	
	Increase in temperature 5 min after start, °F	Decrease in temperature 5 min after shutoff, °F	Increase in temperature 5 min after start, °F	Decrease in temperature 5 min after shutoff, °F
7,000	520	210	970	715
25,000	330	110	905	635
45,000	140	45	740	430

The temperature differences existing at the rim of the turbine disk between the 12.37-inch radius and the bottom of the serrations (12.85-in. rad.) are shown in figure 6. The rate of increase of temperature differences and the maximum value reached are lower at the higher altitudes (fig. 6(a)), where the air mass flow and resulting heat transfer are lower. At steady-state conditions (fig. 6(b)), the temperature differences between these sections are higher at tne higher altitudes, probably

as a result of the lower temperatures of the disk cooling air bled from the compressor at the higher altitudes. In this engine, the cooling air is introduced to both front and rear disk faces near the hub.

Transient Operation

Starts. - Five starts were made. The conditions under which these starts were made are listed in the following table:

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Altitude, ft	Mach number
7,000	0.5
7,000	.8
25,000	.5
25,000	.8
40,000	.8

Records of the runs in which the maximum temperature differences occurred in turbine blades and nozzle guide vanes are shown in figures 7(a) and (b), respectively.

A comparison of the temperatures encountered during the starting runs is shown in table I. There are no considerable temperature peaks of high temperature differences during any of the starting sequences. The lower Mach number runs are more severe with regard to the temperature differences in the turbine blades because of lower windmilling speed; at an altitude of 25,000 feet and a Mach number of 0.5, the temperature difference between the leading edge and midchord reach a maximum of 260° F. The most severe conditions for the nozzle guide vanes occur at 40,000 feet, where the maximum temperature difference measured is 330° F between the trailing edge and three-fourth chord.

The sea-level starting data from reference 1 are included in table I. Temperature differences measured in turbine blades and nozzle guide vanes during sea-level starts are about two or three times greater than the differences recorded during altitude starts. The large temperature differences occur during sea-level starts primarily because high temperatures result from igniting at 7 to 8 percent rated speed, while altitude starts from windmilling speeds of 24 to 39 percent rated speed are relatively cool.

Accelerations and decelerations. - Eight acceleration runs were made at the following conditions:

Altitude, ft	Mach number	Speed, percent rated	
		From	To
7,000	0.5	50	99
7,000	.8	72	99.5
7,000	.5	85	100
7,000	.8	85	100
25,000	.8	72	100
25,000	.5	85	101
25,000	.8	85	102
45,000	.8	85	100

Five deceleration runs were made at the following conditions:

Altitude, ft	Mach number	Speed, percent rated	
		From	To
7,000	0.5	99	57
7,000	.8	99.5	73
25,000	.5	101	69
25,000	.8	100	73
45,000	.8	100	84

Records of the runs in which the most severe temperature differences occur in the turbine blades and nozzle guide vanes are shown in figures 8(a) and (b), respectively. A summary of the temperatures measured during the acceleration and deceleration runs is shown in table II.

The temperature differences for the nozzle guide vanes during the transient runs of this investigation are in all cases lower than the temperature differences measured during steady-state operation at rated speed. The data given in table II for the maximum temperature difference between the trailing edge and three-fourth chord were measured at the end point of each transient when the engine was at rated speed. The high temperature differences occur at rated speed because an appreciable volume of air flows through the hollow nozzle vanes and cools the center portion of the chordwise section. During the transient part of the acceleration and deceleration runs, the rate of gas temperature change is not sufficiently high to cause severe temperature differences from trailing edge to three-fourth chord. During the acceleration and deceleration runs, the turbine blades show the same range of temperature differences as during the starting runs.

SUMMARY OF RESULTS

A J47-25 engine was operated at altitudes of 7000, 25,000, and 45,000 feet and at inlet Mach numbers of 0.5 and 0.8 in order to determine the operating temperatures at altitude in the turbine section. The following results were obtained:

1. Turbine disk temperatures and temperature differences responded most rapidly to gas temperature changes at the 7000-foot-altitude conditions. At this altitude, temperatures were within 25° F of stable conditions 8 minutes after ignition, compared with 13 minutes and 23 minutes for the 25,000- and 45,000-foot-altitude runs, respectively.

2. The temperature differences recorded for the nozzle guide vanes during transient runs were lower than during steady-state operation at rated speed. Nozzle-guide-vane temperatures and temperature differences were generally lower than in previous sea-level tests.

3. The turbine blade maximum-temperature zone tended to move outward on the blade with increasing altitude. The turbine blade temperatures were lower at high altitudes, except for the region beyond 75 percent span, where the temperature increased with altitude.

4. Turbine blade temperature differences during altitude starts were considerably lower than in sea-level zero-ram starts. Altitude accelerations and decelerations caused temperature differences generally comparable with the results of sea-level runs.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, March 13, 1956

REFERENCES

1. Morse, C. R., and Johnston, J. R.: Temperatures in a J47-25 Turbojet-Engine Combustor and Turbine Sections During Steady-State and Transient Operation in a Sea-Level Test Stand. NACA RM E54K30a, 1955.

2. Scadron, Marvin D., and Warshawsky, Isidore: Experimental Determination of Time Constants and Nusselt Numbers for Bare-Wire Thermocouples in High-Velocity Air Streams and Analytic Approximation of Conduction and Radiation Errors. NACA TN 2599, 1952.

3. Ames Research Staff: Equations, Tables, and Charts for Compressible Flow. NACA Rep. 1135, 1953. (Supersedes NACA TN 1428.)

TABLE I. - STARTS

Altitude, °F	Mach number	Wind milling, percent rated	Maximum tailpipe gas temperature, °F	Nozzle guide vanes			Turbine blade			
				Maximum temperature at trailing edge, °F	Temperature at trailing edge after 10 sec, °F	Maximum temperature difference from trailing edge to 3/4 chord, °F	Maximum temperature at leading edge, °F	Temperature at leading edge after 10 sec, °F	Maximum temperature difference to midchord from leading edge, °F	Maximum temperature difference to midchord from trailing edge, °F
7,000	0.5	24	770	660	645	275	660	660	200	105
7,000	.8	39	445	590	260	125	520	385	115	70
25,000	.5	22	985	610	470	200	755	705	260	100
25,000	.8	37	465	565	325	125	505	380	125	70
40,000	.8	34	1110	755	670	330	650	635	225	115
Sea level (ref. 1)	0	[a]7	1620	1220	1030	540	1180	1000	600	360

[a]Starter cranking speed.

TABLE II. - ACCELERATIONS AND DECELERATIONS

Altitude, ft	Mach number	Speed, percent rated		Maximum tailpipe gas temperature, °F	Nominal time to speed, sec	Nozzle guide vanes		Turbine blade		
		From	To			Maximum temperature at trailing edge, °F	Maximum temperature difference from trailing edge to 3/4 chord, °F	Maximum leading edge temperature, °F	Maximum temperature difference from leading edge to midchord, °F	Maximum temperature difference from trailing edge to midchord, °F
7,000	0.5	50	99	1360	7	1510	390	1360	---	---
7,000	.8	72	99.5	1305	15	----	---	1535	300	280
25,000	.8	72	100	1285	5	1505	420	1375	300	210
45,000	.8	85	100	1490	7	1470	300	1355	140	120
7,000	.5	99	57	1185	22	1520	390	1360	---	---
7,000	.8	99.5	73	1320	25	----	---	1540	250	200
25,000	.5	101	69	1300	20	1555	405	1460	350	180
25,000	.8	100	73	1265	20	1525	405	1405	155	190
45,000	.8	100	84	1270	20	1500	370	1385	50	80
7,000	.5	85	100	1440	3	1585	400	1430	180	135
7,000	.8	85	100	1305	11	----	---	1520	190	205
25,000	.5	85	101	1335	5	1545	395	1395	160	135
25,000	.8	85	102	1355	4	1545	410	1425	185	150
Sea level (ref. 1)	0	38	100	1490	12	1790	780	1510	170	60

