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LIFE PREDICTION OF TURBINE COMPONENTS: ON-GOING STUDIES AT THE NASA LEWIS RESEARCH CENTER

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An overview is presented of the many studies at NASA-Lewis that form the turbine component life prediction program. This program has three phases: (1) development of life prediction methods for major failure modes through materials studies, (2) evaluation and improvement of these methods through a variety of burner rig studies on simulated components, and (3) application of a unified life prediction method to prototype turbine components in research engines and advanced rigs. These three phases form a cooperative, interdisciplinary program. A bibliography of Lewis publications on fatigue, oxidation and coatings, and turbine engine alloys is included.

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Lewis Research Center

SUMMARY

The purpose of this report is to present an overview of the many studies at the NASA Lewis Research Center which together form the turbine component life-prediction program. This program has three phases: (1) development of life prediction methods for each of the major potential failure modes through a wide range of materials studies, (2) evaluation and improvement of these methods through a variety of burner rig studies on simulated components, and (3) application of a unified life-prediction method to prototype turbine components in research engines and advanced rigs.

In different temperature ranges, different properties become dominant in determining engine component life. The resistance of materials to fatigue, creep, and oxidation are being determined through closely controlled laboratory tests. In addition to conventional testing machines, specialized equipment has been developed to obtain material properties under simulated engine environments. For example, automatic cycling furnaces are used to determine changes in weight, surface chemistry, microstructure, and oxide scale. Fluidized beds are used to study thermal-fatigue cracking in various alloys and coatings and to evaluate fatigue-life theories.

Because the engine environment is much more aggressive than that in furnaces or fluidized beds, it can cause important changes in material behavior. Tests in high-velocity burner rigs have shown drastic increases in weight loss, consumption of coatings, and creep rates. Large decreases have been found in rupture and fatigue lives. Thus, rig and furnace test data must be integrated before the lives of engine components can be predicted.

Computer codes are now being developed that consider fatigue, creep, and oxidation life prediction in a unified manner. The first two of these failure modes are now included in a computer code called THERMF1. With this code, thermal-fatigue life can be calculated for known temperature and deformation cycles using conventional mechanical properties. THERMF1 has been verified with a wide variety of laboratory and rig tests. Studies are in progress to extend this code to include failure by coating consumption during long hold times at elevated temperature.

A bibliography of Lewis publications in the fields of fatigue, oxidation and coatings, and turbine engine alloys is included in this report.

INTRODUCTION

The Lewis Research Center is the principal NASA laboratory for research and development of aerospace propulsion systems. A major goal of Lewis is to advance the technology of aircraft gas turbine engines, from component details to complete systems. One highly complex area of special importance is the prediction and improvement of the life of turbine blades and vanes. The purpose of this report is to present an overview of the many studies at Lewis that together form the turbine component life-prediction program.

The program has three phases: (1) development of life prediction methods for major potential failure modes through a wide range of materials studies, (2) evaluation and improvement of these methods through a variety of burner rig studies on simulated components, and (3) application of a unified life prediction method to prototype turbine components in research engines and advanced rigs. These three phases form a cooperative, interdisciplinary program involving mission analysis, fluid and solid mechanics, thermodynamics, metallurgy, and statistics.

Predicting the lives of turbine components is complicated by the complex geometry of the parts themselves. Typical air-cooled components are shown in figure 1. These are small, intricate, thin-walled structures acting both as highly loaded airfoils and high-flux heat exchangers. They must perform this dual role at extreme metal temperatures, in an oxidizing atmosphere, and, in the case of blades, while moving at speeds approaching sonic velocities. Moreover, they are routinely subjected to vibration and to severe transient loading during frequent starts and stops. Finally, a failure in one of these critical components can quickly escalate to loss of performance and, potentially, to the loss of an engine.

Figure 2 shows the complex internal geometries required for advanced cooling methods (refs. 1 and 2), that make the modern cooled turbine airfoil a costly as well as a critical component. Thus, the ability to predict and eventually improve the life of a turbine blade or vane can result in higher performance, lower engine and maintenance costs, and increased safety.

In general, the scope of this review will be limited to those studies at Lewis that include both turbine components and life prediction. A number of other Lewis publications provide comprehensive reviews of related areas: references 1 to 3 review efforts on aircraft gas turbines; references 4 to 8 review efforts to understand and develop better turbine materials; and references 9 to 11 deal with the areas of stress analysis and fatigue.

A bibliography of related NASA-Lewis publications is included in this report. It includes sections on fatigue, on oxidation and coatings, and on turbine engine alloys.

TURBINE COMPONENT LIFE-PREDICTION PROGRAM

Potential Failure Modes

The major potential failure modes for turbine components are presented schematically in figure 3. Stresses high enough to produce premature fracture or buckling are generally avoided by a preliminary elastic stress analysis. The long-term failure mechanisms are those that dictate life. At temperatures below approximately 800° C mechanical fatigue is often the dominant failure mode. The engine environment usually exerts only a second-order influence in this temperature range. At the higher temperatures, above about 1000° C, creep, oxidation, and thermal fatigue (acting alone or together) usually cause failure. Environmental effects are dominant in this temperature range. In the intermediate temperature range, 800° to 1000° C, any of the several failure modes shown in the figure can be dominant, depending on the structure, the material, and the engine cycle. This temperature range is particularly critical for sulfidation, a failure mode of importance for marine gas turbines.

Protective coatings can alter the mode of failure and extend the life of the component until the coating itself is depleted by oxidation or cracked by fatigue. Generally, mechanical fatigue and creep form an upper bound on life, for a given application. Although figure 3 is merely a schematic representation of possible interactions of the major failure modes, it does illustrate that several failure mechanisms combine to produce a region of available life. One of the goals of life-prediction methods is to define this region.

Phases of the Life-Prediction Program

The three major phases of the Lewis life-prediction program for turbine components are illustrated in figure 4. These phases are in various stages of development, as will be discussed in subsequent sections of this report. The first phase includes materials tests such as uniaxial tensile, creep, and mechanical fatigue. These tests are conducted on very simple specimens and are supplemented by static and cyclic furnace oxidation studies. Basic methods for predicting life have been developed from the resulting data. Thermal-fatigue tests on relatively simple wedge specimens in fluidized beds are used to evaluate these methods.

In the second phase of the program, evaluation of life-prediction methods continues in burner rig tests directed toward a better simulation of the hot gas environment of an engine. Wedge specimens are used to study cyclic oxidation behavior and to evaluate methods for predicting coating life. Airfoil specimens are used to evaluate thermal-fatigue life predictions in a simulated engine environment for complex geometries. As a result of burner rig tests, the life-prediction techniques are expanded or modified to integrate additional factors such as high gas velocity, rapid temperature transients, stress concentrations, combustion products, etc.

The third and final phase of the program is the prediction of lives for prototype components tested in engines and rigs. This provides the best evaluation of life-prediction methods and the first step in developing improved turbine components.

PHASE I: DEVELOPMENT OF PREDICTION METHODS THROUGH MATERIALS STUDIES

The purpose of the first phase of the general program is to develop a prediction method for each of the potential failure modes in its "pure" form and then to integrate these methods into a unified life-prediction technique. Each failure mode requires detailed study to understand the damage mechanisms and to describe the damage process quantitatively. Quantitative description is the basis of any life-prediction method.

Materials studies are usually conducted on small samples (coated and uncoated) under carefully controlled laboratory conditions. These conditions are seldom as severe as engine service unless temperatures, stresses, or environments are deliberately altered to accelerate damage. The assumption is made that the engine environment may increase damage rates, but the damage mechanisms remain the same. Thus, life-prediction methods developed from materials studies must provide for the changing of rates to suit engine service.

Basic Mechanical Tests and Data Analysis

Test procedures for obtaining conventional tensile, creep-rupture, and mechanical-fatigue data are widely used and well documented. These tests are usually isothermal, and they provide the basic strength and deformation information that characterize the material. Methods have been developed for interpolation and extrapolation of these data. For example, time-temperature parameters for the analysis of creep-rupture data have been studied extensively at Lewis (refs. 12 to 14). Methods are also required for applying isothermal test data to cycles that are not isothermal. Two such methods now being used to predict thermal-fatigue life are the Method of Universal Slopes (ref. 15) for mechanical fatigue and the Method of Life Fractions for creep (refs. 14 and 16).

Method of Universal Slopes. - This is an empirical equation relating cyclic life to strain range, using tensile ductility, ultimate tensile strength, and Young's modulus. It is used to predict failure in the pure fatigue mode. Temperature is assumed to affect fatigue life indirectly, through its effect on tensile properties. Time effects such as creep and oxidation are assumed to be absent. For nonisothermal cycles, the temperature in the cycle that gives the shortest calculated life is used.

Method of Life Fractions. - This is a rule for calculating creep-rupture life under cyclic conditions of temperature and stress. The cycle is divided into small time intervals, each having a nominal temperature and stress, and thus a nominal rupture time. The fraction of life consumed in each interval is then assumed to be the ratio of the interval time to the rupture time. The life fractions are summed for a complete cycle to obtain the damage per cycle. The reciprocal of this sum is assumed to be the cyclic life in the pure creep mode.

Other methods for characterizing the resistance of materials to low-cycle fatigue are being studied at Lewis. One of the most promising of these is Strainrange Partitioning (refs. 17 and 18). With this method, any inelastic strain cycle, no matter how complex, can be subdivided into four basic components. These components are unique combinations of plastic and creep strains. They are related independently to cyclic life by equations that are generalizations of the well-known Manson-Coffin equation. A linear life fraction rule is used to sum the damages resulting from each of the strain range components. Failure is assumed to occur when the summation of life fractions equals unity. This method has the potential of guiding the generation of fatigue data (ref. 17), improving the understanding of fatigue mechanisms, and interpreting the effects of frequency, hold time, temperature, and environment.

Oxidation Testing in Furnaces

The vast majority of oxidation studies have been conducted under isothermal, noncyclic conditions so as to continuously measure weight gain of oxygen per unit area of the specimen. These data were then used to calculate an oxygen pickup or scale growth rate constant, a number long used as an index of oxidation resistance. Recently, a few programs have explored the influence of thermal cycling on the scaling and spalling behavior of turbine alloys (refs. 20 and 21). Such studies have shown that thermal cycling accelerates surface attack, promotes spalling of oxide scales, and eventually results in weight loss rather than gain in the specimen. Of special importance is the observation that protective coatings are often consumed during thermal cycling, when isothermal tests showed little or no consumption. For these reasons, Lewis has adopted the use of cyclic furnace testing of coated turbine alloys as the first step in establishing their oxidation resistance and coating behavior.

A typical cyclic oxidation furnace facility is shown in figure 5. Specimens are suspended from platinum wires to minimize the influence of the support material on oxide scale composition. Each specimen is in its own tube to eliminate cross contamination from oxide vapors. The transfer mechanism lifts the specimens out of the furnace for slow cooling to room temperature. A small cup is moved into place beneath each specimen so that the oxide spall can be collected for analysis. Cycles are usually 1 hour long, to approximate an average flight cycle. Furnaces of this type are operated around the clock, unattended, with periodic interruptions for weighing of specimens and collecting of spalled oxide.

