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Coal-Fueled Turbines: Deposition Research

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ABSTRACT

The U.S. Department of Energy, Office of Fossil Energy, through its Morgantown Energy Technology Center, has initiated a program for the application of less expensive fuels for use in gas turbines; the overall objective is to develop an environmentally sound integrated direct-fired, coal fueled gas turbine system which will produce cost-competitive energy. The fuel is coal and may be in several forms which include a micronized powder, a slurry (with water, methanol, etc.), or a minimally cleaned, coal-derived gas.

The application of coal fuels to gas turbines raises a number of technical questions, a principal one being the development of deposits within the turbine. Several programs have been initiated, that are aimed at development of an understanding of turbine deposition from coal fuels. Some of DOE's research activities which are discussed within this paper include efforts in: (a) nozzle cascade tests utilizing advanced and conventional blade cooling to minimize deposition, (b) bench-scale combustion/deposition tests, (c) laboratory research aimed at defining particle stickiness, and (d) theoretical efforts to model gas stream nucleation of particles and the resulting deposition on blades cooled to various temperatures.

INTRODUCTION

Traditionally, gas turbine fuels have been limited to the "clean" fuels such as natural gas or distillate fuels. Clean fuels minimize the three interrelated degradation processes of deposition, erosion, and corrosion. While methods or approaches are available for combating oil fuel-related corrosion and erosion, they tend to worsen deposition within the gas turbine. These three processes constitute the central problem affecting turbine reliability and service life when using lower grade fuels.

Since 1944, there have been several studies to fuel gas turbines with lower cost, "nonpristine" fuels (1). Success has been rather limited as deposition has proven to be one of the limiting factors. Coal in its conventional form has been unable to meet the fuel quality specifications and, therefore, has not been used as a turbine fuel.

Discussions of the history of the early coal-fueled gas turbine research activities can be found in several documents (1,2,3,4,5). Curtailment of this earlier research was primarily driven by the availability of cheap energy from oil. The technical difficulties encountered consisted of severe erosion, deposition, and materials handling problems. Test data indicated that turbine machinery would require extensive modifications (e.g., reinforcing critical blade areas and redesign of the combustor to allow for particulate removal from the expansion gas). While the earlier tests might be viewed as disastrous, it is significant to note that the test machines did run and that a technology base was established for coal-fueled gas turbines.

In 1983, DOE Fossil Energy through its Morgantown Energy Technology Center initiated a new program for direct coal-fired gas turbines (6). Deposition was one critical area identified. Although results from previous coal-burning efforts were encouraging, the deposition phenomena in direct, coal-fired turbines (in light of developments in coal preparation and blade cooling technology) presented one of the greatest uncertainties.

The propensity for and nature of deposition when using coal fuels processed by advanced techniques (micronization, beneficiation, slurry formation) was totally unknown at the onset of the program (7). In addition, techniques such as advanced cooling and ingenious combustion control were believed to be attractive means (than the conventional methods used in previous tests) to minimize turbine deposition. These advanced technologies when coupled with the technology base from previous tests formed the basis for the DOE initiative to directly fire coal into a gas turbine.

BACKGROUND

In development of an understanding of the critical parameters for coal-fuel related deposition, it must be

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understood that the chemical and physical processes that affect the ash constituents during coal combustion are complex and are not well understood. The physical phases (gas, liquid, or solid) of the ash constituents are dependent on the actual chemical compounds formed during combustion.

Coal combustion can be described as a rapid devolatilization process (one-tenth second) followed by slow burnout (less than two seconds) of the char. A schematic (reprinted from Reference 8) of a coal particle combustion process is shown in Figure 1. Whether the process is direct or indirect combustion of an ash-containing coal-derived fuel, the ash particle residue is key to the deposition process. Trace amounts of some compounds can make the critical difference between an ash particle being solid, liquid, or vapor. This variation in phase drastically affects how the ash will interact within the turbine.