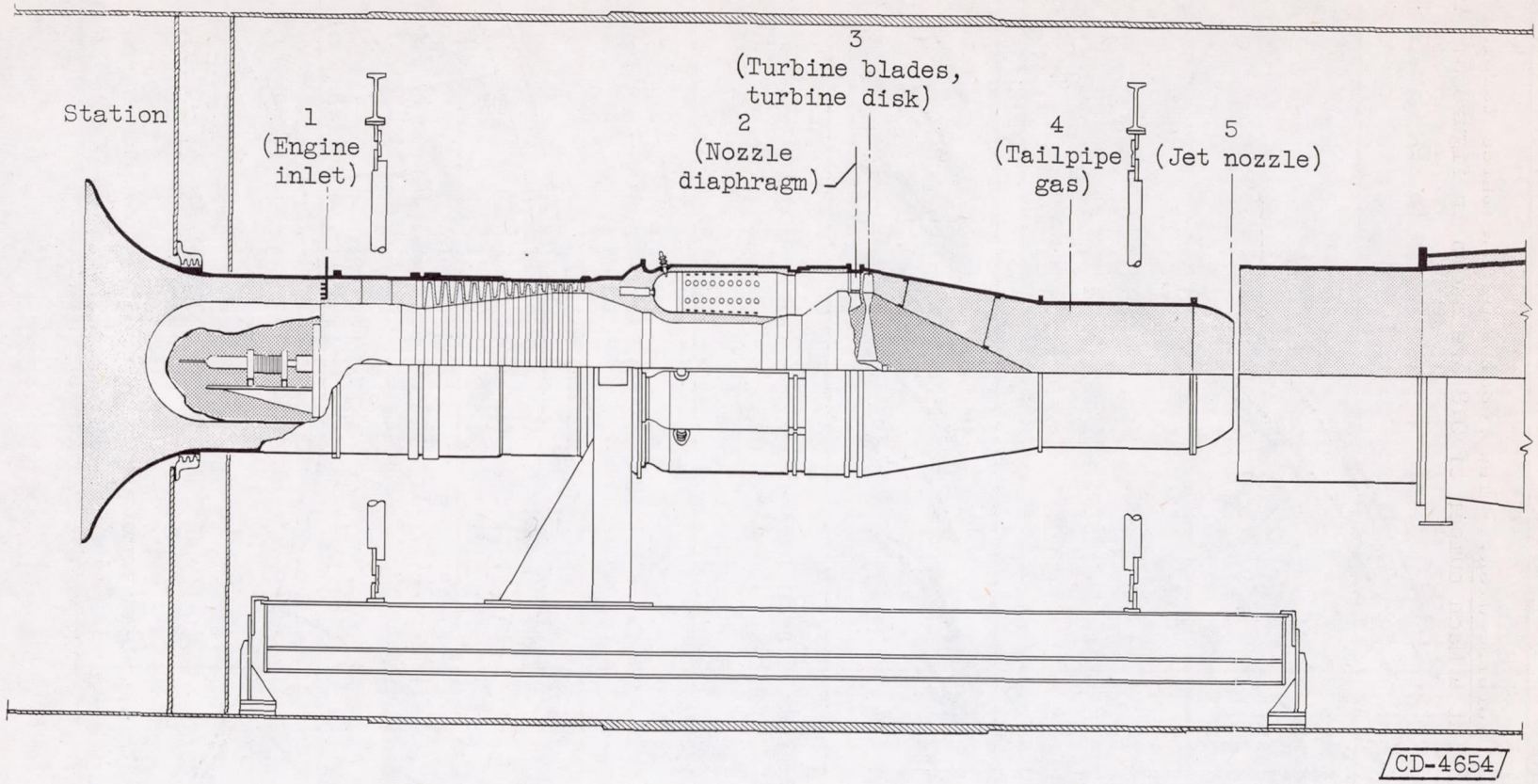

Figure 1. - Instrumentation of J47-25 engine for altitude tests.

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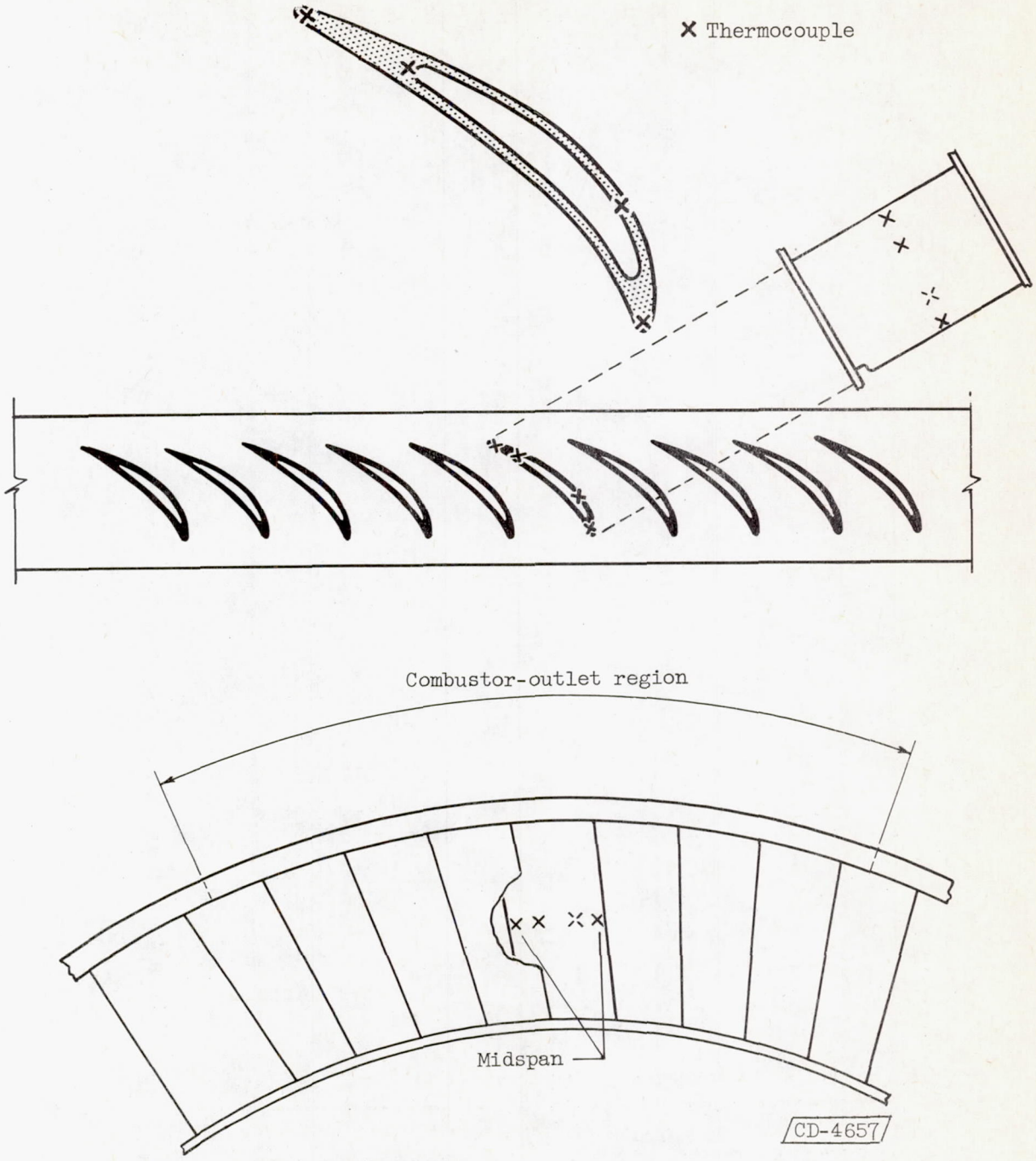

(a) For transient temperatures of nozzle guide vanes.

Figure 2. - Thermocouple location.

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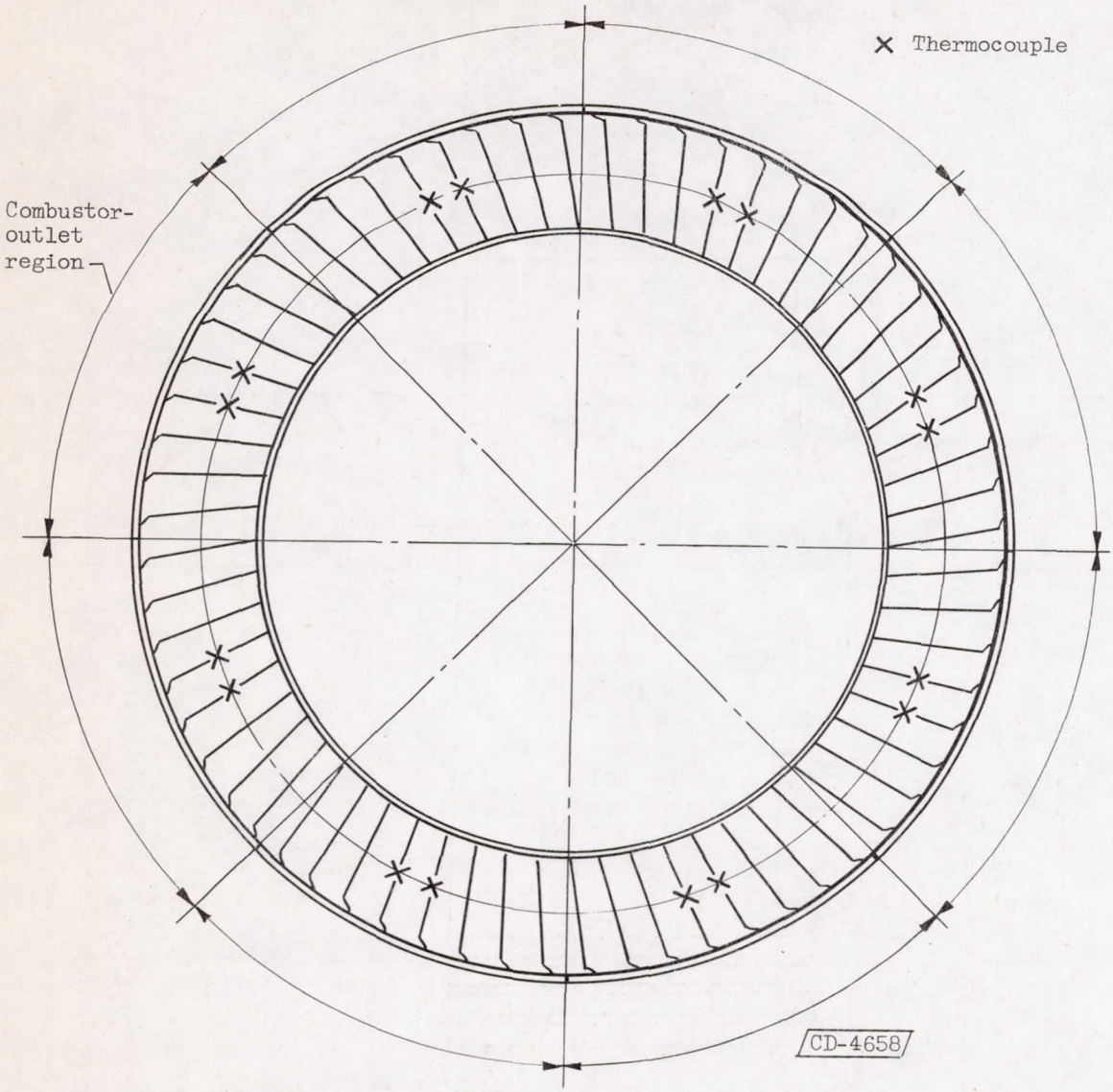

(b) For annular survey of nozzle-guide-vane temperatures.

