INTRODUCTION

The ingestion of foreign materials into turbines can result in impact damage (erosion) or accumulation of material in the turbine to block flow passages and degrade aerodynamics (deposition) or chemical attack of turbine surfaces (corrosion). The resulting nature and extent of damage to a turbine depend on many interactive factors such as fuel chemistry, gas temperature, metal surface temperature, gas/surface temperature differential, foreign material particle size distribution, particle chemistry, and particle phase (molten versus solid). Consequently, the dominant mechanisms and degree of turbine degradation will vary with turbine operating conditions, foreign material source, and the way particles are formed or affected in the combustion process.

MECHANISMS OF DEC

Deposition, erosion, and corrosion result from foreign particulate (including molecules) in turbine expansion gases being delivered to turbine surface.
Mechanisms of delivery of foreign particulate material to surfaces
Mechanisms of interaction of foreign material with those surfaces

Interaction includes chemical attack of surfaces, removal of surface by high speed impact, and sticking and buildup of material on surfaces, which can depend on rates and conditions (e.g., velocities) of particle delivery.

Delivery of particles to surfaces is amenable to analysis using advancements in recent years of multiphase flow evaluation approaches. Models that can predict particle delivery rates and conditions at surfaces due to the various mechanisms of transport (e.g., inertial impaction, thermophoresis, etc.) have been developed. However, quantitative assessment of particulate interaction with surfaces is not usually amenable to analysis and must rely primarily on experimental evaluation.

The simplified turbine DEC test/data extrapolation approach discussed here separates the DEC processes into the two mechanism categories of 1) particle delivery and 2) particle interaction at surfaces. Particle interactions with surfaces are represented experimentally and are determined as a function of particle arrival conditions (arrival rates, impact velocities and angles) for the particulate and surface materials and conditions (e.g., gas and surface temperatures) of operating turbines. Particle arrival at turbine conditions can be represented without the cost of reproducing complex turbine vane and blade flow passages. Data can in many cases be obtained at lower flow path areas and decreased operating pressures. This reduces the scale of the experiment and decreases facility air and fuel requirements necessary to produce high flow rates of pressurized combustion gases.

As will be described in greater detail, the complex flow geometries of turbine passages are represented in particle transport models that calculate particle delivery conditions (rates, velocities and angles of impact) over vane and blade airfoil surfaces. Using the experimental data on particle surface interaction with surfaces as a function of delivery conditions, DEC degradation of the surfaces versus location can be estimated. Not only does this approach extrapolate data to turbines, but it also isolates particle delivery variables and surface interaction variables to provide a greater understanding of DEC processes. Dominant mechanisms and important factors affecting DEC can be identified and varied for the purposes of evaluating methods to control turbine degradation.

Inertial impact is typically the dominant mode of particle mass delivery to turbine surfaces (Wenglarz, 1985). This is because a significant mass fraction of contaminant particle sizes in products of combustion is usually larger than about two microns in diameter. Particles in this size range have sufficiently large inertias that their trajectories deviate from flow streamlines and the particles impact surfaces of blade passages where the flow is turned. Inertial impact can dominate other mechanisms even for a relatively small fraction of particulate mass larger than about two microns due to much higher transport rates per unit particulate mass for inertial impact compared to other delivery mechanisms (Wenglarz, 1981). The simplified test/data extrapolation approach described here applies to particle size distributions for which inertial impaction is the dominant transport mechanism contributing to deposition and erosion. The next sections describe the simplified test approach and data extrapolation models.

SIMPLIFIED TEST APPROACH

Figure 1 shows results of simple erosion tests using flat specimens exposed to a high velocity gas stream containing small particles (Grant and Tabakoff, 1975). Specimen material erosion rates per unit mass of impacting particles are given as a function of particle impact angle and velocity. The orientation of the flat specimen with respect to the flow determined the particle impact angle, and the gas velocity determined the particle impact velocity. Impact rates were obtained from the gas stream particle concentration and the exposed area of the specimens normal to the velocity of particulate-laden gas stream. Specimen material erosion loss was determined by highly accurate weighing of the specimens before and after the test. Weight resolution of 1/10,000 gm provides accurate erosion data in one to two orders of magnitude shorter test durations than test durations for accurate dimensional measurements.