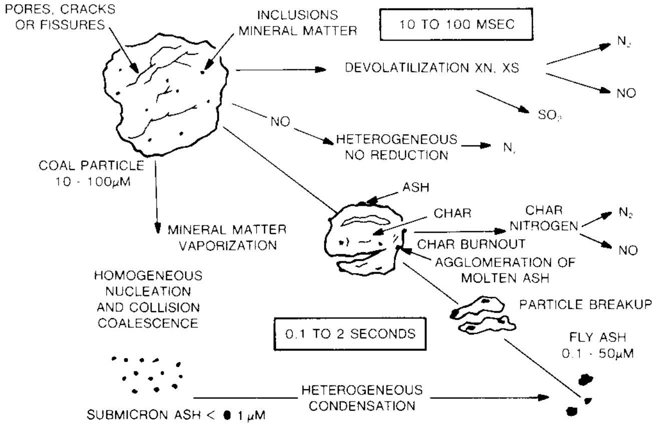

Figure 1. Coal Particle Combustion

In general, deposition will occur when low-melting contaminants either are present in or are condensed out onto particle surfaces during or immediately following combustion. These low-melting materials form a "sticky" surface (Figure 2) on the particles that causes them to adhere to themselves and to the turbine metals which thus forms the deposit. Eventually the deposit will block the turbine flow path, thereby degrading the ability of the turbine to transform the flow energy into the rotational energy that drives the electric generator. Performance will fall off until it is no longer practical to run the system.

The mechanism of deposit formation can be divided into two distinct phenomena: (a) transport of the depositing species to the surface and (b) the adhesion process resulting in deposition (1). Because of the dependence of various transport and adhesive mechanisms on the physical characteristics of the depositing species (i.e., particle size, stickiness, shape, etc.), the formation of deposits is very dependent on the chemical properties of the corresponding surface and the precursor forms of the depositing species.

The deposition probability of a particle is governed by its melting point, vapor pressure, and its chemical affinity to the surface. This group of parameters can be considered to be a partial list of the intrinsic properties of the deposit-forming species. Other parameters which affect deposition can be considered as extrinsic to the deposit-forming species. These are the combustion temperature, equivalence ratio, residence time, dilution ratio, blade and vane temperatures, surface stickiness and the time-pressure history in a gas turbine system. These factors also affect the amount and type of deposition and are the factors which ultimately could be adjusted to minimize deposition if the critical parameters can be identified.

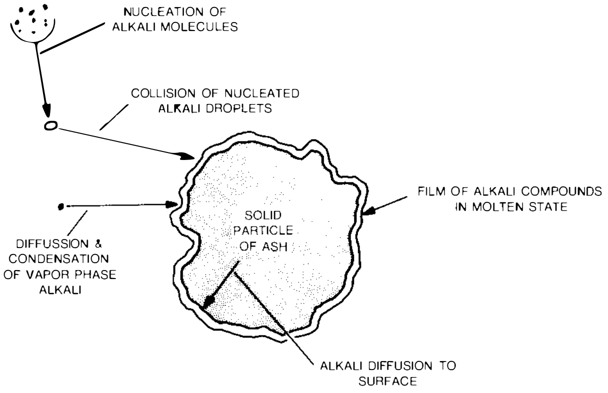

Figure 2. Formation of "Sticky" Particles

The primary modes of transport (9) are divided into several different mechanisms (Figure 3). For particles, the major mechanisms of delivery in gas turbines are (a) inertial impaction, (b) turbulent eddy diffusion, and (c) Brownian motion with minor mechanisms that include thermophoresis and vapor diffusion (molecular-sized particles).

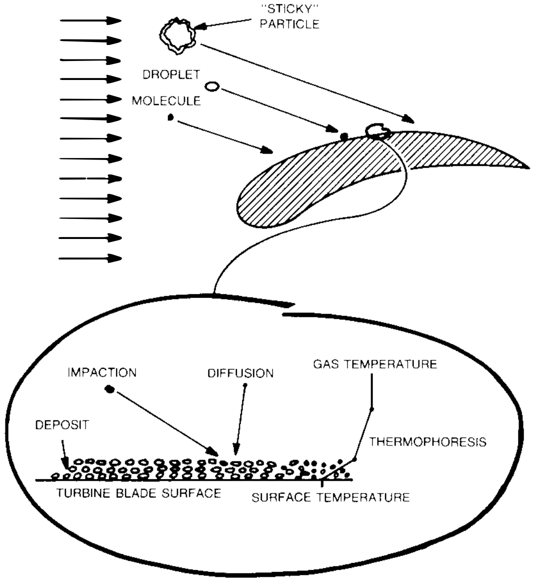

Figure 3. Deposition Type

For inertial impaction, particle inertia overcomes forces that the particle has experienced from the flow stream lines near the blade and vane passages. The resultant trajectories lead to impaction. Equations of motion can yield estimates of the proportion of particles that will strike the surface. This mechanism is the dominant one for particles larger than five micron in diameter, but is believed to contribute negligibly to particle delivery for particle diameters less than one micron. Inertial impaction may lead to adhesion to the surface and the buildup of deposits depending on size and velocity of the impacting particles, the angle of impaction, and the elastic properties of the colliding species and surface.

