NACA

RESEARCH MEMORANDUM

EFFECT OF NOZZLE SECONDARY FLOWS ON TURBINE PERFORMANCE

AS INDICATED BY EXIT SURVEYS OF A ROTOR

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RESEARCH MEMORANDUM

EFFECT OF NOZZLE SECONDARY FLOWS ON TURBINE PERFORMANCE AS

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SUMMARY

   Detailed circumferential and radial surveys of total pressure and
total temperature were made downstream of the turbine rotor of a high-
speed, high-specific-mass-flow turbine at design operating conditions.
The results of these surveys, when plotted as efficiency contours over
the survey range of approximately $1\frac{1}{4}$ nozzle passages, indicated that
large circumferential-loss gradients existed downstream of the turbine
rotor, effecting a variation in the local efficiency of 14 points. These
losses were caused by disturbances originating in the nozzle and prob-
ably represent the effect of nozzle secondary-flow vortices and wakes
carrying through the rotor. From the indications of the survey results,
it was concluded that losses in the nozzle blades due to secondary-flow
vortices and wakes, although normally small, can induce much greater
losses in the turbine rotor and can cause an appreciable effect on the
over-all turbine performance.

INTRODUCTION

   In order to increase efficiencies of turbines, as well as to in-
crease the mass flow per unit frontal area and work per stage for which
high efficiency can be obtained, it is necessary to determine the sources
and relative magnitudes of the various losses. Survey measurements
between nozzle and rotor and downstream of the rotor of a conservatively
designed turbine (ref. 1) have indicated that the major losses are
located near the blade ends. On the basis of the large difference
between the measured losses and the estimated sum of blade-profile loss
and tip-clearance loss, particularly in the blade-end regions, it was
deduced that a large part of these losses could be attributed to sec-
ondary flows. Surveys just downstream of an annular row of turbine-
nozzle blades have disclosed large secondary-flow cores at the junction
of blade wakes and end-wall boundary layers for both low and high Mach
numbers (ref. 2). A more complete discussion and visualization of these

phenomena is presented in reference 3. Although the energy loss in these cores on a mass-averaged basis is quite small, as indicated by measured nozzle efficiencies of the order of 0.98, it is reasonable to expect that these secondary-flow cores might induce losses in the following blade row, or rotor, due to unfavorable relative flow angles and interference with the main stream. Unpublished results from exploratory surveys with hot-wire anemometers at turbine exits have indicated that these nozzle secondary flows have been identified downstream of the rotor. In order to investigate further the effect of nozzle secondary flows on turbine performance, detailed circumferential and radial surveys of total pressure and total temperature were made just downstream of the rotor of the high-speed, high-specific-mass-flow turbine of reference 4 at design operating conditions. The purpose of this report is to examine these results to determine whether the effect of nozzle secondary flows on the rotor flow results in an appreciable loss in turbine efficiency. The criterion to be used is whether the losses measured at the rotor exit are axially symmetric or take the form of large circumferential gradients that are fixed in space and can be related to nozzle circumferential position.

This investigation was conducted at the NACA Lewis laboratory.

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SYMBOLS

The following symbols are used in this report:

P_1 turbine-inlet total pressure, lb/sq ft

P_3 turbine-outlet total pressure, lb/sq ft

T_1 turbine-inlet total temperature, $^\circ$R

T_3 turbine-outlet total temperature, $^\circ$R

γ ratio of specific heats

η_B local adiabatic efficiency, $\eta_B = \dfrac{1 - (T_3/T_1)}{1 - (P_3/P_1)^{\frac{\gamma-1}{\gamma}}}$

θ_{cr} squared ratio of critical velocity at turbine-inlet temperature T_1 to critical velocity at NACA standard sea-level temperature

$\Delta T/\theta_{cr}$ corrected total-temperature drop, $(T_1 - T_3)/\theta_{cr}$, $^\circ$R

$(\Delta T/\theta_{cr})_{des}$ design value of corrected total-temperature drop, $^\circ$R

