

RESEARCH MEMORANDUM

INVESTIGATION OF TURBOJET ENGINE PERFORMANCE AT
SPEEDS AND GAS TEMPERATURES ABOVE RATED USING
TURBINE-BLADE EXTERNAL WATER-SPRAY COOLING
FROM STATIONARY INJECTION ORIFICES

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NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

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The first part of the document discusses the importance of maintaining accurate records of all transactions. It emphasizes that every entry should be supported by a valid receipt or invoice. This ensures transparency and allows for easy verification of the data.

In the second section, the author outlines the various methods used to collect and analyze the data. This includes both primary and secondary data collection techniques. The analysis focuses on identifying trends and patterns over time, which is crucial for making informed decisions.

The third part of the document provides a detailed breakdown of the results. It shows that there has been a significant increase in sales volume, particularly in the online channel. This is attributed to the implementation of the new marketing strategy and the improved user experience on the website.

Finally, the document concludes with a set of recommendations for future actions. It suggests continuing to invest in digital marketing and exploring new product lines to further drive growth. Regular monitoring and reporting will be essential to track the success of these initiatives.

The data indicates a clear upward trend in revenue, which is a positive sign for the company's financial health. However, it is important to remain vigilant and address any potential risks or challenges that may arise.

Overall, the findings of this study are encouraging and provide a solid foundation for strategic planning. The company is well-positioned to continue its growth trajectory in the coming year.

Prepared by: [Name]
 Date: [Date]

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RESEARCH MEMORANDUM

INVESTIGATION OF TURBOJET ENGINE PERFORMANCE AT SPEEDS AND GAS TEMPERATURES ABOVE RATED USING TURBINE-BLADE EXTERNAL WATER-SPRAY

COOLING FROM STATIONARY INJECTION ORIFICES

By John C. Freche and Roy A. McKinnon

SUMMARY

As another phase of an investigation of external water-spray cooling of turbine rotor blades, a turbojet engine with a centrifugal-flow compressor which permitted overspeed, overtemperature operation was modified for spray cooling. A stationary water-injection configuration which consisted of two large (0.200-in. diam.) and two small (0.052-in. diam.) stationary orifices located in the inner ring of the stator diaphragm near the stator blade trailing edges was used. The effectiveness of spray cooling as a method which permits operation at overspeed, overtemperature conditions with this engine was investigated and the overspeed, overtemperature performance was obtained.

Operation with spray cooling was conducted over a range of speeds from rated (11,750 rpm) to approximately 107 percent rated and turbine inlet-gas temperatures up to 2000° F. At approximately 107 percent rated speed, 1940° F inlet-gas temperature, and a coolant-to-gas flow ratio of 0.029 (9070 lb of coolant/hr), both the blade root and midspan were apparently cooled satisfactorily. The average blade root temperature was about 200° F with a maximum temperature difference of 100° F existing between the blade leading and trailing edges. The average midspan temperature was approximately 600° F, and the maximum temperature difference between the leading and trailing edges was about 400° F. Substantial chordwise temperature differences, approximately 1000° F, occurred at the blade tip, between the midchord and the trailing edge. Several rotor blade failures occurred near the tip which could be attributed to thermal stresses induced by these temperature differences. The failures indicated the need for more uniform cooling at the blade tip, although the injection configuration employed may be satisfactory for limited application and appears promising for blades of shorter span.

Substantial thrust increases over the rated thrust condition were realized. At 107 percent rated speed and 2000° F inlet-gas temperature, the engine thrust obtained was 20 percent above rated. At the same operating point the specific fuel consumption was 21 percent above rated. Introduction of water into the gas stream at the turbine rotor inlet up to a coolant-to-gas flow ratio of 0.029 and overspeed, overtemperature operation apparently did not adversely affect turbine performance for this engine.

INTRODUCTION

Water-spray cooling of turbine rotor blades is being investigated at the NACA Lewis laboratory as a means of externally cooling the blade surfaces to permit turbine operation at elevated stress and temperature levels in order to provide increases in thrust for brief intervals. In the spray cooling process, a liquid is injected into the hot gas stream upstream of the turbine rotor and the liquid droplets are transferred by the gas stream onto the rotor blade surfaces where boiling occurs. The process thus utilizes the latent heat of vaporization of the liquid to cool the blades.

Several factors must be taken into consideration before spray cooling may be applied to an aircraft turbine engine installation. These are:

1. If spray cooling is to be of value, the turbine must be operated at gas temperatures and speeds above rated so that thrust increases may be realized (ref. 1).
2. Turbine operation over a range of gas temperatures above rated at a specific overspeed point requires a substantial operating margin between the compressor operating point and the compressor surge region, a design factor which determines whether a particular engine should be considered for a spray cooling application.
3. Turbine operation at speeds above design also requires that the turbine disk and compressor can safely withstand the elevated stress levels.
4. Since the coolant is expended in the gas stream, spray cooling is restricted to periods of short duration, such as take-off, climb, or combat manuever.
5. The rotor blade material must be able to withstand thermal shock and stresses induced by the sudden impingement of water sprays upon heated rotor blade surfaces.

An analytical and experimental investigation of water-spray cooling was made in reference 1. The analytical results indicated large potential gains in thrust if water-spray cooling could adequately cool the turbine rotor blades so that turbine operation at speeds up to 10 percent overspeed and at inlet-gas temperatures up to 2000° F could be tolerated. The analysis also indicated that if compressor water injection is employed at similar overspeed, overtemperature conditions together with spray cooling, still greater thrust increases would be possible, but the total liquid consumption would be considerably higher. The experimental results showed that the water-injection configurations employed for spray cooling produced large blade chordwise temperature differences, which may have been the cause of blade failures encountered at rated engine speed.

In reference 2 the results of an experimental investigation of water-spray cooling at rated engine speed are compared for several water injection configurations designed to improve the rotor blade temperature distributions observed in the investigation of reference 1. Large chordwise temperature differences were eliminated at the root and midspan blade sections with the use of the most favorable type of injection configuration described in reference 2. Use of this injection configuration resulted in a chordwise temperature difference of 100° F between the blade leading and trailing edges at the midspan and in an average blade midspan temperature of about 300° F at rated engine speed (11,500 rpm), a turbine inlet-gas temperature of about 1570° F, and a coolant-to-gas flow ratio of 0.0278 (7600 lb water/hr). The investigation of reference 2 was restricted to rated engine speed operation because of the mechanical strength limitations of the compressor.

An investigation was conducted with a later model engine which had a compressor that permitted overspeed, overtemperature operation to illustrate experimentally the turbine stress and gas temperature levels permissible with water-spray cooling. The engine was modified for spray cooling utilizing the most favorable type of injection configuration described in reference 2, and the results of this investigation are presented herein. The engine was operated over a range of speeds from rated (11,750 rpm) to 107 percent of rated and a range of turbine inlet-gas temperatures from 1566° to 2000° F with an approximately constant coolant-to-gas flow ratio of 0.029. At approximately rated engine conditions the coolant-to-gas flow ratio was varied from 0.015 to 0.031. Cooling-system, turbine, and engine performance were obtained over the range of engine operating conditions specified.

APPARATUS AND INSTRUMENTATION

A centrifugal-flow turbojet engine was modified for operation with external water-spray cooling. The test installation was similar to that

described in reference 2 except that a later model engine was employed and additional instrumentation was used to permit evaluation of turbine performance.

Apparatus

Engine. - The engine had a double-entry centrifugal-flow compressor, 14 cylindrical combustion chambers, and a single-stage turbine. The compressor in this engine was sufficiently strong to permit overspeed operation. The compressor air flow characteristics were such that a sufficient margin existed between the engine operating line and the surge region to permit a range of overtemperature operating points at each overspeed condition. The turbine rotor blades were made of S-816 alloy and had a nominal span of 4.25 inches. The nominal military rating of the engine was 4600 pounds of thrust with a rotor speed of 11,750 rpm and a tail-pipe gas temperature of 1265° F at sea-level, zero-ram conditions.

Engine installation. - The engine installation is illustrated in figure 1. A swinging frame engine mount suspended from the test cell ceiling was provided. The engine tail pipe extended through a diaphragm-type seal in the wall between the test cell and the sound-muffling chamber. A null-type air-pressure diaphragm was provided to balance and measure engine thrust. Engine inlet air was ducted from the atmosphere into the test cell through two 18-inch-diameter venturi meters. A clamshell-type variable-area exhaust nozzle was used to permit adjustment of tail-pipe temperature independent of engine speed. Cooling air from an external source was directed against the hub on the rear face of the turbine rotor in order to maintain the blade thermocouple-junction temperature below the melting point of the insulation employed, as indicated in reference 2. Cooling air was also directed against the front face of the rotor to help reduce the main turbine bearing temperature. A slip-ring thermocouple pickup was mounted on the engine accessory case to provide transition from the rotating thermocouples to the stationary potentiometer. The cooling-air-flow measurements were obtained by means of a standard flat-plate orifice.

Water-spray injection method. - The engine was modified to provide an injection configuration consisting of two large (0.200-in. diam.) and two small (0.052-in. diam.) orifices located in the inner ring of the stator diaphragm. Figure 2 shows a cutaway view of the engine which illustrates the relative axial position of the injection orifices which are located near the stator blade trailing edges. The orifices were spaced equally around the stator ring circumference with orifices of equal diameter located diametrically opposite each other. Although the most favorable type of injection configuration described in reference 2

was employed in this investigation, different orifice sizes were used in order to achieve the high coolant-flow rates desired. City water was again employed as the spray-cooling medium, and the water supply system was the same as that described in reference 1.

Instrumentation

Water coolant and engine fuel measurements. - Water-flow and engine fuel-flow rates were measured by calibrated rotameters.