Figure 2. - Continued. Thermocouple location.

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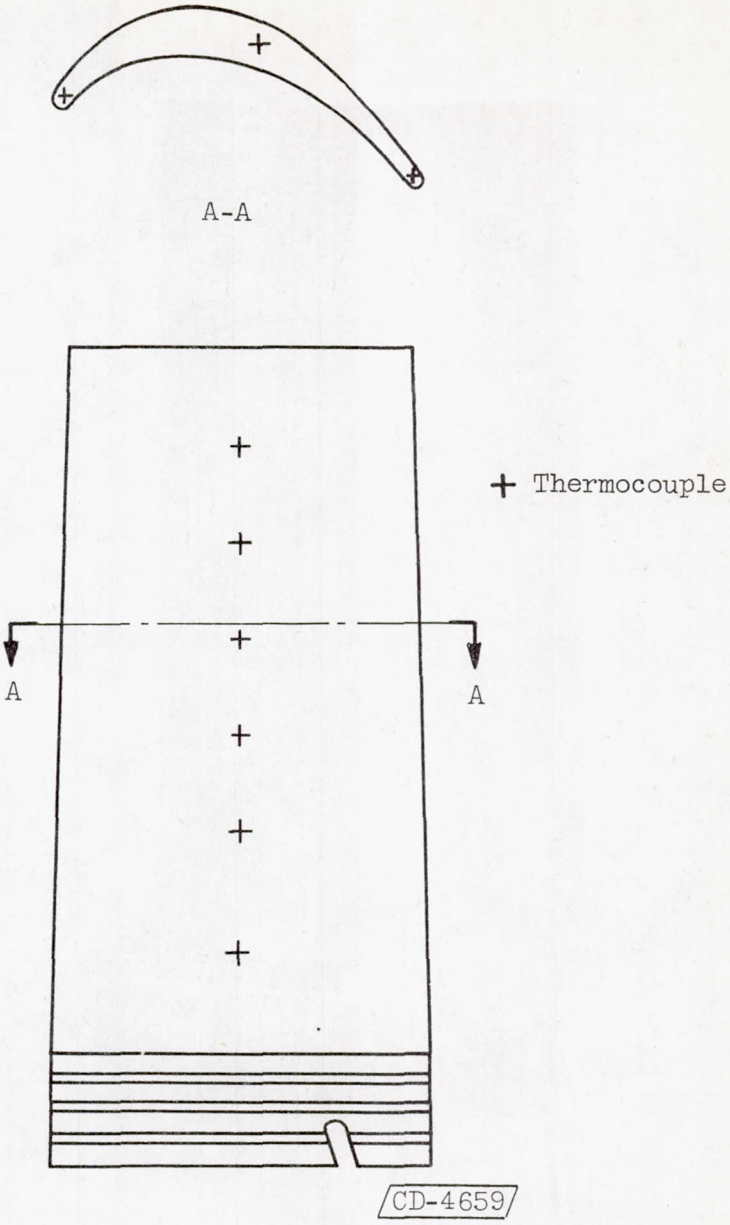

(c) Position on turbine blades.

Figure 2. - Continued. Thermocouple location.

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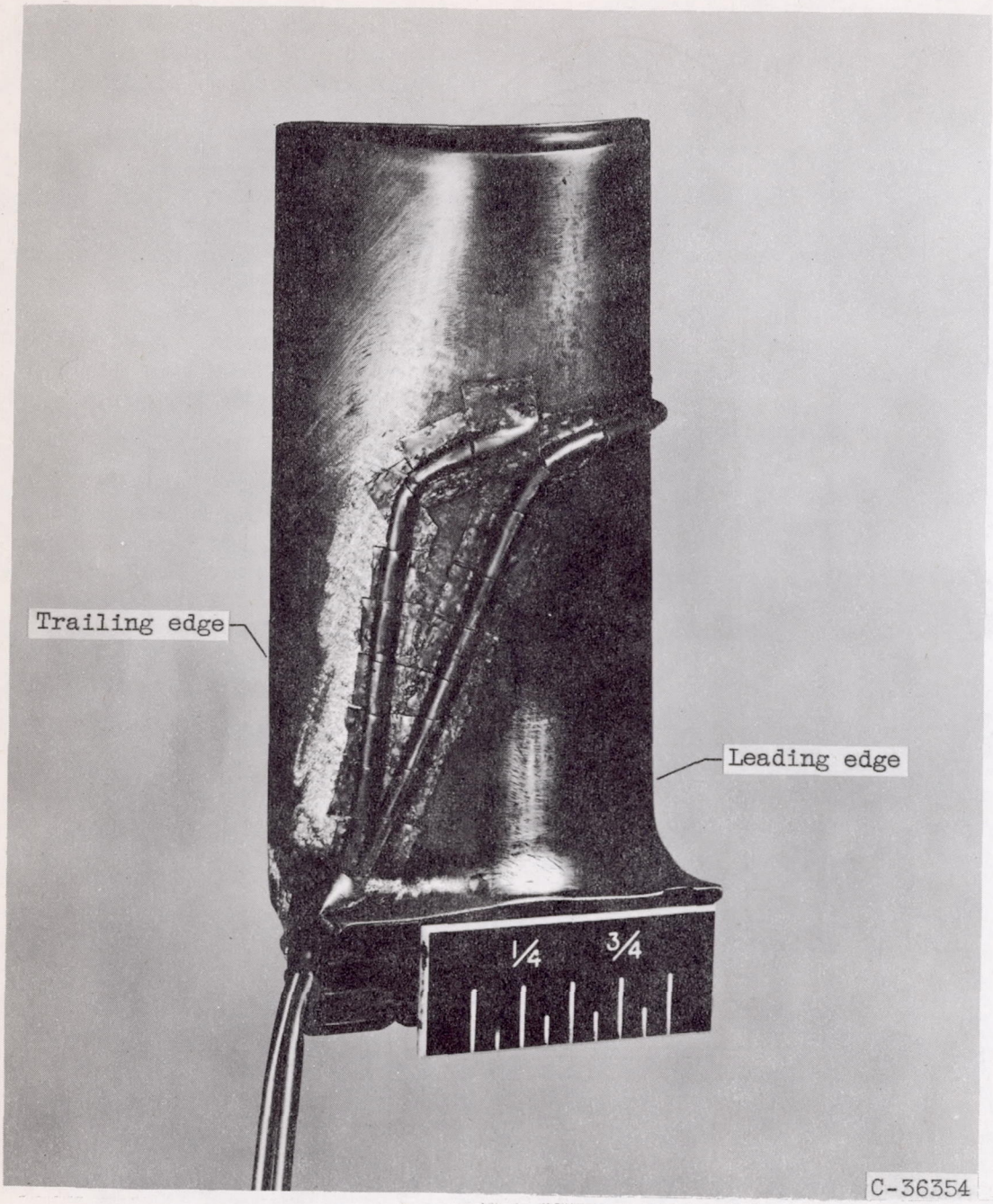
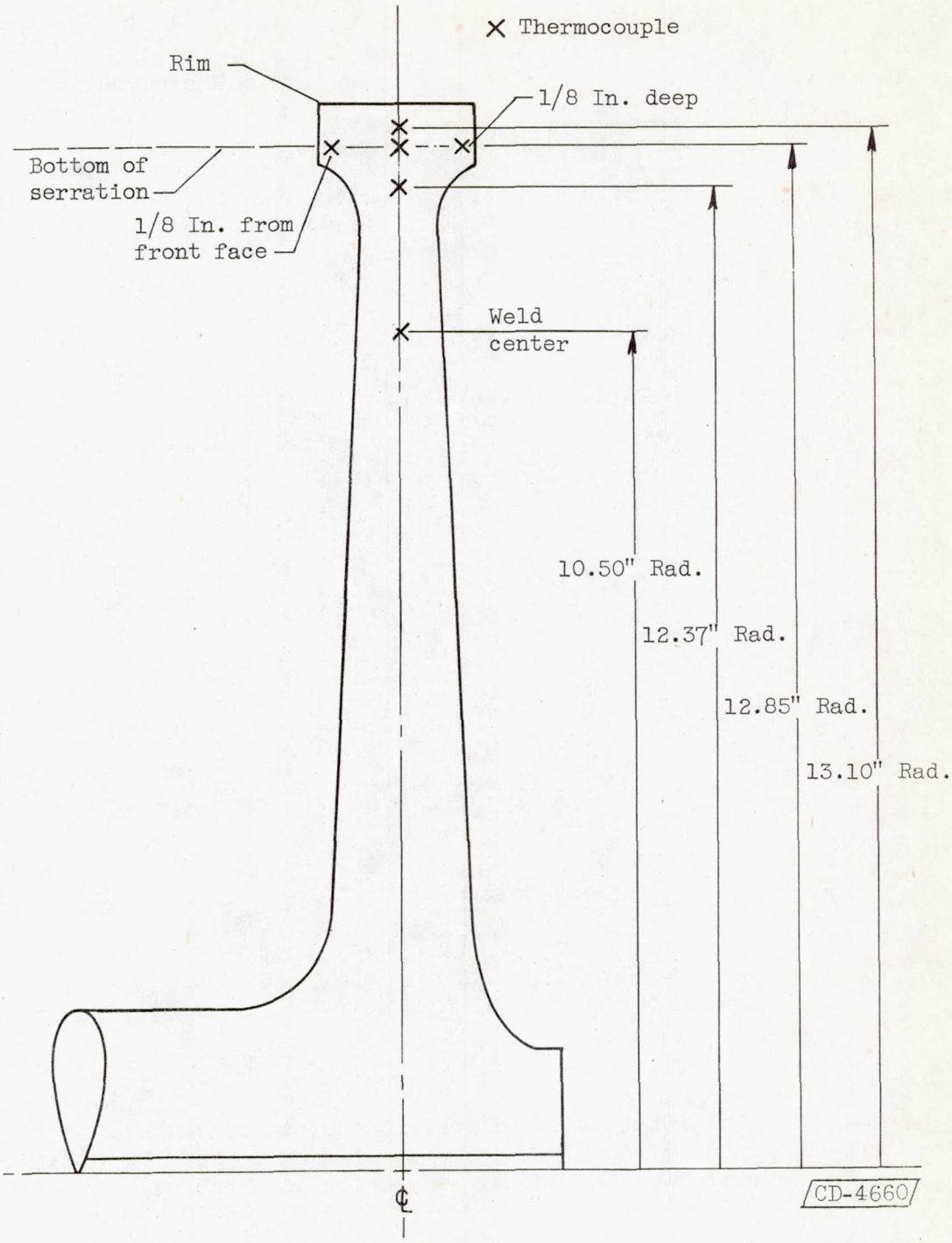
CS-3 back