Cyclic oxidation tests indicate that coating failures are usually preceded by the thinning and subsequent breaking up of a key protective layer or phase (refs. 22 and 23). These observations are described in more detail in the appendix and have led to the concept of "layer break-up" for predicting coating life. This concept is now in its early stages of development. Hopefully, it will provide a model for the calculation of the pure coating life from its composition and the cyclic environment.

Thermal-Fatigue Testing in Fluidized Beds

The thermal-fatigue resistances of various alloys and coatings are being determined under contract at the Illinois Institute of Technology Research Institute, using the fluidized-bed technique (refs. 24 and 25). The objectives of this continuing program are (1) to determine the comparative resistances of the latest alloys, coatings, and claddings of interest for turbines, and (2) to provide carefully controlled data for development and evaluation of life-prediction methods.

Figure 6(a) is a schematic view of the facility and of a typical group of double-wedge specimens. Two beds are used, one each for heating and cooling. A bed consists of a retort filled with fine sand through which air is pumped. The flow of air causes the sand particles to develop a churning, circulating action. The large mass of the beds and their mixing action promote uniform, high heat-transfer rates, making them ideal for thermal-fatigue studies. Fluidized beds were first used for this purpose at the National Gas Turbine Establishment in England in 1958. Since that time the technique has become widely accepted for evaluating both materials and components.

Typical data on some turbine materials are shown in the bar chart in figure 6(b). The most crack resistant alloys were either directionally solidified or coated or both. Tests continue on the best of these alloys plus 20 new alloys and conditions, bringing to 38 the total number of systems being evaluated.

Figure 6(c) shows a typical comparison between calculated and observed thermal-fatigue lives. The method of life calculation is explained briefly in the next section. The alloy is B 1900, with and without an aluminide coating. Tests of this type have verified the life-calculation method for simple thermal-fatigue tests of the fluidized-bed type.

Toward a Unified Life-Prediction Method

The materials testing phase of the program has led to the conclusion that a life-prediction method for turbine components must unify fatigue, creep, and oxidation. The first two of these failure modes have already been combined in a computer code for predicting thermal-fatigue life. Figure 7 shows a schematic diagram of this code which is called THERMF1. Calculations start with a thermal and stress analysis for both transient and steady-state conditions, including plasticity and creep. This is often the most difficult step in the life analysis of a complex component. On the basis of this analysis, two lives are calculated: (1) a fatigue life, using the Method of Universal Slopes and the tensile properties of the material, and (2) a cyclic creep life, using the Method of Life Fractions and the creep-rupture properties of the material. These two methods were described briefly at the beginning of this section. The fatigue and creep lives are then combined to give the thermal-fatigue life, assuming a simple linear interaction (refs. 26 and 27).

Figure 8 shows the progress to date in using THERMF1 to calculate the thermal-fatigue lives of coated and uncoated specimens tested in fatigue machines, fluidized beds, and burner rigs (ref. 28). Calculated and observed lives agree within a factor of two for 114 of the 125 tests examined thus far. The error is distributed approximately in a log normal fashion and reflects both the inaccuracies in the calculations and the experimental error. Twenty of these tests were on simulated turbine blades tested in a Mach 1 burner rig, which will be described later in the report. Distribution of error in these tests is similar to that in figure 8 for all of the tests.

Only a few of the tests analyzed thus far have included long hold times at elevated temperature. For this reason, it has not been necessary to include the oxidation failure mode directly. However, life analysis of actual turbine components will require that THERMF1 be expanded to include this mode, particularly for coatings. When this is done, a unified method will be available for predicting the lives of prototype components under service conditions.

PHASE II: EVALUATION OF PREDICTION METHODS THROUGH BURNER RIG STUDIES

Open-Jet Burner Rigs

Open-jet burner rigs, which burn jet fuel or natural gas, are the simplest facilities that can provide the combustion environment, gas velocities, and thermal gradients similar to those encountered in actual engines. Because the specimens are not enclosed, their temperature distributions can be readily observed and strains can often be measured optically. The specimens can be moved out of the burner exhaust for cooling, which allows the burner to operate at steady state, prolonging its life.

Two types of open-jet rigs are in operation at Lewis: large Mach 1 burners with mass flows of 0.5 kilogram per second and small burners with mass flows less than 0.07 kilogram per second. Three large and nine small burner rigs are presently available. One of the large rigs uses natural gas; all the remaining rigs use jet fuel.

A large Mach 1 burner rig is shown in figure 9 (ref. 29). A rotating specimen holder supports eight wedge specimens in front of the burner nozzle, inside clam-shell radiation shields. For cooling, the specimen holder moves downward, positioning the specimens in front of the sonic cooling air stream. The three Lewis rigs of this type are used for studies on oxidation, coating, cladding, and thermal fatigue. Two of the rigs have provisions for salt injection for sulfidation studies.

Oxidation tests. - Tests have shown that bare alloy oxidation and coating degradation occur at significantly higher rates in the Mach 1 rigs than in cyclic oxidation furnaces (refs. 23 and 29 to 31). For example, figure 10 presents a comparison of the weight changes in aluminide coated B 1900 under the two test conditions. At 1090° C, cyclic furnace specimens showed a small weight gain followed by a very gradual weight loss. The rig tests, however, produced an immediate, rapid weight loss. Coating consumption rates have been found to be 10 to 20 times higher in the burner rig. However, the same sequence of growth, consumption, and break up has been observed. This is discussed further in the appendix.

Creep-rupture tests. - Burner heating has been found to increase creep as well as oxidation rates and reduce rupture times (ref. 32). Figure 11(a) shows one of the Lewis burner rigs for creep-rupture testing. It is a conventional lever-loaded creep machine fitted with a small (0.07 kg/sec) jet-fueled burner. Specimens are conventional 6-millimeter-diameter, uniaxial test bars. The small size of the burner requires that auxiliary electrical resistance heating be used to keep the test section at a uniform temperature. The power leads can be seen in figure 11(b). A similar rig using a large Mach 1 burner does not require the auxiliary heating.

Comparison of rupture lives in a burner rig and in a furnace is shown in figure 11(c). Burner heating has drastically reduced the rupture times for the same stress and temperature combinations. At 980° C the burner heated life is only 10 percent of the furnace life for two turbine alloys, one of which was aluminide coated. At 1040° C only 5 percent of the furnace life was obtained. These data suggest that creep rates are 10 to 20 times higher than those in the furnace tests, increases very similar to those observed for oxidation. The two phenomena are closely related, and studies are underway to determine the relationship.

As explained previously, the Method of Life Fractions has been used to calculate cyclic creep life. One part of this method is the calculation of creep-rupture life as a function of temperature and stress. This is usually done by means of empirical formulas called time-temperature parameters. When calculating the creep life of a component in a moving gas environment, these parameters should be corrected in accordance with data similar to that given in figure 11(c). When this is done, cyclic creep life in a turbine environment can be accurately calculated using the Method of Life Fractions.

Thermal-fatigue tests. - Simulated turbine blades, both cooled and uncooled, are being tested in a burner rig to evaluate life-prediction methods for turbine components (ref. 32). The test facility is shown in figure 12(a). A loading fixture has been added to a large burner (of the type shown in fig. 9(a)) to allow the application of simulated centrifugal loads. The entire loading fixture pivots to move the airfoil specimen between heating and cooling positions. Cyclic heating and cooling in this rig produce high thermal stresses and leading-edge cracks similar to those found in turbine components.

Specimen shape and typical data are shown in figure 12(b). Cyclic life is shown as a function of the leading-edge temperature at steady state for coated and uncoated IN 100. Theoretical lives, calculated using THERMF1, are also shown in the figure. Agreement between experiments and theory is good. The agreement verifies the computer code and its applicability to turbine components. Studies are now being carried out to include stress concentrations such as film cooling holes.

Hot Gas Tunnel

High gas pressure is one aspect of the turbine environment that is lacking in the open-jet burner tests. To include this factor, a fully automated, programmable, hot-gas tunnel rig has been constructed for thin-walled, cooled airfoils (ref. 2). Both the specimens and the environment represent a turbine component more closely than those in the open-jet rigs. Pressure levels can be raised to 11 atmospheres - an important factor in sulfidation studies. The mass flow rate is approximately 1.0 to 2.2 kilograms per second, which produces realistic heat fluxes through the airfoil walls. Figure 13(a) presents a schematic view of this rig. Figure 13(b) shows a typical cooled, symmetrical airfoil specimen in the test section. The tunnel is equipped with a fatigue machine capable of applying steady loads of 130 kilonewtons and cyclic loads of ±44 kilonewtons at frequencies up to 60 hertz. The combustor exhaust gases can be cycled in temperature from 540° C to as high as 1650° C. Cooling air can be heated to 650° C to simulate a compressor bleed condition.

Life tests are now being conducted on aluminide coated IN 100 airfoil specimens under various conditions of temperature, load, coolant flow, and hold time. These data will be used for the final evaluation of a unified life-prediction method before using the method to calculate the lives of prototype turbine components.

PHASE III: APPLICATION OF PREDICTION METHODS TO TURBINE COMPONENTS

High Temperature Turbine Technology Project

The third phase of the program is predicting the lives of prototype components tested in advanced rigs and engines. This phase is one part of a major research program at Lewis - the High-Temperature Turbine Technology Project. The objective of this project is to develop advanced gas turbines with increased performance and reliability, compared with the best of present-day turbines. The project includes research on cooled turbine heat transfer, aerodynamics, and life. Other technical areas involved are mission analysis, materials and fabrication, mechanical design, rig and engine operations, instrumentation development, and data reduction.

The turbines under investigation range in size from relatively large ones, which would be applicable to supersonic cruise turbojets, to very small turbines with a flow capacity of only 0.5 to 1 kilogram per second, which could be used on small aircraft. Intermediate sized turbines under investigation include those applicable to high-pressure cores of engines for military multimission aircraft and advanced subsonic cruise commercial transports. Turbines for helicopter engines of about 1500 shaft horsepower are also included in the project.

In the third phase of the program, lives will be predicted for turbine components tested in four facilities: a static cascade rig, a modified J75 research engine, a high-pressure - high-temperature turbine rig, and the Lewis propulsion systems laboratory.

Static Cascade Rig

A static cascade rig originally designed for heat-transfer studies (refs. 1, 2, and 33) is being modified for a vane life testing program. This program will provide the first comparison at Lewis between predicted and observed lives of actual cooled engine components. The cascade rig is shown in figure 14. It was designed for continuous operation at an average inlet gas temperature of 1350° C and pressures up to 11 atmospheres. It can be operated at temperatures up to 1650° C for short times.

As shown in figure 14(b), the specimen pack contains four vanes of J75 size. Test data are obtained from the central two vanes. The outer two vanes are slave vanes, which act as flow channels and radiation shields. The test and slave vanes have separate cooling air systems. This allows preheating of the test vane cooling air to about 650° C to simulate compressor bleed air. The two slave vanes can also receive more cooling than the test vanes, to ensure longer life.