Engine temperature and pressure measurements. - Figure 3 shows the location of the engine instrumentation stations. The number and type of instruments employed at each station are as follows:

- (a) Station 0 - engine inlet: one static tap and one thermocouple in quiescent zone of test cell
- (b) Station 1 - compressor inlet: 12 shielded thermocouples fastened to compressor inlet screens; six thermocouples were spaced approximately equally around the front screen and six around the back screen
- (c) Station 2 - compressor outlet: three combination total-pressure and total-temperature probes located upstream of combustion chambers 4, 9, and 13
- (d) Station 3 - turbine inlet: three combination total-pressure and total-temperature probes located in the transition sections between combustion chambers 4, 9, and 13 and the stator diaphragm
- (e) Station 4 - turbine rotor blades: 22 thermocouples on eight rotor blades located in 17 positions as shown in figure 4. Thermocouples at the root and tip sections were located $5/8$ inch from the base and tip sections, respectively
- (f) Station 5 - turbine exit: eight static taps, four on the outer and four on the inner shell of the tail cone located to form a helix and nominally spaced 1 inch apart both axially and circumferentially
- (g) Station 6 - tail pipe: a combination total-pressure, static-pressure, and thermocouple rake providing 22 total pressures, 10 total temperatures, and 5 static pressures
- (h) Station 7 - exhaust-nozzle discharge: three static-pressure tubes installed in the sound-muffling chamber in the plane of the exhaust nozzle

PROCEDURE

Engine Operation

The complete range of engine operating conditions reported in this investigation is presented in table I. The engine was operated without cooling over a range of speeds and inlet-gas temperatures up to rated at a constant exhaust-nozzle setting which provided the military rated tail-pipe-gas temperature of 1265° F. The engine was also operated at rated speed over a range of coolant flows and at overspeed with a constant coolant-to-gas flow ratio. At each overspeed point the exhaust nozzle was progressively closed from the wide open position until compressor surge was encountered. Thus a range of turbine inlet-gas temperatures was obtained at each speed setting. Manual adjustments of the water supply pressure provided the variations in coolant flow necessary to maintain an approximately constant coolant-to-gas flow ratio of 0.029. As in the investigations described in references 1 and 2, water sprays were turned on simultaneously with the engine starts to minimize thermal shock conditions in the blades.

Data Calculations

The calculation procedure for reducing the data obtained in this investigation to provide spray-cooling-process efficiency, turbine rotor blade stress level, and turbine and engine performance is as follows.

Spray-cooling efficiency. - The spray-cooling-process efficiency derived in reference 1 is expressed as

$$\sigma = K \left(\frac{T_{g,e}^{0.75}}{T_{B,av}} \right) \left(\frac{T_{g,e} - T_{B,av}}{\frac{w_w}{w_3} \cdot 0.75} \right) \quad (1)$$

(All symbols are defined in the appendix.) Equation (1) was evaluated for every operating point with spray cooling for which sufficient blade temperature data were available. In equation (1) the average blade temperature, $T_{B,av}$, was taken as the integrated average of the blade midspan temperatures. The blade root temperatures were not included because of thermocouple failures at the root position after several runs. The effective gas temperature, $T_{g,e}$ (average uncooled blade temperature), was calculated from turbine inlet conditions by the procedure of reference 3 which utilizes the relation

$$\Lambda = \frac{T_{g,e} - T_{g,3}}{T_{g,3}'' - T_{g,3}} = \frac{T_{g,e} - T_{g,3}}{\frac{W_3^2}{2Jgc_p}} \quad (2)$$

where Λ is taken as 0.86.

Blade stress level calculations. - A procedure was employed that provided for comparison of the blade operating stress levels at various overspeed, overtemperature conditions with the allowable stress values. The operating blade stress level at any overspeed condition was considered to be the tensile stress at the blade root and was determined from the calculated blade centrifugal load and the blade root cross-sectional area. The allowable blade stresses under conditions of spray-cooling operation were obtained from the average of measured temperatures around the blade root (available for several runs) and a curve of yield strength against temperature for S-816 alloy. Since it was not safe to operate the engine at overspeed, overtemperature without spray cooling, temperature data around the blade root could not be measured for the uncooled case. Consequently, for any designated overtemperature, overspeed condition without cooling, the value of $T_{g,e}$ was calculated from equation (2) and assumed to be equivalent to the average uncooled blade temperature as shown in reference 3. The allowable stress was then obtained by employing this temperature and a curve of 100-hour stress-to-rupture data against temperature for S-816 alloy. Stress-to-rupture data rather than yield strength data were employed because for the uncooled overspeed, overtemperature condition, the calculated blade temperature always exceeded the highest temperature (1200° F) for which yield strength data were available.

Turbine performance. - The turbine performance was expressed in terms of corrected specific turbine work and turbine efficiency. Turbine work was assumed equal to compressor work. Consequently, the corrected specific turbine work could be expressed as

$$\frac{\Delta H_T^i}{\theta_3^*} = \frac{H_3^i - H_5^i}{\theta_3^*} = \frac{w_1(H_2^i - H_1^i)}{w_3\theta_3^*} \quad (3)$$

In equation (3) the enthalpies at the compressor inlet and outlet were obtained from chart I of reference 4 and the temperatures, from an average of the thermocouples at stations 1 and 2 (fig. 3). The weight flow at the compressor inlet w_1 was obtained by the addition of the measured air flow through the test cell venturi meters and the test cell leakage

as determined from a prior calibration. Weight flow at the turbine inlet w_3 was taken as the sum of the compressor air flow and the fuel flow and was expressed as

$$w_3 = w_1 + w_f \quad (4)$$

The turbine-inlet temperature T_3' was required to obtain θ_3^* . This temperature was determined by solving the following equation for the specific enthalpy H_3' at the turbine inlet and employing chart II of reference 4:

$$w_1 H_2' + w_f \eta_b \bar{H}_f = w_3 H_3' \quad (5)$$

The preceding equation was obtained by transforming equation (8) of reference 4 to the nomenclature employed in this report and neglecting the enthalpy of the entering fuel $w_f \bar{H}_f$. In equation (5) the combustion efficiency η_b was considered to be 95 percent, and the heating value of the fuel \bar{H}_f , 18,750 Btu per pound.

The turbine adiabatic efficiency was defined as

$$\eta_T = \frac{H_3' - H_5'}{H_3' - H_{5,i}'} \quad (6)$$

The procedure for obtaining H_3' has already been discussed. With a knowledge of H_3' , the term H_5' may be determined from equation (3). The term $H_{5,i}'$ was obtained by the procedure of reference 4 using the turbine total-pressure ratio P_5'/P_3' and T_3' . The turbine-inlet total pressure P_3' was taken to be the average of the total-pressure probe readings at station 3 (see fig. 3). The turbine-outlet total pressure P_5' was calculated from continuity and isentropic relations from the static pressure measured at station 5 (see fig. 3). At this station the measured static pressures obtained on the outer and inner shells of the tail cone were plotted against their axial distance downstream of the turbine blades. The value chosen for conversion to total pressure was taken as the average of the inner and outer shell readings at the point where the pressure level became constant. The area A_5 , employed in the continuity relation was the cross-sectional flow area at the station where the pressure level became constant (station 5). The total temperature of the gas, corrected for heat loss to the water, $T_{5,c}'$, was determined from the following equation and the charts of references 4 and 5:

$$\frac{w_5 H_5' - w_w c_{p,w} (T_{BP} - T_w) - 0.25 w_w H_{ev}}{w_5} = H_{5,c}' \quad (7)$$

where

$$w_5 = w_3 + w_a \quad (8)$$

and H_{ev} and T_{BP} were evaluated at the static pressure P_5 . On the basis of previous experimental experience, 25 percent of the water was assumed evaporated. The enthalpy values for the water and the vapor were obtained from reference 5. The injected water was assumed to reduce the total temperature of the gas at station 5, but was not included in the total weight flow at that station.

Engine performance. - The engine performance was expressed in terms of corrected thrust, corrected specific fuel consumption, and engine temperature ratio. The corrected thrust was calculated from the following equation:

$$\frac{F}{\delta_1} = \frac{w_6 V_7}{\delta_1 g} = \frac{w_6}{\delta_1} \sqrt{\frac{2\gamma_6 R T_6'}{g(\gamma_6 - 1)} \left[1 - \left(\frac{P_7}{P_6'} \right)^{\frac{\gamma_6 - 1}{\gamma_6}} \right]} \quad (9)$$

where

$$w_6 = w_5 + w_w \quad (10)$$

The static pressure in the muffler (station 7, fig. 3) rather than the static pressure at the tail-pipe rake (station 6, fig. 3) was used in determining the velocity term in equation (9) because station 6 was upstream of the exhaust-nozzle exit. No conditions of supercritical pressure ratio were encountered; however, the muffler pressure was higher than the cell pressure. Since the engine was producing this pressure difference, it was credited with the added thrust available. The additional thrust expressed in equation form is

$$F = A_6 (P_7 - P_0) \quad (11)$$

where A_6 equals the cross-sectional area of the tail pipe (fig. 3). The thrust increment so obtained was added to that obtained from equation (9) after applying the pressure correction for NACA sea-level standard conditions. Values of thrust obtained as described were compared with the measured values obtained from the null-type air-pressure diaphragm.

The second engine performance parameter employed, the corrected specific fuel consumption, was defined as $3600 w_f / F \sqrt{\theta_1^*}$. The engine temperature ratio was defined as the ratio of the absolute total gas temperature at the turbine inlet, determined from equation (5), to the absolute total air temperature at the compressor inlet (an average of the thermocouple readings at station 1, fig. 3).

RESULTS AND DISCUSSION

Cooling system performance, turbine performance, and engine performance results are presented and discussed in the following sections.