Figure 1 shows that surface erosion loss depends on particle impact rates, angles, and velocities. Such erosion data can be obtained for turbine materials at turbine gas velocities and temperatures with particulate material that would be ingested by the turbine. These data can be used to estimate turbine erosion rates if information on particle impact rates, angles, and velocities over vanes and blade surfaces is available. Turbine inertial impaction models can be used to generate this information and thereby extrapolate simple flat specimen erosion test data to turbines.

If a significant fraction of gas stream particles were molten or semimolten rather than hard and erosive in the relatively simple test described, deposi-

![Figure 1. Erosivity Characteristics for a Ductile (Aluminum) Alloy. (Grant and Tabakoff, 1975)](https://example.com/figure1.png)
its would accumulate on the specimens. In that case, comparison of deposit mass buildup rate on the specimens with particle mass impact rate (determined as described previously) yields the particle "sticking fraction," i.e., the mass fraction of arriving particles that adhere to the surface and contribute to deposit buildup.

A plot similar to Figure 1 could then be generated giving sticking fraction as a function of particle impact angle and velocity. These data collected in the simplified experiment reproducing turbine passage gas temperatures, vane or blade surface temperatures, and the particulate of concern can then be extrapolated to the turbine using a turbine impaction model. The impact rates, angles, and velocities predicted by the model versus location on the vane or blade surface, combined with the simplified test data on the fraction of particulate sticking on surfaces as a function of impact angle and velocity, enable the estimation of deposit buildup on these surfaces.

In summary, these discussions show that impaction erosion and deposition on small flat specimens in relatively simple experiments (compared with turbine or cascade tests) may be extrapolated to turbines. The simplified experiments must reproduce gas and surface temperatures, particulates, and gas chemistry for the turbine passage of concern but not the complex passage flow geometry. Such conditions also produce a comparable corrosion environment so that turbine corrosion can be estimated in addition to erosion and deposition. In fact, many corrosion tests for gas turbines have used relatively simple (and low cost) specimen and test flow-path geometries (Felix, 1973; Spengler, et al., 1973; Barkalow et al., 1980) rather than cascades or operating turbines. These tests are usually conducted at reduced pressures, often at atmospheric pressure. Geometry differences have not been seen to cause substantial differences between specimen corrosion and turbine vane and blade corrosion. Simplified tests have provided data for choices of corrosion resistant alloys and coatings in commercial turbines and corrosion data to warranty commercial engines offered for operation with residual and crude oils.

DATA EXTRAPOLATION MODELS

Turbine inertial impaction models integrate the equations of motion of particle flight in vane and blade passages. Forces on these particles must be determined for these calculations. For particles of diameters in the inertial impaction range (> few microns), the most significant forces that affect their delivery to turbine surfaces are particle inertial forces and aerodynamic drag forces (Lapple and Shephere, 1940). Consequently, the flow field throughout a turbine flow passage must be specified to determine forces on a particle at any passage location. Standard turbine passage aerodynamic computer codes used in the design of gas turbine airfoils (e.g., blade-to-blade flow analysis codes (Delaney, 1983)) can be used to determine passage flow velocity fields.

The integration of equations of motion using velocity flow field input to obtain forces on particles yields their trajectories (Figure 2) and impact rates, velocities (Figure 3), and angles (Figure 4) at airfoil surfaces. Impacts are accumulated over the surfaces. As discussed earlier, empirical data on particle "sticking fractions" versus impact conditions are used to predict deposit buildup rates for molten particles. Empirical data on turbine alloy erosivity (amount of surface material removed per unit mass of impacting particles as a function of impact angle and velocity) are used to predict erosion over the blade surface for hard particles (Figure 5).

SIMPLIFIED DEC TEST FACILITIES

Early Facilities

A few simplified test facilities have been developed using approaches similar to those described above to provide relatively low cost data that can be extrapolated to turbines. The data also isolate
variables and facilitate an understanding of critical factors affecting DEC. A blowdown facility at the University of Cincinnati (Tabakoff and Hamed, 1977) using simulated turbine gas streams seeded with particles has obtained data for many turbine erosion evaluations (Beacher and Mansour, 1986). Westinghouse has utilized a simplified test facility (Wengljarz and Cohn, 1985) in which the turbine gas stream is not simulated by seeding but rather is reproduced from operation of a turbine combustor with candidate ash-bearing fuels. Cylindrical specimens have been used in this facility to estimate turbine corrosion (Beacher and Mansour, 1986; Elkabes, 1979) and the error in the predicted erosion rates appeared to be within the uncertainty of the alloy erosion response data (Elkabes, 1979). Deposition rates predicted for droplets by inertial impaction models have also agreed with measured deposition rates over the surfaces of nozzle guide vanes and rotor blades (McCrea, 1982).

