EXPERIMENTAL DETERMINATION OF THE INFLUENCE OF FOREIGN PARTICLE INGESTION ON THE BEHAVIOR OF HOT-SECTION COMPONENTS INCLUDING LAMILLOY®

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ABSTRACT

The effect of foreign particle ingestion on hot-section components has been investigated with a series of experiments performed using a one-quarter sector F100-PW-100 annular combustor. The combustor was operated so that the engine corrected conditions were duplicated. The experiments were designed to determine the influence of cooling hole size, hole roughness (laser-drilled vs. EDM), combustor exit temperature and dust concentration on the cooling capability of the component in the presence of dust particles. Cylindrical Lamilloy® specimens, film cooled Inconel cylinders, and F100-PW-220 first stage turbine vanes were investigated. The size distribution of the foreign particles injected into the air stream just upstream of the turbine vanes were investigated. The size distribution of the foreign particles injected into the air stream just upstream of the combustor was consistent with distributions measured at the exit of high compressors for large turbofan engines. The foreign material was a soil composition representative of materials found around the world. This and other trace particulate impurities can melt at a lower temperature than other constituents of a mixture and thus have the tendency to become a collection site for impurity calcium carbonate, which is known to be found in soils around the world. Kim's results demonstrated that significant deposition occurs on the airfoil cooling air holes influencing metal temperature. The research presented here targeted mechanism (4), but also obtained useful information relating to mechanism (2).

INTRODUCTION

The potential damage caused to gas turbine propulsion systems and stationary power plants by ingestion of foreign material is an area of concern from both a missions and a maintainability perspective. Previous measurement programs (Dunn, et al. [1987(a)], Batcho, et al. [1987], and Dunn, et al. [1987(b)]) have indicated four major mechanisms by which propulsion gas turbine engines are damaged by foreign particle ingestion: (1) compression system erosion resulting in the loss of surge margin, (2) deposition of glassified material on engine hot section components reducing flow area at the high pressure turbine inlet, (3) partial or complete blockage of combustor fuel nozzles adversely influencing atomization, and (4) partial or complete blockage of airfoil cooling air holes influencing metal temperature. The research presented here targeted mechanism (4), but also obtained useful information relating to mechanism (2).

The measurements presented here were obtained using a F100 Hot Section Test System (HSTS) which duplicates the engine corrected hot section conditions, with the advantage of lower costs than full engine tests. A previous Calspan measurement program in a similar facility was presented by Dunn and Kim [1991]. That study concentrated on dust blend behavior. Dunn and Kim's results demonstrated that significant deposition occurs on the turbine inlet guide vanes for soil blends containing the impurity calcium carbonate, which is known to be found in soils around the world. This and other trace particulate impurities can melt at a lower temperature than other constituents of a mixture and thus have the tendency to become a collection site for deposition of material on hot section components.

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Similar results were obtained by Whitlow et al. [1982] in simulated turbine combustion tests with residual oil. They found that deposition on Udiment 500 specimens was approximately 3 times greater for residual oil doped with calcium at 5.7 ppm than oils doped without calcium. Likewise, Mutik. et al. [1985] found that calcium is a primary candidate for deposition enhancement for turbine operation with SRC-II coal-derived liquid fuel.

Other previous HSTS experiments are described in Kim, et al. [1992]. The results indicate that deposition is dependent upon several parameters: (1) the chemical composition of the ingested material, (2) the concentration of the ingested material, (3) the magnitude of the Combustor Exit Temperature (CET), and (4) the metal (surface) temperature of the component exposed to the gas path flow. Deposition was found to occur when the CET was above 1177°C (2150 °F) and for a metal surface temperature exceeding 816°C (1500 °F). For CET values of 1177°C (2150 °F) and above, if the metal surface temperature was less than 816°C (1500 °F), then deposition did not occur.

It was determined by analyzing the deposited material under a microscope that once these molten particles stick on the surface, other particles which may or may not be molten will stick to the existing deposit material. The deposit itself forms an insulator which reduces conduction from the outer surface of the deposit to the cooled specimen. Hence the importance of the trace impurities tendency to melt at a lower temperature than other constituents and thus forming a site to which other particles attach. Deposition experiments conducted on coal-water fuels in a staged sub scale turbine combustor (Wenzhao and Fox [1990]) produced similar results. They found that the deposition rate was greatly influenced by both the gas and surface temperatures. The deposition rate was proportional to the percent ash in the products of combustion, but magnitudes less than that experienced in the dust ingestion experiments by Kim, et al. [1992]. The elemental composition of the ash is similar to the dust blends used in Kim, et al. [1992]. The particle size distributions are also similar. However, the mechanism for heating the particles is quite different. The ash is a product of combustion carried to the surface by larger carbon particles which combust, while the dust particles are heated as they pass through the combustor. Therefore, the results are not directly comparable, but do complement one another.