APPARATUS AND PROCEDURE

The turbine and apparatus (fig. 1) are the same as those described in reference 4, except that the turbine casing was equipped with a motorized saddle in order to take circumferential surveys in a plane approximately 2 inches (about one blade chord) downstream of the turbine rotor. The special survey instrumentation consisted of a total-pressure and angle probe and a self-alining thermocouple probe, both shown in figure 2. The pressure and angle probe was made from two pieces of 0.020-inch tubing soldered together, the axes of the tubing being separated by only 0.020 inch. The ends of the tubing were face-ground to an included wedge angle of 160°. This angle was selected experimentally to give the probe good yaw sensitivity as well as satisfactory total-pressure-recovery characteristics. The object of using a probe of this type was to keep the two elements as close together as possible so that the effect of the circumferential total-pressure gradient on flow-angle alinement would be minimized. Measurements were obtained with this probe by automatically balancing the pressure in the two legs, and total pressure was obtained from the pressure in one leg in combination with a pressure-recovery calibration. The total pressure from the probe was fed into a calibrated strain-gage pickup, which was used to eliminate the relatively large volume of a manometer line and tube and thereby enable a more rapid response of alinement to the flow.

The directional thermocouple probe (fig. 2) consisted of a thermocouple and two pressure ports which were connected directly to a balancing capsule to make the probe self-alining. The survey thermocouple was connected such that the differential electromotive force between the turbine-inlet thermocouples and the survey thermocouple could be read directly.

The thermocouple probe and the total-pressure probe were calibrated for recovery over a range of Mach number corresponding to that encountered in test conditions. The static pressure was obtained from four inner-wall and four outer-wall static taps, which were located at the survey plane (station 3, fig. 1), by assuming a linear static-pressure variation from inner wall to outer wall. The recovery correction for each probe was then obtained by using the ratio of indicated total pressure to static pressure and the calibration curve.

The surveys were made with the turbine set at equivalent design speed and design work output with turbine-inlet conditions maintained constant at the nominal values of 32 inches mercury absolute and 600° R. Circumferential surveys of total pressure and total temperature were taken at various radial positions spaced 1/4 inch apart, except near the walls where they were spaced approximately 1/8 inch apart. The circumferential spacing of survey points was approximately 1°, and the circumferential travel was about 14° corresponding to about $1\frac{1}{4}$ nozzle passages which were

$11\frac{1}{4}°$. The circumferential traverse made at the innermost radius was 0.055

inch from the inner wall, while that at the outermost radius was 0.095 inch from the outer wall.

RESULTS AND DISCUSSION

Contours of total-pressure ratio P_3/P_1 and total-temperature-drop ratio $(\Delta T/\theta)/(\Delta T/\theta)_{des}$ over the survey range of $1\frac{1}{4}$ nozzle pitch are presented in figures 3 and 4, respectively. Regions of low total-pressure ratio and temperature-drop ratio can be noted that appear similar to nozzle-blade wakes from the standpoints of shape and circumferential spacing. There are also marked circumferential gradients at all radii which would have to result from phenomena originating in the stationary component of the turbine. It is not known how nozzle secondary-flow losses are manifested downstream of a turbine rotor in terms of either total temperature or total pressure. In regions possessing radial and circumferential variations of total temperature (representing a varying amount of energy extraction by the rotor) and of total pressure, the local losses are functions of both temperature and pressure at the point. Consequently, to identify high-loss regions, it is necessary to combine the two in the form of a contour plot of local adiabatic efficiency.

Contours of local efficiency η_B based on detailed surveys of total temperature and total pressure just downstream of the rotor (station 3) are shown in figure 5. Extremely large gradients in efficiency are shown to exist at this station, with the total variation amounting to 14 points. Furthermore, the regions of low efficiency, or high loss, are shown to be localized. The regions of efficiency of 0.92 or lower are arbitrarily shaded to show the high-loss regions. Since gradients or losses originating in the rotor-blade row would result in a variation with time with respect to a stationary instrument rather than a variation with circumferential position, the circumferential gradient is evidently the result of some stationary circumferential maldistribution of flow upstream of the rotor. Since the efficiency pattern is approximately repetitive circumferentially at very nearly the value of nozzle pitch $(11\frac{10}{4})$, it appears that these gradients originate in the nozzle blades. This contention is substantiated by the similarity between these patterns and the loss patterns obtained just downstream of the turbine-nozzle blades as illustrated in reference 2. The large secondary-flow cores at the junction of the nozzle-blade wakes and end-wall boundary layers, as well as the nozzle-blade wakes, then evidently affect the flow through the rotor sufficiently to cause large losses in efficiency.