Cooling System Performance

Blade temperature distributions. - Chordwise temperature distributions around the blade root, midspan, and tip, obtained with an approximately constant coolant-to-gas flow ratio of 0.029 at three turbine speeds, 98, 106, and 107 percent of rated speed (turbine inlet-gas temperatures of 1623°, 1832°, and 1940° F, respectively), are presented in figure 5. Broken lines are used to connect the temperature data points where an intermediately located thermocouple had failed. At each spanwise station the chordwise temperature distributions follow a different trend. A virtually flat temperature distribution occurs at the root with no noticeable difference in temperature level for the three speeds. At 107 percent of rated speed the average blade root temperature is about 200° F with a maximum temperature difference of 100° F existing between the blade leading and trailing edges. At the midspan the temperature curves remain relatively flat except for a dip near the leading edge. An increase in temperature level is also apparent with an increase in speed. At the condition of 107 percent rated speed the average midspan temperature was approximately 600° F, and the maximum difference between the leading and trailing edge temperatures was about 400° F. At the blade tip a marked deviation from a flat curve is apparent with temperature differences of about 1000° F occurring between the midchord and the trailing edge on both the blade pressure and suction surfaces. In general, a slight increase in temperature level also occurs with speed at this spanwise station. The most significant features of these temperature distributions are (a) the relatively flat nature of the curves at the highly stressed root and midspan sections and (b) the relatively sharp increase in temperature between the midchord and trailing edge at the blade tip. Condition (b) is also indicated in reference 2.

The necessity for eliminating chordwise temperature differences at the highly stressed root and midspan sections is discussed in detail in reference 2. The injection configuration employed is apparently satisfactory at overspeed conditions for the midspan and root sections, since

no failures occurred at these locations. The presence of temperature differences of the magnitude encountered at the blade tip was at first not considered significant since this portion of the blade is not highly stressed. After approximately $7\frac{1}{2}$ hours of operation, however, blade failures of the type shown in figure 6 were encountered. The portion of the blade broken off corresponds to the portion subjected to the large chordwise temperature differences. The failure appears to be directly traceable to the thermal stresses introduced in the trailing-edge tip region. Therefore, although the injection configuration employed permitted overspeed, overtemperature operation and eliminated some of the high thermal stresses previously encountered with spray cooling, the configuration is not entirely satisfactory for the blades of this engine. For blades of shorter span, however, the injection configuration employed in this investigation appears promising. Since unfavorable chordwise temperature differences occurred at the blade tip, injection from the outer ring of the stator diaphragm or from the tail cone appeared to be a method of eliminating these differences. Such injection configurations have been investigated and some of them are described in reference 2. The results, however, were unsatisfactory in that these temperature differences were not substantially reduced.

It should be noted that the $7\frac{1}{2}$ hours elapsed operating time prior to the first blade failure consisted in large part of overspeed, overtemperature operation. Since an aircraft spray-cooling application is limited to brief intervals, perhaps of 1 minute duration, the water injection configuration employed may be satisfactory for limited application. The effect on blade life of short periods of spray-cooling operation with the attendant thermal stresses introduced by chordwise temperature differences is unknown. Consequently, spray cooling with the type of injection configuration described herein should be applied with caution.

Spray-cooling efficiency. - The cooling efficiency σ of the injection configuration employed is plotted in figure 7 against a cooling

parameter $\left(\frac{T_{g,e}^{0.75}}{T_{B,av}^{0.425}} \right) \left(\frac{T_{g,e} - T_{B,av}}{\frac{w_w}{w_3} 0.75} \right)$ for the entire engine operating

range. The cooling parameter represents the experimental evaluation of the variables on the right side of equation (1). The value of the constant K in equation (1) was determined in reference 1 and found to be 1.024×10^{-6} at rated engine speed. Since the terms entering into the determination of K (weight flow, heat-transfer coefficient, turbine inlet-gas temperature, and so forth) change with engine speed, the constant

would appear to have different values for each overspeed considered. Unpublished calculations performed for this engine for a speed range below rated indicate that the constant remained unchanged. The range covered in these calculations represented a greater increment of speed than the speed increase above rated reported herein. On this basis K was assumed to be constant over the speed range investigated, and the spray-cooling-process efficiency was calculated accordingly. In figure 7 it can be seen that the experimentally evaluated cooling parameter extended approximately from 1.0×10^5 to 3.0×10^5 . This range included effective gas temperatures up to 1720° F and corrected engine speeds up to 107 percent of rated. This represents an effective gas temperature increase of approximately 300° F over the experimental limit previously attained with this general type of injection configuration in reference 2.

It should be noted that the blade temperature and the coolant flow for a given injection configuration are related by the efficiency σ . Since σ must be evaluated experimentally for any injection configuration on a given engine, the values presented in figure 7 are not applicable to the design of spray-cooling systems for other engines. The efficiency values presented in figure 7 are, however, indicative of the efficiency level attainable with this general type of injection configuration over a wide range of operating conditions with this engine.

Blade stress characteristics. - A comparison of the allowable blade root stress with spray cooling ($\dot{w}_w/\dot{w}_3 = 0.029$) and without spray cooling at various conditions of overtemperature is shown in figure 8. Superimposed are the operating centrifugal stress levels for 100 and 107 percent rated speed, respectively. At approximately rated conditions, effective gas temperature of 1300° F (inlet-gas temperature of 1545° F), the allowable blade root stress is 41,000 pounds per square inch for uncooled blades, which is well above the rated speed operating stress of 25,700 pounds per square inch. As the effective gas temperature increases from 1300° to 1720° F, the allowable stress decreases for the uncooled condition from 41,000 to 9,000 pounds per square inch, which is well below the 100 percent rated speed operating stress level. At an effective gas temperature of 1720° F, which is equivalent to a turbine inlet-gas temperature of 2000° F, the allowable blade root stress with spray cooling is 59,500 pounds per square inch, well above the operating stress level indicated for both 100 and 107 percent rated speed. This figure graphically illustrates that uncooled operation at gas temperature levels more than 150° F above rated is impossible with the engine under investigation on the basis of 100 hour stress-to-rupture data for the blade material. In general, production jet engines are similarly designed so as to operate near the allowable stress limit of the blade material. Consequently, to obtain thrust increases by overspeed, over-temperature operation, a method, whereby appreciable increases in the allowable stress limit of the blade material at elevated temperatures

can be realized, is required. Spray cooling achieves this aim in part by drastically reducing the average blade temperature. Although the average blade temperature is reduced, failure-inducing thermal stresses are also introduced by spray cooling which are not reflected in a stress determination such as shown in figure 8.

Turbine Performance

It should be noted that even though this engine was instrumented to obtain turbine performance data it was not primarily operated in that manner. As stated previously, the engine was operated at a series of corrected engine speeds with variable exhaust-nozzle areas to obtain thrust data. As a result, none of the conventional turbine performance parameters (turbine efficiency, corrected specific work, corrected tip speed, and pressure ratio) was held constant. Consequently, the results could not be produced in the form of a turbine performance map. However, these parameters were evaluated from the data, and two of them, turbine adiabatic efficiency and corrected specific work, are listed in table I. Thus the magnitude of these parameters and the variation encountered at all conditions of spray-cooled operation are indicated. In order to provide a comparison with uncooled turbine performance at rated operating conditions, the uncooled turbine efficiency and corrected specific turbine work at approximately rated conditions were calculated and are listed in table I. The adiabatic efficiency for uncooled rated conditions was determined using the gas measurements at the tail-pipe rake (station 6, fig. 3) because no instrumentation was available immediately downstream of the turbine (station 5, fig. 3) during the uncooled runs. This procedure probably results in a slightly lower efficiency value than one obtainable using pressures immediately downstream of the turbine because whatever pressure losses exist in the tail cone are charged to the turbine. However, the efficiency value obtained (0.782) is of an order of magnitude similar to that shown in unpublished data for earlier models of this engine and appears valid for qualitative comparison with the efficiencies obtained at overspeed, overtemperature conditions. The specific turbine work at rated uncooled conditions was determined in the same manner as the overspeed, overtemperature cooled data because calculation of the corrected specific turbine work was not affected by lack of knowledge of the gas conditions immediately downstream of the turbine. The turbine efficiencies obtained at all conditions of overspeed, overtemperature operation with spray cooling ranged from 0.757 to 0.793, as shown in table I. Comparison of these values with the uncooled efficiency (0.782) indicates that for this engine no drastic loss in turbine adiabatic efficiency is experienced as a result of the combination of water injection at the rotor inlet and overspeed operation. It is also apparent that the specific work values obtained at overspeed, overtemperature with spray cooling are of the same order of magnitude as the

value obtained at the uncooled rated condition. For this engine the results indicate that the combination of water injection into the gas stream at the rotor inlet and overspeed, overtemperature operation does not adversely affect turbine performance.

Engine Performance

Uncooled engine performance. - The uncooled engine performance over a range of corrected engine speeds from idle to approximately rated is shown in figure 9. Figure 9(a) shows the variation of engine thrust with speed, and figure 9(b) shows the variation of specific fuel consumption with engine speed. The experimental results obtained in the present investigation are compared with the military rated values. Slightly higher than military rated values were obtained and the differences were less than 5 percent for both thrust and specific fuel consumption. The close agreement indicates that the investigation procedure is satisfactory and experimentally establishes base conditions for comparison with overspeed, overtemperature results.

The values of thrust shown in the figures of this report were all calculated from data measurements by the methods discussed previously. In all cases prior comparison was made between these values and those measured with the null-type air-pressure diaphragm. Agreement was good in all instances, the average variation being approximately 5 percent.