The measurement program reported here was designed to build on the previous results and take the next step toward obtaining quantitative data which would be directly applicable to the designer's needs concerning turbine cooling performance in flows containing foreign particles. There were two basic objectives in the program. The first was to determine which of the following parameters have the most significant effect on cooling (or the lack thereof): hole roughness (EDM or laser drilled), cooling passage size, CET, or dust concentration. The second objective was to compare the results obtained with simple cylinders to those obtained with much more expensive and difficult to obtain engine vanes.

HOT SECTION TEST SYSTEM

A schematic of the Hot Section Test System used to perform the experiments is shown in Fig. 1. The total flow rate is set by the choke nozzle between the high and low pressure chambers and measured with the venturi flow-meter. Choke flaps at the exit of the exhaust duct are used to set the combustor pressure. The dust is injected into the main air stream in the low pressure chamber. The flow is transitioned to a one quarter annulus section in the low pressure chamber, as shown in Fig. 2. The dust/air mixture is given an ample mixing length after the transition before entering the combustor section.

The combustor section is an F100-PW-100 diffuser case and annular combustor liner. Three quarters of the combustor annulus has been filled with high temperature ceramic leaving only the bottom quarter as the test section. A quarter section was used to reduce the flow requirements to a value that could be economically supplied by external compressors. Four F100-PW-220 fuel nozzles were used to inject fuel A into the combustor sector. The test articles are housed in the F100 vane case which has been modified to allow for independent cooling air to be supplied to selected specimens.

The dust injection system consists of a BIF disk feeder placed inside a pressure vessel which is supplied by an auxiliary line from one of the external compressors. The air is dried with a desiccant air dryer before entering the vessel to prevent condensation. The metered dry air flows through the vessel picking up the dust and transporting it into the low pressure chamber. The mass flow from the feeder is calibrated against a potentiometer which sets the feed rate.

The independent cooling air supply system, shown in Fig. 3 consists of a one inch insulated pipe used to bypass air from the high pressure chamber to select specimens. This cooling air is dust free and metered to both the inside and outside supply ports on the independently cooled specimens.

TEST SPECIMENS

Three different categories of test articles were used in the experiments: (1) film cooled cylinders, (2) Allison Engine Co. Lamilloy® cylinders, and (3) F100-PW-220 first stage turbine vanes. The four different configurations of the 12.7 mm (0.500 in) diameter Inconel 617 cylinders are defined in Table 1. The post-experiment photographs discussed later in the paper show the leading edge cooling hole patterns.

Table 1--Film cooled Inconel cylinder configurations

| conf. no. | film cooling hole size (mm, in) | film cooling hole roughness |
|----------|--------------------------------|----------------------------|
| 1        | 0.38 mm (0.015 in) laser       |
| 2        | 0.38 mm (0.015 in) laser       |
| 3        | 0.63 mm (0.025 in) EDM         |
| 4        | 0.38 mm (0.015 in) EDM         |

The cylindrical test specimens were housed in one quarter sector annular segments. Three of the four segments contained six cylinders, with the center four cylinders being the test specimens, and the outer two sector setting the boundary condition. The fourth segment contained the three additional Lamilloy® cylinders for a total of nine cylinders. The cylinders were 9.5 mm (0.375 in) in diameter with 0.30 mm (0.012 in) diameter Lamilloy® passages on the leading edge and 0.30 mm (0.012 in) diameter film cooling holes on the trailing edge.

Half of the eight F100-PW-220 inlet guide vanes tested were modified for independent cooling. The independent cooling air supply was free of any dust, while the dust laden combustor bypass air cooled the Dependent Cooling Vanes (DCV's). It was necessary for the supply air conditions for the Independently Cooled Vanes (ICV's) to match the bypass air conditions feeding the DCV's so that a direct comparison between the ICV's and...
DCVs could be made. The DCV supply air plumbing was designed accordingly and instrumentation was provided to verify the matched conditions.