Modified J75 Research Engine

Life studies on actual blades and vanes will be conducted in the research engine shown in figure 15(a) (refs. 1, 2, and 33). Only the high-pressure spool of the basic J75 engine is used. This modified engine can operate for long periods of time at an average turbine inlet temperature of 1350° C. A cross-sectional diagram of the turbine test section is shown in figure 15(b). The standard uncooled single-stage turbine of the J75 high-pressure spool has been replaced with a single-stage air-cooled turbine. Five of the 72 vanes and five of the 76 blades are test components. The remaining blades and vanes are slave components provided with more cooling than the 10 test parts to ensure longer life. Several special features are incorporated in the turbine section to make a versatile test bed. These features include the following:

(1) Independent metering of cooling air to the test and slave components from either the compressor or from an external air supply

(2) Individual replacement of all airfoils without removing the turbine disk

(3) Extensive instrumentation for gas temperatures, gas pressures, and metal temperatures on both blades and vanes

Up to this time, the engine has been used exclusively for turbine cooling studies. A program of life tests in this engine is now in its early stages. One of the goals of this program is to develop improved vanes and blades using life prediction methods verified by rig tests.

High-Pressure - High-Temperature Turbine Test Rig

The Lewis Research Center is now designing and building an advanced turbine test rig that will operate at the high temperatures and pressures expected in future engines (ref. 2). In the turbine test section of this facility, gas temperatures may reach 2000° C, and pressures may be as high as 40 atmospheres. The facility will consist of a combustor, a single-stage turbine, a water brake power absorber, an auxiliary compressor system with integral turbine drives, and the required service, control, and instrument systems. The turbine will have a tip diameter of approximately 50 centimeters, a blade span and chord of about 4 centimeters, and a shaft speed of 17 600 rpm. The combustor, turbine disk, blades, and vanes will all be replaceable in the facility.

Propulsion Systems Laboratory

Performance testing of engines and components will be conducted in the propulsion systems laboratory shown in figure 16. Here large commercial and military engines can be operated under simulated altitude, speed, and temperature conditions. New designs to increase performance, minimize noise, and reduce pollution will be evaluated. Life predictions will be made for critical components to improve the reliability of these test engines.

CONCLUDING REMARKS

This report has reviewed the turbine component life-prediction program at the NASA Lewis Research Center. The program is composed of a wide variety of on-going studies covering many aspects of materials research, environmental testing, and component development. It is divided into three general phases in various stages of completion.

Much progress has been made in the first phase: the development of life-prediction methods through materials studies. The basic modes of failure such as fatigue, creep, and oxidation are sufficiently well understood at this time to be described quantitatively. Computer codes are being written to include these failure modes in a unified manner.

A limited amount of progress has been achieved in the second phase of the program: the evaluation of prediction methods through combustion rig studies. Material properties are being measured in high-velocity gas atmospheres, and simulated turbine components are being tested in thermal fatigue.

The third phase of the program is now in the planning stage: the application of a unified life-prediction method to prototype turbine components in rigs and engines. This is the area where increased effort would be of greatest benefit. To be successful, this phase must involve program planners and specialists alike in mission analysis, materials, component design, fabrication, test operations, maintenance, and repair.

Lewis Research Center,
National Aeronautics and Space Administration,
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501-21.

APPENDIX - MECHANISMS OF COATING FAILURE

It has been observed that coating failures are usually preceded by a certain sequence of changes in composition and structure (refs. 22 and 23). Figure 17 shows typical changes in the microstructure of a coated turbine alloy, caused by cyclic oxidation. The system shown in the figure is an aluminide coating deposited on a B 1900 substrate (a typical cast nickel-base alloy). As shown in figure 17(a), the coating actually consists of four distinct layers between the surface oxide and the B 1900 substrate. It has been determined that oxidation protection in this coating is obtained primarily from layer II, composed of nickel-monoaluminide, NiAl. If the NiAl layer is broken, rapid oxidation of the substrate begins. Thus, the thickness and integrity of the NiAl layer is critical to the oxidation resistance of coated turbine components.

Two simultaneous processes combine to change the thickness of the NiAl layer: (1) a growth process that thickens the layer at the II/III interface, through inward diffusion of aluminum and outward diffusion of nickel and (2) a consumption process that thins the layer at the I/II interface, through oxidation and depletion.

The growth process is generally dominant in the early stages of exposure to high temperature. In figure 17(a), after 100 1-hour cycles at 1090° C, the NiAl layer is approximately 50 percent thicker than it was at the start of testing. The consumption process then becomes dominant. In figure 17(b), layer II has become much thinner after 400 1-hour cycles. Finally, after additional exposure, the NiAl layer breaks up (see fig. 17(c)), opening paths for the oxidation of the substrate. This layer breakup can be considered to be the start of a coating failure, as proposed by Grisaffe (ref. 31).

The processes of growth and consumption leading to breakup are shown graphically in figure 18 for aluminide coated B 1900. Starting from an initial thickness of 43 micrometers, the layer grows to a peak thickness that is strongly dependent on the exposure temperature. The higher the temperature, the smaller the net amount of growth above the initial thickness. After reaching its peak thickness, the NiAl layer becomes thinner at a rate that is assumed to be constant for a constant temperature. The consumption rates shown in the figure were calculated using the Arrhenius equation:

$$\frac{dh}{dt} = Ae^{-Q/RT}, \quad h_b \le h \le h_{max}, \ \mu m/hr$$

where

h thickness of NiAl layer, μm

t exposure time, hr

A curve-fit constant, μm/hr

Q	activation energy, J/mole
R	universal gas constant, J/mole-K
T	exposure temperature, K
h_b	thickness below which breakup occurs, approximately 30 μm
h_{max}	peak layer thickness, μm

The activation energy Q was found to be approximately equal to that for the diffusion of nickel in NiAl.

The indicated breakup thickness of 30 micrometers is a preliminary value measured for NiAl. Once breakup occurs, consumption of the broken layer continues at an increasing rate, as is indicated by the dashed lines in figure 17. Similar thickness data have been reported for aluminide coated WI-52, a cobalt-base alloy (ref. 22).

The concept of layer breakup is an attempt to quantitatively describe the processes shown in figures 17 and 18. With this concept the pure coating life could be calculated from its composition and a knowledge of the growth rates, consumption rates, and minimum unbroken layer thickness.

The same sequence of structural changes have been observed in burner rig specimens, but at much higher rates. Similarities can be seen between the microstructures of a typical wedge-shaped specimen (fig. 19) and a typical furnace specimen (fig. 17) of the same alloy and coating. Figure 19 shows a NiAl layer that has grown in thickness after 100 1-hour cycles on the side of the wedge specimen in a lower temperature region. However, in a hotter region near the leading edge (fig. 19(b)), the layer has become thinner and broken. On the leading edge itself, in the area of severest spalling, the protective NiAl layer has been completely consumed. Similar comparisons have been made between rig and furnace tests of aluminide coated WI-52 (ref. 22). However, the differences in rates were not as great as for the aluminide coated B 1900. It can be concluded, then, that the concept of layer breakup might also be used to predict coating life in a Mach 1 gas stream using increased rate constants.

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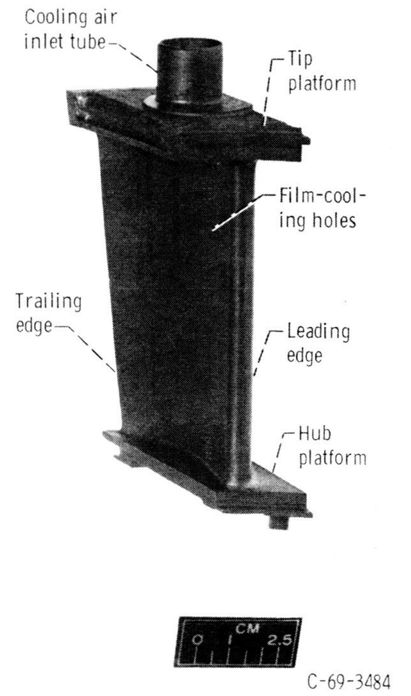
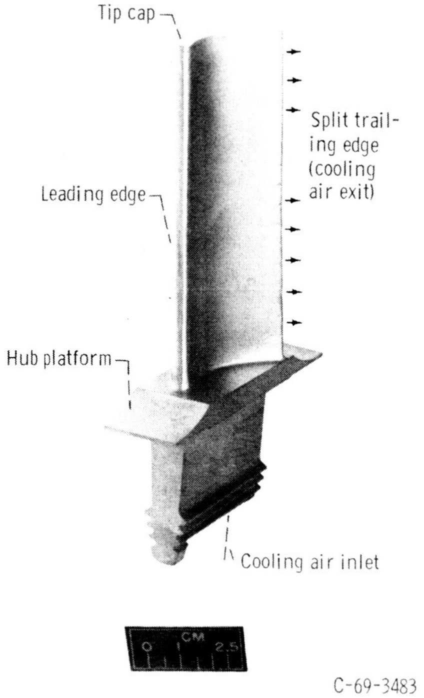




(b) Blade.

Figure 1. - Typical cooled turbine components.

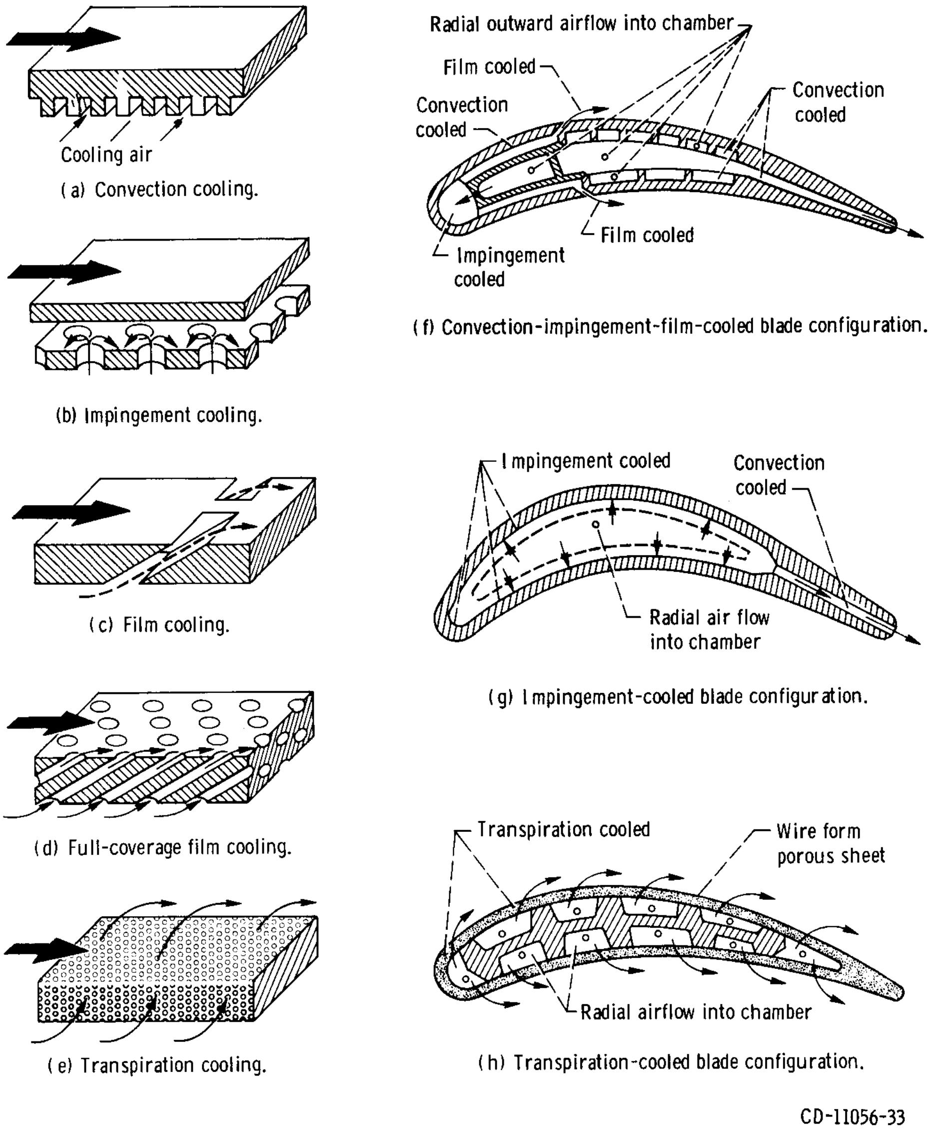


Figure 2. - Complex turbine blade configurations required for various cooling methods.

