AIRFOIL DEPOSITION MODEL

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Aircraft gas turbine failures associated with sea-salt ingestion and sulfur-containing fuel impurities focus attention on salt deposition and the attendant hot corrosion and fouling of gas turbine blades. However, in the past, quantative understanding of deposition from gas turbine combustion gases has been impeded by the lack of a comprehensive yet tractable theoretical framework for organizing new deposition rate information. The present research program deals with the further development and exploitation of such a theory, and builds upon the foundation provided by previous NASA LeRC-sponsored research (Refs. 1-3 and references contained therein). The goal of this program is to develop the methodology to predict deposit evolution (deposition rate and subsequent flow of liquid deposits) as a function of fuel and air impurity content and relevant aerodynamic parameters for turbine airfoils. The program is carried out under a HOST-supported grant, "Theory of Mass Transfer from Combustion Gases" (NAG 3-201), with Professor Daniel E. Rosner and associates of the Chemical Engineering Department of Yale University.

The spectrum of deposition conditions encountered in gas turbine operations includes the mechanisms of vapor deposition, small particle deposition with thermophoresis, and larger particle deposition with inertial effects. In the present program the focus is on using a simplified version of the comprehensive multicomponent vapor diffusion formalism to make deposition predictions for (1) simple geometry collectors and (2) gas turbine blade shapes, including both developing laminar and turbulent boundary layers. For the gas turbine blade the insights developed in previous programs are being combined with heat and mass transfer coefficient calculations using the "STAN 5" boundary layer code to predict vapor deposition rates and corresponding liquid layer thicknesses on turbine blades. A computer program is being written which utilizes the local values of the calculated deposition rate and skin friction to calculate the increment in liquid condensate layer growth along a collector surface. Preliminary results are now available for deposition and aerodynamic shear-driven flow of Na_2SO_4 on stationary cylinders and turbine blades.

Detailed results of progress to date appear in several papers and preprints (Refs. 4-9), copies of which can be obtained from Professor D. E. Rosner at Yale University, Department of Engineering and Applied Science, New Haven, CT 06520.

REFERENCES

1. D. E. Rosner, B.-K. Chen, G. C. Fryburg, and F. J. Kohl: "Chemically Frozen Multicomponent Boundary Layer Theory of Salt and/or Ash Deposition Rates from Combustion Gases," Comb. Sci. and Tech. 20, 87 (1979).

2. D. E. Rosner: "Thermal (Soret) Diffusion Effects on Interfacial Mass Transport Rates," Physicochemical Hydrodynamics 1, 159 (1980).

3. D. E. Rosner and K. Seshadri: "Experimental and Theoretical Studies of the Laws Governing Condensate Deposition from Combustion Gases," 18th Sympos. (Intl.) on Combustion, The Combustion Institute, 1981, p. 1385.

4. D. E. Rosner and J. Fernandez de la Mora: "Small Particle Transport Across Turbulent Nonisothermal Boundary Layers," ASME Trans., J. Engin. for Power, in press, 1982.

5. S. Gökoğlu and D. E. Rosner: "Correlation of Thermophoretically-Modified Small Particle Deposition Rates in Forced Convection Systems with Variable Properties, Transpiration Cooling and/or Viscous Dissipation," submitted to Int. J. Heat and Mass Transfer, 1982.

6. R. Israel and D. E. Rosner: "Use of a Generalized Stokes Number to Determine the Aerodynamic Capture Efficiency of Non-Stokesian Particles from a Compressible Gas Flow," Aerosol Sci. and Tech., in press, 1982.

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8. D. E. Rosner, D. Günes, and N. Anous: "Aerodynamically-Driven Condensate Layer Thickness Distributions on Isothermal Cylindrical Surfaces," submitted to Chem. Engin. Commun., 1982.

9. D. E. Rosner, S. Gökoğlu, and R. Israel: "Rational Engineering Correlations of Diffusional and Inertial Particle Deposition Behavior in Non-Isothermal Forced Convection Environments," Engineering Foundation Int. Conference on Fouling of Heat Exchange Surfaces, White Haven, PA, Oct. 31-Nov. 5, 1982.

AIRFOIL DEPOSITION MODEL

GRANT NAG 3-201: "THEORY OF MASS TRANSFER FROM COMBUSTION GASES," WITH PROFESSOR D. E. ROSNER, ChE DEPARTMENT, YALE UNIVERSITY

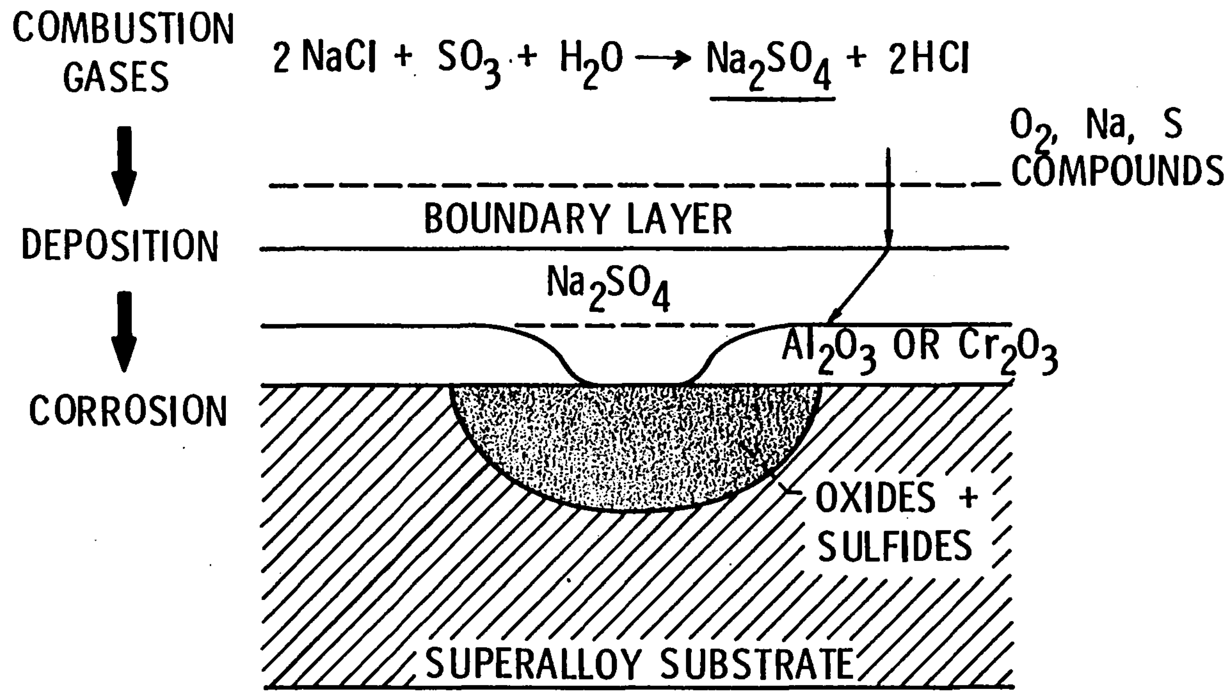
EMPHASIS: TRACE SALT VAPOR DEPOSITION AND CORRESPONDING SHEAR-DRIVEN CONDENSATE LAYER FLOW

OBJECTIVE:

- OVERALL - DEVELOP MODEL TO PREDICT CORRODANT DEPOSITION ON TURBINE AIRFOILS
- 1ST YEAR - MODEL DEPOSITION RATE FOR SEVERAL SIMPLE GEOMETRIES
- 2ND YEAR - PREDICT AND DISPLAY LIQUID LAYER EVOLUTION ON TURBINE VANES AS A RESULT OF VAPOR DEPOSITION AND LIQUID LAYER FLOW

CS-82-2576

HOT CORROSION PROCESS



CS-82-2624

CHARACTERISTICS OF DEPOSITION FOR SPECTRUM OF PARTICLE SIZES

SIZE RANGE*	MASS TRANSPORT MODE	DEPOSITION SPECIES	TRANSPORT MECHANISM	DEPOSITION CHARACTERISTICS
1-10Å	Vapor Diffusion	Atoms and Molecules (Vapors)	Fick Diffusion Soret Diffusion Eddy Diffusion	1. $T_{dp} < T_e$ 2. Low η and deposition on side away from line-of-sight 3. Low sensitivety to T_e-T_w 4. Rate levels off for $T_w << T_{dp}$
10Å-10^{-1} μm	Vapor Diffusion Transition	Heavy Molecules (Condensate Aerosols, Clusters, Submicron Particles)	Brownian Diffusion Eddy Diffusion Thermophoresis	1. $T_{dp} = T_e$ 2. Lowest η 3. High sensitivity to T_e-T_w 4. Rate nearly linear with T_e-T_w
10^{-1} - 100μm	Inertial	Macroscopic Particles	Inertial Impaction Eddy Impaction	1. No apparent T_{dp} 2. Highest η 3. Independent of T_e-T_w 4. Preferential deposition on side facing flow

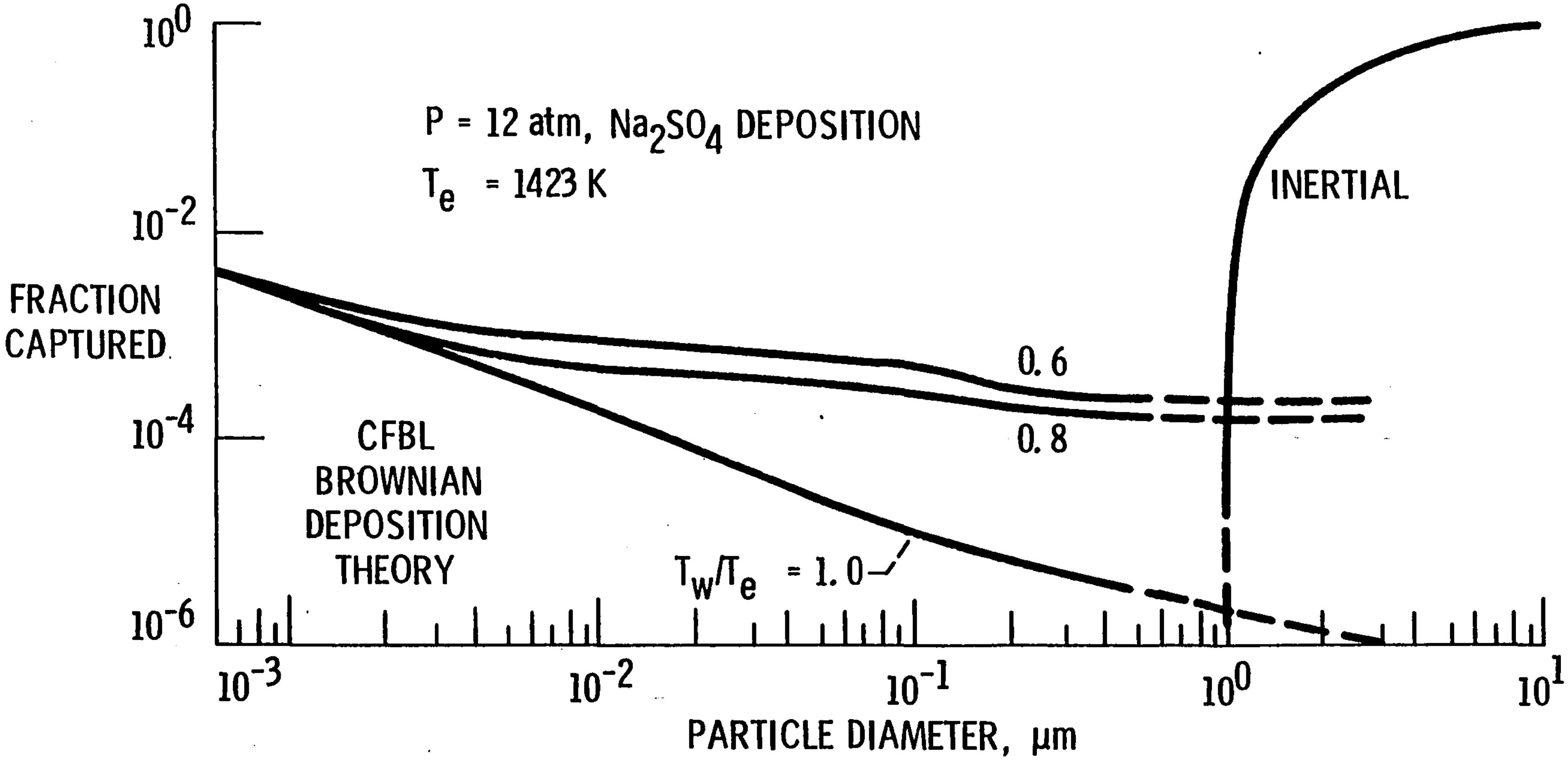
* Mode of deposition is not fixed by particle size alone

η = deposition or collection efficiency, T_{dp} = dew point temperature,

T_e = gas mainstream temperature, T_w = wall temperature

CS-81-1182

PREDICTED DEPENDENCE OF SODIUM SULFATE DEPOSITION RATE ON PARTICLE SIZE



CS-81-1178

CHEMICALLY FROZEN BOUNDARY LAYER THEORY-CFBL

GOAL: PREDICT THE DEPOSITION RATE FOR TRACE INORGANIC SPECIES AS A FUNCTION OF SEED LEVEL, COLLECTOR GEOMETRY, THERMAL AND FLUID DYNAMIC PARAMETERS, ETC.

BASIC ASSUMPTIONS:

1. NO CONDENSATION OR CHEMICAL REACTION WITHIN THE MASS TRANSFER GASEOUS BOUNDARY LAYER

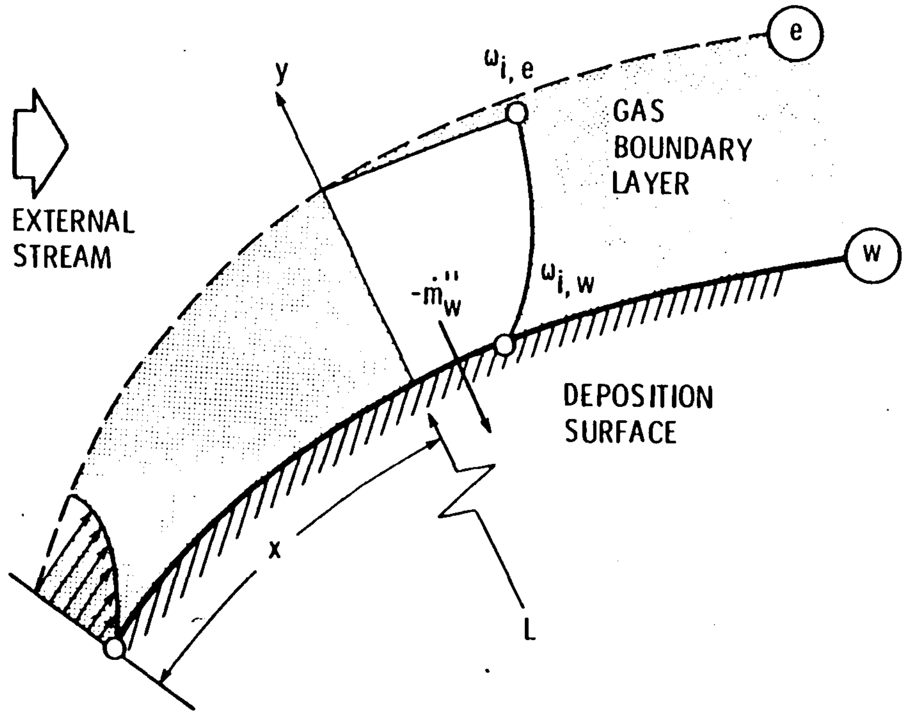
2. CHEMICAL EQUILIBRIUM EXISTS AT THE VAPOR-CONDENSATE INTERFACE

3. CHEMICAL SPECIES FOR TRANSPORT ACROSS THE BOUNDARY LAYER ARE VERY LOW IN CONCENTRATION

4. TRANSPORT BY BODY FORCES AND PRESSURE DIFFUSION IS NEGLIGIBLE

CS-82-2575

VAPOR DEPOSITION THEORY—CFBL

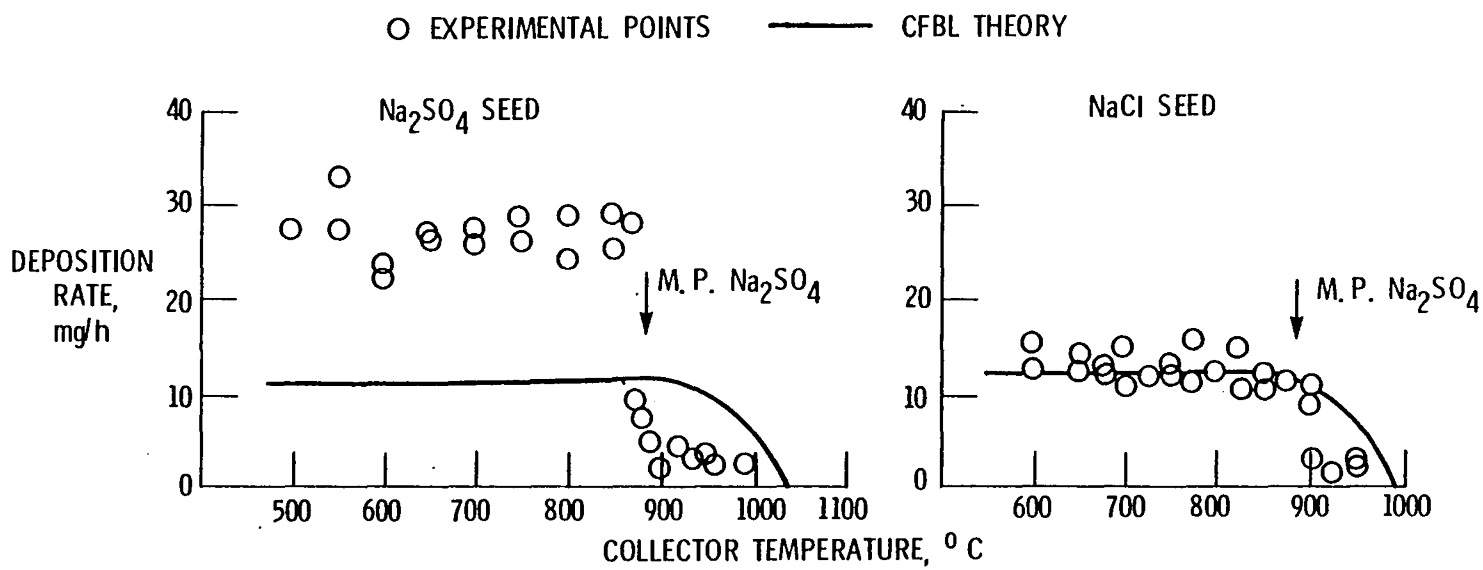


INTEGRATED DEPOSITION FLUX IS GIVEN BY

$$\dot{m}_i'' = \underbrace{\frac{(D_i\rho)_e}{L} \cdot F(\text{turb}) \cdot F_i(\text{Soret}) \cdot Nu_{m,i}(Re, Sc_i)}_{\text{TRANSFER COEFFICIENT}} \cdot \underbrace{\left[\overset{(\text{Fick})}{\Delta\omega_i} + \overset{(\text{Soret})}{\frac{\tau_i}{F_i(\text{Soret})}} \cdot \omega_{i,w}\right]}_{\text{DRIVING FORCE}}$$

CS-82-2579

MACH 0.3 BURNER RIG DEPOSITION OF Na_2SO_4 ON ROTATING CYLINDRICAL COLLECTORS



CS-82-2570

LIQUID DEPOSIT LAYER FLOW

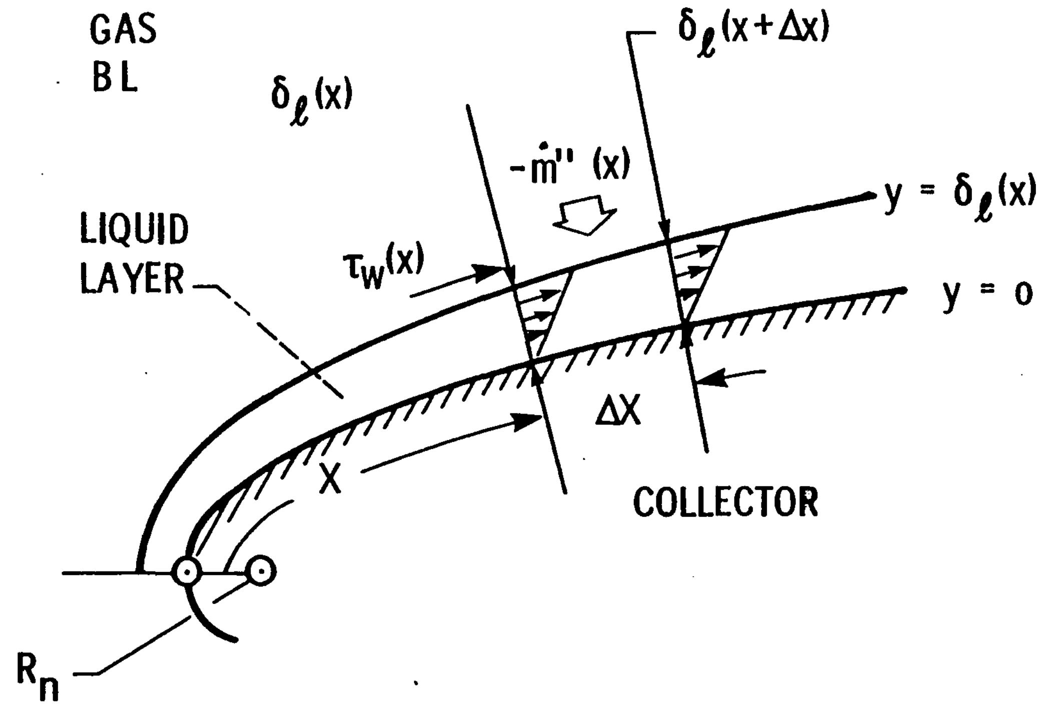
GOAL: PREDICT THE DISTRIBUTION OF LAYER THICKNESS WHEN AERODYNAMIC SHEAR IS THE DOMINANT MECHANISM OF CONDENSATE FLOW ALONG THE SURFACE