The quarter sector test section contained six full vane pairs and two partial pairs; one at each end. Only the four center vane pairs were considered test specimens. Two of the four vane pairs were ICVs and they were located to the right of bottom center when aft looking forward.

**INSTRUMENTATION**

The harsh environment required rugged instruments which would be reliable under conditions of elevated temperature and vibration. Therefore, the instruments used were relatively common industrial type pressure transducers and thermocouples. The Inconel cylinder wall temperatures were measured with a 0.51 mm diameter type N thermocouple installed as shown in Fig. 4. Similarly, the Lamillloy® cylinder wall temperatures were measured with 0.81 mm diameter type K thermocouples.

**DUPLICATION OF ENGINE CONDITIONS**

The engine conditions that must be duplicated are as follows: (1) combustor inlet and combustor exit temperature, (2) flow function, and (3) thermal behavior of the foreign material. The air supplied to the combustor was elevated using a natural gas fired STAHL heat exchanger. With the correct combustor inlet temperature, the engine bypass cooling gas temperatures should be duplicated. Unfortunately, the heat exchanger had been previously adjusted for a mass flow rate that was less than the value used for these measurements and time constraints did not permit a readjustment. Thus, the incoming air was heated to 350°C (662°F) instead of the desired 482°C (900°F). The CET was duplicated by adjusting the fuel to air ratio.

The flow function, given by Eq. 1, was duplicated in the combustor at a pressure of 483 kPa (70 psia) and mass flow rate of 3.40 kg/s (7.5 lbm/s). The pressure drop across cooling holes was not performed because of the lack of any effect on the atomization of the fuel.

\[ FF = \frac{\Delta T}{T} \]  

(1)

The thermal behavior of the material is duplicated by matching the particle size and the residence time within the combustor at the correct temperature. The residence time was matched since the velocity through the combustor was duplicated with the correct flow function. The particle size present at the inlet to the combustor was determined during several full engine experiments (e.g., Dunn, et al. [1987(a)]). By sampling the air at the fan bypass exit and at the compressor exit, the mean particle size was measured to be ~6 microns (µm). This suggests that the larger particles ingested at the engine inlet (38 µm) were pulverized in passing through the fan and the compressor.

The soil blend used in the measurements reported here was composed of equal amounts, by weight, of the following commonly found constituents: quartz, red art clay, and feldspar.

**EXPERIMENTAL CONDITIONS**

A list of significant parameters (given below) was compiled based on a review of the existing Calspan engine and combustor data with input from the engine community. They are categorized as either part of the test article configuration or as part of the test conditions to be set in the Hot Section Test System (HSTS).

**Test Article Parameters**

1. Film cooling hole size
2. Impingement cooling hole size in tube insert
3. Location of film cooling holes; especially with respect to the cooling passage
4. Orientation of film cooling holes; incidence angle with the surface and free stream
5. Film cooling hole manufacturing technique; hole roughness
6. Cooling passage geometry

**Test Conditions**

1. Core flow dust concentration
2. Cooling flow dust concentration
3. Particle type: size, shape, composition, and source
4. Vane surface temperature
5. Pressure drop across cooling holes
6. Compressor exit temperature

The measurement program was limited to two test article parameters with the film cooled Inconel cylinders. The two parameters were film cooling hole size and film cooling hole manufacturing technique as given in Table 1. The -220 vanes and Lamillloy® cylinders were run with fixed geometries.

The two test condition parameters investigated are given in Table 3. The core dust flow concentration is that at the inlet face of the engine. The CET and the vane surface temperature are a coupled pair since the cooling air temperature and flow rate are constant for each CET. The Lamillloy® cylinders were run with the high CET and low dust concentration, run 3. A fourth run at the low CET and low dust concentration conditions was not performed because of the lack of any effect on the specimens during run 2 as described in the results.

The -220 vanes investigated the cooling flow dust concentration. The independently cooled vanes were supplied with dust free cooling air while the dependently cooled vanes were cooled with the combustor bypass air containing the foreign particles. The vanes were run at conditions similar to those of runs 1 and 3 below.