Particles may also be deposited after becoming entrained in eddies of turbulence near blade and vane surfaces. These turbulent currents effectively toss the particle to the surfaces of the blades and vanes. Once in the vicinity of the surface, the particles may experience either inertial or diffusional forces which proceed to drive them to contact with the surface. Although the turbulent eddies dissipate before reaching the surface of the turbine blades, the entrained particles may continue through the boundary layer to the surface due to their inertia. The particle arrival rates fall off rapidly for particle sizes smaller than about three-tenths micron in diameter. Although this mechanism is not actually a diffusional motion, the eddy motion imparts a cross-stream movement just as diffusion does, and it is described mathematically using diffusion-like terms.

Thermophoresis is the movement of particulate matter in a gas under the influence of a temperature gradient towards cooler surfaces. Thermophoretic effects are significant for particles smaller than about one-half micron in diameter. In gas turbines, the temperature gradient is the result of the blades and vanes of a turbine being cooler than the combustion gas passing through the system. Thermophoresis is expected to have a greater role in deposition when advance blade cooling techniques are used.

An earlier advanced blade cooling program (10) demonstrated the thermophoretic affect. Reprinted from Reference 10, the following chart (Figure 4) indicates that deposition increased with temperature, with the peak rate of deposition occurring in the range of 1,200°F wall temperature. However, metal blade surface temperatures in the 600° to 800°F range resulted in improved resistance to hot corrosion and ash deposition. Thus, thermophoretic effects or low blade surface temperatures minimize deposition.

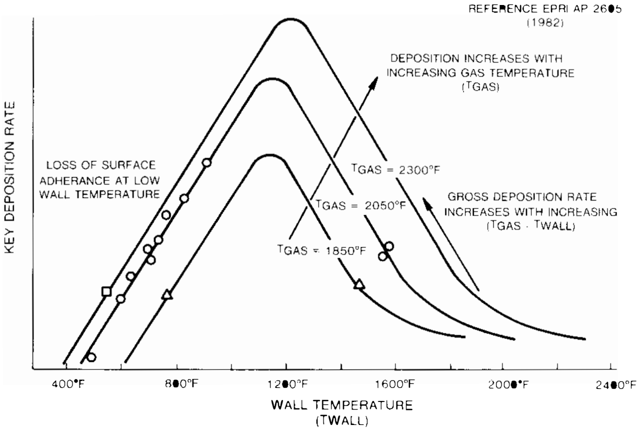

Figure 4. Deposition Rate Versus Surface Temperature

Although not a thermophoretic effect, a similar relationship demonstrating that low metal temperatures will retard turbine deposition can be found in the Australian Coal-Burning Gas Turbine Project (3). The Australians doped coal-derived, ash-laden gas with additives to suppress deposition. Although the Australians did not vary metal temperature, they did vary gas temperature which had the effect of surface temperature variation. Reprinted from Reference 3, Figure 5 depicts the same general trend that deposition will follow a bell-shaped curve and will be minimized when low blade metal temperatures exist.

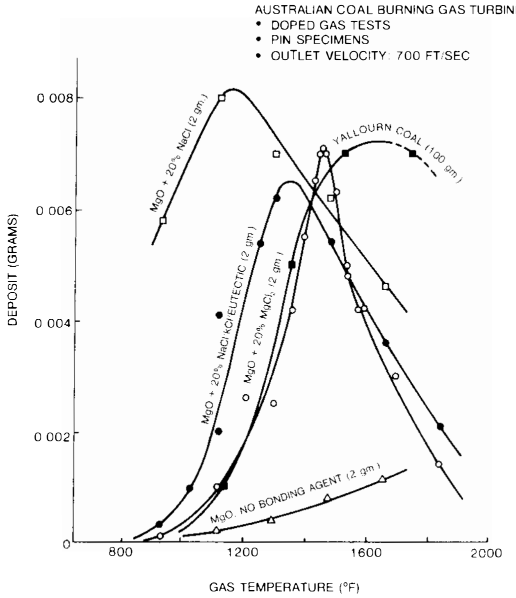

Figure 5. Deposit Versus Gas Temperature

Another mode of deposition, due to Brownian motion or diffusion, is the movement of a particle due to the random collision of the molecules of gas in which the particles are suspended. The physical process is identical to molecular diffusion. Since molecular impaction affects smaller particles more significantly than larger ones, arrival rates due to Brownian diffusion increase as particle size decreases. At particle diameters less than one-tenth micron, Brownian diffusion becomes more important than turbulent eddy diffusion.