BASIC ASSUMPTIONS:

1. FILM IS THIN AND FLOW IS LAMINAR
2. LIQUID IS NEWTONIAN AND SHEAR STRESS ACROSS LAYER IS CONSTANT
3. OTHER BODY FORCES, SURFACE TENSION, ETC. ARE NEGLIGIBLE
4. SURFACE IS ISOTHERMAL

CS-82-2568

AERODYNAMICALLY-DRIVEN THIN CONDENSATE LAYER FLOW



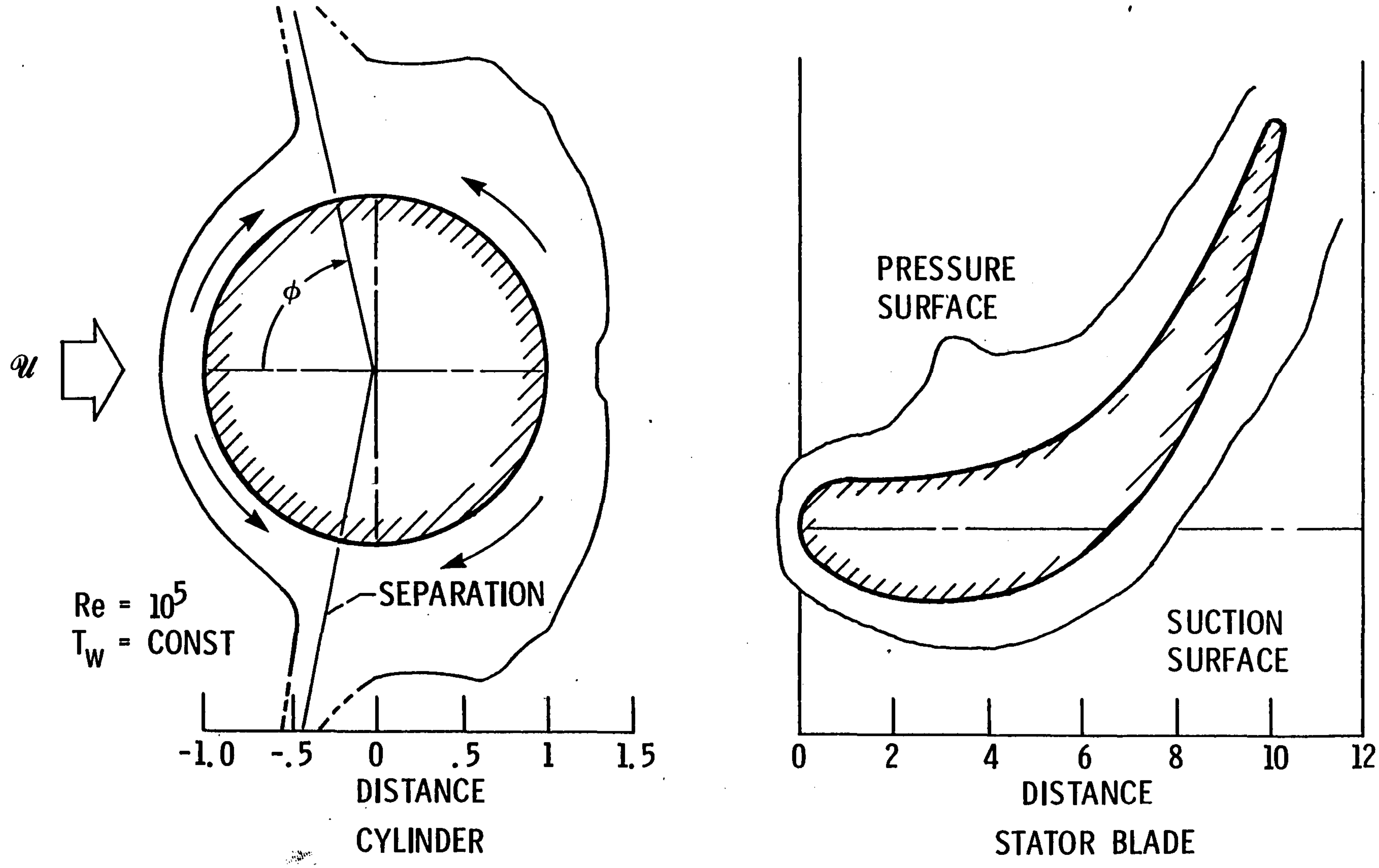
LIQUID LAYER THICKNESS, $\delta_\ell(x)$, IS GOVERNED BY

$$\frac{\partial \delta_\ell}{\partial t} + \frac{\partial}{\partial x}\left(\frac{\tau_W(x)}{2\mu_\ell}\cdot\delta_\ell^2\right) = -\frac{\dot{m}''(x)}{\rho_\ell}$$

CS-82-2573

DEPOSIT THICKNESS AS A FUNCTION OF POSITION

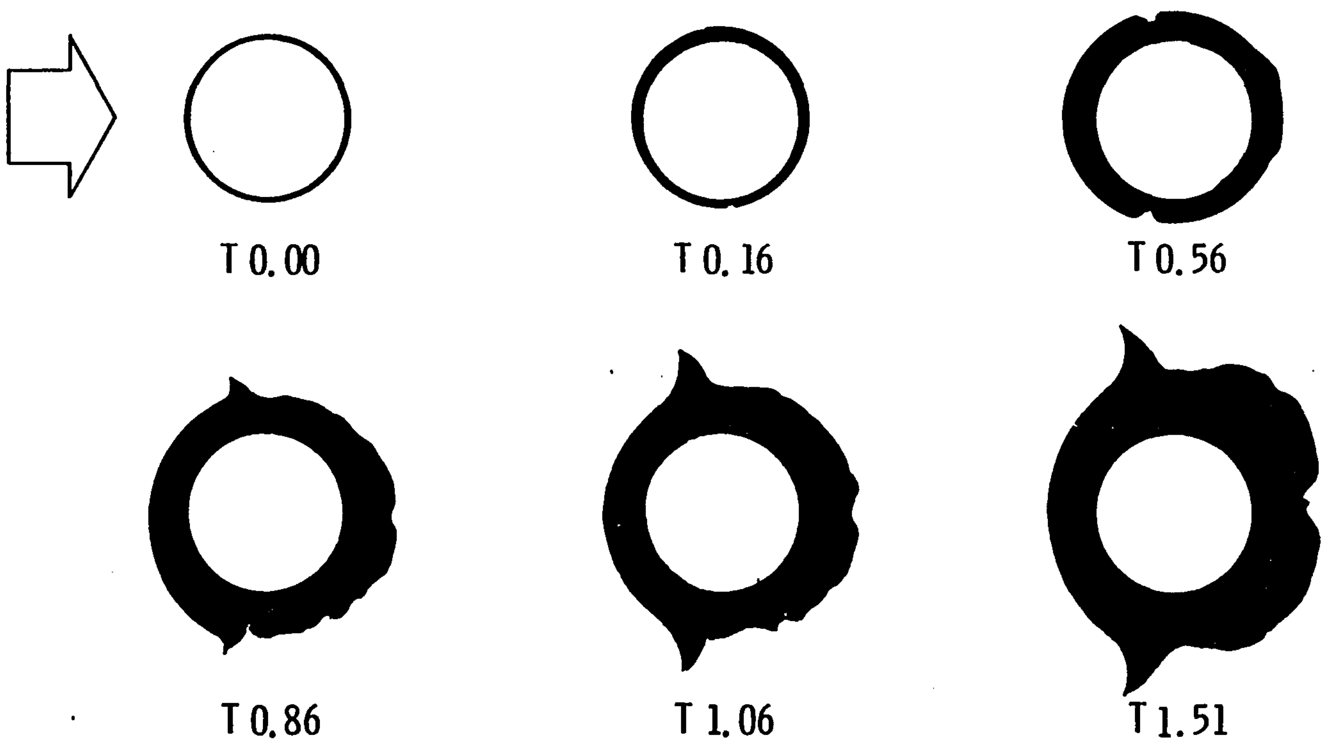
VAPOR DEPOSITION AND LIQUID LAYER FLOW (NO SHEDDING)