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**Table 2--Soil particle distribution**

| Constituent  | Mean (µm) | 90% (µm) |
|--------------|-----------|----------|
| Quartz       | 6.1       | 11.56    |
| Red art clay | 8.3       | 14.37    |
| Feldspar     | 14.5      | 26.97    |

**Table 3--Core dust flow concentration**

| Test Condition Parameters | Test Article Parameters | Test Conditions |
|---------------------------|-------------------------|-----------------|
| Core flow dust concentration | Film cooling hole size | 1. Core flow dust concentration |
| Cooling flow dust concentration | Impingement cooling hole size in tube insert | 2. Cooling flow dust concentration |
| Particle type: size, shape, composition, and source | Location of film cooling holes; especially with respect to the cooling passage | 3. Particle type: size, shape, composition, and source |
| Vane surface temperature | Orientation of film cooling holes; incidence angle with the surface and free stream | 4. Vane surface temperature |
| Pressure drop across cooling holes | Film cooling hole manufacturing technique; hole roughness | 5. Pressure drop across cooling holes |
| Compressor exit temperature | Cooling passage geometry | 6. Compressor exit temperature |
The rougher laser drilled holes may be more tolerant to particles. Specimens can be found in Weaver and Dunn [1995]. These results passages occurred. The pre- and post-test flow results for all the was concluded that no significant clogging of the cooling holes or again, it is difficult to draw concrete conclusion from these results. experiment are given in Fig.'s 14 and 15, respectively. Once of a smooth hole. Visual inspection of the specimens verified that of the film cooling passages would have been present at the engine inlet. difficult to draw any concrete conclusions; however, there are several consistent patterns in the data. The cylinders exposed to the lower dust concentration have less flow reduction, and the laser drilled cylinders have less flow reduction than the EDM cylinders. The rougher laser drilled holes may be more tolerant to particles captured in the passage; i.e., a particle lodged on an already rough surface may not reduce the flow as much as a particle on the surface of a smooth hole. Visual inspection of the specimens verified that none of the film cooling passages were significantly clogged. The pre- and post-test flow results for the cylinders from the high CET (1371°C) runs are summarized in Fig. 13. The uncertainty in the flow measurements is estimated at ±5%. The slight variations shown in the pre- to post-test flows make it difficult to draw any concrete conclusions; however, there are several consistent patterns in the data. The cylinders exposed to the lower dust concentration have less flow reduction, and the laser drilled cylinders have less flow reduction than the EDM cylinders. The rougher laser drilled holes may be more tolerant to particles captured in the passage; i.e., a particle lodged on an already rough surface may not reduce the flow as much as a particle on the surface of a smooth hole. Visual inspection of the specimens verified that none of the film cooling passages were significantly clogged. The pre- and post-test flow results for the dependently cooled vanes and the independently cooled vanes from the high CET (1371°C, 2500°F), high dust concentration (Dc=182.4 mg/m³) and high CET (1371°C, 2500°F) condition is shown in Fig. 11. This figure gives the flow rate through the cooling holes as a function of the pressure ratio across the cooling holes. A typical set of Lamillloy® pre- and post-test flow results are given in Fig. 12, with the Allison pre-test flow results comparing well with the Calspan measurements at the higher pressure ratios. All the pre- and post-test flow results for the cylinders from the high CET (1371°C) runs are summarized in Fig. 13. The uncertainty in the flow measurements is estimated at ±5%. The slight variations shown in the pre- to post-test flows make it difficult to draw any concrete conclusions; however, there are several consistent patterns in the data. The cylinders exposed to the lower dust concentration have less flow reduction, and the laser drilled cylinders have less flow reduction than the EDM cylinders. The rougher laser drilled holes may be more tolerant to particles captured in the passage; i.e., a particle lodged on an already rough surface may not reduce the flow as much as a particle on the surface of a smooth hole. Visual inspection of the specimens verified that none of the film cooling passages were significantly clogged. The pre- and post-test flow results for the dependently cooled vanes and the independently cooled vanes from the high CET (1371°C, 2500°F), high dust concentration (Dc=191 mg/m³) experiment are given in Fig.'s 14 and 15, respectively. Once again, it is difficult to draw concrete conclusion from these results. However, the visual post-test inspection found that the cooling holes and passages were virtually free of particles. Therefore, it was concluded that no significant clogging of the cooling holes or passages occurred. The pre- and post-test flow results for all the specimens can be found in Weaver and Dunn [1995]. These results suggest that none of the parameters under the conditions chosen had a significant effect on the internal blockage of film cooling holes. However, the results do indicate that the magnitude of the CET has a significant effect on foreign particle deposition on the specimen surfaces. The previous combustor measurement program by Kim, et al., [1992], discussed in the Introduction, determined that there are two different thresholds which must be met to allow for deposition of material on a surface. The first being a CET sufficiently high so that a portion of the gas path particles are in a molten state, and the second, a sufficiently high surface temperature to allow those molten particles to stick to that surface upon impact. The first threshold condition of CET for deposition is addressed by looking at the different results obtained from the two high CET (1371°C) and the one low CET (1149°C) experiments with the cylinders. Fig. 16 gives the CET time histories for the three cylinder experiments. The second CET probe from run 1 and both CET probes for run 3 were lost during the experiments due to excessive thermal fatigue and deposition, but the run conditions were maintained by holding the fuel to air ratio constant. Deposition occurred on the cylinders, as well as the CET probes during the two high temperature runs. The low CET run (run 2) did not produce any deposition; not even on the CET probes which had a surface temperature of approximately 1149°C (2100°F). Fig. 17 through 19 give the positions of each of the cylinders for the three experiments. Photographs of the two cylinders (LAS015, EDM025) from the high temperature, high dust concentration experiment that experienced deposition are given in Fig.'s 20 and 21. Photographs of the four cylinders from the low temperature, high dust concentration experiment, given in Weaver and Dunn [1995], reveal that none of these cylinders experienced deposition nor did the CET probes. The photographs from the other high temperature, but low dust concentration experiment, are given in Fig.'s 22 through 25. They show a similar pattern of deposition on the specimens located on the right side of the sector. The LAMI and LAS015 specimens both had significant deposition. The deposits were recovered and are shown in Fig.'s 23 and 25. LAS025 showed signs that deposition was starting near the hub portion of the leading edge, but no other specimen showed any sign of deposition. Though it was possible to recover deposited material from the test specimen, as illustrated above, it was difficult because the deposits are shed off the specimens upon shut down. Upon shutting down from the high CET experiments, the video camera viewing the combustor exhaust recorded a significant amount of hot material exiting. This observation is consistent with those made during dust ingestion measurements with full-scale engines upon shut down and upon rapid throttle excursions (Dunn, Baran, and Miatech, [1994]). The reason for this shedding is felt to be due to the difference in the coefficient of thermal expansion between the metallic components and the deposited material. The specimen wall temperature histories (Fig.'s 26-28) show a hot-spot on the right side of the test section due to the discrete fuel injection which explains why only those specimens on the right experienced deposition. The actual CET at this hot-spot is difficult to determine from the two CET probe measurements because neither probe was directly in line with the hot-spot. However, from their data it is deduced that this hot-spot temperature was on the order of 100°C above the CET given in Fig. 16. The three functioning cylinder wall temperatures from run 3 are given in Fig. 26 along with the time in which the dust was flowing. Only the hottest cylinder, EDM025, of these three