Cooled engine performance. - The engine performance with cooling is illustrated in figures 10 and 11. The corrected engine thrust obtained at overspeed, overtemperature conditions with a constant coolant-to-gas flow ratio of 0.029 is plotted against engine temperature ratio in figure 10. Individual curves are presented for four corrected engine speed conditions, 101, 103, 106, and 107 percent of rated. The dotted line indicates the approximate condition of compressor surge which limits the maximum gas temperature attainable at each overspeed condition with this engine. As indicated by analysis (ref. 1), gains in thrust result from higher mass flows and increases in gas temperature. The maximum thrust increase above rated was 20 percent and was obtained at 107 percent of rated speed with an engine temperature ratio of 4.72. The latter value is equivalent to a turbine inlet-gas temperature of 2000° F with a compressor-inlet temperature of 60° F. This relatively substantial gain over the rated condition was obtained at a cost of approximately 18 gallons per minute of coolant.

The 20 percent thrust increase obtained experimentally compares with an increase of 32 percent predicted for a similar engine in the analysis of reference 1. This difference may be explained by the assumptions contained in the analysis. A basic limitation of the analytical procedure was the use of an idealized compressor performance map for calculating

thrust at overspeed, overtemperature conditions. In the present case, portions of the compressor map were constructed from experimental data obtained at engine overspeed, overtemperature conditions. When the analytical procedure of reference 1 and the experimentally determined portions of the compressor map were employed, calculations of thrust increase attainable with this engine were found to agree within 2 percent of the experimental values.

The cost in terms of fuel requirements is illustrated in figure 11. The corrected specific fuel consumption for each overspeed condition is plotted against engine temperature ratio. At the maximum operating condition considered the increase in corrected specific fuel consumption was 21 percent above the rated value. The shapes of the curves are such that the lowest value of corrected specific fuel consumption does not occur at the maximum engine temperature ratio. Reference to figure 10 indicates that in some cases very nearly maximum thrust may be obtained at a given overspeed condition by operation at less than the maximum engine temperature ratio. It may be advantageous in certain instances to operate with slightly lower thrust in order to reduce specific fuel consumption. The data are insufficient to establish the optimum thrust and specific fuel consumption relations at various overspeed conditions for this engine. The trends of the curves serve to indicate, however, that it would be advantageous to determine such relations in any spray-cooling engine application intended to permit overspeed, overtemperature operation.

The overspeed, overtemperature performance investigation was limited to operation with spray cooling only. A phase of operation with a combination of compressor water injection and spray cooling was initiated, but a stator blade burnout occurred early in the test. In view of this and the adverse chordwise temperature differences encountered on the rotor blades at the tip, further operation was deferred pending continued investigation of methods to eliminate the rotor blade temperature differences.

SUMMARY OF RESULTS

The following results were obtained from an investigation of water-spray cooling of turbine rotor blades in a turbojet engine with a centrifugal-flow compressor which permitted engine operation at speeds and gas temperatures above rated:

1. At all overspeed, overtemperature conditions the blade root and midspan were apparently cooled satisfactorily with an injection configuration consisting of two large (0.200-in. diam.) and two small (0.052-in. diam.) stationary orifices located in the inner ring of the stator

diaphragm at a coolant-to-gas flow ratio of 0.029. Substantial chordwise temperature differences, up to 1000° F, occurred at the blade tip between the midchord and the trailing edge with this configuration at the same operating conditions.

2. After $7\frac{1}{2}$ hours of operation several rotor blade failures occurred near the tip which could be attributed to thermal stresses induced by large chordwise temperature differences. These failures indicated the need for providing more uniform cooling at the blade tip, although the injection configuration employed may be satisfactory for limited application and appears promising for blades of shorter span.

3. Substantial increases over the rated thrust condition were realized with overspeed, overtemperature operation. At 107 percent rated speed the engine thrust obtained was 20 percent above rated, and a corresponding increase in corrected specific fuel consumption of 21 percent was noted.

4. The combination of the introduction of water into the gas stream at the turbine rotor inlet up to a coolant-to-gas flow ratio of 0.029 and overspeed, overtemperature operation apparently did not adversely affect turbine performance for this engine.

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

APPENDIX - SYMBOLS

The following symbols were used in this report:

A	area, sq ft
c_p	specific heat at constant pressure, Btu/(lb)(°R)
F	thrust, lb
g	gravitational constant, 32.2 ft/sec ²
H	specific enthalpy, Btu/lb
\bar{H}_f	average heating value of fuel, 18,750 Btu/lb
J	mechanical equivalent of heat, 778.2 ft-lb/Btu
K	constant, (lb/sec) ^{0.25} /°R ^{1.225}
p	pressure, lb/sq ft
R	gas constant, 53.3 ft-lb/(lb)(°R)
T	temperature, °R or °F
V	absolute velocity, ft/sec
W	velocity relative to rotor, ft/sec
w	weight flow, lb/sec
γ	ratio of specific heat at constant pressure to specific heat at constant volume
δ	pressure-correction ratio, P'/P'_s
η_T	turbine adiabatic efficiency
η_b	combustion efficiency
θ^*	temperature-correction ratio, $\frac{\left(\frac{2\gamma}{\gamma+1} gRT'\right)}{\left(\frac{2\gamma}{\gamma+1} gRT'\right)_s}$

Λ temperature recovery factor
 σ spray-cooling-process efficiency

Subscripts:

a cooling air
av average
B blade
BP boiling point
c corrected for heat loss to the water
e effective
ev evaporation
f fuel
g gas
i ideal
s NACA sea-level standard conditions
w water
0-7 engine stations

Superscripts:

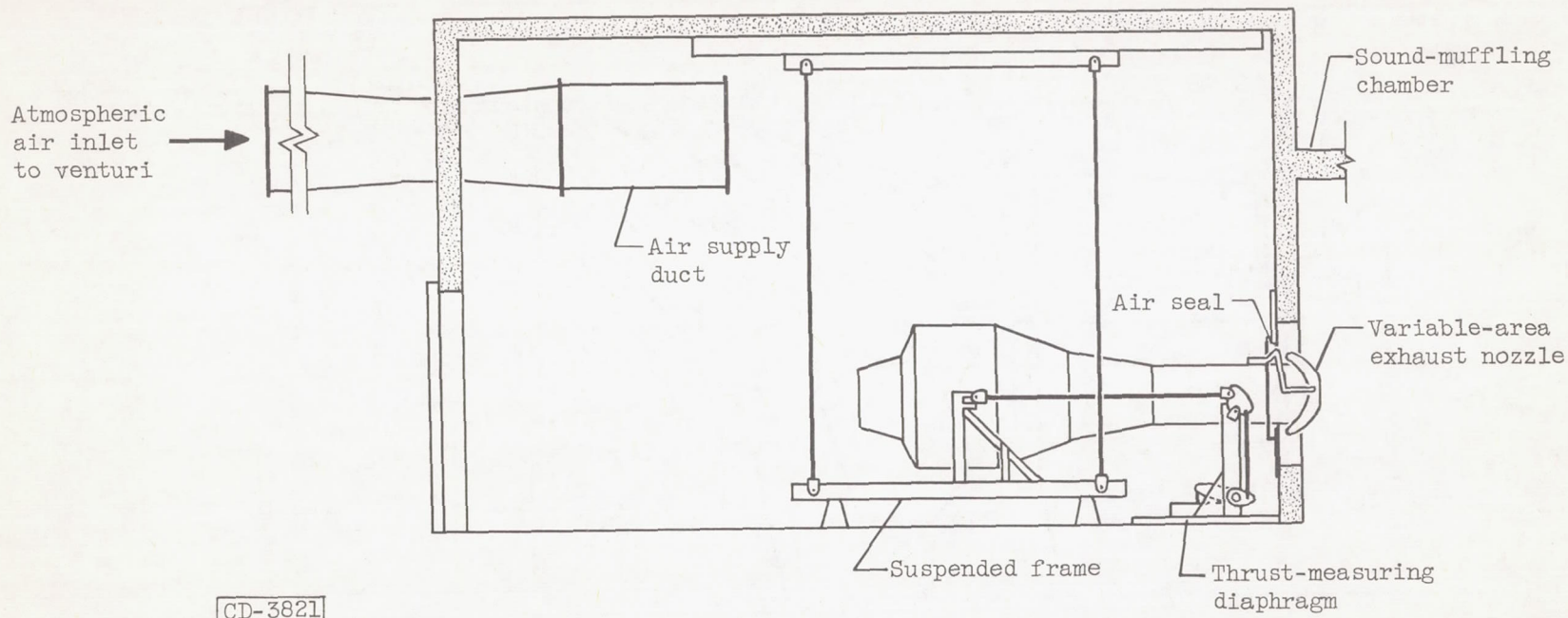
' indicates total or stagnation conditions absolute
" indicates total conditions relative to rotor

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4. English, Robert E., and Wachtl, William W.: Charts of Thermodynamic Properties of Air and Combustion Products from 300° to 3500° R. NACA TN 2071, 1950.
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TABLE I. - RANGE OF OPERATING CONDITIONS

Corrected engine speed, $\frac{N}{\sqrt{\theta_3^*}}$	Turbine-inlet temperature, T_3' $^{\circ}\text{F}$	Coolant-to-gas flow ratio, $\frac{w_w}{w_3}$	Turbine adiabatic efficiency, η_T	Corrected specific turbine work, $\frac{\Delta H_T'}{\theta_3^*}$, Btu/lb
11565	1545	0	0.782	22.86
11075	1356	0	-----	-----
10435	1295	0	-----	-----
9833	1185	0	-----	-----
8853	1109	0	-----	-----
6932	977	0	-----	-----
4944	955	0	-----	-----
11539	1623	.0291	.794	22.13
11510	1625	.0311	.786	22.06
11556	1618	.0201	.804	22.45
11553	1595	.0150	.797	22.33
11834	1566	.0297	.778	23.85
11835	1664	.0298	.790	23.04
11846	1691	.0295	.792	22.70
11856	1746	.0301	.793	22.31
12170	1697	.0291	.757	23.74
12080	1755	.0297	.786	23.15
12125	1815	.0292	.781	22.74
12451	1832	.0287	.767	23.82
12356	1910	.0297	.772	22.84
12429	1940	.0285	.770	22.89
12659	1940	.0284	.760	23.49
12586	2000	.0296	.775	22.75



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Figure 1. - Schematic diagram of engine installation.