CS-82-2571

TRANSIENT EVOLUTION OF DEPOSIT LAYER
STATIONARY CYLINDER IN CROSSFLOW

VAPOR DEPOSITION AND LIQUID LAYER FLOW (NO SHEDDING)
T WALL = CONSTANT

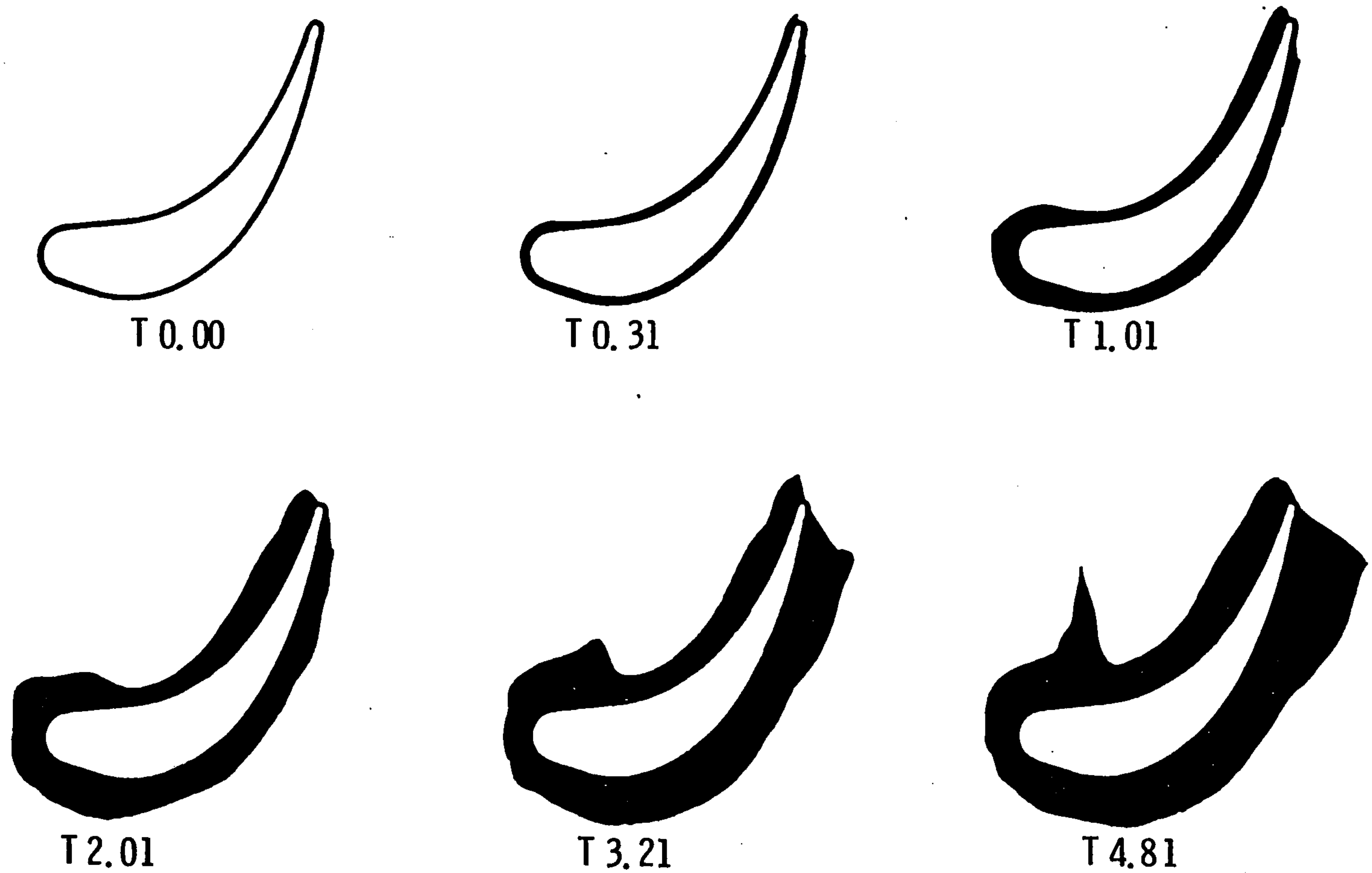


RELATIVE TIME (T)

CS-82-2572

TRANSIENT EVOLUTION OF DEPOSIT LAYER
STATOR BLADE

VAPOR DEPOSITION AND LIQUID LAYER FLOW (NO SHEDDING)
T WALL = CONSTANT



RELATIVE TIME (T)

CS-82-2578

FUTURE EMPHASIS OF DEPOSITION THEORY AND LIQUID LAYER FLOW

- BLADE ROTATION
- NONISOTHERMAL SURFACE TEMPERATURE DISTRIBUTION
- SALT SHEDDING; STEADY STATE
- MULTICOMPONENT VAPOR TRANSPORT
- SEED LEVEL TRANSIENTS
- ALTERNATE DEPOSITION MECHANISMS

    A. CONVECTIVE DIFFUSION

    B. THERMOPHORETIC ENHANCEMENT

    C. PARTICLE IMPACTION

CS-82-2569

COATING LIFE PREDICTION

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Metallic coatings are widely used on hot section components of advanced gas turbine engines in order to take full advantage of the strength capabilities of turbine materials. Proper design to coating life limits can allow components to operate either for longer times or at higher temperatures, both of which are cost effective. However, costly engine inspections and component refurbishment or replacement are made many times on a conservative basis because component life and/or reliability are generally unknown. An analytical method for predicting life of metallic coatings on turbine airfoils should, therefore, result in substantial savings in maintenance and materials costs as well as providing an improved basis for initial design. The work to be discussed herein addresses itself to developing an improved methodology for predicting cyclic oxidation life of metallic coating on gas turbine airfoils.