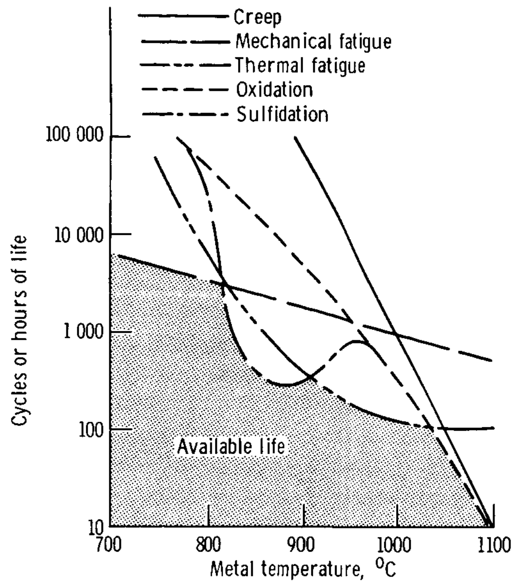


Figure 3. - Factors influencing turbine component life.

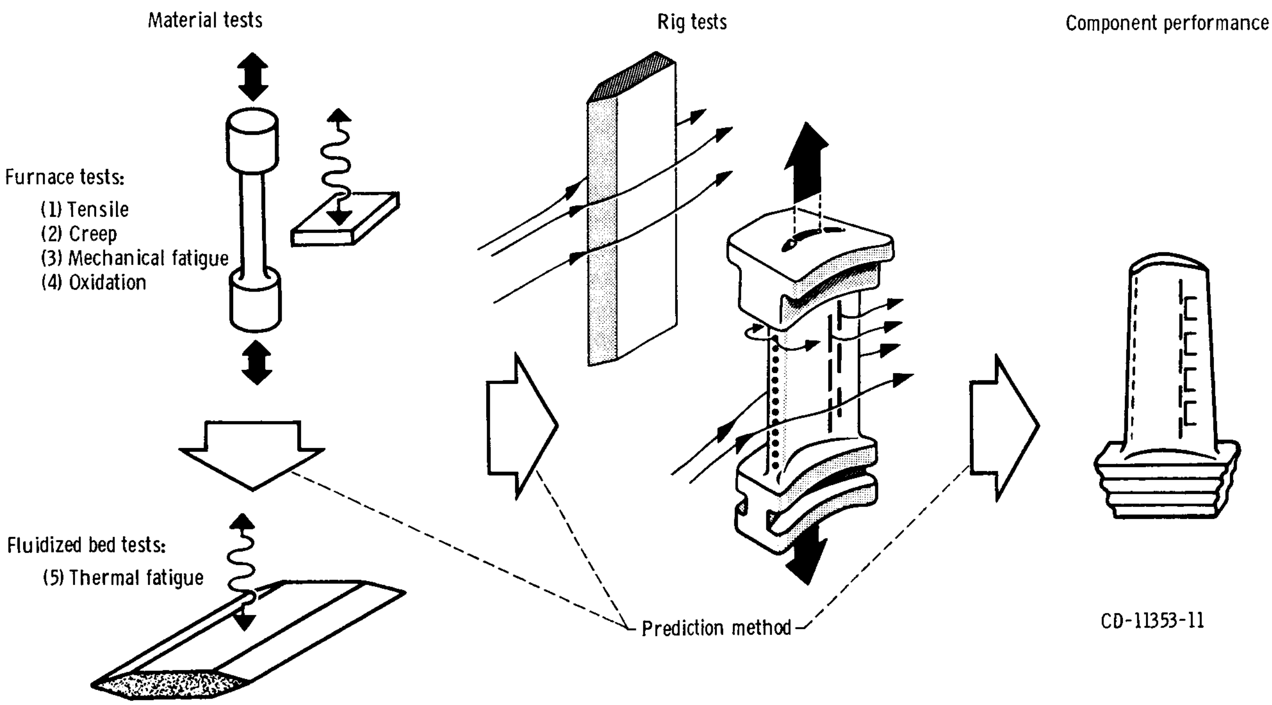
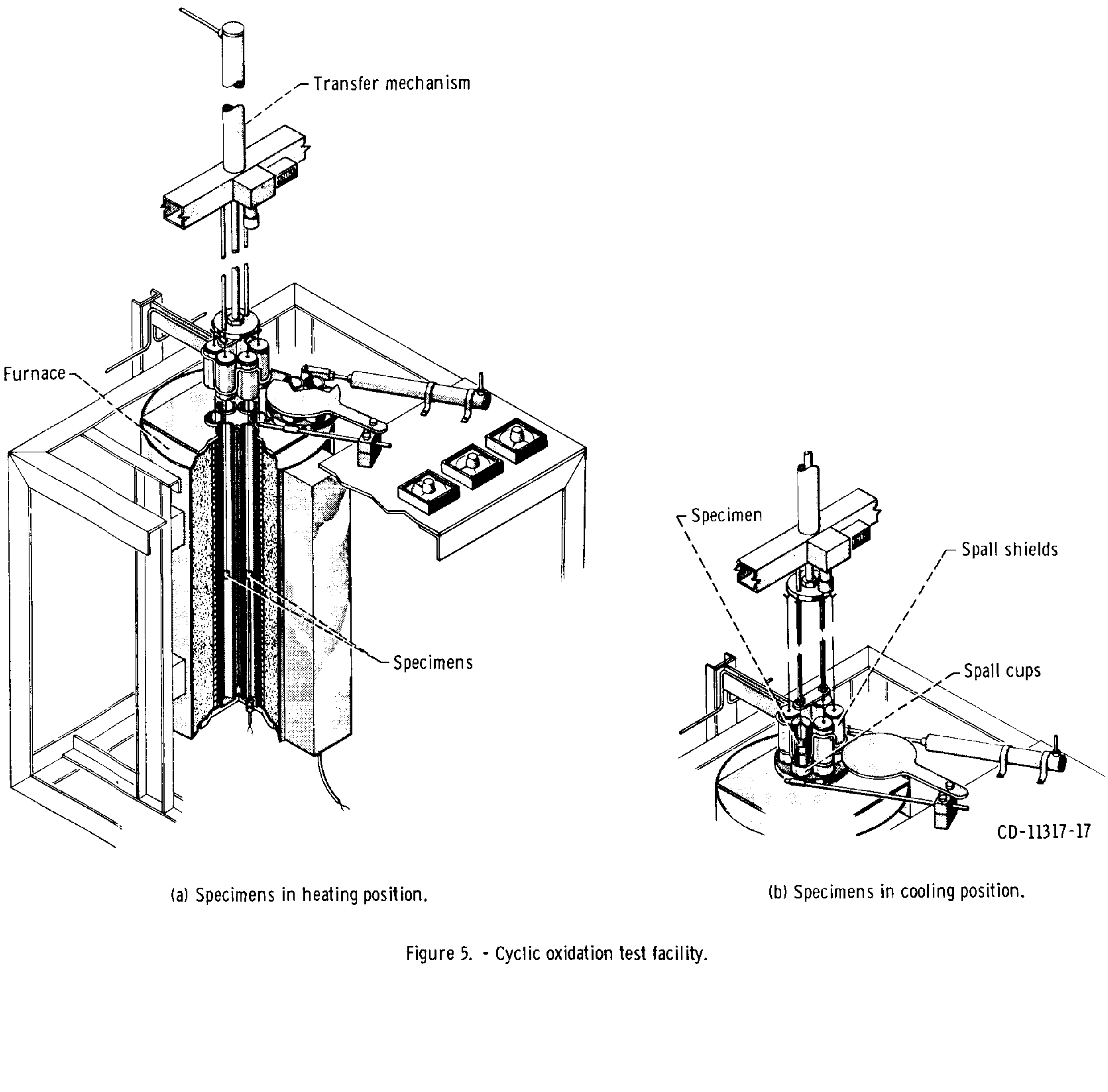