| Run | Ce | CET (°C) | T5 (°C) | Duration (min) |
|-----|----|----------|--------|----------------|
| 1   | 182.4 | 1371°C | 582-871°C | 8.5 |
| 2   | 149.5 | 1149°C | 494-716°C | 8.5 |
| 3   | 37.5  | 1371°C | 558-844°C | 18.0 |

Where MAF is the Main Air mass Flow rate and DAF is the Dust Air mass Flow rate.
experienced deposition; LAS015's wall thermocouple was not functioning. Deposition on EDM025 begins approximately 3.5 minutes after the dust is turned on, causing the decrease in wall temperature which continues for almost 25 minutes until the deposit is shed and the wall temperature takes a step increase. This occurs because the deposition on the leading edge is an insulator covering the thermocouple. The other two cylinders did not show a similar decrease in wall temperature.

The cylinder wall temperature histories from the low CET run are given in Fig. 27. The wall temperatures reflect the same pattern factor, but the levels are approximately 94°C (200°F) lower than the high CET run. Recall that post-test inspection concluded that there was no deposition on any of the cylinders from this run. The wall temperature histories reflect this with the lack of any significant descent in wall temperature. The variations shown in Fig. 27 are due to readjustments in the run conditions.

The wall temperatures for the cylinders that experienced deposition during the high CET, low dust concentration run (run 3) are given in Fig. 28. The deposition begins first on LAS015 at time equal to 80 minutes, corresponding to a slow descent in wall temperature. Cylinder LAS015 ran approximately 121°C (250°F) hotter than LAM1, which is felt to be the reason why deposition occurred on this cylinder first. At time equal to 120 minutes, LAS015 experienced a 94°C (200°F) step increase in temperature indicating that a portion of its deposit was shed. The wall temperature does not reach its original level of 816°C because a residue portion of the deposition remains on the cylinder which insulates the thermocouple. This is shown in the Fig. 22 photograph. Sparks were also seen to exit the exhaust duct at time equal to 120 minutes. This event corresponds to a rapid decrease in wall temperature for LAM1 from the 816°C (1500°F) level, which indicates deposition on its leading edge. Neither cylinder fully shed its deposit during the remainder of the test and the LAM1 leading edge temperature actually dropped below its trailing edge temperature which started out 110°C (230°F) lower.