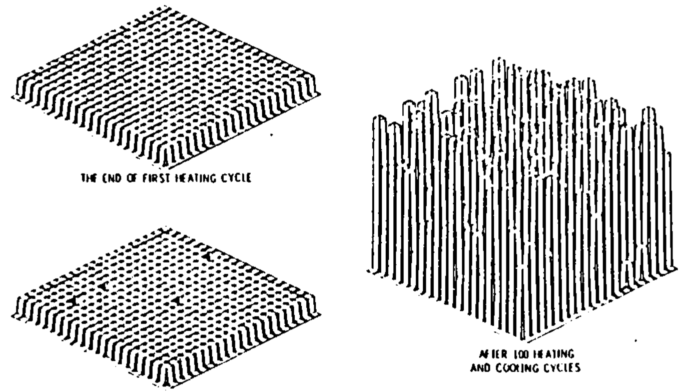
A cyclic oxidation/spalling model was developed at LeRC that predicts long time cyclic furnace oxidation behavior of alloys. The computer inputs for the model are obtained from simple, short-time isothermal oxidation tests. In the present study, the model is being applied to an aluminide coating on U-700, a low pressure plasma sprayed (LPPS) NiCoCrAlY coating on U-700, and a monolithic LPPS NiCoCrAlY. An empirical diffusion model to account for coating degradation will be integrated with the oxidation/spalling model to predict coating life in cyclic furnace oxidation. The integrated model will then be verified/adjusted to predict cyclic burner oxidation. Further verification/adjustment will lead to a life prediction model for coated turbine airfoils. Preliminary results of isothermal and cyclic furnace oxidation of aluminide coated U-700 are presented.