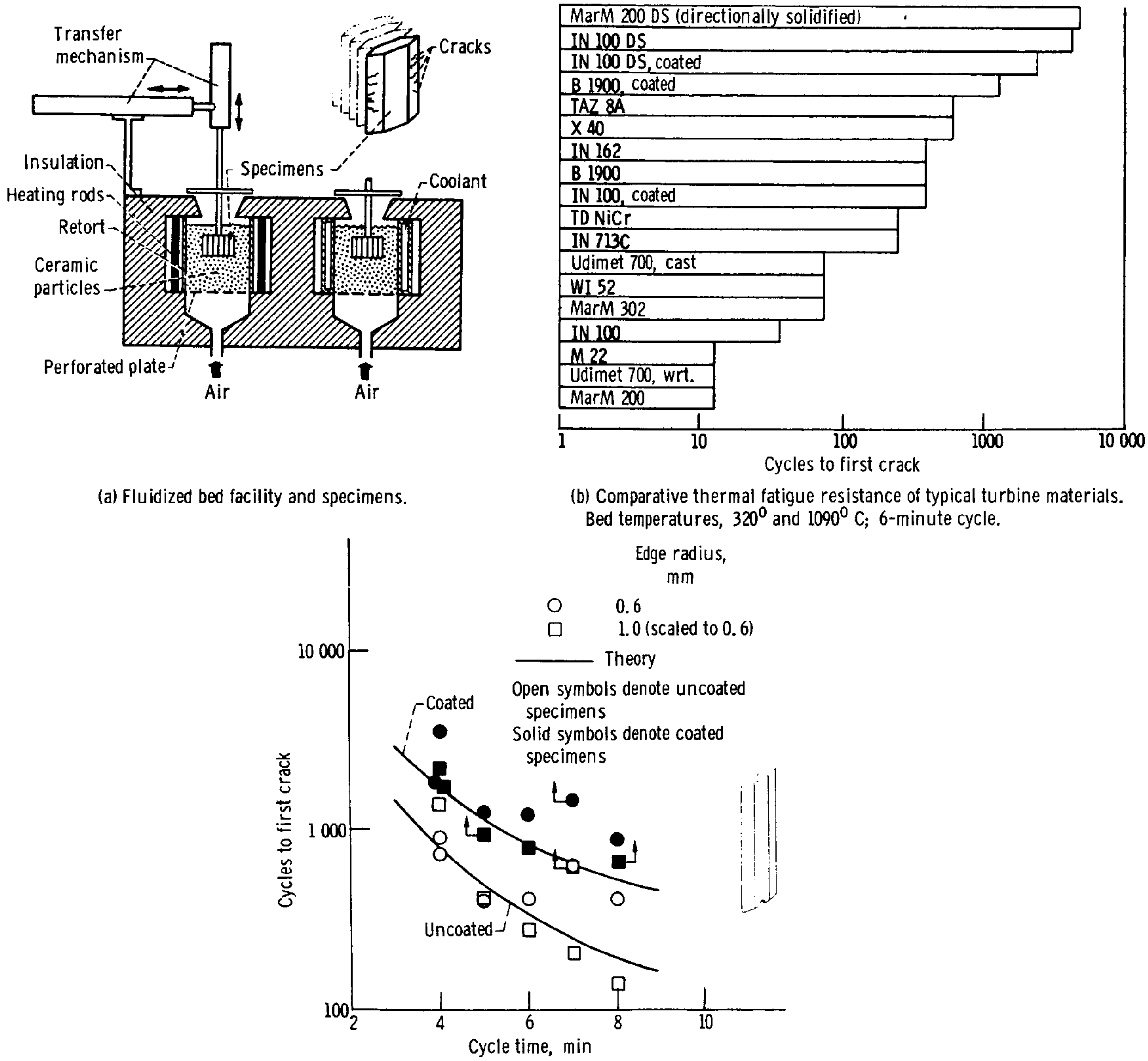
Figure 4. - Turbine component life-prediction program.



(a) Specimens in heating position.

(b) Specimens in cooling position.

Figure 5. - Cyclic oxidation test facility.



(a) Fluidized bed facility and specimens.

(b) Comparative thermal fatigue resistance of typical turbine materials. Bed temperatures, 320° and 1090° C; 6-minute cycle.

(c) Theoretical and experimental thermal fatigue lives for B 1900. Bed temperatures, 320° and 1090° C.

Figure 6. - Thermal fatigue testing using the fluidized-bed technique.

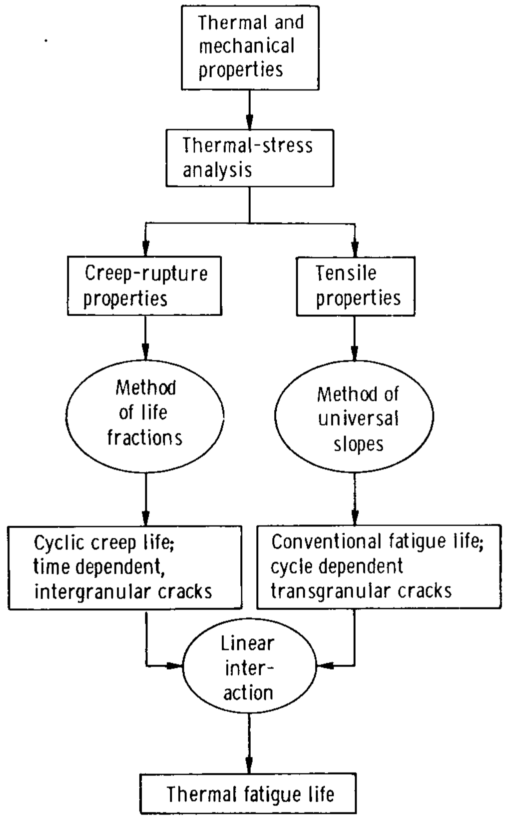


Figure 7. - Schematic diagram of THERMF1, a computer code for calculating thermal fatigue life.

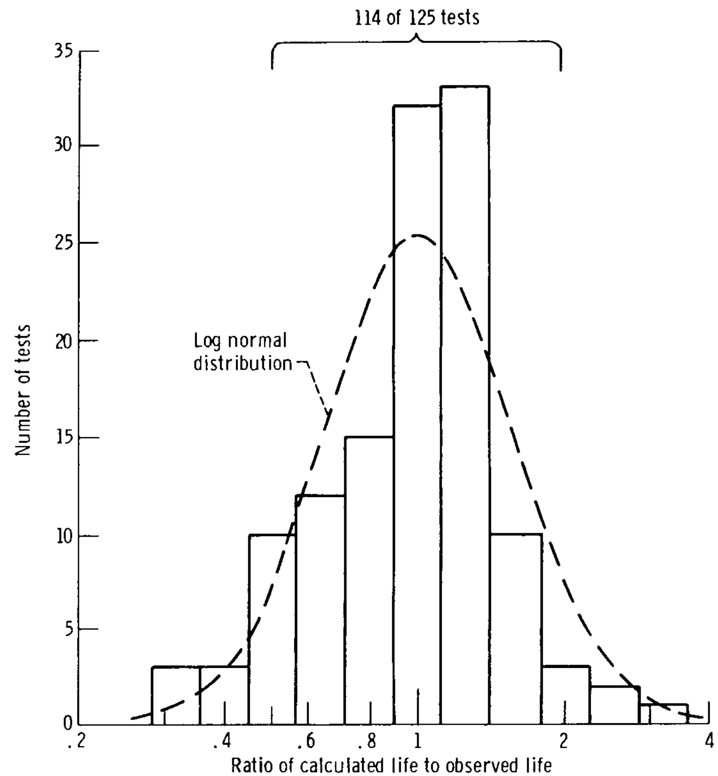
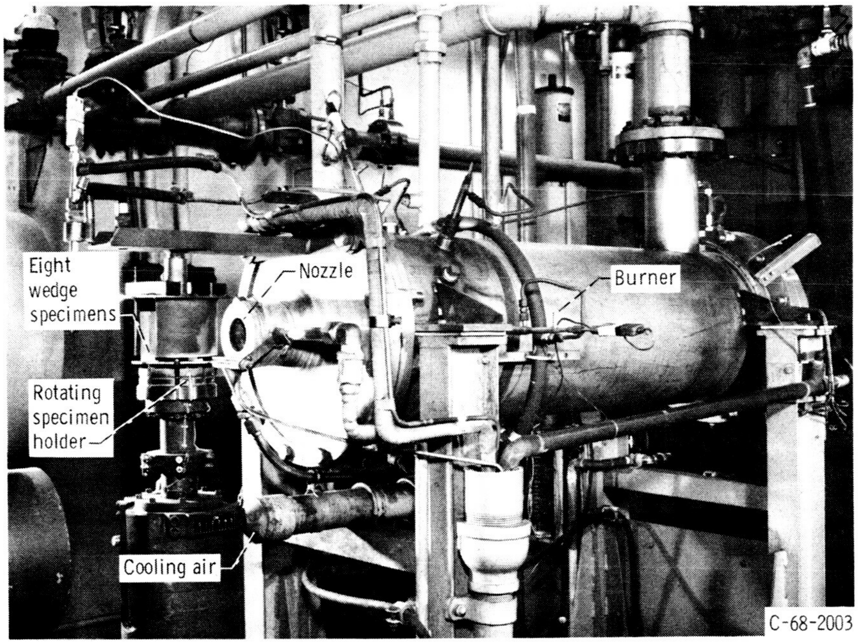
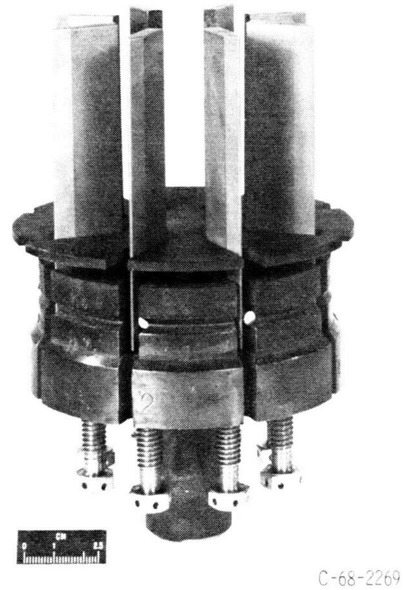


Figure 8. - Progress in calculating life of thermal fatigue specimens using THERMF1.



(a) General view of rig.



(b) Wedge specimens in holder.

Figure 9. - High-velocity open-jet burner rig for oxidation and thermal fatigue studies.