Vapor condensation and diffusion involve the molecular diffusion of contaminant molecules to surfaces where condensation and/or chemical reactions may occur. The flux of contaminant molecules to the surface is governed by the concentration gradient of that particular vapor-phase species. Surface condensation only occurs if the temperature of the surface is sufficiently cool to produce a local saturation of the vapors. However, chemical reactions may occur which appear to result from condensation. In this case the deposition rate is still governed by molecular diffusion but is coupled with gas-solid reaction kinetics.

Once particles have been transported to the surface, deposition will be dependent on the stickiness of the particle. Some contaminants will have a greater chance to adhere to the surface. For example, in general terms, the vapor-condensed species would more likely form "sticky" surfaces than inertial impacting particles since the condensates are probably liquid. The various modes of transport will have differing compositions of the ash material which will ultimately lead to differing adhesive fractions or sticking coefficients.

Deposits will form only if retention occurs upon contact with the surface or with other particles on the surface. Adhesive forces, which cause the particles to stick to the surface, may be explained by several possible processes. The forces are the result of microscopic and macroscopic effects which are discussed in detail in other published documents and are the subject of research at the Morgantown Energy Technology Center to be discussed within this paper.

The above mechanisms of deposition are predominately dependent on ash particulate characteristics from coal-fueled combustion systems. Advanced techniques to clean the coal fuel of offending contaminants to acceptable levels may be utilized in coal-fueled turbine systems. Advanced blade design techniques to minimize deposition may include advanced cooling (e.g., water-cooled (11), or transpiration cooled blades (12) and/or electrostatic charged blades (13)). In addition, the turbines may need to be modified through the use of new materials, application of cooling techniques, methods of construction, or by changes in physical configuration. A third choice may be to remove contaminants during or immediately after combustion.

A successful coal-fueled system probably will use more than one of these options to minimize deposition and to produce a workable minimum cost system. At this stage of development, however, a best choice or balance cannot be made. Recent advances in both coal preparation technology and advanced turbine cooling methods and materials show considerable promise in being able to minimize deposition and to achieve the right choice for these systems. The aim of the current DOE program for coal-fueled turbines is to provide for this base information.

RESEARCH ACTIVITIES

The DOE Fossil Energy interest in direct coal-fueled turbines has evolved because of significant advances in coal preparation coupled with advanced gas turbine machine design considerations. New methods of coal grinding and of separating mineral matter from finely ground coal have been developed which should reduce the amount of ash in the combustion gas stream and thus minimize turbine deposition. Fine grinding liberates mineral particles from the coal matrix allowing them to be physically separated. Chemical treatment of coal provides for additional beneficiation of the coal fuel. Deposition can also be suppressed through the use of advanced cooling techniques. The synergistic effect of the advanced technologies should minimize deposition within the gas turbine.

Research is underway to use the advanced fuel forms and technologies to develop the required data base. In addition to internal activities at the Morgantown Center contract efforts are underway to develop data relevant to deposition. The activities include those with major turbine manufacturers (e.g. Allison, General Electric, Solar, United Technologies, and Westinghouse), with coal fuel manufacturers (AMAX, United Coal), with universities (Massachusetts Institute of Technology, Purdue, Yale), with national laboratories (Argonne, Sandia), and private industrial organizations (General Applied Science Laboratory, Physical Science Incorporated). All activities are not directed toward deposition research, but should provide useful data that will aid in the understanding of deposition phenomena. The specific areas of research to be discussed within this paper include large-cascade tests, bench-scale tests, laboratory studies, and theoretical modeling.

Cascade Tests: Blade Cooling Effects

DOE studies have shown that turbines capable of accepting a broader range of impurities in the fuel offer significant opportunities for more economic systems. Typically, these studies show that the cost of electricity for coal-fueled gas turbine cycle plants will compete favorably with nuclear and pulverized coal systems. In the case of a gasification combined cycle, the advantages accrue if the turbine can accept the fuel gas without extensive cleaning. In this case, sensible heat is maintained, and the capital and operating costs for downstream cleanup processes can be reduced. For a fixed-bed gasification system, coal pile to bus-bar efficiency gains of 6 to 10 percentage points have been projected (14).