COATING LIFE PREDICTION

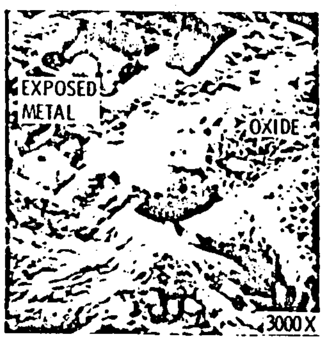
OBJECTIVE-

DEVELOP IMPROVED METHODOLOGY FOR PREDICTING CYCLIC OXIDATION LIFE OF METALLIC COATINGS ON GAS TURBINE AIRFOILS

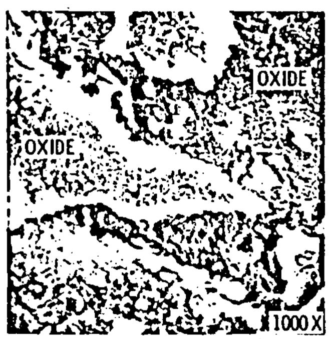
CYCLIC OXIDATION VISUALIZATION



SEM MICROGRAPHS OF SPALLED Al_2O_3 SCALES



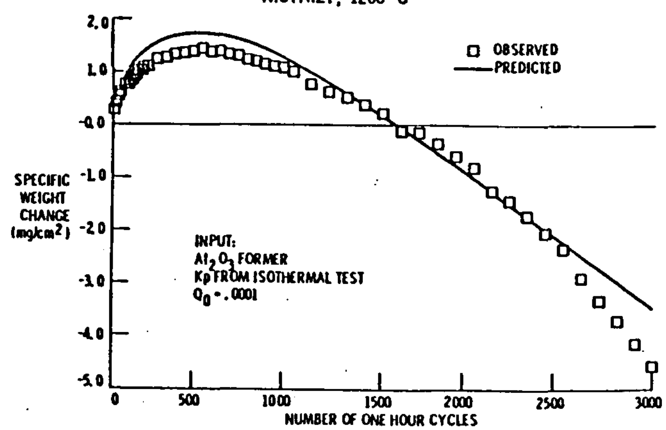
Ni-40 Al, 1200° C, 217 CYCLES



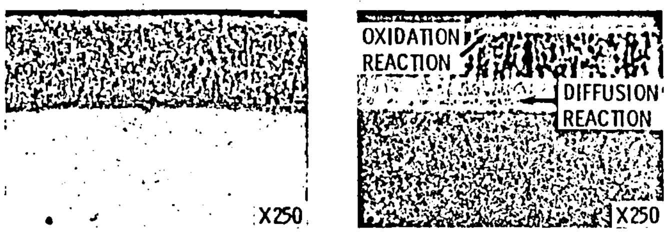
Ni-15Cr-24Al-0.3Zr, 1100° C, 500 CYCLES

PREDICTIONS FROM ISOTHERMAL DATA AGREE WITH CYCLIC DATA

NiCrAlZr, 1200° C

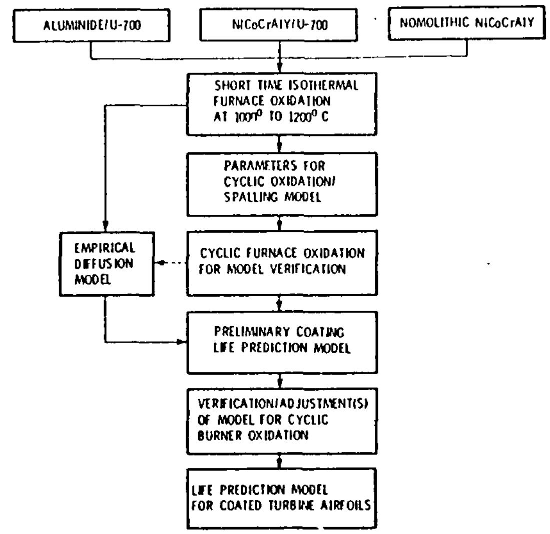


ENVIRONMENTAL AND SUBSTRATE REACTIONS DEGRADE COATINGS



AS-DEPOSITED NiCrAlY COATING — AFTER 200 hr AT 2000° F

APPROACH



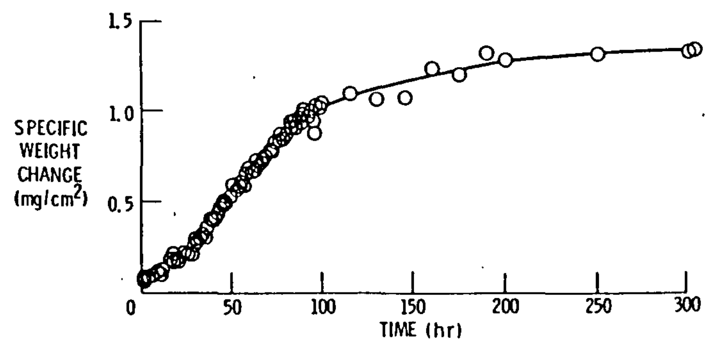
COATING LIFE PREDICTION

$$\text{LIFE} = F(f_O, f_D)$$

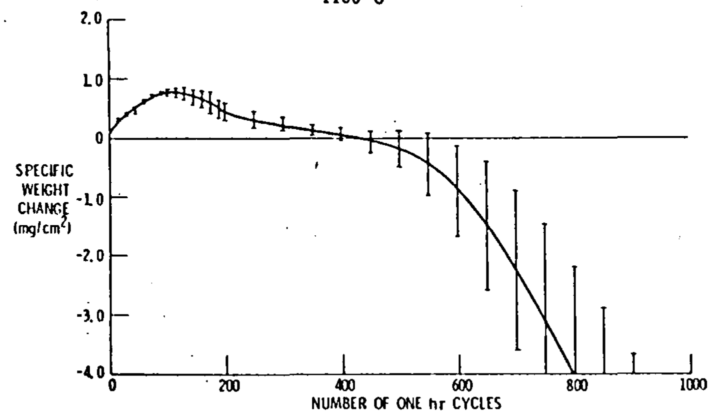
WHERE f_O = OXIDATION COMPONENT FOR GROWTH/SPALLING OF OXIDE SCALE

f_D = DIFFUSION COMPONENT FOR CRITICAL ELEMENT(S) OF THE COATING

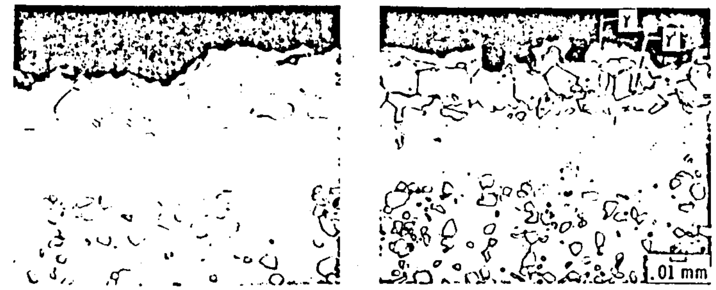
ISOTHERMAL FURNACE OXIDATION OF ALUMINIDE COATED U-700 1100° C



CYCLIC FURNACE OXIDATION OF ALUMINIDE COATED U-700
1100° C



ALUMINIDE COATED U-700 AFTER FURNACE OXIDATION AT 1100° C



300 hr ISOTHERMAL

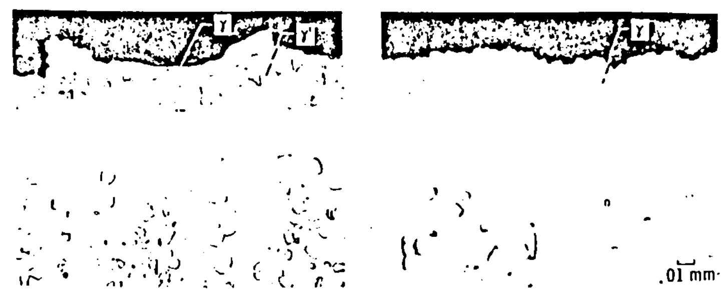
300-1 hr CYCLES

ALUMINIDE COATED U-700 AFTER FURNACE OXIDATION AT 1100° C

100 hr ISOTHERMAL

100-1 hr CYCLES

ALUMINIDE COATED U-700 AFTER FURNACE OXIDATION AT 1100° C



500-1 hr CYCLES

1000-1 hr CYCLES

EFFECTS OF SURFACE CHEMISTRY ON HOT CORROSION LIFE

OVERVIEW

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This program concentrates on analyzing a limited number of hot corroded components from the field and the carrying out of a series of controlled laboratory experiments to establish the effects of oxide scale and coating chemistry on hot corrosion life. This is to be determined principally from the length of the incubation period, the investigation of the mechanisms of hot corrosion attack, and the fitting of the data generated from the test exposure experiments to an empirical life prediction model. It is a six task program.

GENERAL SCOPE OF WORK

Task I involves the analysis of six field components which were removed from service. The hot corrosion condition of these six will vary from slight to massive attack. Concurrent with the metallurgical analysis of field components in Task I, specimens of bare and coated alloys will be subjected in Task II to exposures in a high velocity burner rig (under conditions specified by NASA-LeRC) for not more than 1000 hours or until hot corrosion occurs. In Task III, the Contractor shall age specimens (bare and coated) in an inert atmosphere, in furnace oxidation (cyclic and isothermal), and in cyclic high velocity burner rig oxidation at 1100C (2012F) for 100, 300, 600, and 1000 hours. In Task IV, the Contractor shall determine the effect of the various aging treatments on the hot corrosion mechanisms involved under the burner rig conditions specified in Task II.

Throughout Tasks I through IV, the results should be viewed not only in terms of identifying a model for the actual materials and test conditions run, but from the point of view of identifying a methodology whereby a life prediction model for other materials can be developed based on the results of one or more simple laboratory tests. After all the test exposures, the Contractor will review all the data and provide: (1) a preliminary hot corrosion life prediction model and (2) a recommendation of other test parameters to be evaluated so that simple laboratory tests can be used to predict hot corrosion life. The methodology to develop a hot corrosion life prediction technique shall be submitted to the NASA Project Manager for review and approval.

In Task V, based on NASA Project Manager's approval, the Contractor shall complete an experiment to determine the capability of the suggested methodology to predict the hot corrosion life of selected alloys and coatings.

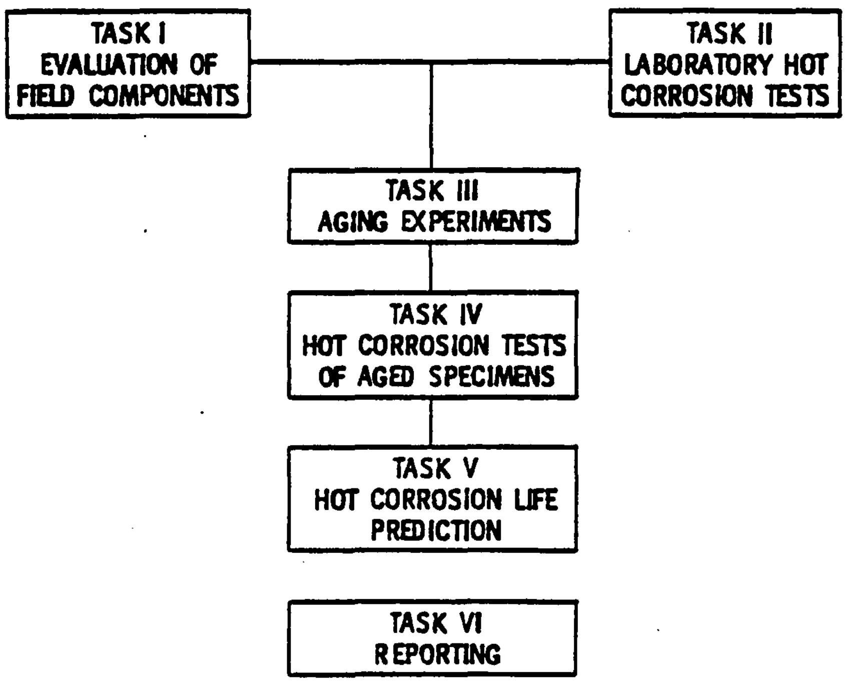
The last Task, VI, covers the reporting requirements.

RFP 3 - 412777

OBJECTIVE: DETERMINE EFFECTS OF SURFACE CHEMISTRY ON HOT CORROSION LIFE

BACKGROUND: PRIMARY MECHANISMS OF HOT CORROSION - FLUXING OF OXIDE SCALES BY LIQUID SALTS

- RIG TESTS GIVE INCONSISTANT RESULTS
- NEW TECHNIQUE DEVELOPED TO
  - DETERMINE THE INCUBATION/THRESHOLD PERIOD
  - CARRY OUT REPRODUCIBLE HOT CORROSION TESTS



- ANALYSIS OF HOT CORROSION COMPONENTS FROM THE FIELD
- CONTROLLED LABORATORY EXPERIMENTS TO ESTABLISH EFFECTS OF SURFACE CHEMISTRY ON HOT CORROSION LIFE
- DEVELOPMENT OF EMPIRICAL LIFE PREDICTION MODEL BASED ON DATA GENERATED

EFFECTS OF SURFACE CHEMISTRY ON HOT CORROSION LIFE

TASK I EVALUATION OF FIELD COMPONENTS

SIX FIELD COMPONENTS (LITTLE TO MASSIVE CORROSION)
EVALUATION (METALLURGICAL AND CHEMICAL)