The results indicate that the nozzle core near the inner wall causes considerably higher losses than the nozzle core at the outer wall since a much greater area, and consequently a greater mass flow, is affected. The core near the inner wall shifted out from the wall in passing through the rotor, probably as a result of the combined effects of the contoured inner wall (see ref. 4) and of the difference between the equilibrium radial pressure gradients of the main stream and the core resulting from their different absolute components of tangential velocity. Between the nozzle

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wakes and cores exist regions of comparatively high efficiency. The efficiency values given are probably somewhat in error because of the unsteady state of the flow out of the rotor; however, the trends are believed to be significant. These regions of high efficiency indicate the rotor secondary flow and other rotor losses, exclusive of those induced by nozzle secondary flows, to be comparatively small for this turbine. This result is of particular interest in the rotor-tip region, where the rotor-blade losses would normally be expected to be high. From these results, it appears likely that a favorable balance among the tip-clearance vortex, the passage vortex, and the scraping vortex, as discussed in reference 3, was obtained in this turbine.

Although the results of the present investigation are too meager to disclose the mechanism by which the nozzle secondary flows induce these large losses in turbine efficiency, several effects may be suggested as contributors. First, the through-flow velocities of the fluid in secondary-flow core regions issuing from the nozzle are known from the results of reference 2 to be considerably lower than free-stream velocity; this results in large negative angles of incidence at the rotor inlet each time a rotor blade passes through a nozzle core, which may cause alternating separation and reattachment of the flow over the rotor blade if the boundary-layer response is sufficiently rapid. Another possible source of loss is the total-pressure loss resulting from the mixing of fluids of varying energy levels. Still another probable effect is that caused by the loss cores tending to deviate from the main stream in the rotor passage rather than being turned with the main stream (see ref. 3), which may displace the main-stream fluid and upset the rotor-blade-surface velocity distributions with consequent losses.

From these results, it appears that nozzle secondary flows are one of the major sources of loss for this turbine, and an appreciable improvement in performance might result from a reduction of secondary-flow vortices in the nozzles.

SUMMARY OF RESULTS

Detailed circumferential and radial surveys of total temperature and total pressure were made downstream of a turbine rotor at design operating conditions, and the pertinent results are as follows:

1. Local regions of high loss corresponding to nozzle secondary-flow vortices and wakes were observed downstream of the turbine rotor, effecting variations in local efficiency of 14 points.

2. This result indicates that nozzle secondary-flow vortices and wakes, even though they usually comprise only a small loss at the nozzle

outlet, can induce much greater losses in the turbine rotor and thus cause an appreciable effect on over-all turbine performance.

Lewis Flight Propulsion Laboratory
     National Advisory Committee for Aeronautics
         Cleveland, Ohio, February 3, 1954.