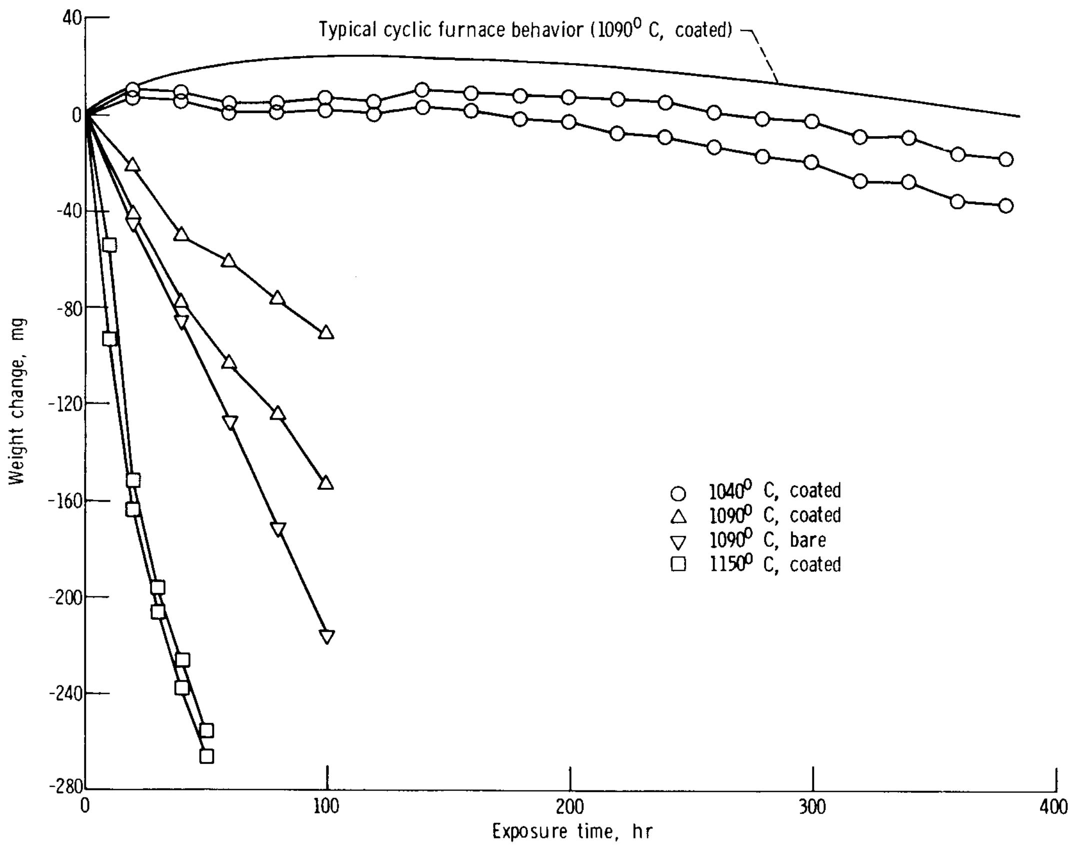
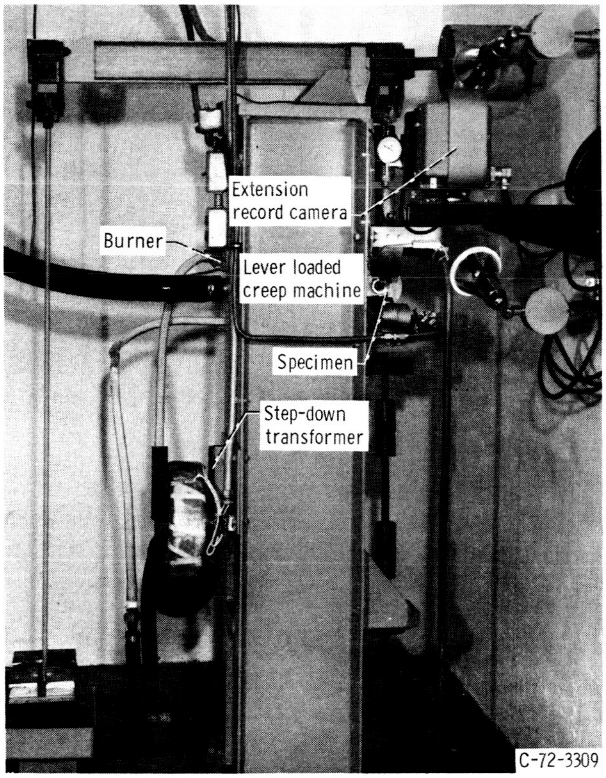
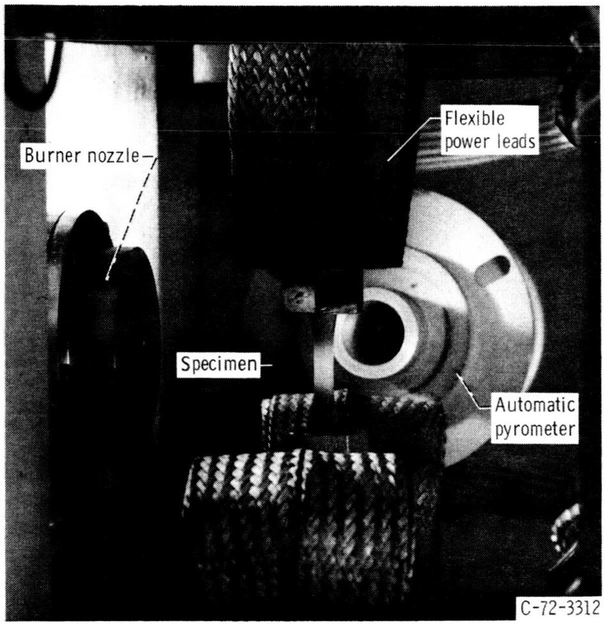


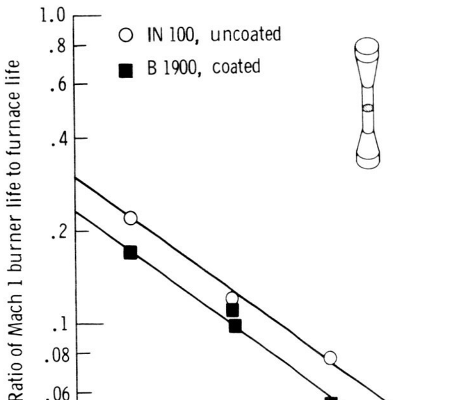
Figure 10. - Weight change of B 1900 specimens during cyclic burner-rig oxidation compared with cyclic furnace behavior. Minimum temperature, 20° C; 1 cycle per hour.



(a) General view of rig.

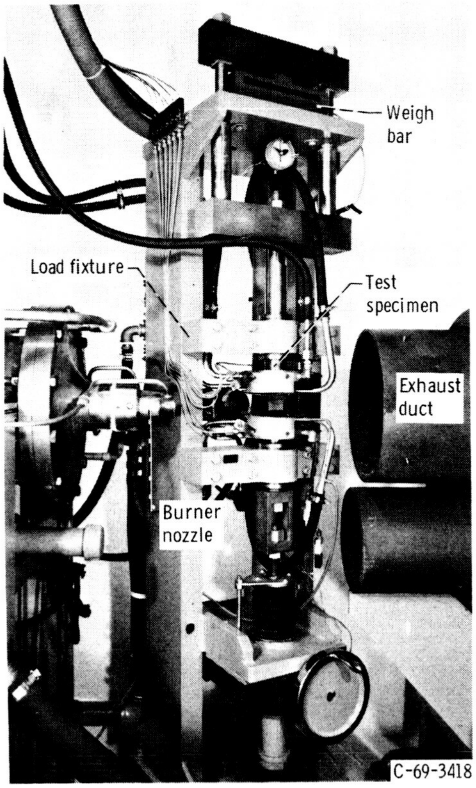


(b) Test section.

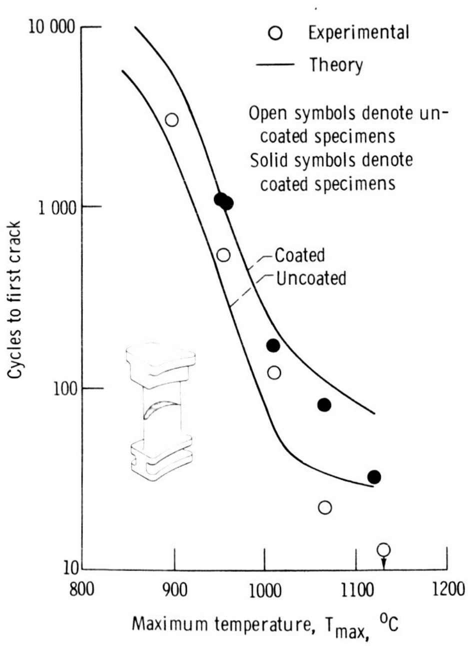


(c) Typical data showing effect of burner heating on creep-rupture life.

Figure 11. - Creep-rupture testing using burner rig.

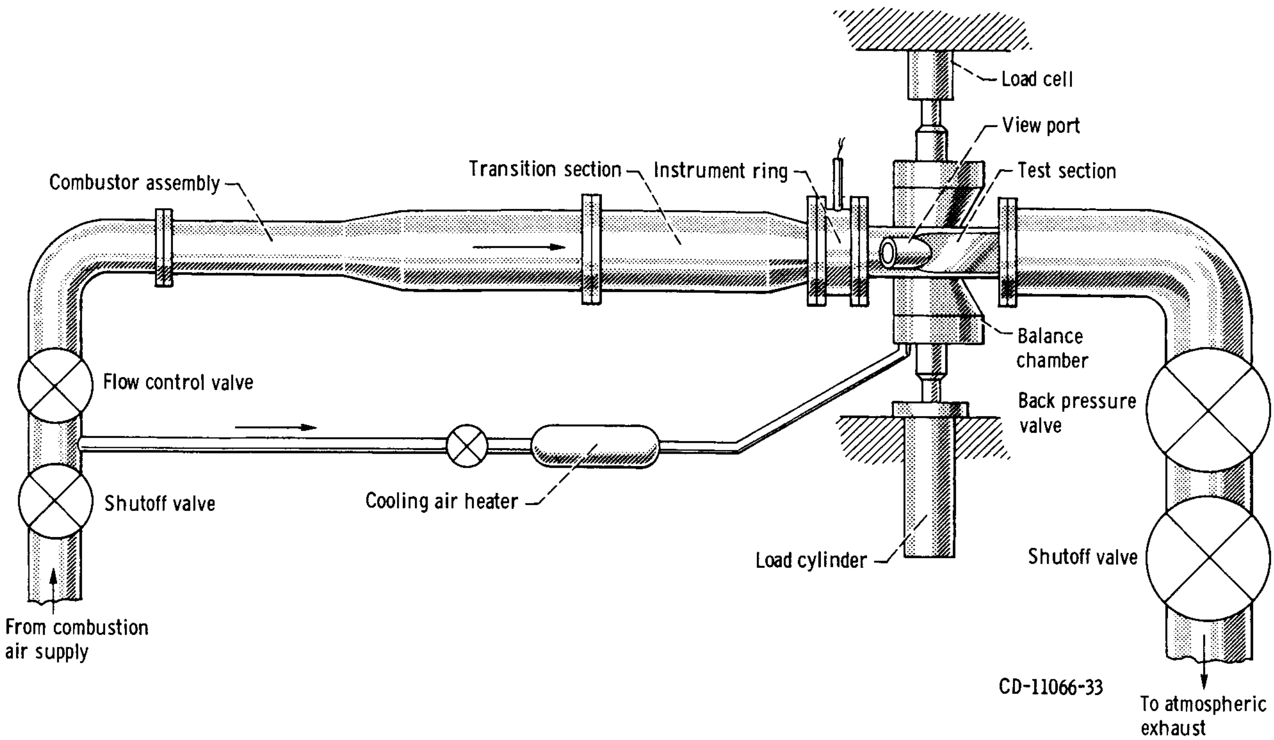


(a) General view of rig.

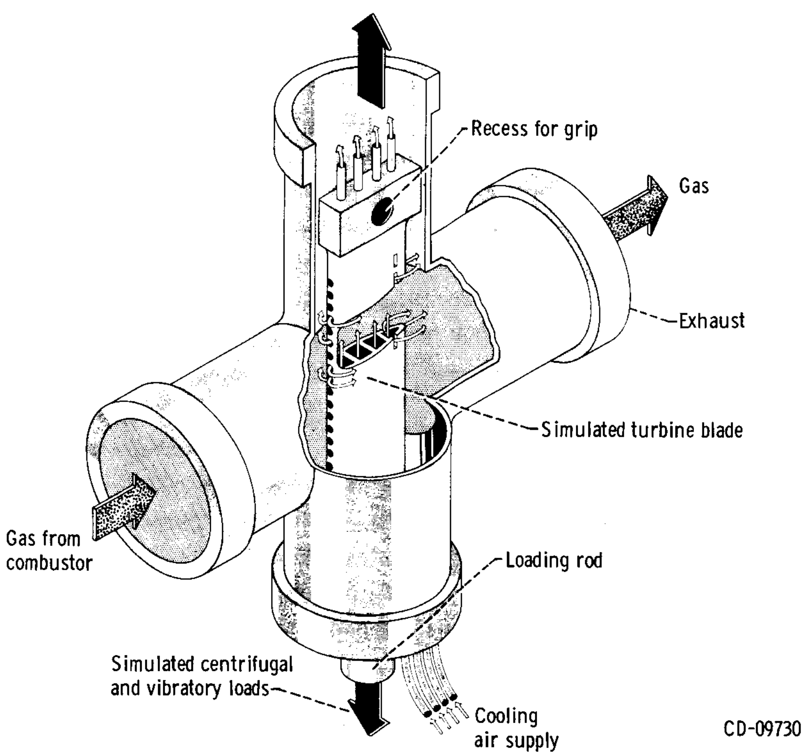


(b) Theoretical and experimental thermal fatigue lives for IN 100 airfoil specimens. Heating time, 3 minutes; rapid air cooling to 75° C.