To explore the technical feasibility of operating a gas turbine on minimally cleaned coal-derived gas, a test program utilizing gasifier output, a hot cyclone, a gas turbine combustor, and advanced-cooled components was initiated. The first test series utilized advanced water-cooled nozzle components. A second series of tests has substituted air-cooled nozzles in the configuration for comparative analysis. A schematic of the test configuration is depicted in Figure 6.

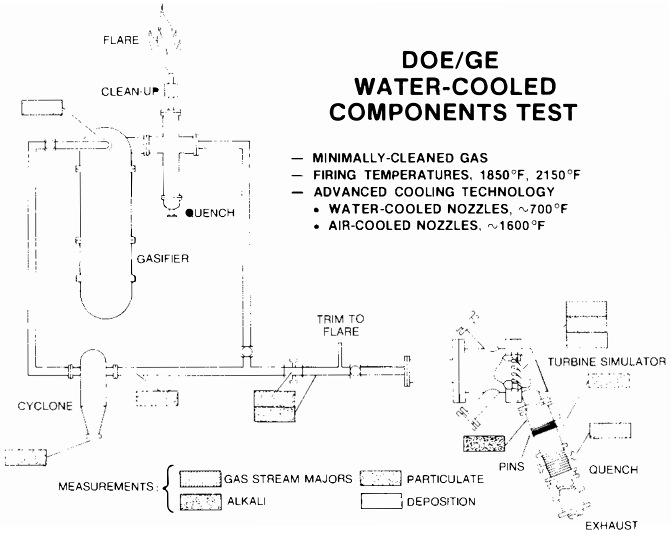

Figure 6. Advanced Cooled-Components Tests

The overall objectives of this project (15) are to quantitatively assess the deposition phenomena on advanced-cooled turbine nozzles in a gas stream which is fueled with minimally cleaned coal-derived gas. Deposition is being assessed with respect to gas stream temperature, blade surface temperature, and fuel quality. Data from the test will provide early insight into the ability of advanced cooling to inhibit deposition.

For the water-cooled nozzle tests, an existing low-Btu gas combustor developed for the General Electric MS6001 gas turbine was modified to burn the hot, dust-laden coal gas fuel. A corresponding MS6001 transition piece was modified for transition from the cylindrical combustor liner to a two-vane/three-throat, water-cooled first-stage nozzle, airfoil section. The full-scale, water-cooled (composite structure), first-stage turbine nozzles developed under an earlier DOE-sponsored program (11) were operated at surface metal temperatures below 700°F.

The first series of tests has been completed and a discussion of the results can be found in Reference 14. The fuel gas was delivered to the turbine simulator at approximately 1,000°F with a particle dust loading of 100 parts per million (ppm). Only 11 percent (11 ppm) of the gas stream dust was ash. The combusted gas stream was within the particulate limits of the New Source Performance Standards. Firing temperatures were 1,800° and 2,150°F for the two tests. The nozzle metal temperature for each test was maintained at levels below 700°F. In total, more than 135 hours of operation at test conditions were conducted. Inspection of the nozzle airfoil surfaces after each of the tests revealed essentially no deposit on the concave surfaces and a very thin coating (less than 0.003 inch) on the convex surfaces. This deposit was found to be water soluble and easily removed after each test.

With respect to the second series of tests (15) which used conventional air-cooled nozzles, no measurable deposition was observed following more than 140 hours of operation. The tests were conducted at a gas-stream temperatures of 2,150°F. These tests used standard MS6001 air-cooled nozzles which operated with 1600°F metal temperatures.

In both tests, alkali metals level in the product gas were less than one part-per-million which reduces the propensity for ash deposition and reduces the likelihood for hot corrosion attack of high-temperature turbine components. It is speculated that alkali metals condensed on the particles and were removed by the cyclone separator in these tests.

The tests are of key significance in that they pave the way for a low-cost, simplified coal-dervied/gas turbine combined cycle-cycle system. These tests have provided increased confidence in the viability of the turbine to survive in a minimally cleaned gasification system.

Bench-Scale Tests: Combustion and Deposition

The Morgantown Energy Technology Center is using a refractory-lined, bench-scale pressurized combustor (15) to investigate combustion phenomena and deposition characteristics of coal-derived fuels (coal slurries, minimally cleaned coal-derived fuel gas, and coal pyrolysis products). Tests primarily with coal slurry fuels have been conducted at elevated pressures up to eleven atmospheres. Advanced laser-based and fiber optic on-line instrumentation techniques are used with conventional instrumentation to measure particulate and alkali metal loadings in the gas stream.