TASK II LABORATORY HOT CORROSION TESTS

BURNER RIG CONDITIONS: 0.3 MACH, PRE-CONDITIONED AIR
MATERIALS: U700 AND CONTRACTOR'S CHOICE - BARE AND COATED (DUPLICATES)
COATINGS: RT21 ALUMINIDE, LOW PRESSURE PLASMA NiCoCrAly, CONTRACTOR'S CHOICE
CYCLE: 60 min HOT, 6 min AIR BLAST COOL
SPECIMEN SURFACE TEMPERATURE: 900C (1750F)
TIME: 1000 HOURS OR UNTIL HOT CORROSION OCCURS
RUN ADDITIONAL SPECIMENS 100, 300, 500 HOURS: TIME NOT TO EXCEED 2/3rds OF THE TIME IN WHICH HOT CORROSION OCCURS
MONITOR: VISUAL AND INDUCTANCE EVERY 20 CYCLES
EVALUATION: METALLURGICAL AND CHEMICAL (OXIDE, ALLOY AND COATING COMPOSITION AND STRUCTURE)

TASK III AGING EXPERIMENTS

TEMPERATURE: 1100C (2012F)
MATERIALS: AS IN TASK II (TRIPLICATES)
AGING CONDITIONS:

- TIME: 100, 300, 600, AND 1000 hrs
- ENVIRONMENT: INERT; ISOTHERMAL FURNACE OXIDATION; CYCLIC FURNACE OXIDATION; CYCLIC BURNER RIG OXIDATION

MONITOR: INDUCTANCE CHANGES AND WEIGHT CHANGES AS APPROPRIATE
CHARACTERIZATION: ONE SPECIMEN PER CONDITION AS IN TASK II

EFFECTS OF SURFACE CHEMISTRY ON HOT CORROSION LIFE

TASK IV HOT CORROSION TESTS OF AGED SPECIMENS

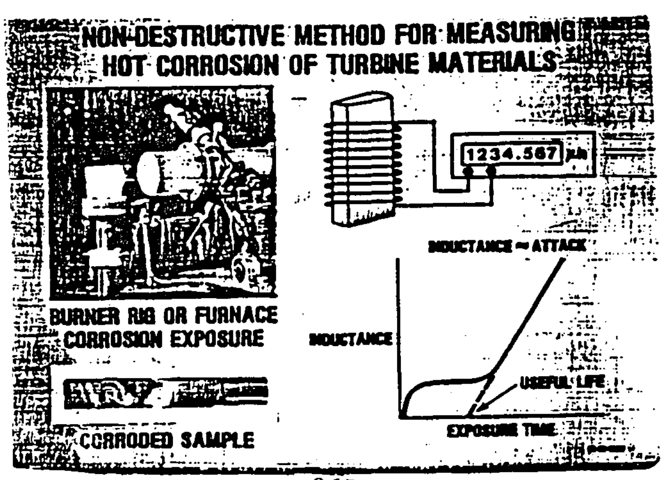
TEST CONDITION: AS IN TASK II, UNTIL HOT CORROSION OCCURS (DUPLICATES)
MONITOR: VISUAL AND INDUCTANCE EVERY 20 HOUR PERIOD
HOT CORROSION OCCURS: VISUAL SIGNS FOR THREE 20 hr PERIODS.
EVALUATION: (METALLURGICAL AND CHEMICAL)
PROPOSE: PRELIMINARY HOT CORROSION LIFE PREDICTION MODEL
SUGGEST: METHODOLOGY TO PREDICT HOT CORROSION LIFE BASED ON LAB EXPERIMENTS

TASK V HOT CORROSION LIFE PREDICTION

- VERIFY LIFE PREDICTION MODEL
- TEST METHODOLOGY

TASK VI REPORTING REQUIREMENTS

FINANCIAL
MONTHLY
ANNUAL
FINAL
ORAL PRESENTATIONS



COMBUSTION HOT SECTION TECHNOLOGY

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Propulsion Laboratory
AVRADCOM Research and Technology Laboratories
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Cleveland, Ohio

The overall objective of the Turbine Engine Hot Section Technology Combustion Project is to develop and verify improved and more accurate analysis methods for increasing the ability to design with confidence the combustion system for advanced aircraft turbine engines. The analysis methods developed will be generically applicable to combustion systems and not restricted to one specific engine or manufacturer.

This projects approach is to first assess and evaluate existing combustor aerothermal analysis models by means of a contracted effort initiated during FY '82. This evaluation effort will quantify known models strengths and deficiencies. A balanced contract and in-house program will then be conducted to support, focus, and accelerate the development of new methods to more accurately predict the physical phenomena occurring within the combustor. This balanced program will include both analytical and experimental research efforts in the areas of aerothermal modeling and liner cyclic life.

It is expected that the combustor model development effort will generate improved understanding in the areas of: high pressure flame radiation characteristics, model numerical methods and solution schemes, complex geometrical boundary conditions, fuel spray - flow field interactions, combustion kinetics, flow and mixing of dilution jets, turbulence and heat transfer, and soot and carbon formation. The primary in-house effort in this area will be the determination of high pressure flame radiation characteristics in a full annular combustor. This experiment will be conducted in the NASA LeRC High Pressure Facility with the results compiled into a comprehensive flame radiation and liner heat flux model.

In the area of liner cyclic life, HOST will develop a test apparatus to economically determine combustor thermal strains and cyclic life. This test apparatus will be run in-house at NASA LeRC and will be the test vehicle for many of the advanced high temperature instruments developed under HOST sponsorship. The fundamental data generated in this project will be used to assess and develop current analytical liner life programs.

TURBINE ENGINE HOT SECTION TECHNOLOGY

NASA
Lewis Research Center

OBJECTIVE

TO DEVELOP IMPROVED ANALYTICAL MODELS OF THE INTERNAL COMBUSTOR FLOW FIELD AND LINER HEAT TRANSFER AS A MEANS TO SHORTEN COMBUSTOR DEVELOPMENT TIME AND INCREASE TURBINE ENGINE HOT SECTION LIFE.

TURBINE ENGINE HOT SECTION TECHNOLOGY

NASA
Lewis Research Center

APPROACH

- UTILIZE EXISTING MODELS - DETERMINE THEIR DEFICIENCIES
- CONDUCT SUPPORTING RESEARCH TO IMPROVE PHYSICAL MODELS
- REFINE MODELS TO IMPROVE NUMERICS AND NUMERICAL DIFFUSION
- INTEGRATE NEW AND IMPROVED ROUTINES INTO EXISTING MODELS AND VERIFY THEIR IMPROVED PREDICTIVE CAPABILITY

C-82- 193

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TURBINE ENGINE HOT SECTION TECHNOLOGY

NASA

COMBUSTION

PROGRAM ELEMENT	FISCAL YEAR 81	82	83	84	85	86	87	EXPECTED RESULT
AEROTHERMAL MODELING ASSESSMENT								KEY MODEL AND DATA DEFICIENCIES IDENTIFIED
COMBUSTION MODELING DEVELOPMENT								NEW PHYSICAL MODELS AND COMPUTING METHODS
MULTIPLE JET DILUTION MIXING								EXIT TEMPERATURE PROFILE PREDICTION TECHNOLOGY
FLAME RADIATION/HEAT FLUX	(IH)							HIGH PRESSURE FLAME RADIATION AND HEAT FLUX
DILUTION JET ANALYSIS	(IH)							JET MIXING MODEL
LINER CYCLIC RIG	(IH)							CYCLIC TEST FACILITY

CD 82-13386