A New Facility

A new simplified DEC test facility has been fabricated and tested at Allison Division of General Motors. This facility was developed in the Department of Energy Gas Turbine Component Screening Program involving tests of coal-water fuels. While earlier facilities were designed for erosion or deposition/corrosion, the new test facility has been designed to evaluate all three degradation processes (deposition, erosion and corrosion). Turbine combustion gases are reproduced using a rich-quench-lean (RQL) staged, subscale turbine combustor designed to reduce NO\textsubscript{x} emission levels when operated with alternate fuels. RQL combustion and NO\textsubscript{x} performance has been previously demonstrated in earlier programs using distillate, heavy petroleum residual, synthetic coal-derived liquid, and coal-water fuels (Novick and Troth, 1981; Wilkes et al., 1985).

A schematic for the new DEC test facility is illustrated in Figure 6. Primary components consist of the RQL combustor, a gas and particle acceleration section, and two test sections. The first and second test sections simulate maximum gas and specimen surface temperatures of the first stage stator and rotor airfoil passages, respectively, of the turbine represented. Both the first stators and rotors are represented because turbine operating experience (Zaba, 1980) and mechanistic evaluations (Wengljarz, 1981; Wengljarz, 1983) indicate that first stator vanes are often the most susceptible to deposition (due to the highest gas temperatures) while first rotor blades are often the most susceptible to erosion (due to high flow turning angles) of all the turbine airfoil rows. Cooling air is injected between the two test sections to lower the gas temperature entering the second test section to a value representative of the first rotor gas temperature.

Referring to Figure 6, combustion gases exit the RQL combustor into an area reduction section which accelerates these gases to values approaching turbine velocities. Since particle velocities lag that of the gas, a 30 cm (12 in.) particle acceleration distance is provided to enable particles to "catch up" to the gas velocity and produce particle impact velocities on downstream test specimens controlled to the gas velocity. The 30 cm distance was chosen to accelerate all particles with diameters less than about 25 microns to greater than 95% of the gas velocity. Since virtually all particles in the products of combustion must likely be smaller than 10-15 microns for acceptable turbine deposition/erosion lifetimes (Wengljarz, 1985), the acceleration distance of 30 cm is adequate to evaluate fuels of practical concern.

Although commercial turbines have not operated with coal-derived liquids, the estimated deposition maintenance intervals based on the Westinghouse residual oil tests have been in agreement with field experience (Sherlock et al., 1983). Similar simplified test/data extrapolation approaches to those described above have been applied to engines operated in the early direct coal fired turbine programs at the U.S. Bureau of Mines (Smith et al., 1966) and the Australian Aeronautical Research Laboratories (Interdepartment Gas Turbine Steering Committee, 1973). Erosion patterns observed on vanes and blades were predicted (Beacher and Mansour, 1986; Elkabes, 1979) and the error in the predicted erosion rates appeared to be within the uncertainty of the alloy erosion response data (Elkabes, 1979). Deposition rates predicted for droplets by inertial impaction models have also agreed with measured deposition rates over the surfaces of nozzle guide vanes and rotor blades (McCrea, 1982).
Figure 7 shows the specimen arrangement and typical gas and specimen surface temperatures for the two test sections. Specimens in each test section are arranged in two rows spaced such that the aerodynamic and thermal wakes from the first row do not impinge on back row specimens. Specimens are hollow to allow cooling to prescribed temperatures monitored by thermocouples embedded in their surfaces. Some specimens are cooled to surface temperatures of vanes and blades of existing turbines while others might be cooler to lower temperatures to evaluate possible reductions in deposition and corrosion. Specimens upstream surfaces are machined flat at prescribed angles to control particle impact angles. This allows materials erosivity and particle "sticking fraction" data as functions of impact angle to be obtained. Changing the volumetric flow rate through the combustor or changing the test section flow area can be used to control the particle impact velocities. Specimens are constructed with alternate materials and coatings to identify those most erosion- and corrosion-resistant.

