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# Upgrade and Operation of the DNA Dust Erosion Test Facility

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Technical Report

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This report summarizes the technical effort on the Upgrade and Operation of the DNA Dust Erosion Test Facility. This facility is located at the PDA Engineering laboratory facilities in Santa Ana, California and has been upgraded and operated by PDA Engineering under DNA sponsorship during the period from September 1986 through May 1990. During this period, the facility has logged approximately 3,000 hours of test time which includes over 1,500 dust exposures involving over 500 test specimen arrays. Test support has been provided to a variety of customers including government agencies, directed contractors and industry.

In addition to test support provided since September 1986, a number of significant facility upgrades have been installed and new test procedures developed. Upgrades have included the relocation of the facility and expansion of the laboratory floor space, the development and installation of a Laser Doppler Velocimeter (LDV) for particle velocity calibration, the expansion of post test analysis capabilities, extension of critical component service life, enhancement of facility performance capabilities, development of specimen temperature control system, installation of a computer based data acquisition system and the development of test procedures to measure specimen mass loss histories and haze build-up in transparencies.

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## PREFACE

This report summarizes the technical effort on the Upgrade and Operation of the DNA Dust Erosion Test Facility conducted by PDA Engineering under Contract No. DNA001-86-C-0105 for the Defense Nuclear Agency (DNA). The effort summarized in this document was performed during the period from September 1986 through May 1990. The DNA Contract Technical Monitor was Major Vayl Oxford. His assistance during the course of this program is gratefully acknowledged.

The technical effort for this program was coordinated by the Defense Technology Division of PDA Engineering. The PDA Program manager was Mr. R. G. Oeding. Laboratory test support was provided by Mr. C. O. Lennon.

# CONVERSION TABLE

Conversion factors for U.S. Customary to metric (SI) units of measurement

| MULTIPLY → TO GET | BY → BY | TO GET ← DIVIDE |
|---|---|---|
| angstrom | 1.000 000 X E -10 | meters (m) |
| atmosphere (normal) | 1 013 25 X E +2 | kilo pascal (kPa) |
| bar | 1 000 000 X E +2 | kilo pascal (kPa) |
| barn | 1 000 000 X E -28 | meter$^2$ ($m^2$) |
| British thermal unit (thermochemical) | 1.054 350 X E +3 | joule (J) |
| calorie (thermochemical) | 4.184 000 | joule (J) |
| cal (thermochemical)/$cm^2$ | 4.184 000 X E -2 | mega joule/$m^2$ ($MJ/m^2$) |
| curie | 3 700 000 X E +1 | *giga becquerel (GBq) |
| degree (angle) | 1.745 329 X E -2 | radian (rad) |
| degree Fahrenheit | $t_k$ = (t°f + 459 67)/1.8 | degree kelvin (K) |
| electron volt | 1.602 19 X E -19 | joule (J) |
| erg | 1.000 000 X E -7 | joule (J) |
| erg/second | 1.000 000 X E -7 | watt (W) |
| foot | 3 048 000 X E -1 | meter (m) |
| foot-pound-force | 1.355 818 | joule (J) |
| gallon (U.S. liquid) | 3.785 412 X E -3 | meter$^3$ ($m^3$) |
| inch | 2 540 000 X E -2 | meter (m) |
| jerk | 1 000 000 X E +9 | joule (J) |
| joule/kilogram (J/kg) (radiation dose absorbed) | 1.000 000 | Gray (Gy) |
| kilotons | 4.183 | terajoules |
| kip (1000 lbf) | 4 448 222 X E +3 | newton (N) |
| kip/inch$^2$ (ksi) | 6 894 757 X E +3 | kilo pascal (kPa) |
| ktap | 1.000 000 X E +2 | newton-second/$m^2$ ($N-s/m^2$) |
| micron | 1 000 000 X E -6 | meter (m) |
| mil | 2.540 000 X E -5 | meter (m) |
| mile (international) | 1.609 344 X E +3 | meter (m) |
| ounce | 2 834 952 X E -2 | kilogram (kg) |
| pound-force (lbs avoirdupois) | 4.448 222 | newton (N) |
| pound-force inch | 1.129 848 X E -1 | newton-meter (N·m) |
| pound-force/inch | 1 751 268 X E +2 | newton/meter (N/m) |
| pound-force/foot$^2$ | 4.788 026 X E -2 | kilo pascal (kPa) |
| pound-force/inch$^2$ (psi) | 6.894 757 | kilo pascal (kPa) |
| pound-mass (lbm avoirdupois) | 4.535 924 X E -1 | kilogram (kg) |
| pound-mass-foot$^2$ (moment of inertia) | 4.214 011 X E -2 | kilogram-meter$^2$ ($kg \cdot m^2$) |
| pound-mass/foot$^3$ | 1 601 846 X E +1 | kilogram/meter$^3$ ($kg/m^3$) |
| rad (radiation dose absorbed) | 1.000 000 X E -2 | **Gray (Gy) |
| roentgen | 2.579 760 X E -4 | coulomb/kilogram (C/kg) |
| shake | 1 000 000 X E -8 | second (s) |
| slug | 1.459 390 X E +1 | kilogram (kg) |
| torr (mm Hg, 0° C) | 1.333 22 X E -1 | kilo pascal (kPa) |