Tests to date have shown that the ash deposits composition from coal slurry fuels, both within the combustor and on cylindrical deposition pins in the effluent stream, differ very little from the elemental make up of the coal fuel. The deposit has been minimal and found to be soft, friable, and water soluble.

Bench-Scale Tests: Two-Stage Combustor

Solar Turbines International is using a two-stage slagging-type combustor to test coal slurry fuels (15). The unit, originally developed as a low NO_x concept for heavy fuels is providing valuable data on the combustion and deposition characteristics of coal fuels. Testing is still ongoing, but preliminary results indicate that the deposit on cylindrical pins is soft, friable, and water soluble.

Laboratory Study: Particle Stickiness Phenomena

One of the most important parameters affecting the rate of deposition is the sticking coefficient of particles which collide with the surface. An effort underway at the Morgantown Energy Technology Center (15) will attempt to develop an understanding of the parameters that influence the sticking coefficient (i.e., angle of impact, particle size, surface chemistry, etc.). The effort includes a literature review (1) pertaining to deposit formation and the fabrication and operation of an experimental deposition test facility at METC.

The data from the facility will be used to help determine which contaminants in a coal-fuel contribute to particle stickiness (i.e., the fraction of particles in a gas stream which adhere to a surface) and what conditions either maximize or minimize the effect. Data from the Morgantown research will quantify particle adhesiveness and provide knowledge of the adhesive fraction (sticking coefficient) of the ash particles which are being influenced by the coal ash chemistry. Preliminary results for bituminous coal indicated that the sticking coefficient is less than 0.1 for stainless steel and platinum substrates.

Additional experimental tests will be needed in order to resolve fundamental factors controlling the stickiness of particles and their role in deposit formation. This effort will provide for the additional theoretical understanding of models of deposition, which are currently limited to methods of particulate arrival.

Mathematical Modeling

Using a number of relevant mathematical models (15,16), Argonne National Laboratory has developed an understanding of the exhaust gas stream nucleation of vaporized species and the resulting deposition of the particles on turbine blade materials.

The analytical models developed described (a) vaporization of the alkali species (sodium and potassium) and other mineral matters (silicon, magnesium, calcium, iron, and aluminum) from coal ash during combustion; (b) subsequent condensation of ash and alkali vapor; (c) deposition of ash, nucleated and entrained, and alkali sulfate particles on the pressure and suction surfaces of turbine blades; (d) vapor deposition of alkali sulfates on turbine blades; and (e) inertial impingement of entrained ash particles on turbine blades.

The specific application intended for the overall model is to predict the influence of operating variables such as coal cleaning, slurry composition, combustion temperature, turbine-firing temperature, and blade cooling on the performance of gas turbines in combined-cycle plants fired by ultraclean coal-water mixture or dirty coal-derived low- to medium-Btu gas.

Additional effort is needed to refine the model; correlate the calculated deposition rates of ash and alkali sulfates to the corrosion, erosion, and fouling criteria used by turbine vendors; and to more systematically apply the model to investigate the influence of plant-operating variables (coal cleaning, combustion temperature, turbine-firing temperature, blade cooling, etc.) on the deposition characteristics of coal-fired gas turbines.

As a result of the Argonne effort, a mechanistic model for vaporization, condensation, and deposition has been developed to trace the fate of the alkali species and fly ash particles from the combustor through the gas turbine. The model predictions will be compared to experimental test data. The model currently is in the process of being used to analyze turbine cascade systems.

SUMMARY

The DOE Office of Fossil Energy has initiated a program to stimulate the development of coal-fueled heat engine technology. A major concern has been deposition of coal ash particles on turbine airfoil surfaces. A broad spectrum of research to understand deposition phenomena is underway with turbine manufacturers, coal-fuel suppliers, National Laboratories, private industrial organizations, and within DOE/Morgantown. The aim of the program is to develop the data base needed to understand and minimize deposition. Research to date has shown that the deposition from coal slurry and coal-derived gaseous fuels is generally soft, friable, and water soluble, which is different than oil-fueled deposits. Of key significance are the results of recent tests at General Electric which used minimally-cleaned coal-derived fuel. No measurable signs of depositions were evident after more than 275 hours of full-scale cascade tests. More parametric type tests are needed to develop the needed data base. However, indications are that the deposit characteristics will be very soft and friable, and will be susceptible to use of conventional techniques to clean the turbine surfaces. DOE research is continuing to more fully understand coal-fueled turbine deposition in an effort to establish the data base needed to prove the viability of a coal-fueled heat engine.

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