Figure 12. - Thermal fatigue testing of simulated turbine blades using high-velocity burner rig.

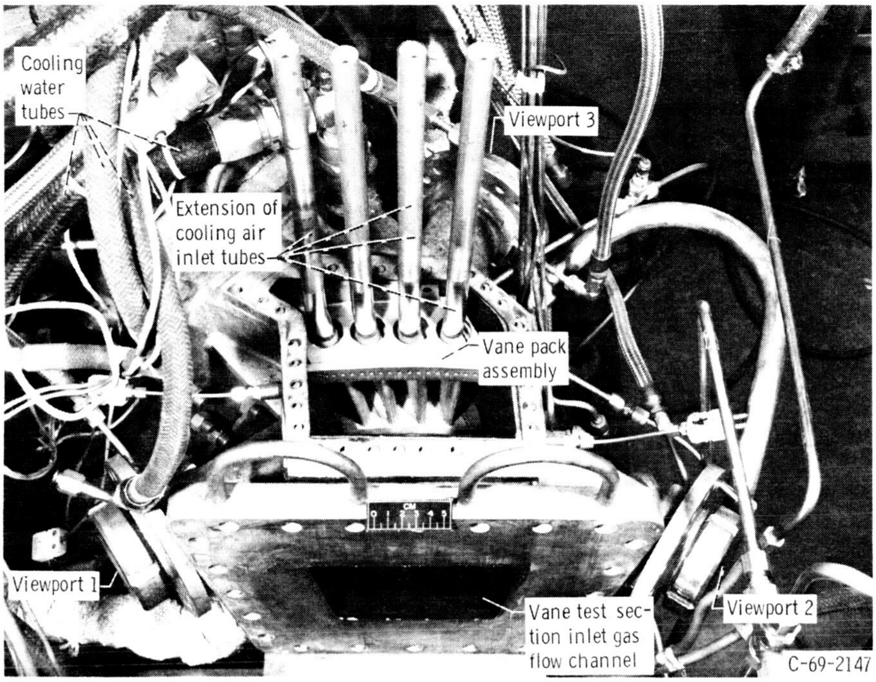


(a) Schematic view, showing major components.

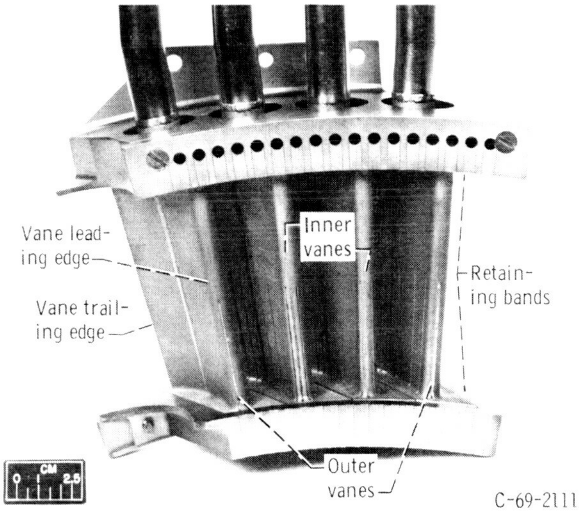


(b) Test section, showing simulated turbine blade.

Figure 13. - Hot-gas tunnel rig for life testing of simulated turbine blades and vanes.

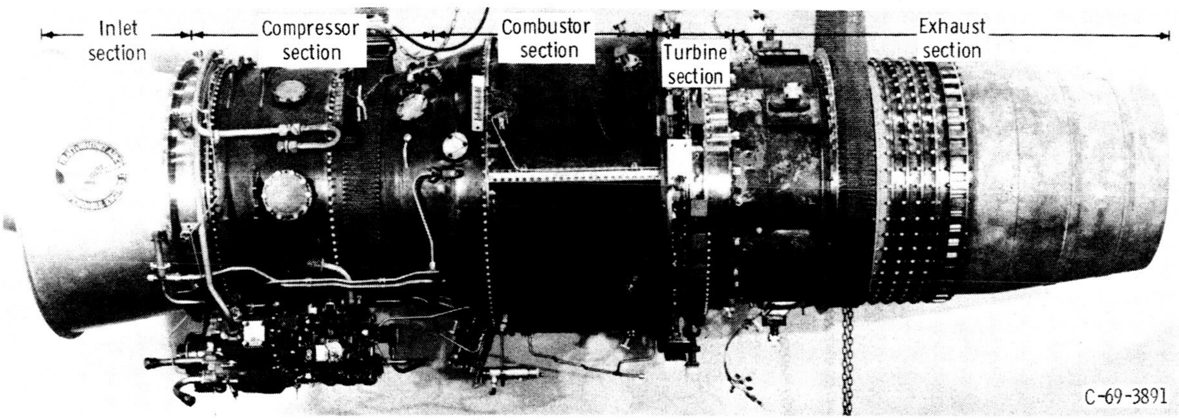


(a) General view.

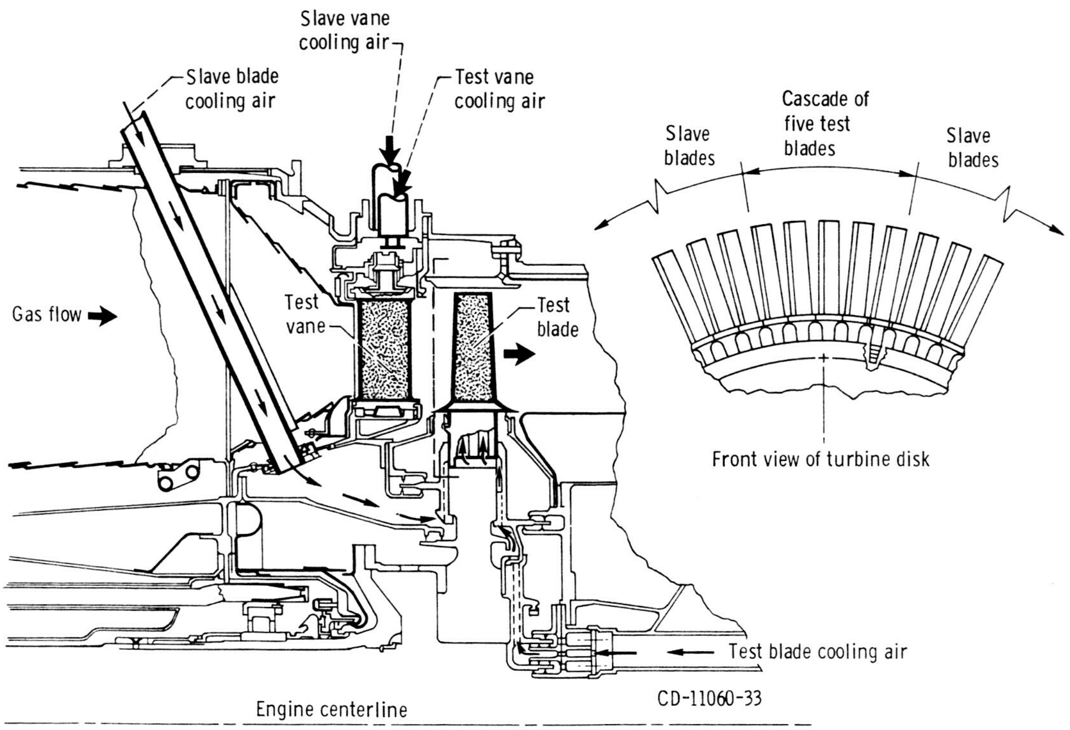


(b) Vane pack assembly.

Figure 14. - Static cascade rig for testing cooled turbine vanes.



(a) General view of engine (modified J75 turbojet).



(b) Schematic of turbine section, showing test blades and vanes.

Figure 15. - Research engine for life testing of turbine components.