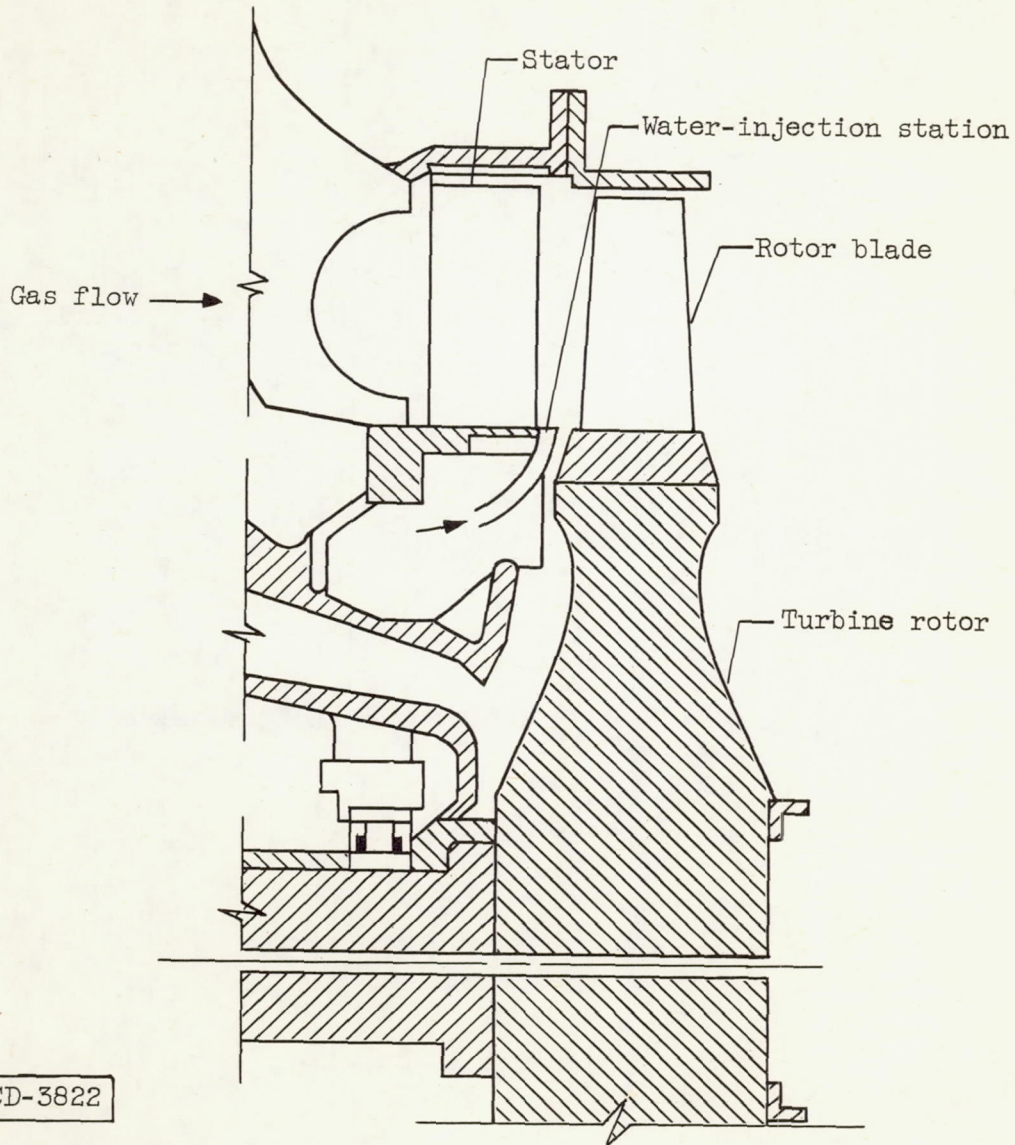


Figure 2. - Section of engine showing axial location of water-injection configuration investigated.

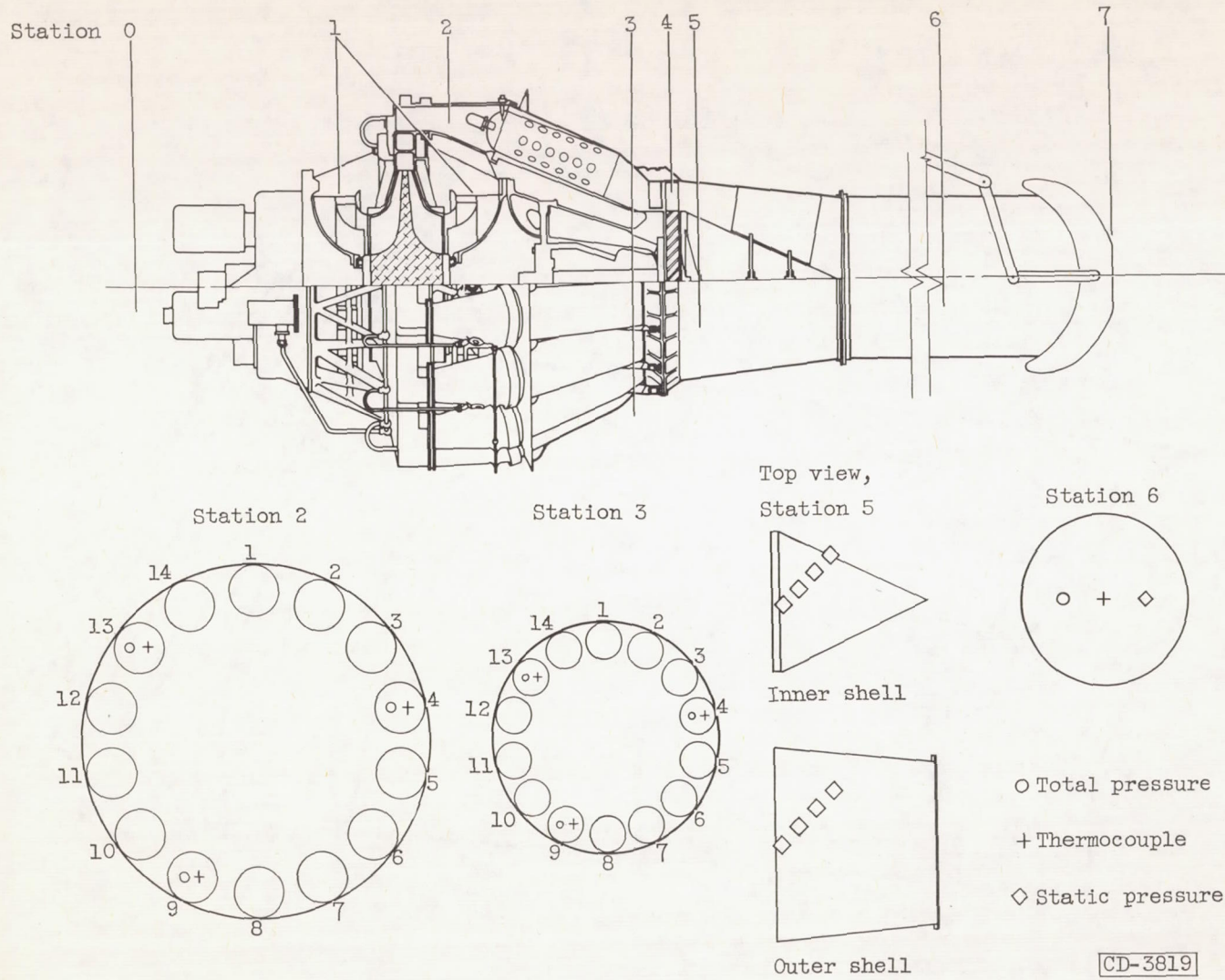
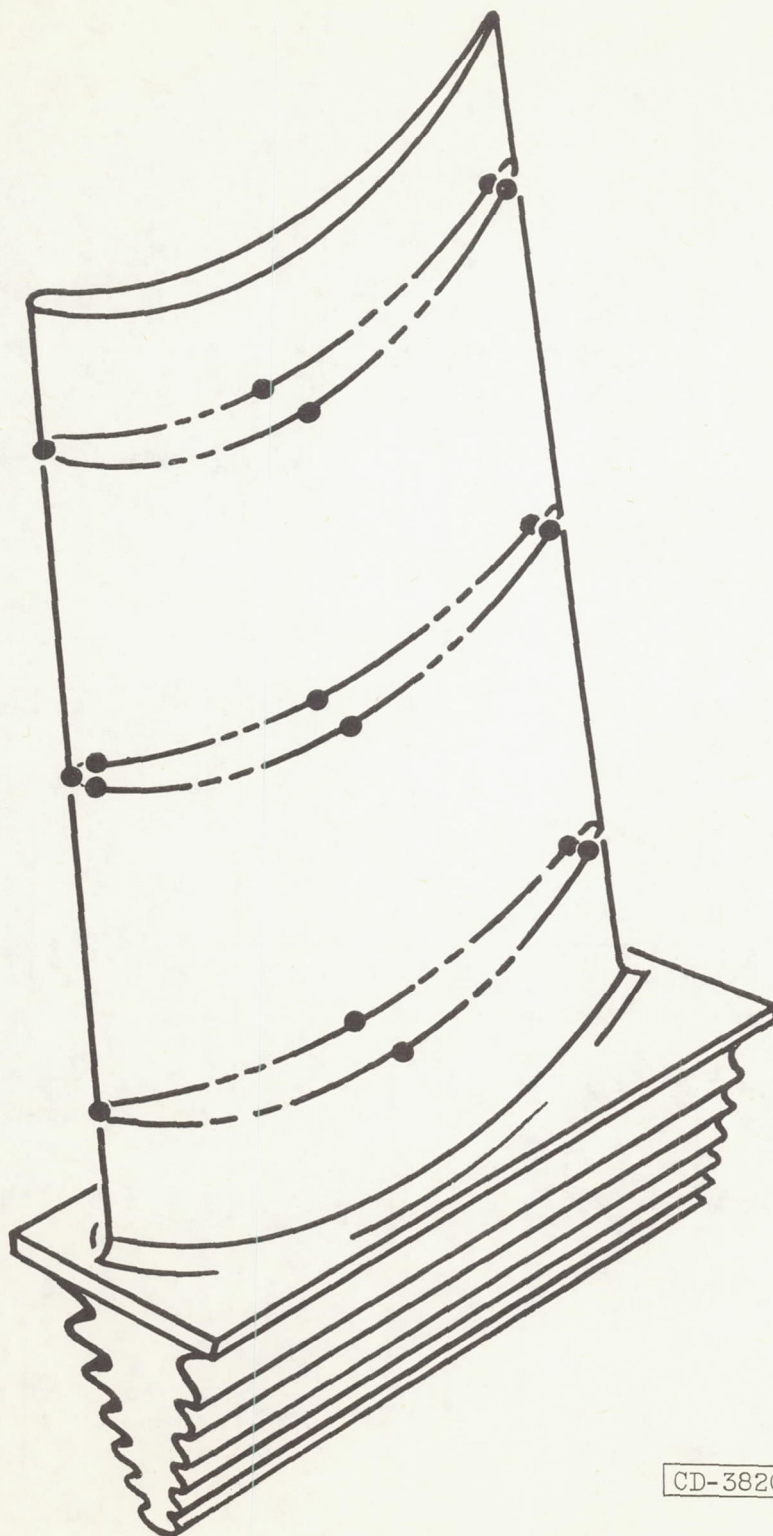