(d) Photograph of typical instrumented turbine blade.

Figure 2. - Continued. Thermocouple location.



(e) On a turbine disk section.

Figure 2. - Continued. Thermocouple location.

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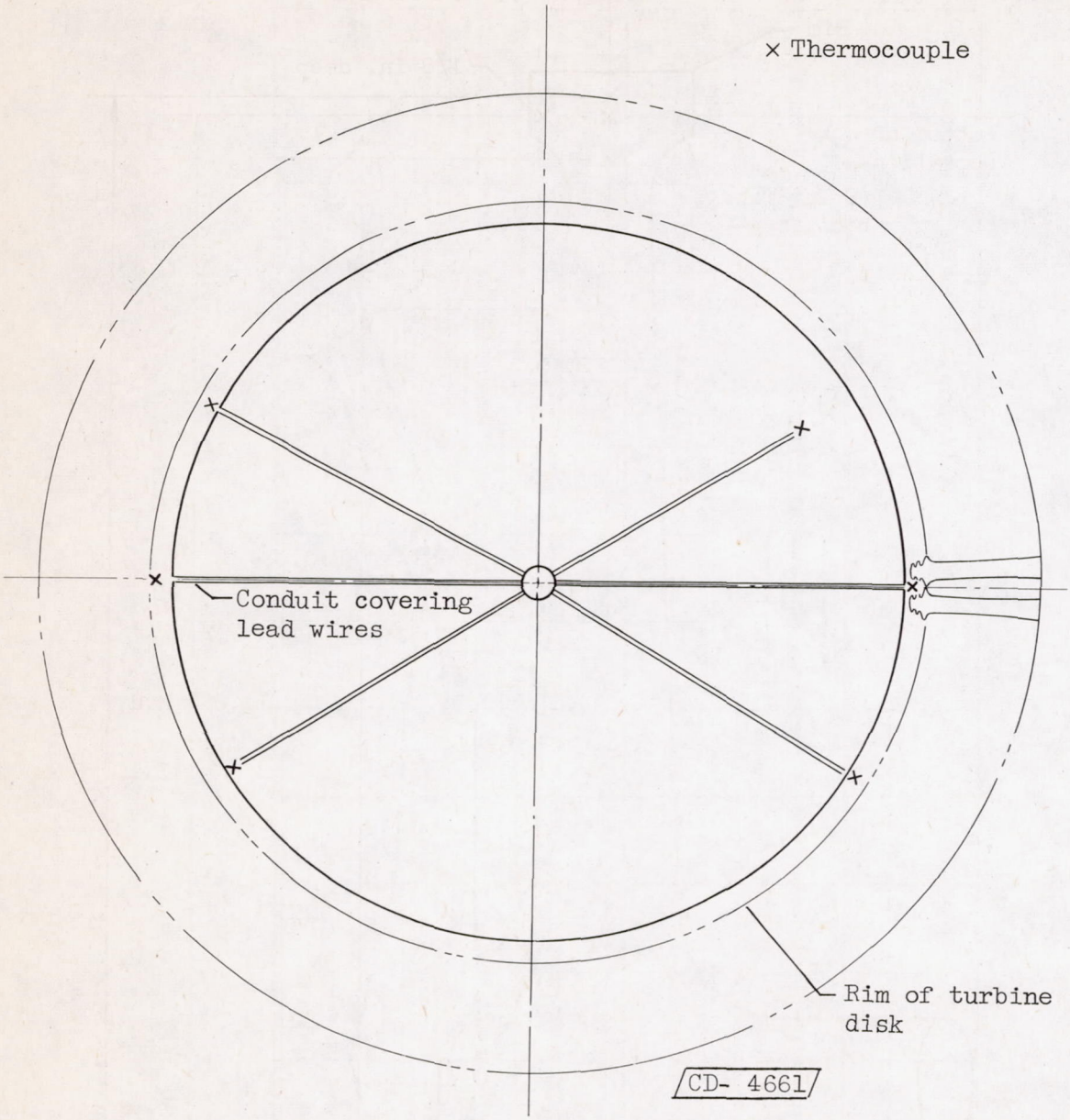

(f) Instrumentation on rear face of turbine disk.

Figure 2. - Concluded. Thermocouple location.

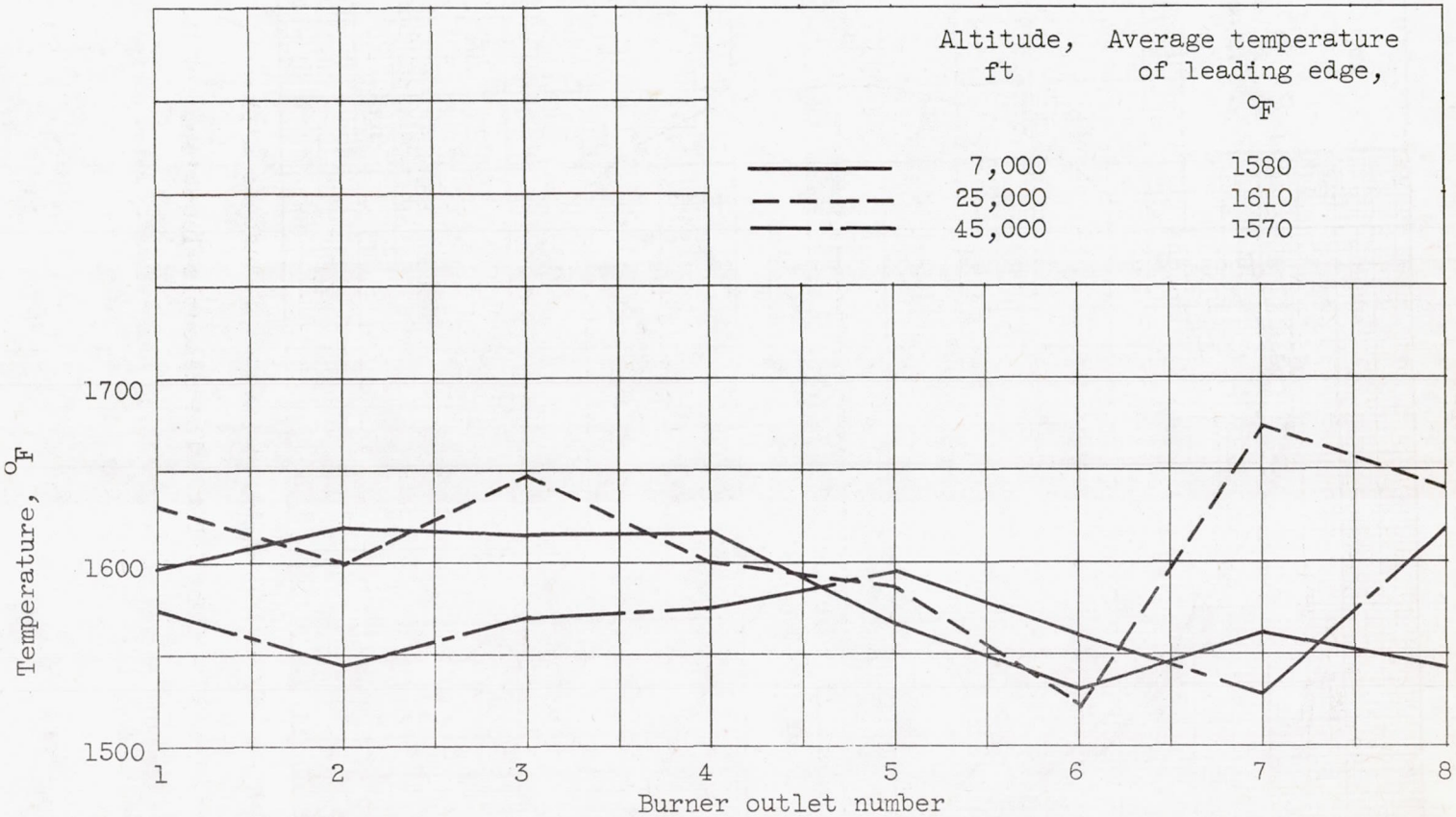

Figure 3. - Annular survey of nozzle-guide-vane temperatures. Steady-state temperatures corrected to tailpipe gas temperature of 1230° F; rated engine speed; inlet Mach number, 0.8; altitudes, 7000, 25,000, and 45,000 feet.