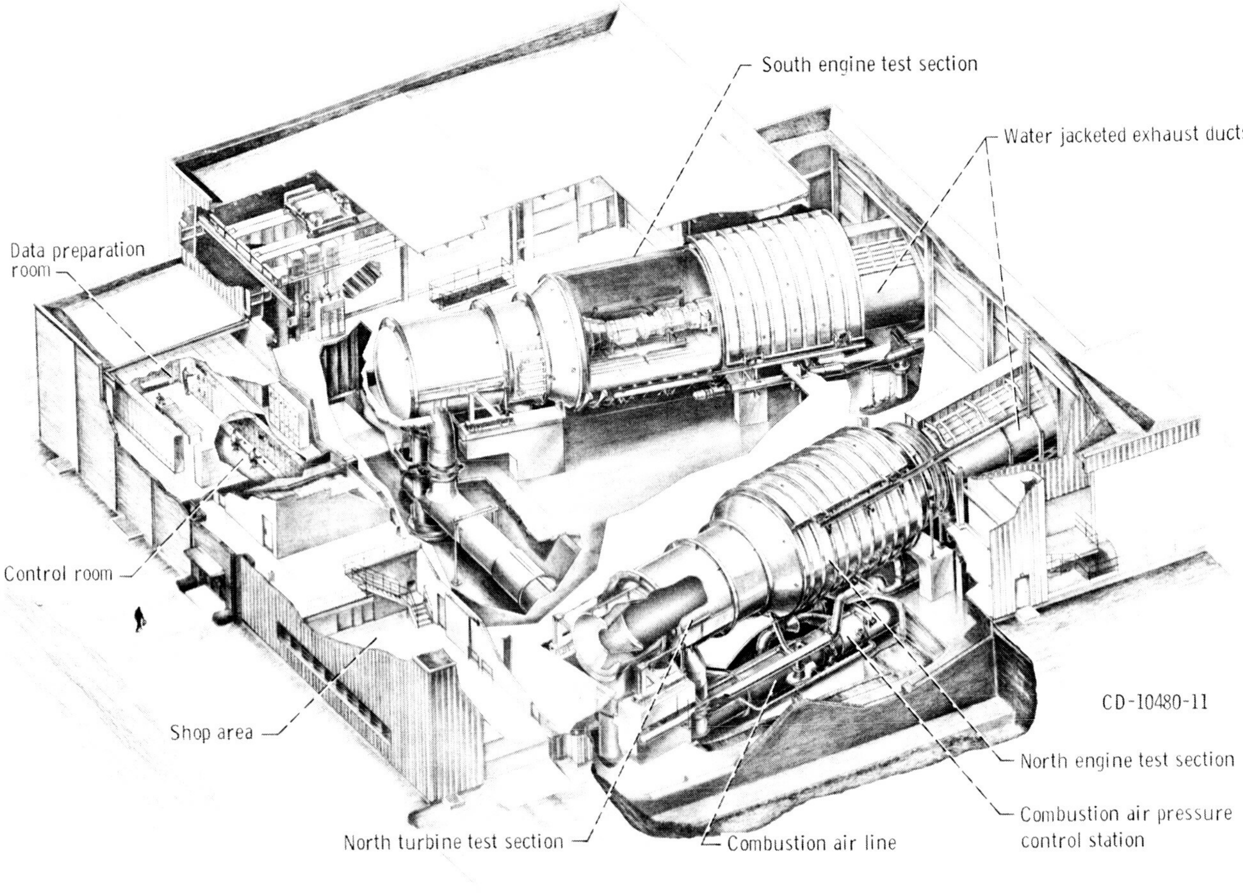
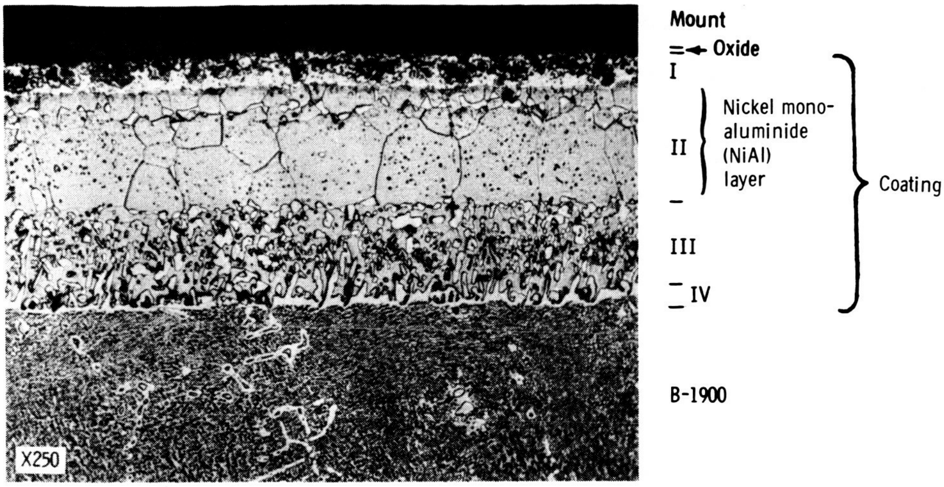
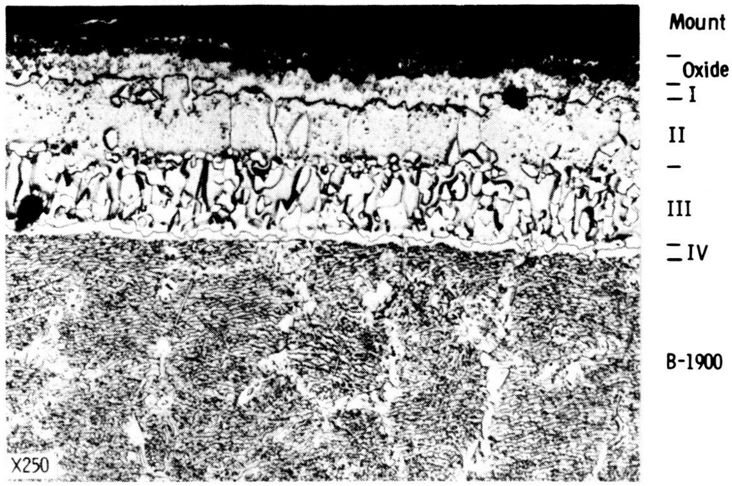


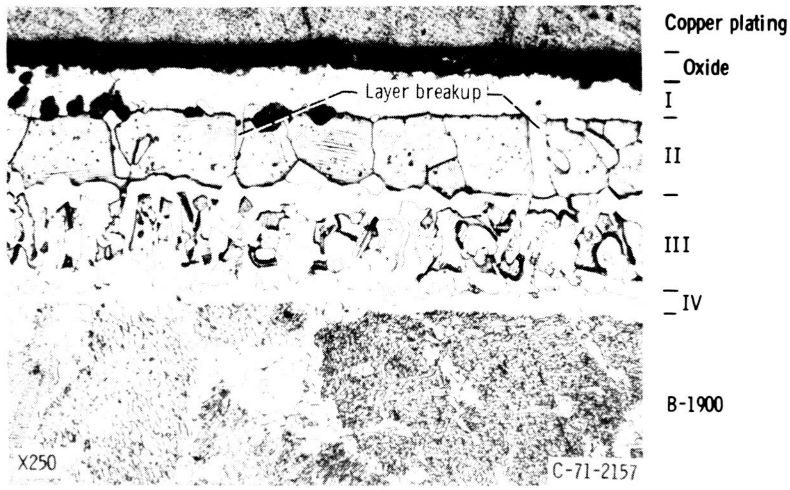
Figure 16. - Propulsion systems laboratory for testing large turbofan and turbojet engines.



(a) Exposure time, 100 1-hour cycles.



(b) Exposure time, 400 1-hour cycles.



(c) Exposure time, 400 20-hour cycles.

Figure 17. - Changes in coating microstructure during cyclic furnace oxidation. Temperature, 1090° C; slow cooled hourly to 50° C.

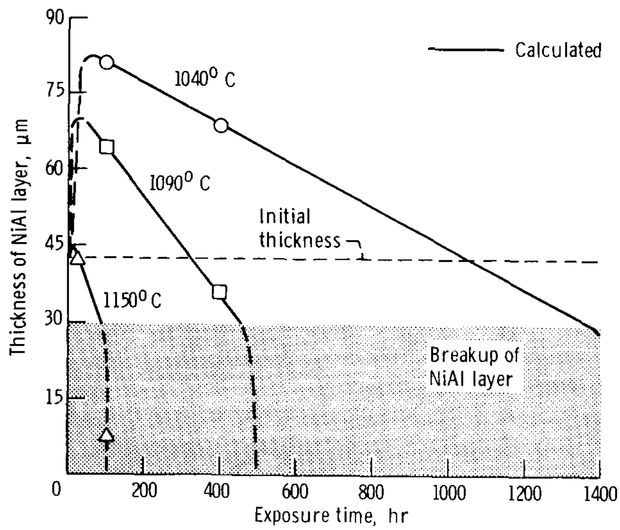
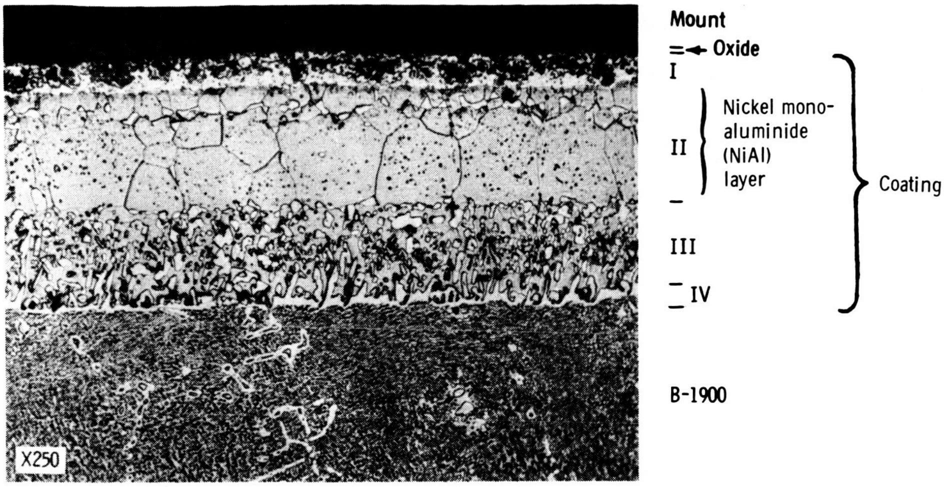
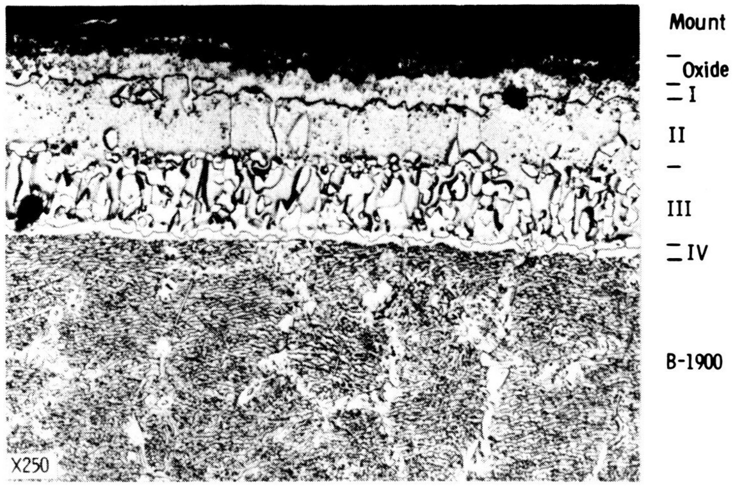


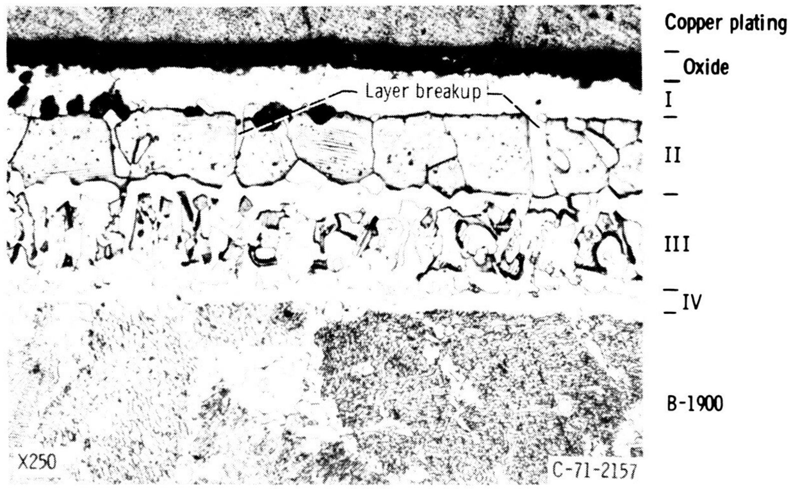
Figure 18. - Growth, consumption, and breakup of nickel monoaluminide (NiAl) layer during cyclic furnace oxidation. Substrate, B 1900; slow cooled hourly to 50° C.



(a) Exposure time, 100 1-hour cycles.



(b) Exposure time, 400 1-hour cycles.



(c) Exposure time, 400 20-hour cycles.

Figure 17. - Changes in coating microstructure during cyclic furnace oxidation. Temperature, 1090^0 C; slow cooled hourly to 50^0 C.