Figure 3. - Schematic diagram of engine showing instrumentation stations.



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Figure 4. - Thermocouple positions on turbine rotor blades.

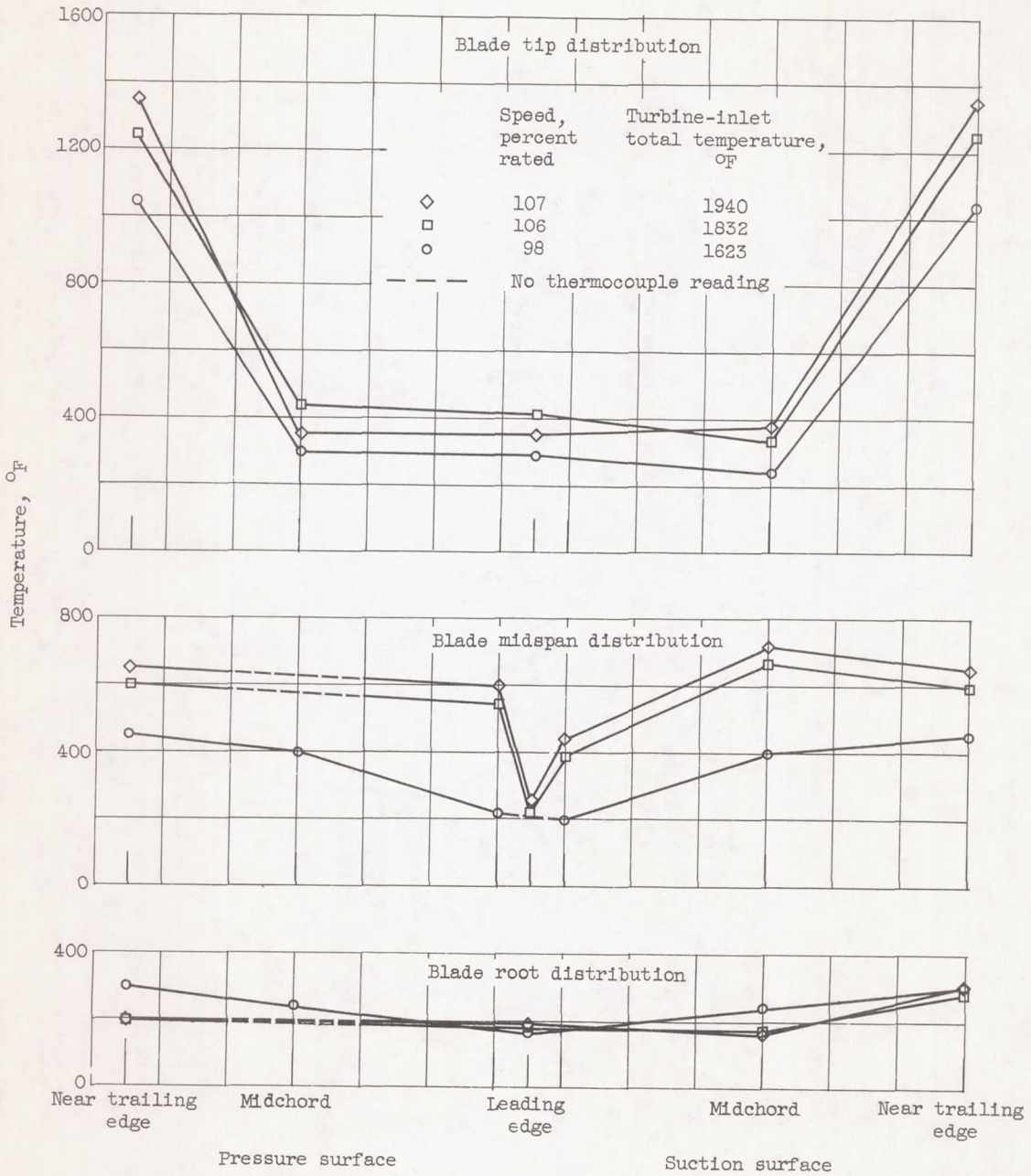


Figure 5. - Typical experimental blade temperature distributions obtained at overspeed, overtemperature conditions with a spray coolant-to-gas flow ratio of 0.029.

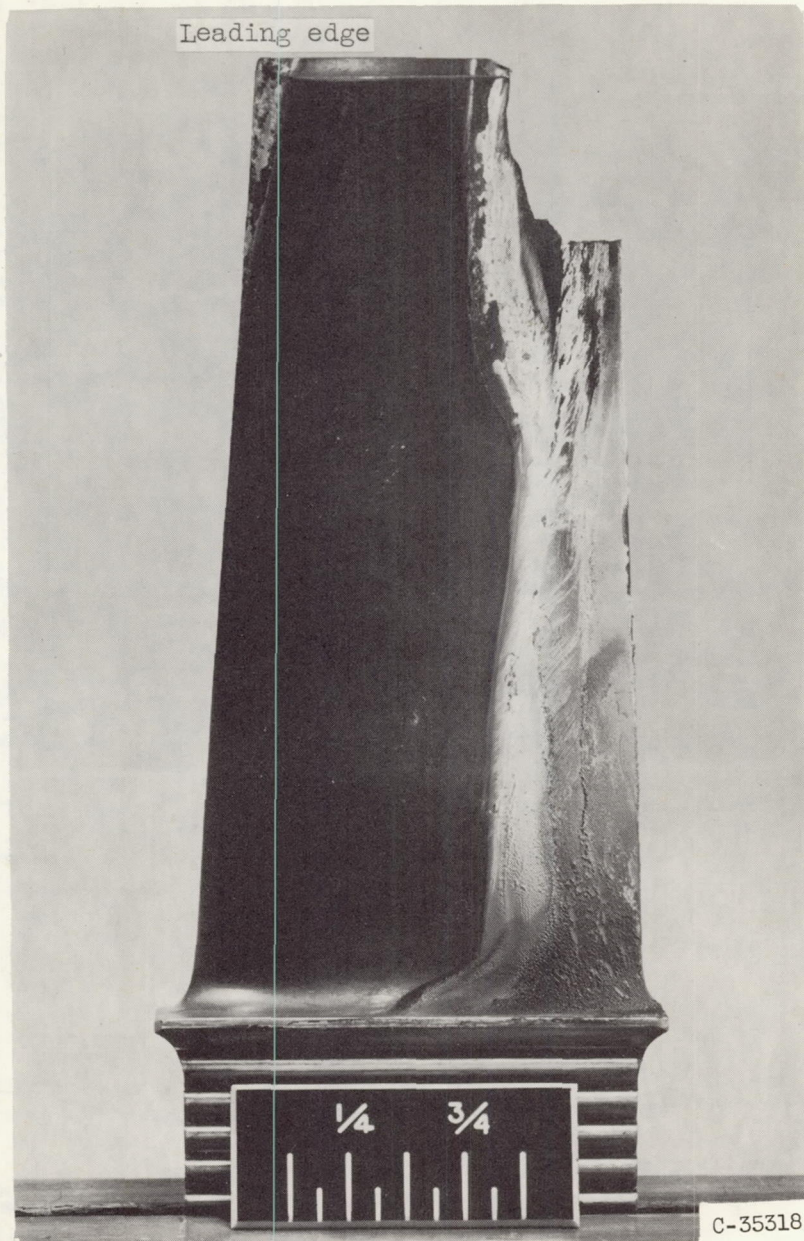


Figure 6. - Experimental blade failure encountered with spray cooling at overspeed, overtemperature conditions.