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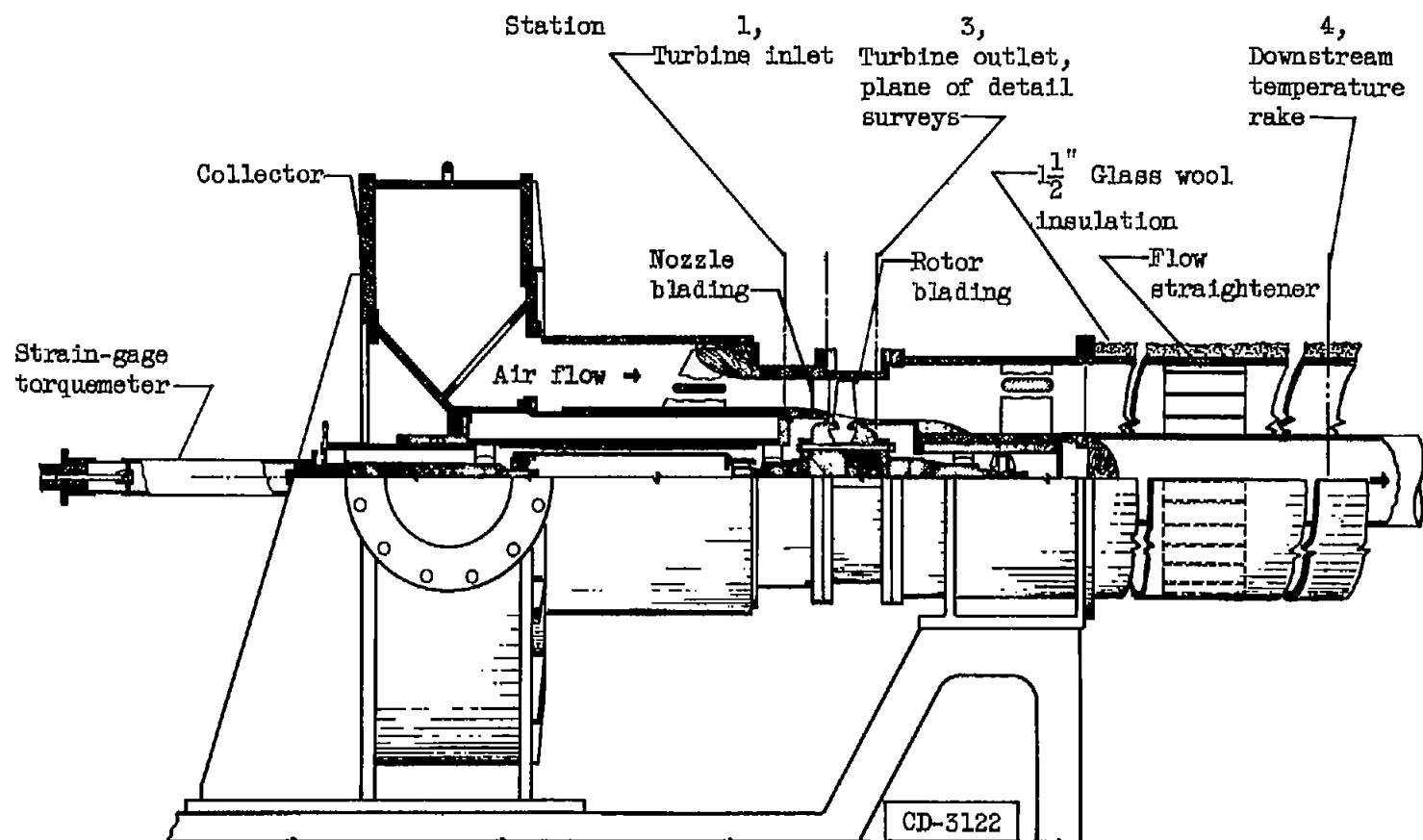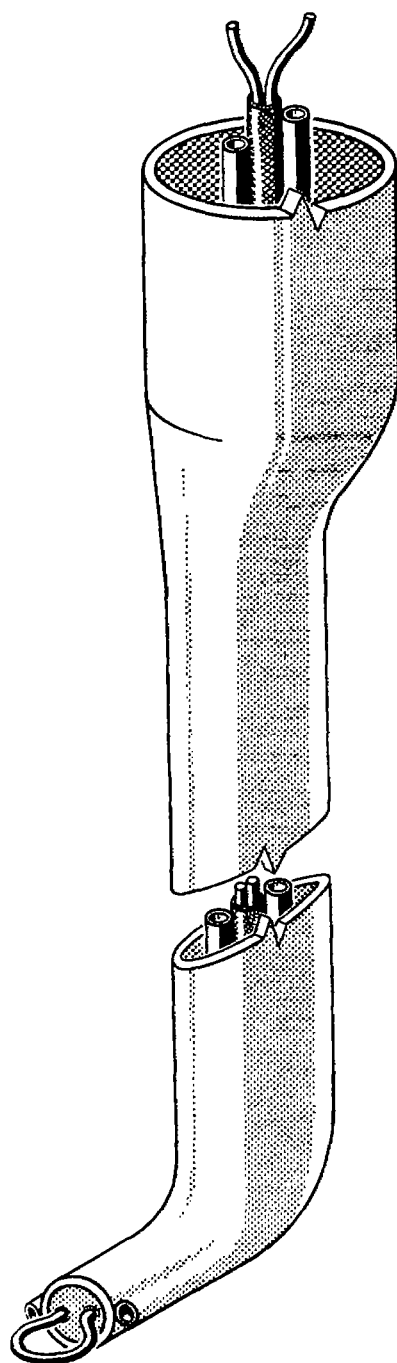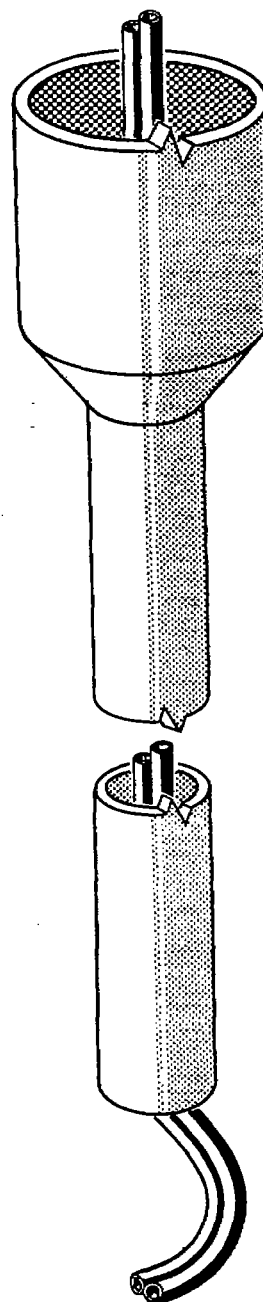
Figure 1. - Turbine test section.