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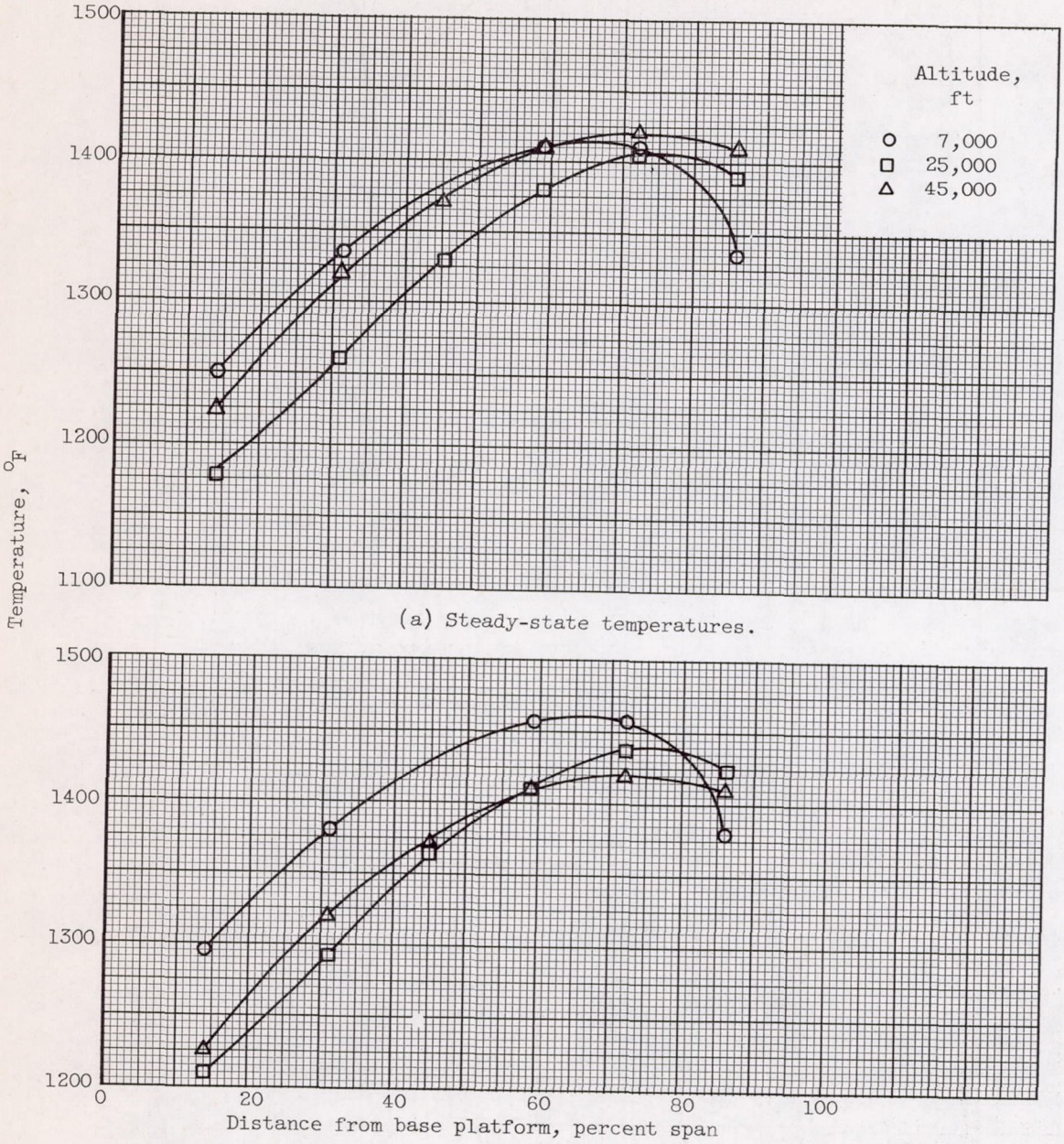
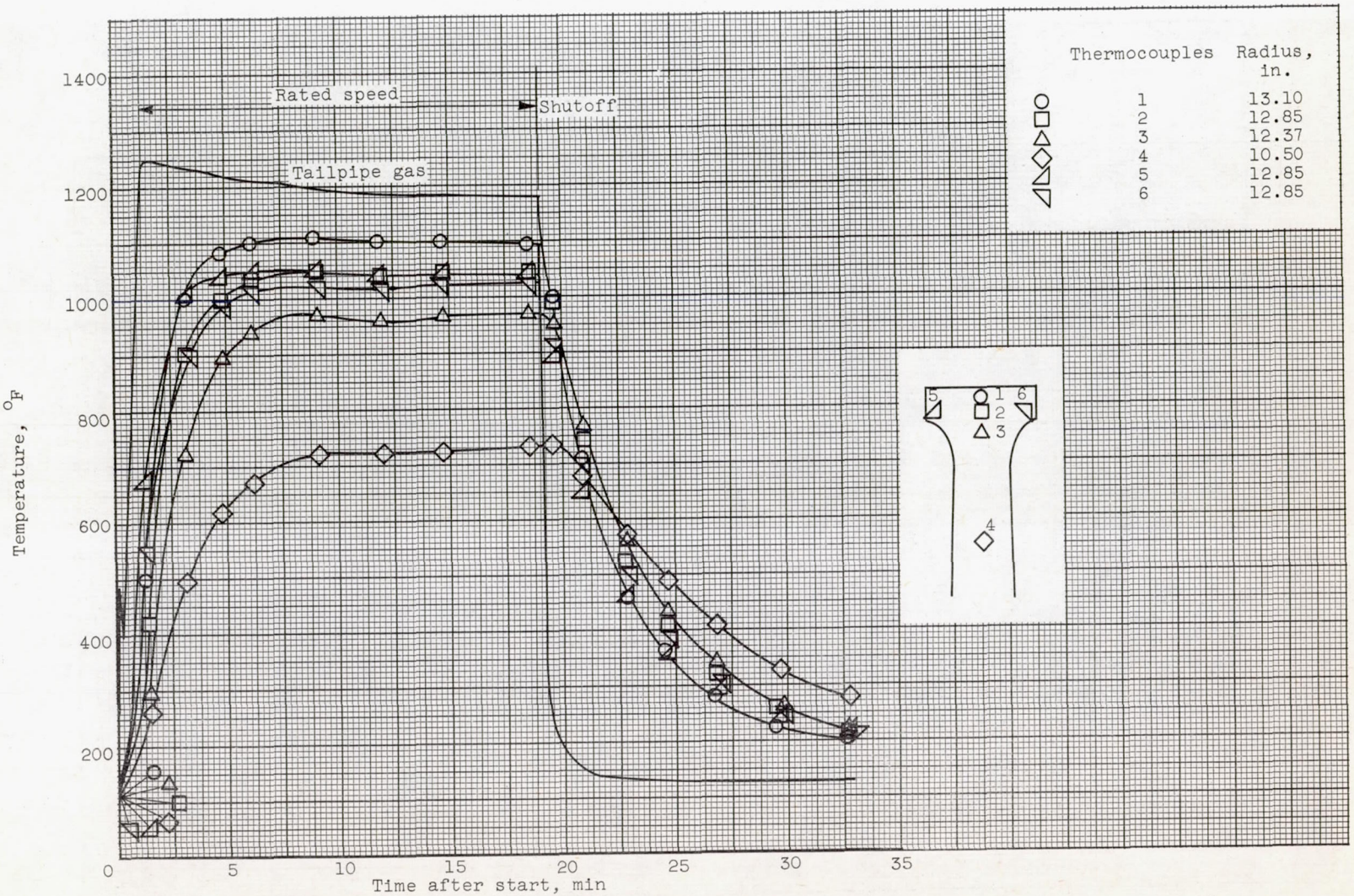


(a) Steady-state temperatures.