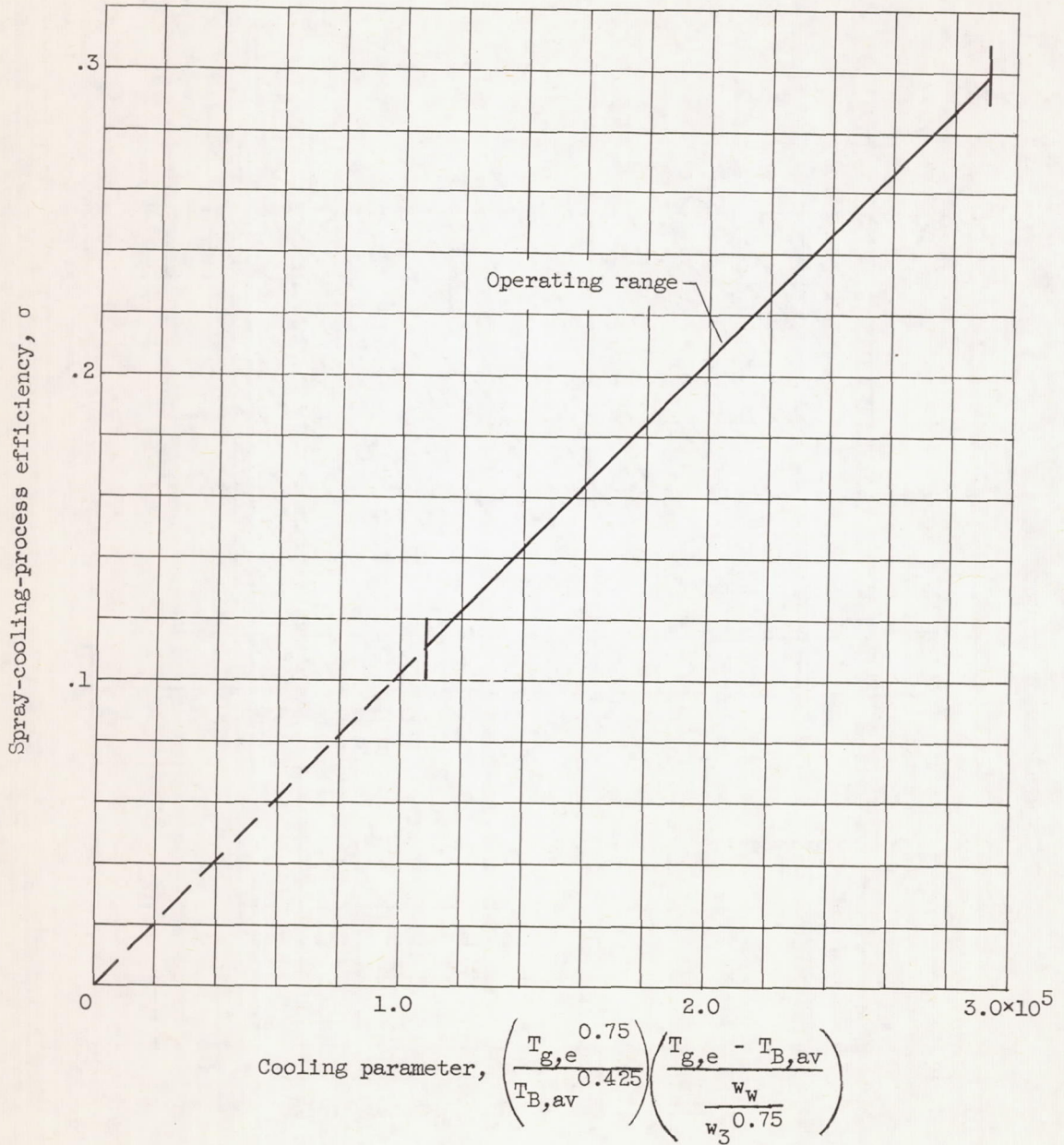


Figure 7. - Spray-cooling efficiency of injection configuration employed as a function of cooling parameter.

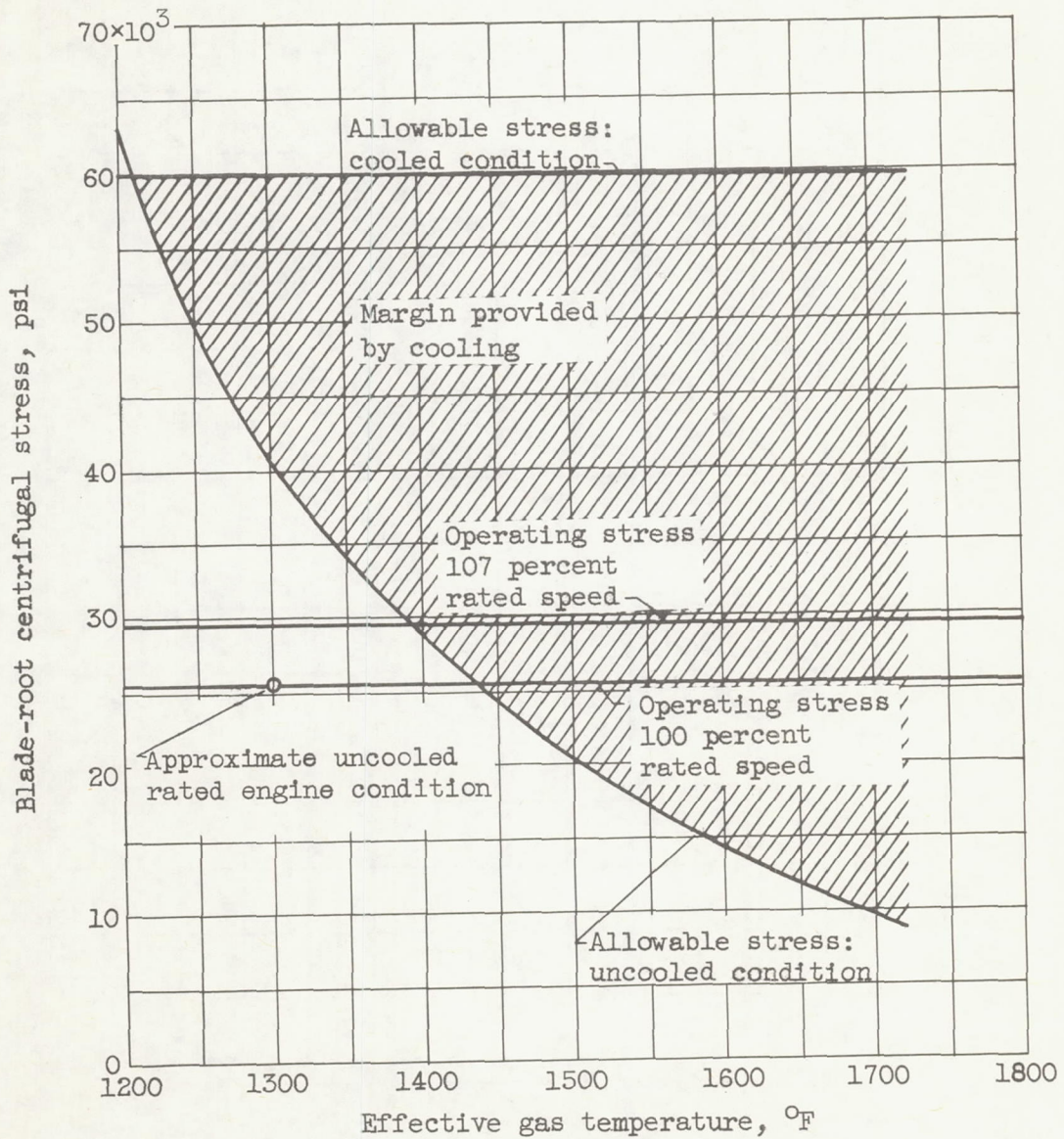
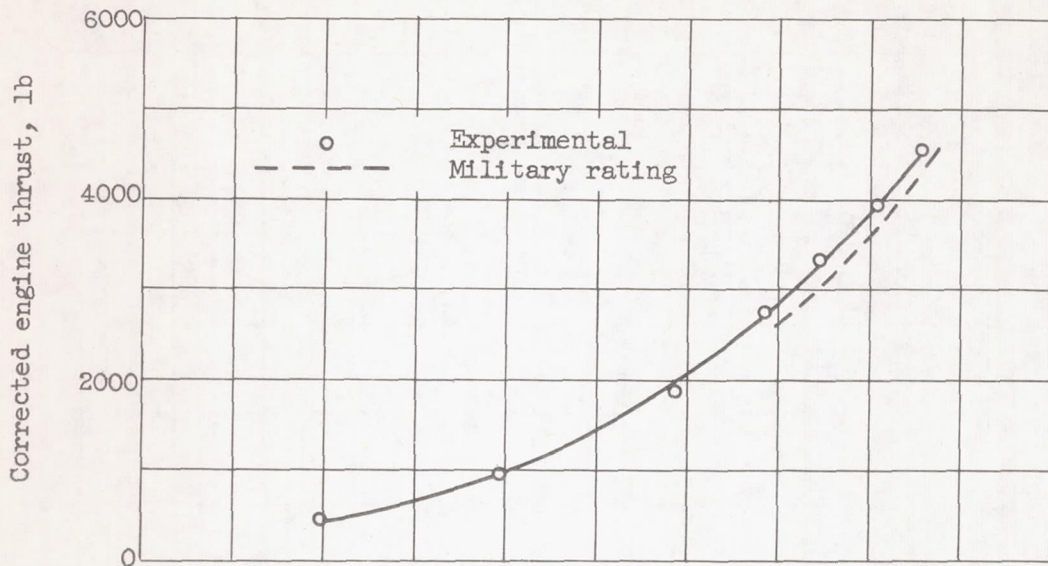
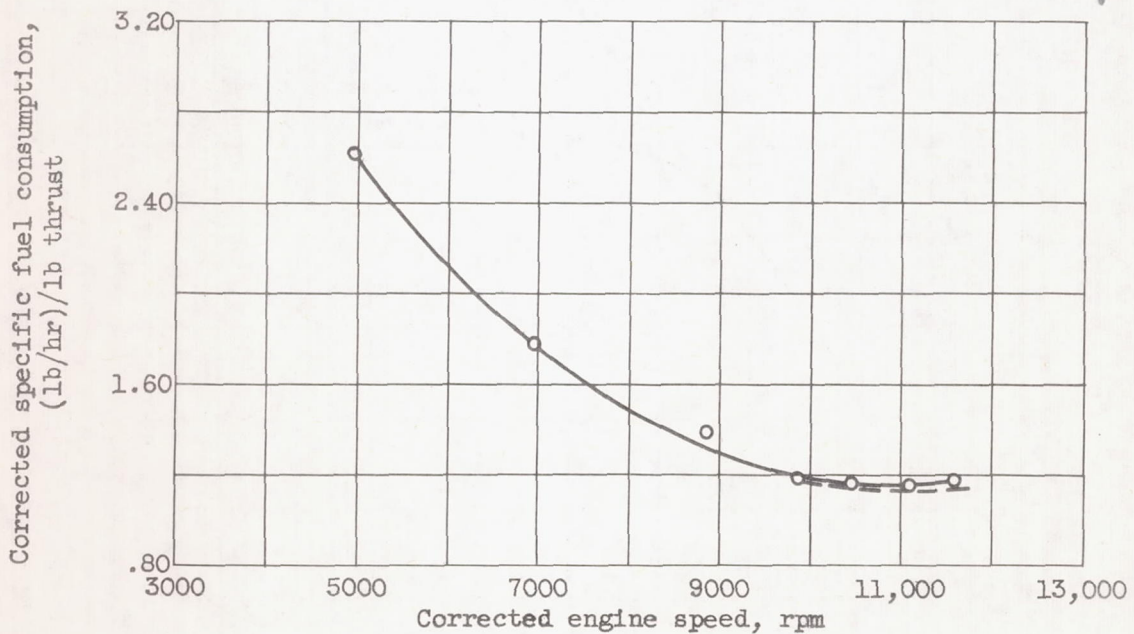