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Directional thermocouple probe　　　　　　　　　　Total-pressure and angle probe

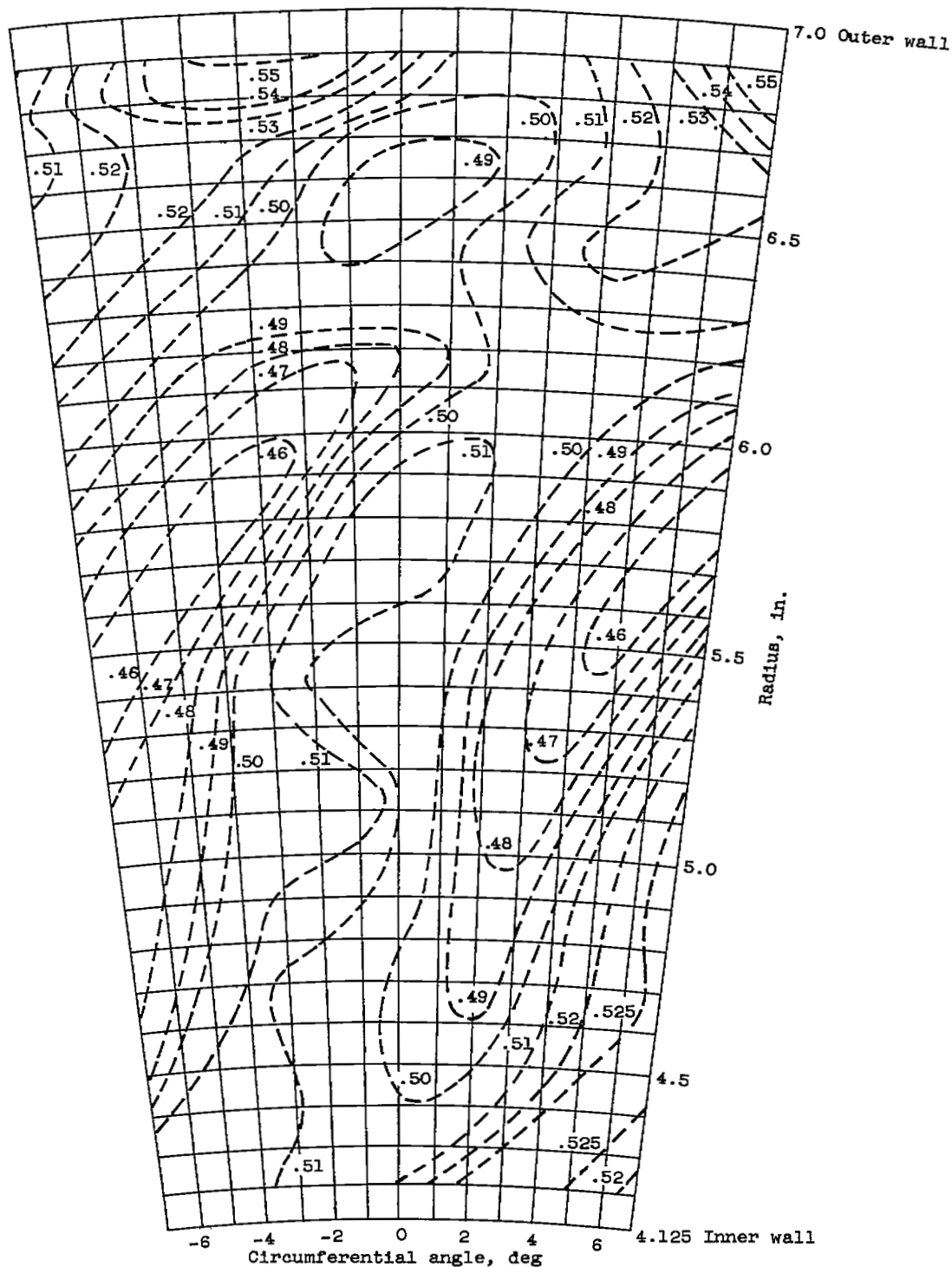Figure 2. - Instrumentation used to survey downstream of turbine rotor.