Air is injected into the combustion gases immediately behind the first test section. The amount of cooling air is determined by the gas temperature desired for the second test section. Although this additional mass flow rate slightly increases the flow velocity and decreases the volumetric particle concentration in the second test section compared to the first, these changes and effects on deposition/erosion are small and can be calculated (Wenglarz and Cohn, 1985). Furthermore, effects of the increasing velocity and decreasing volumetric particle concentration on deposition and erosion tend to counteract. For example, cooling in an extreme case from 2100°F (1149°C) to 1800°F (982°C) results in an additional flow rate of about 15%. The gas velocity increases by less than 4% and volumetric particle concentration decreases by less than 4% such that the product of gas velocity and volumetric concentration remains virtually constant.

A flow section with about 30 cm (12 in.) in length is provided between the first and second test sections. This distance has been calculated to dissipate the wakes of the first section specimens and uniformly redistributes the particles and mixes the cooling gas stream prior to entering the second test section. The second test section is identical in design (five specimens) to the first test section but allows independent choices of materials, specimen surface temperatures, and impact angles exposed to the lower temperature combustion gases. Both test sections are designed to permit the mounting of a particulate probe in place of specimens for the qualifying runs prior to DEC tests. Size distributions measured for the captured particulate are used to predict delivery to turbine airfoil surfaces using the data extrapolation models described earlier. A water quench is located downstream of the second test section to cool and protect the passage pressure control valve.

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**FIGURE 6. DEPOSITION/EROSION/CORROSION TEST FACILITY SCHEMATIC.**

**FIGURE 7. SPECIMEN TEST CONDITIONS.**
The data acquired with this DEC test facility are not necessarily limited in application to a particular turbine passage geometry. Using the inertial impaction models as described previously, the data can be used to estimate DEC for the fuels tested in a wide range of stator and rotor passages represented by the test section gas temperatures and specimen surface temperatures. Consequently, unlike cascade data, the data from the simplified DEC test facility can be applied with inertial impaction model evaluations to explore alternate turbine passage designs for reduced deposition and erosion. Furthermore, the independent control of gas temperature, surface temperature, impact angles, and impact velocities facilitates isolation of critical variables for erosion and deposition and identification of dominant factors and mechanisms controlling these degradation processes.

SUMMARY AND CONCLUSIONS

A deposition, erosion, corrosion (DEC) test approach has been described which uses relatively simple specimen and flow-path geometries and data extrapolation approaches to estimate turbine DEC. A facility designed to implement this approach is less complex and less expensive to operate than cascade or turbine test facilities. Consequently, the simplified test/data extrapolation method offers advantages in screening the wide range of valuables associated with turbine ingestion of air or fuel borne contaminants. Isolation of variables also contributes to improved understanding of critical mechanisms and factors controlling turbine DEC. Reasonable agreement has been achieved between estimated turbine degradation using simplified tests and observed operating turbine degradation for the limited attempts at such comparisons. The simplified DEC test/data extrapolation approach is expected to provide reasonable estimates of turbine DEC for other air or fuel borne contaminant conditions which result in:

- the bulk of gas stream particles larger than a few microns,
- erosion or deposition environments in which most material arriving on surfaces is delivered by inertial impaction
- deposit growth rates predominantly controlled by particle arrival rates and not deposit spallation

The first two conditions are evidenced in tests using simple specimens by upstream surface erosion or (in deposition environments) much thicker deposits on the upstream front surfaces than on the downstream back surfaces. Such deposit patterns have been observed for tests using residual oil, coal-derived liquids and coal-water fuels.

The simplified tests should utilize a) the same fuel, b) the same gas and surface temperatures, and c) the same combustor configuration as for the turbine represented. Based on past experience, turbine corrosion produced by molecular or small particle delivery also appears to be reproduced if conditions a), b), and c) are satisfied.

ACKNOWLEDGEMENT

The development of the simplified DEC test facility described above was accomplished with support from the Department of Energy and the Allison Gas Turbine Division of General Motors. The Department of Energy Morgantown Energy Technology Center contracting officer's technical representatives were Janna Thames and later Nelson Rekos. Their direction and encouragement have been greatly appreciated.

REFERENCES