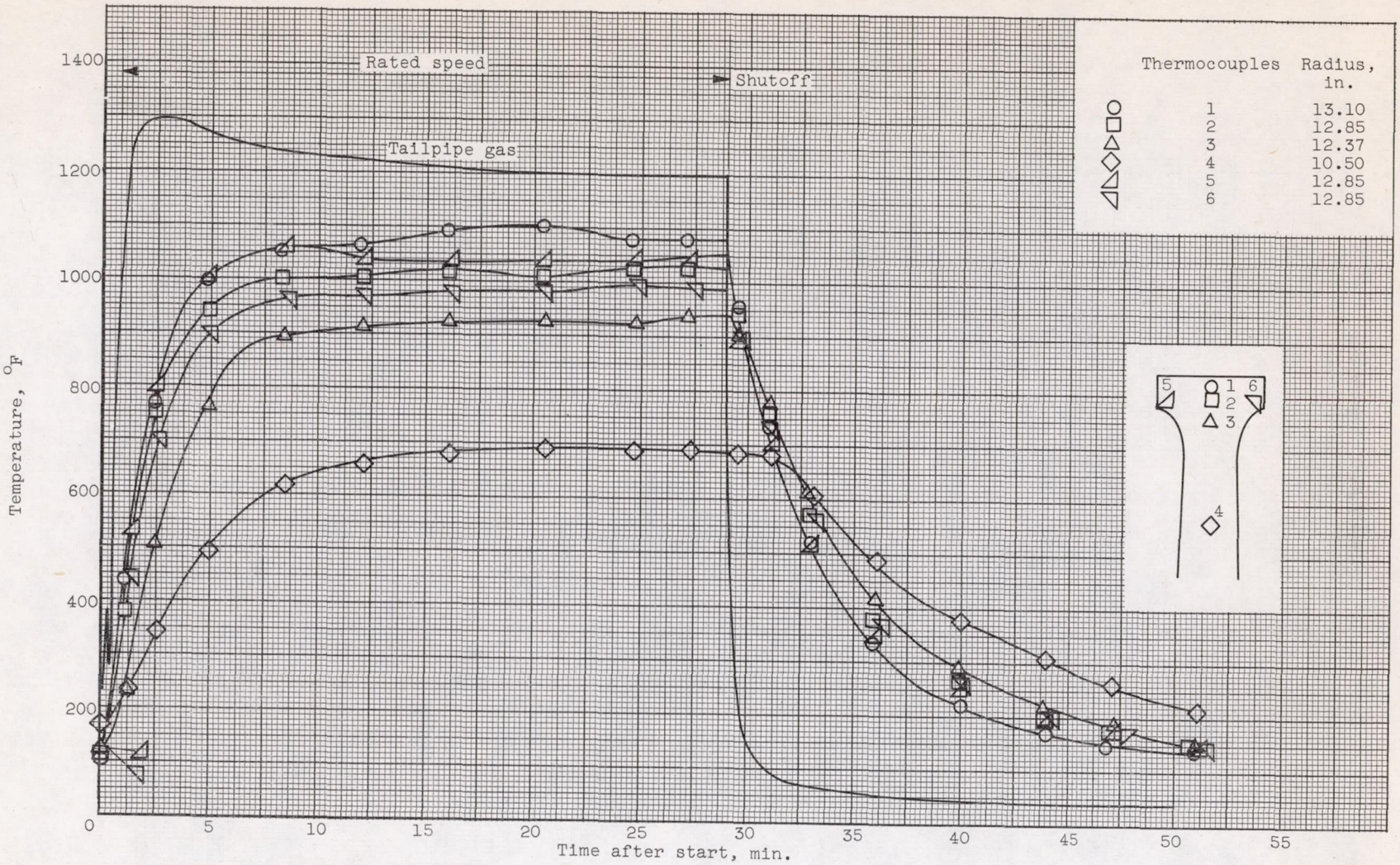
(b) Steady-state temperatures corrected to tailpipe gas temperature of 1230° F.

Figure 4. - Spanwise survey of turbine blade temperatures. Rated engine speed; inlet Mach number, 0.8.



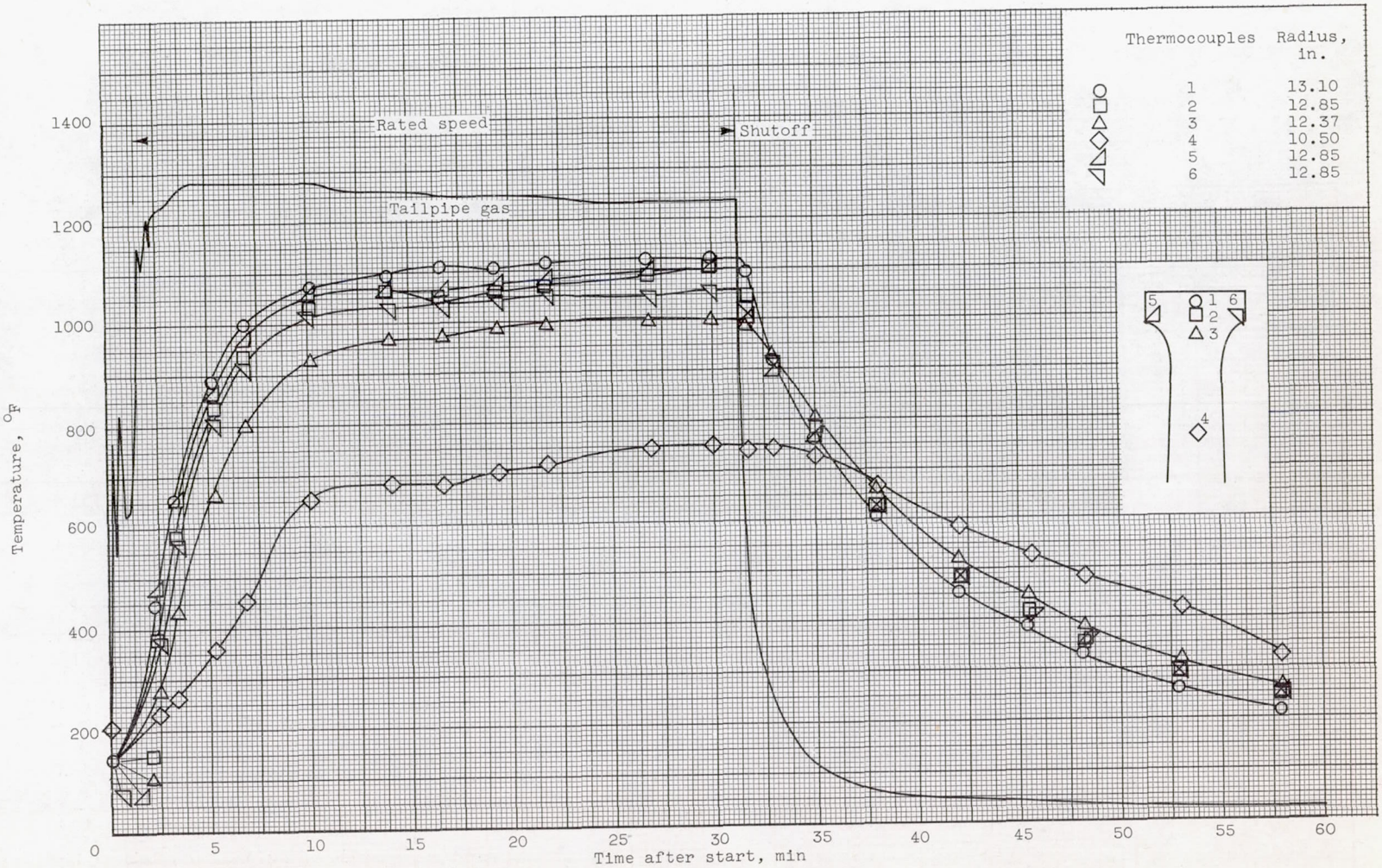
(a) Altitude, 7000 feet; windmilling speed, 40 percent rated; inlet air temperature, 95° F.

Figure 5. - Turbine disk temperatures during cycle of start, acceleration to 100 percent rated speed, and shutdown at inlet Mach number of 0.8.