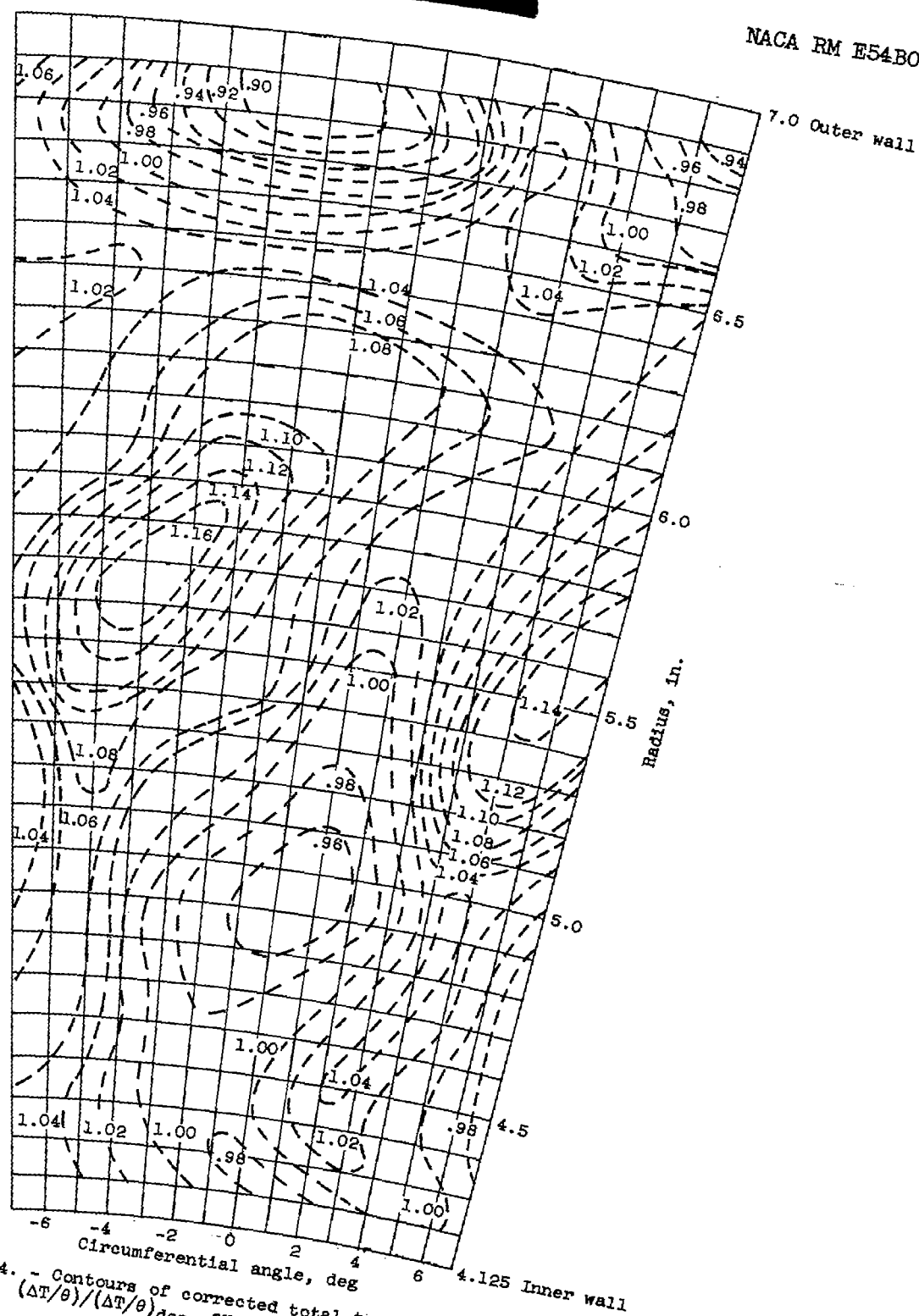Figure 3. - Contours of total-pressure ratio P_3/P_1 over survey range.