CONCLUSIONS

None of the cylinder or vane cooling holes were significantly clogged by dust for the range of cooling hole sizes and dust concentrations used in these measurements. This suggests that Lamilloy® holes 0.30 mm (0.012 in.) in diameter or larger and film cooling holes 0.38 mm (0.015 in.) in diameter or larger, with an s/d ratio less than 10, will not be clogged by the fine dust particles found at the exit of a compressor for concentrations less than those used in these measurements. Previous measurements for two different large turbofan engines have indicated that at the exit of the axial compressor (for either a 13 stage or 9 stage machine), the mean particle size is approximately 6 µm as a result of pulverization of the larger particles as they are processed by the fan and compressor stages. The mean particle size used in these measurements was 9.6 µm with a distribution allowing for 3% of the particles to be over 27 µm in diameter. Therefore, these clogging results were not biased by an unrealistically small particle size distribution.

There are two conclusions that can be drawn from the deposition results. No deposition occurred during the low CET (210°F or 1149°C) run while significant deposition occurred during the high CET (2500°F or 1371°C) experiments. For the low temperature experiments the CET thermocouple probes, with a surface temperature in the vicinity of 1149°C (2100°F), did not have deposited material suggesting that a CET of greater than 1149°C is required for deposition. The previous work referenced by Kim et al. [1992] determined that the CET threshold was 177°C (2150°F).

For the higher CET experiments, deposition was seen on both CET thermocouple probes and on test specimens. All the specimens, with functioning wall thermocouples, which experienced deposition had a surface temperature of 816°C (1500°F) or higher. In fact, the Lamilloy® No. 1 cylinder did not begin deposition until it reached the 816°C level. Again, this result is in excellent agreement with the previous work of Kim et al. [1992].

Another significant result of this investigation was found in the shedding of the deposited material during shut down. This shedding has also been observed in full-scale engine measurements, and is believed to be due to the difference in thermal expansion coefficients between the deposit and the base metal to which the deposits are attached. This indicates that at least a portion of the deposits resulting from some soil materials, may be effectively cleared in the field by a temporary reduction in CET.

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Fuel Supply System

Water Injection System

High Pressure Chamber 930 kPa 330°C

Low Pressure Chamber 685 kPa 316°C

Exhaust

Choke

Main Air Supply

Dust Injection System

Independent Cooling Air Supply System

Figure 1 -- HSTS Facility Schematic

Figure 2--Low Pressure Chamber/Combustor Inlet

Figure 3--Independent Cooling Air Supply System Schematic

Figure 4--Inconel Cylinder Thermocouple
Figure 11--EDM025 Cylinder Pre & Post Flows; CET=1371°C, $D_c=182.4$ mg/m$^3$

Figure 12--LAM1 Cylinder Pre & Post Flows; CET=1371°C, $D_c=37.5$ mg/m$^3$

Figure 13--Summary of Pre & Post Flow Results for Cylindrical Specimens

Figure 14--DCV8 and DCV2 Pre & Post Flows; CET=1371°C, $D_c=191$ mg/m$^3$

Figure 15--ICV8 and ICV3 Pre & Post Flows; CET=1371°C, $D_c=191$ mg/m$^3$

Figure 16--CET Histories for Cylinder Experiments
Figure 17 -- Cylinder Positions for Run No. 1

Figure 18 -- Cylinder Positions for Run No. 2

Figure 19 -- Cylinder Positions for Run No. 3

Figure 20 -- LAS015 Leading Edge; CET=1371°C, D_c=182.4 mg/m^3

Figure 21 -- EDM025 Leading Edge; CET=1371°C, D_c=182.4 mg/m^3

Figure 22 -- LAS015 Leading Edge; CET=1371°C, D_c=37.5 mg/m^3

Figure 23 -- LAS015 Leading Edge Deposit; CET=1371°C, D_c=37.5 mg/m^3

Figure 24 -- LAM1 Leading Edge; CET=1371°C, D_c=37.5 mg/m^3
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