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, quantitative 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 Na₂SO₄ 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


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

COMBUSTION GASES

\[ 2 \text{NaCl} + \text{SO}_3 + \text{H}_2\text{O} \rightarrow \text{Na}_2\text{SO}_4 + 2\text{HCl} \]

DEPOSITION

BOUNDARY LAYER

\[ \text{Na}_2\text{SO}_4 \]

CORROSION

\[ \text{Al}_2\text{O}_3 \text{ OR Cr}_2\text{O}_3 \]

OXIDES + SULFIDES

SUPERALLOY SUBSTRATE

O₂, Na, S COMPOUNDS
# Characteristics of Deposition for Spectrum of Particle Sizes

<table>
<thead>
<tr>
<th>Size Range*</th>
<th>Mass Transport Mode</th>
<th>Deposition Species</th>
<th>Transport Mechanism</th>
<th>Deposition Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-10A</td>
<td>Vapor Diffusion</td>
<td>Atoms and Molecules (Vapors)</td>
<td>Fick Diffusion</td>
<td>1. T_{dp} &lt; T_e</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2. Low \eta and deposition on side away from line-of-sight</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3. Low sensitivity to T_e - T_w</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4. Rate levels off for T_w &lt;&lt; T_{dp}</td>
</tr>
<tr>
<td>10A-10^{-1} \mu m</td>
<td>Vapor Diffusion Transition</td>
<td>Heavy Molecules (Condensate Aerosols, Clusters, Submicron Particles)</td>
<td>Brownian Diffusion Eddy Diffusion Thermophoresis</td>
<td>1. T_{dp} = T_e</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2. Lowest \eta</td>
</tr>
<tr>
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<td></td>
<td></td>
<td></td>
<td>3. High sensitivity to T_e - T_w</td>
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<td></td>
<td></td>
<td>4. Rate nearly linear with T_e - T_w</td>
</tr>
<tr>
<td>10^{-1} - 100 \mu m</td>
<td>Inertial</td>
<td>Macroscopic Particles</td>
<td>Inertial Impaction Eddy Impaction</td>
<td>1. No apparent T_{dp}</td>
</tr>
<tr>
<td></td>
<td></td>
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<td></td>
<td>2. Highest \eta</td>
</tr>
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<td></td>
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<td>3. Independent of T_e - T_w</td>
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<td></td>
<td>4. Preferential deposition on side facing flow</td>
</tr>
</tbody>
</table>

* Mode of deposition is not fixed by particle size alone

\eta = deposition or collection efficiency, T_{dp} = dew point temperature, T_e = gas mainstream temperature, T_w = wall temperature
PREDICTED DEPENDENCE OF SODIUM SULFATE DEPOSITION RATE ON PARTICLE SIZE

\[ P = 12 \text{ atm}, \ Na_2SO_4 \text{ DEPOSITION} \]
\[ T_e = 1423 \text{ K} \]

\[ T_{w/e} = 1.0 \]

FRACTION CAPTURED

PARTICLE DIAMETER, \( \mu \text{m} \)

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
VAPOR DEPOSITION THEORY—CFBL

INTEGRATED DEPOSITION FLUX IS GIVEN BY

\[
\dot{m}_i = \frac{(Dp)e}{L} \cdot F(\text{turb}) \cdot F_i(\text{Soret}) \cdot \text{Nu}_{m_i}(\text{Re, Sc}) \cdot \left[ \Delta \omega_i + \frac{T_i}{F_i(\text{Soret})} \cdot \omega_{i,w} \right]
\]