Figure 4. - Contours of corrected total-temperature-drop ratio $(\Delta T/\theta)/(\Delta T/\theta)_{des}$ over survey range.
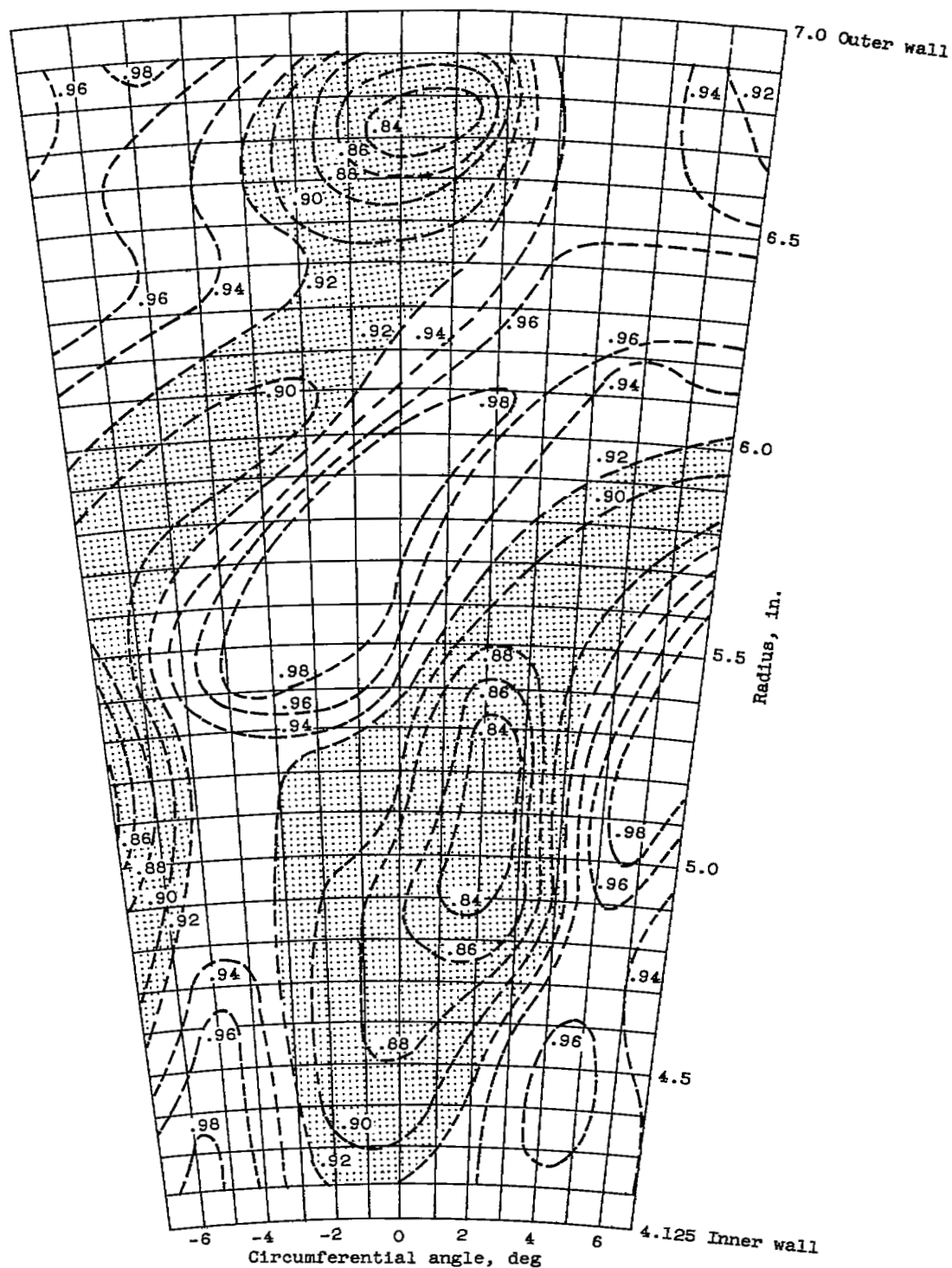
Figure 5. – Contours of local adiabatic efficiency η_B at station 3.