Figure 8. - Comparison of allowable blade-root stress with and without spray cooling as determined from yield strength and 100-hour stress-to-rupture data.



(a) Engine thrust.



(b) Specific fuel consumption.

Figure 9. - Uncooled engine performance.

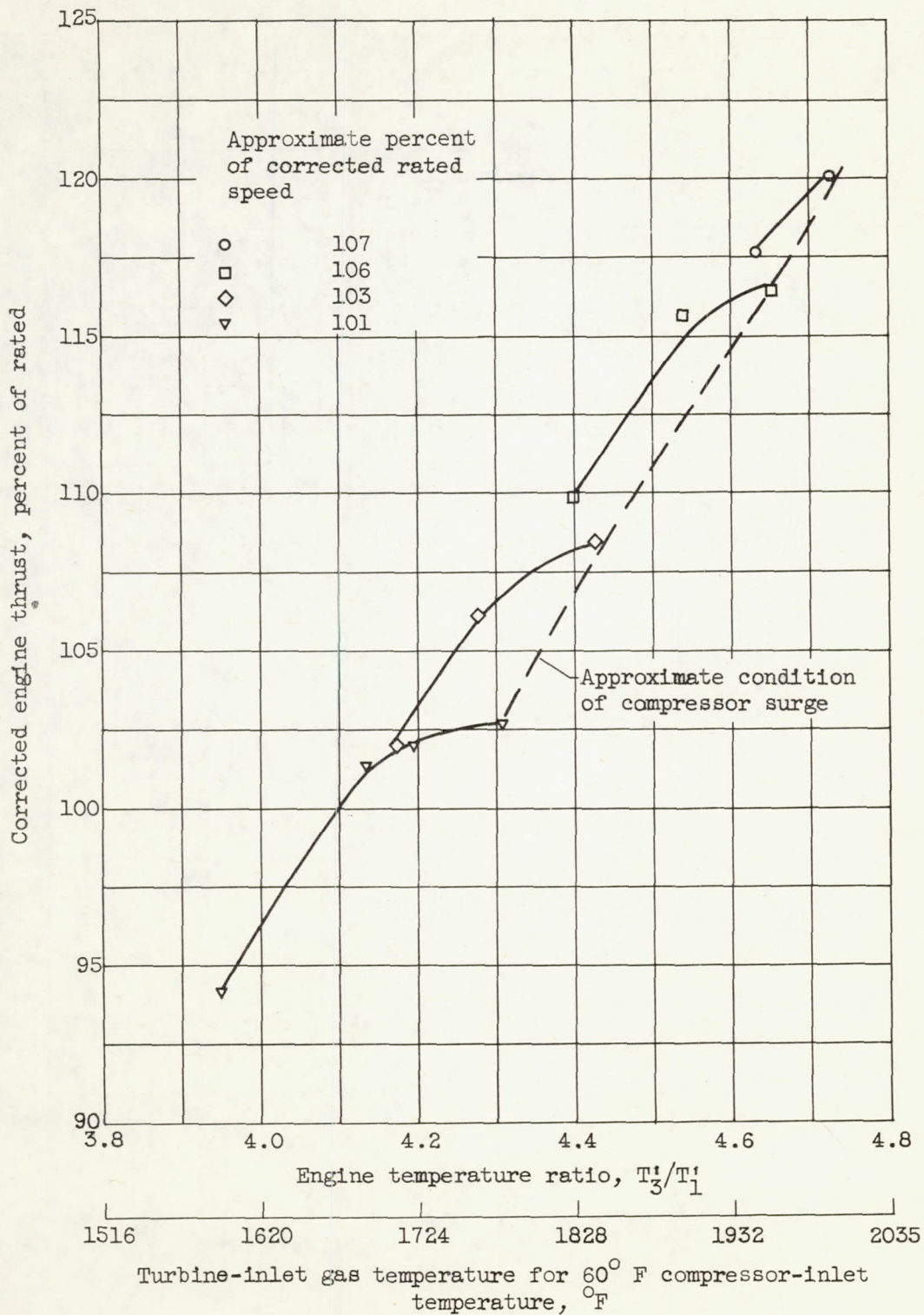


Figure 10. - Engine thrust at overspeed, overtemperature conditions with coolant-to-gas flow ratio of 0.029.

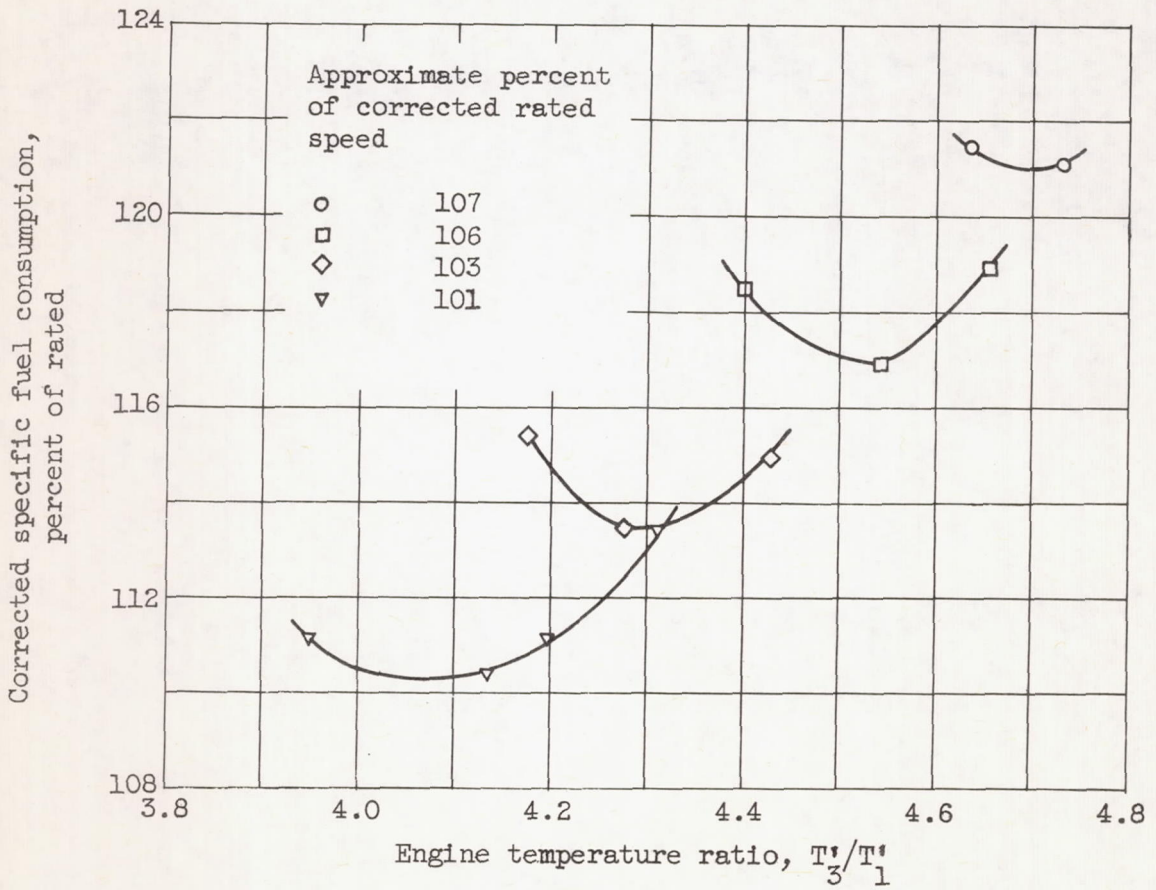


Figure 11. - Engine corrected specific fuel consumption at overspeed, overtemperature conditions with spray coolant-to-gas flow ratio of 0.029.