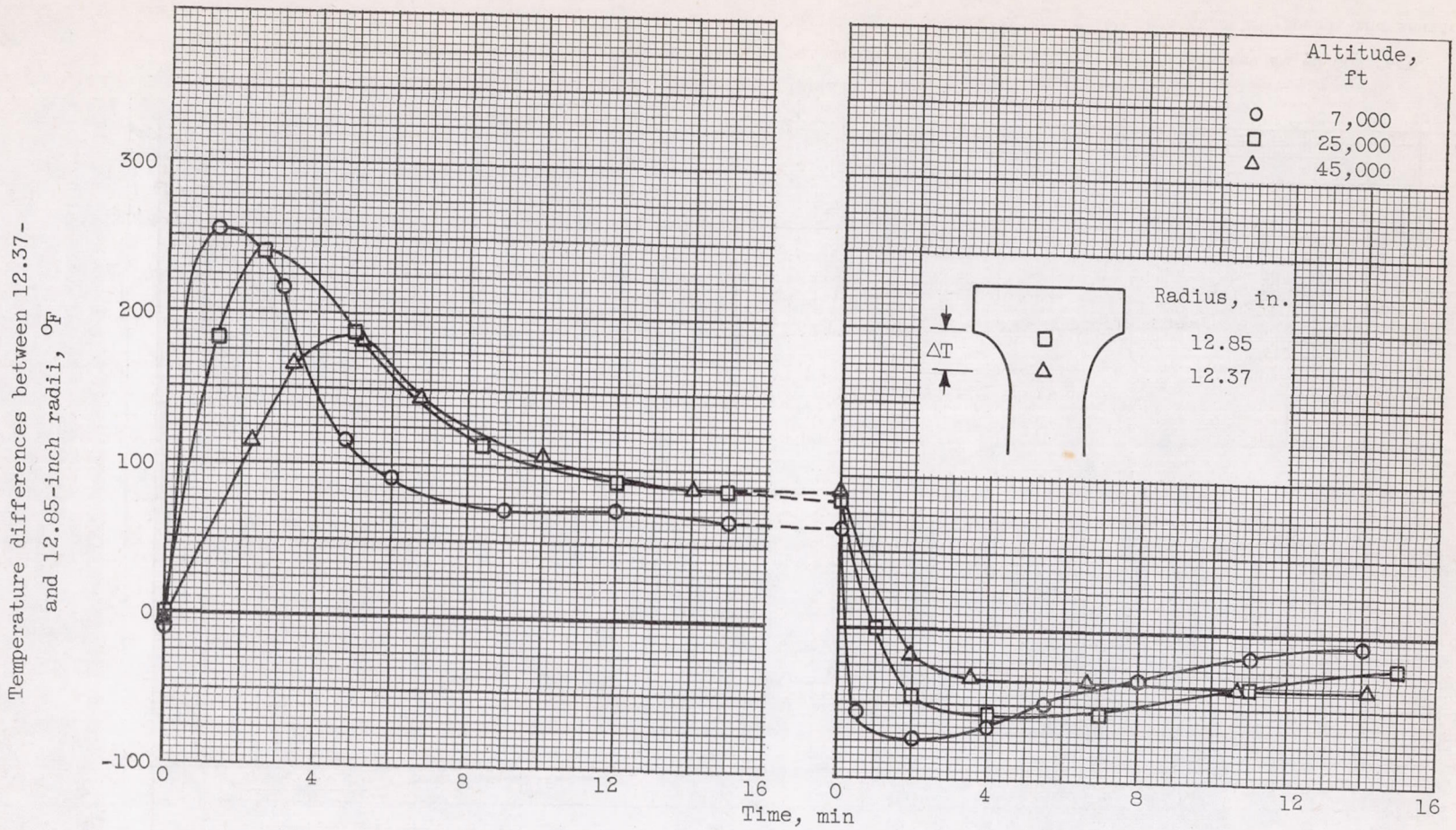
(b) Altitude, 25,000 feet; windmilling speed, 36 percent rated; inlet air temperature, 24° F.

Figure 5. - Continued. Turbine disk temperatures during cycle of start, acceleration to 100 percent rated speed, and shutdown at inlet Mach number of 0.8.



(c) Altitude, 45,000 feet; windmilling speed, 25 percent rated; inlet air temperature, -21° F; started at 40,000 feet.

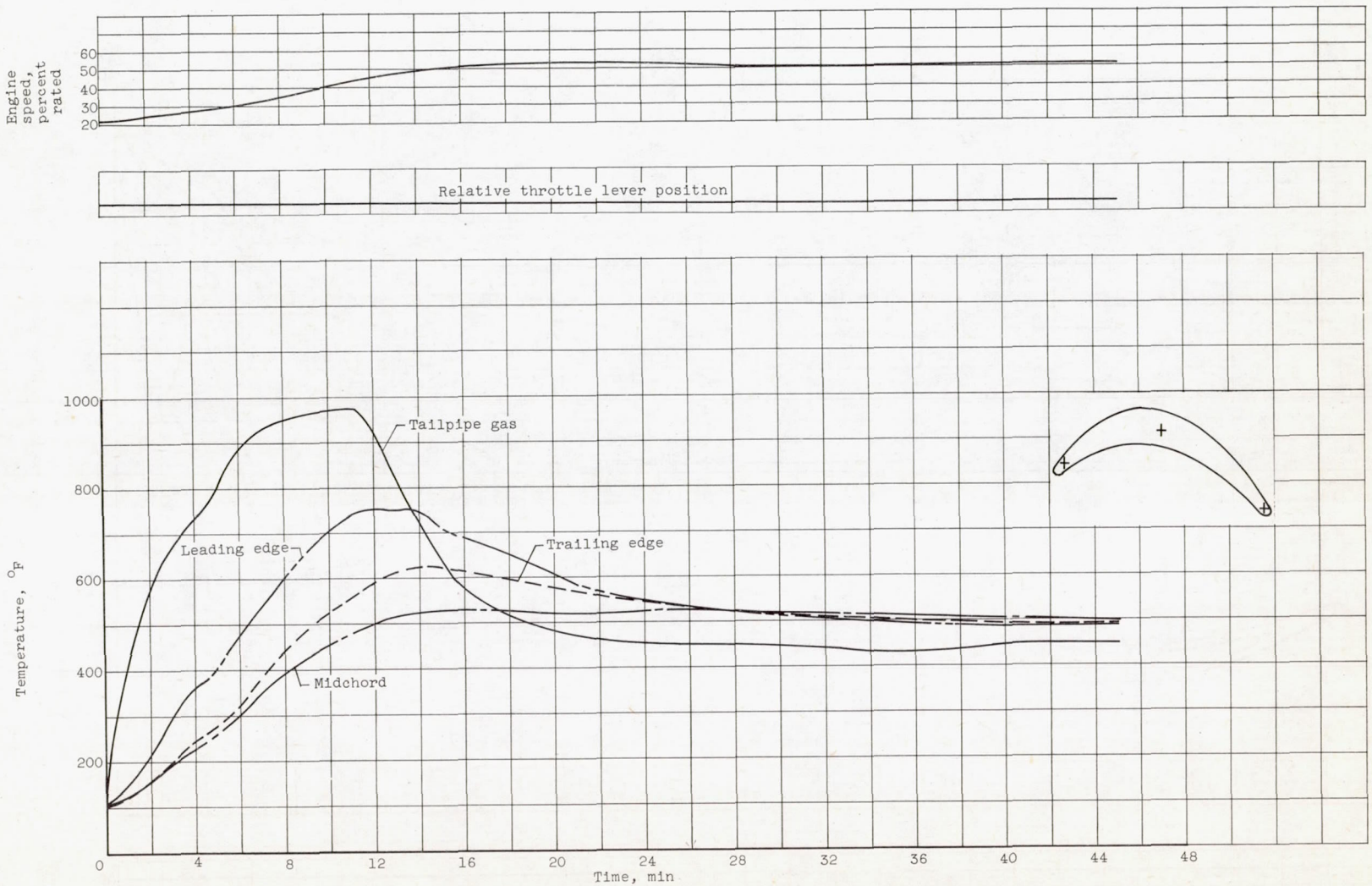
Figure 5. - Concluded. Turbine disk temperatures during cycle of start, acceleration to 100 percent rated speed, and shutdown at inlet Mach number of 0.8.



(a) Time after ignition.

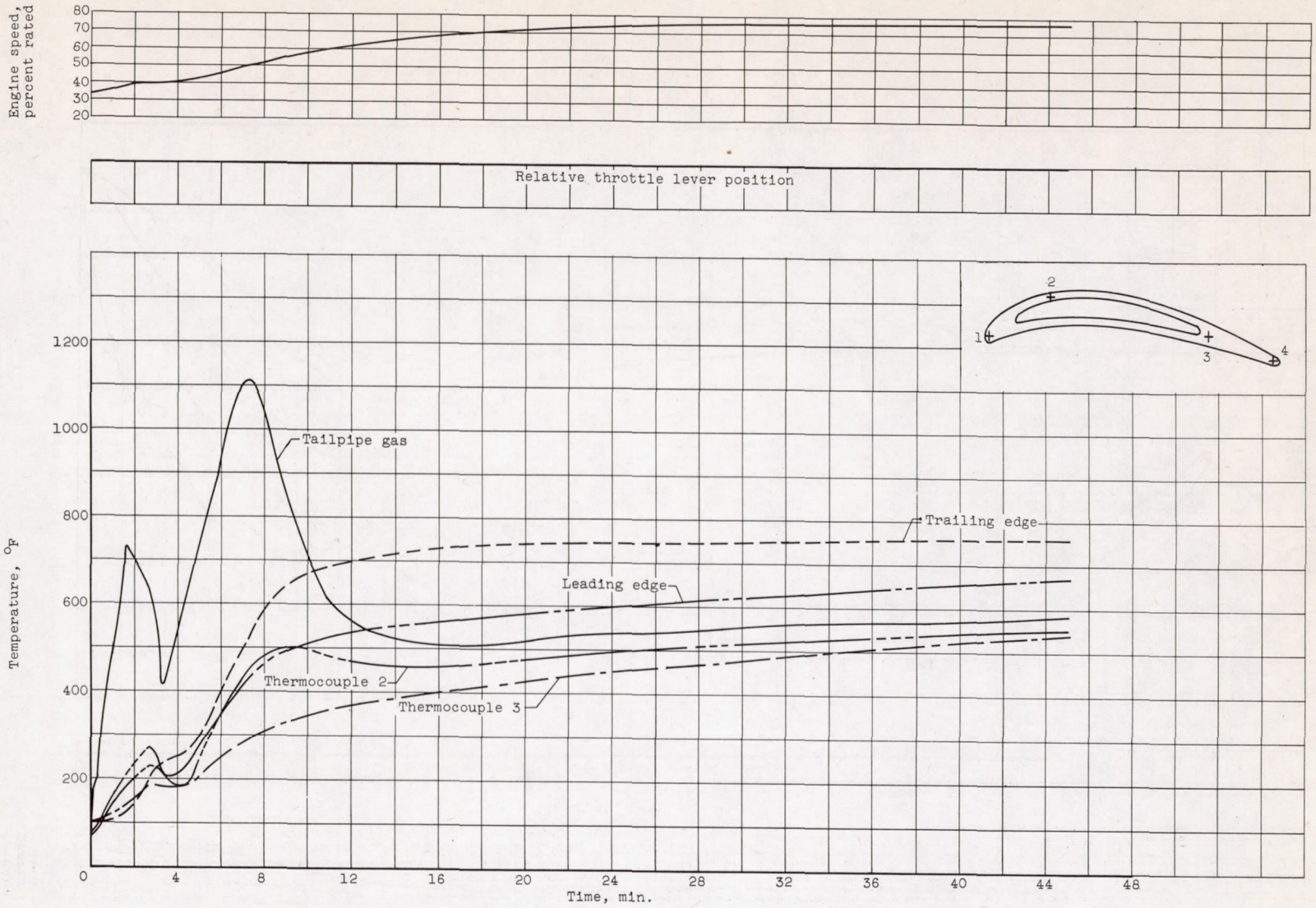
(b) Time after shutdown.