TRANSFER COEFFICIENT

DRIVING FORCE
MACH 0.3 BURNER RIG DEPOSITION OF Na₂SO₄ ON ROTATING CYLINDRICAL COLLECTORS

O EXPERIMENTAL POINTS ——— CFBL THEORY

Na₂SO₄ SEED

DEPOSITION RATE, mg/h

NaCl SEED

COLLECTOR TEMPERATURE, °C

M. P. Na₂SO₄

GS-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
AERODYNAMICALLY-DRIVEN THIN CONDENSATE LAYER FLOW

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

\[
\frac{\partial \delta_L}{\partial t} + \frac{\partial}{\partial x} \left( \frac{\tau_w(x)}{2\mu_L \cdot \delta_L^2} \right) = - \frac{\dot{m}''(x)}{\rho_L}.
\]
DEPOSIT THICKNESS AS A FUNCTION OF POSITION

VAPOR DEPOSITION AND LIQUID LAYER FLOW (NO SHEDDING)

Re = 10^5
T_w = Const

PRESSURE SURFACE

SUCTION SURFACE

CS-82-2571
TRANSIENT EVOLUTION OF DEPOSIT LAYER
STATIONARY CYLINDER IN CROSSFLOW

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

RELATIVE TIME (T)

T 0.00
T 0.16
T 0.56
T 0.86
T 1.06
T 1.51

CS-82-2572
TRANSIENT EVOLUTION OF DEPOSIT LAYER
STATOR BLADE

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

T 0.00
T 0.31
T 1.01
T 2.01
T 3.21
T 4.81

RELATIVE TIME (T)
FUTURE EMPHASIS OF DEPOSITION THEORY AND LIQUID LAYER FLOW

- BLADE ROTATION
- NONISO THERMAL 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
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

SEM MICROGRAPHS OF SPALLED $\text{Al}_2\text{O}_3$ SCALES

Ni-40 Al, 1200$^\circ$ C, 217 CYCLES

Ni-15Cr-24Al-0.32t, 1100$^\circ$ C, 500 CYCLES

PREDICTIONS FROM IsoTHERMAL DATA AGREE WITH CYCLIC DATA

NICrAlZr, 1200$^\circ$ C
ENVIRONMENTAL AND SUBSTRATE REACTIONS
DEGRADE COATINGS

AS-DEPOSITED NiCrAlY COATING

OXIDATION REACTION

DIFFUSION REACTION

X250

AFTER 200 hr AT 2000°F

COATING LIFE PREDICTION

\[ \text{LIFE} = F(t_o, t_d) \]

WHERE \( t_o \) = OXIDATION COMPONENT FOR GROWTH/SPALLING OF OXIDE SCALE

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

APPROACH

ALUMINIDE/U-700

NiCrAlY/U-700

NONLITIC NiCrAlY

SHORT TIME ISOTHERMAL FURNACE OXIDATION AT 1000°F TO 1200°C

PARAMETERS FOR CYCLIC OXIDATION/SPALLING MODEL

OXIDE SCALE

DIFFUSION COMPONENT FOR CRITICAL ELEMENT(S) OF THE COATING

EMPIRICAL OXIDATION MODEL

CYCLIC FURNACE OXIDATION FOR MODEL VERIFICATION

PRELIMINARY COATING LIFE PREDICTION MODEL

VERIFICATION/ADJUSTMENT OF MODEL FOR CYCLIC BURNER OXIDATION

LIFE PREDICTION MODEL FOR COATED TURBINE AIRFOILS

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

SPECIFIC WEIGHT CHANGE (mg/cm²)

0 0.5 1.0 1.5

0 50 100 150 200 250 300 TIME (hr)

XXXII-3
Cyclic furnace oxidation of aluminide coated U-700 at 1100° C.

Specific weight change (mg/cm²) vs. number of one hr cycles.

Aluminide coated U-700 after furnace oxidation at 1100° C.

100 hr isothermal

100-1 hr cycles

300-1 hr cycles

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 1100°C (2012°F) 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.
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

NON-DESTRUCTIVE METHOD FOR MEASURING HOT CORROSION OF TURBINE MATERIALS

BURNT RIB OR FURNACE CORROSION EXPOSURE
CORRODED SAMPLE
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 project's 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.
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.

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
## COMBUSTION

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

**Legend:**
- (IH) indicates high importance.