Figure 6. - Temperature differences in turbine disk rim during cycle of start, acceleration, and shutdown. Inlet Mach number, 0.8.



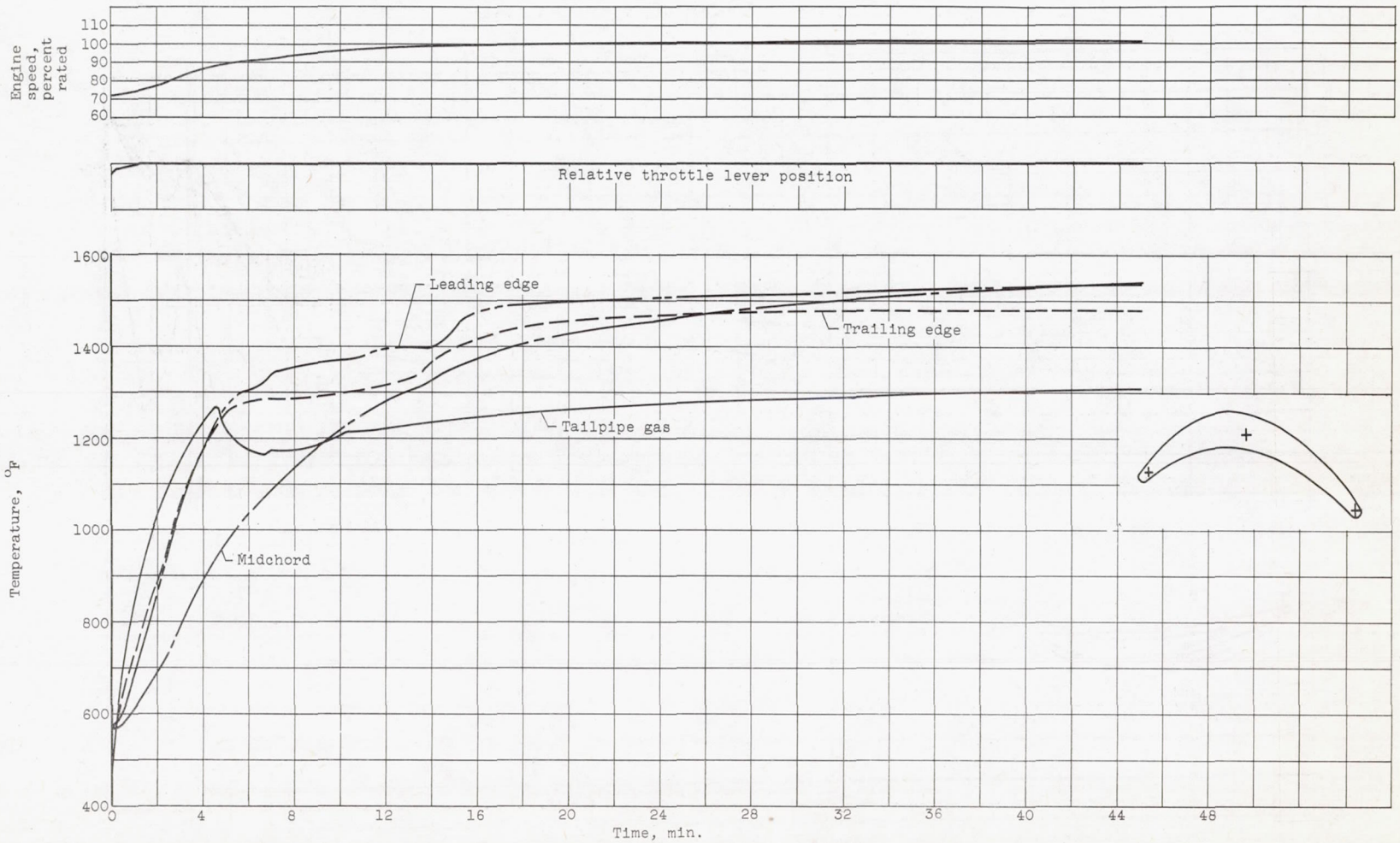
(a) Turbine blade; altitude, 25,000 feet; inlet Mach number, 0.5.

Figure 7. - Temperatures during start.



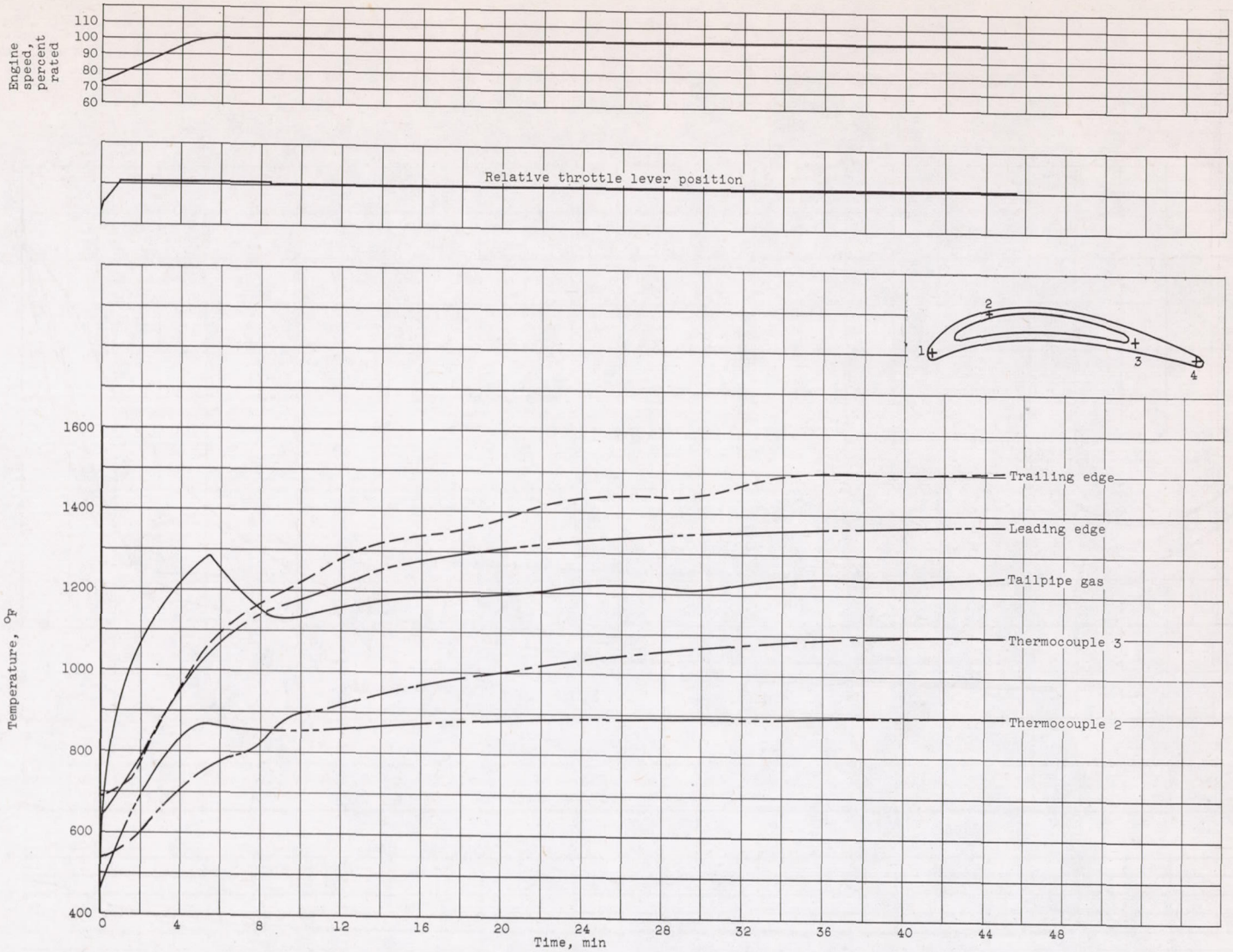
(b) Nozzle guide vane; altitude, 40,000 feet; inlet Mach number, 0.8.

Figure 7. - Concluded. Temperatures during start.



(a) Turbine blades; altitude, 7000 feet.

Figure 8. - Temperatures during acceleration from idle to rated speed. Mach number, 0.8.



(b) Nozzle guide vane; altitude, 25,000 feet.

Figure 8. - Concluded. Temperatures during acceleration from idle to rated speed. Mach number, 0.8.