*The becquerel (Bq) is the SI unit of radioactivity; 1 Bq = 1 event/s
**The Gray (Gy) is the SI unit of absorbed radiation.

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# INTRODUCTION

## 1.1 BACKGROUND.

Both strategic and tactical aircraft may be forced to operate in post-nuclear strike environments which contain significant loadings of dust and debris. Although larger particles such as pebbles and rocks may only be an airborne threat for a relatively short time, small and well-distributed dust particulates can remain in the post-burst environment for significant periods. "Late-time" dust clouds from multiple surface bursts may form large extended dust environments due to natural and weapon-induced winds. Detection and avoidance of such dust environments by operational aircraft may not be feasible within mission constraints. Flight through "late-time" dust clouds may well be the only alternative. Thus, the ability of critical aircraft components to survive flight through extended nuclear dust environments is an important vulnerability issue.

The basic elements required in addressing dust erosion vulnerability issues are (1) definition of the environment, (2) characterization of material response, and (3) understanding of the failure modes. Complex aircraft systems make the latter two elements highly component and/or subsystems dependent. For example, a leading edge may lose up to half of its thickness before it is considered seriously damaged; however, the loss of a few thousandths of an inch of material may seriously impair a radome or eliminate visibility through a windscreen.

A valid experimental simulation of dust erosion effects is required to assess vulnerability of existing aircraft surfaces/components, evaluate erosion resistant materials/protective techniques and to provide an experimental data base for the development of predictive response models. The general requirement for simulation of in-flight dust erosion effects is to effectively match the key physical parameters associated with impact phenomenology. These parameters include particle type/size, mass concentration, impact velocity, impact angle, and gas dynamic pressure. Thus, simulation of aircraft dust erosion effects requires a facility which can produce steady, low-concentration dust flow environments. Since aircraft operation is predominantly at subsonic speeds, supersonic and high velocity test facilities are not a primary requirement. However, highly accurate measurements of impacted dust mass and particle velocity are required over a broad range of subsonic velocities (e.g. 100 to 900 fps) in order to determine the erosion characteristics of critical materials.

Until recently, no suitable facility existed for simulating dust erosion effects on aircraft. The standard erosion facilities such as particle laden arc heaters, combustion tunnels, and rocket

sled facilities could not simulate the subsonic velocity regime, had high uncertainties on particle size and impacted mass, limited (short) test times, and were complex and expensive facilities to operate.

In order to provide a suitable test facility for addressing aircraft erosion issues, PDA Engineering, developed the DNA Dust Erosion Test Facility. This facility was designed to meet a wide range of flight environments and provides precise control over the key physical parameters in a laboratory environment. The facility was developed and is currently located at PDA Engineering's laboratory facilities in Santa Ana, California.

## 1.2 SCOPE.

This report describes efforts associated with the upgrade and operation of the DNA Dust Erosion Test Facility under Contract No. DNA 001-86-C-0105 and covers a period of 45 months which includes a 6 month reporting period. A detailed description of facility capabilities, test procedures and user information is included in a separate facility report (Reference 1) which will be published concurrent with this final report.

An overview of test facility and a description of key upgrades are presented in Section 2. Facility utilization during the period of performance is outlined in Section 3 including hours of operation and types of testing. Summary and recommendations for future development and operation are presented in Section 4.

## SECTION 2
## FACILITY UPGRADES

### 2.1 OVERVIEW.

The DNA Dust Erosion Facility was designed to simulate the effects of flight through a low concentration solid particle (dust) environment. Specific simulation requirements included particle sizes from 50 to 250 μm, particle mass fluxes as low as 3 mg/cm$^2$/min, run times from a couple minutes to over an hour, particle velocities over a broad range of subsonic Mach numbers and adjustable impact angles. In order to accomplish this simulation, dust particles are accelerated in a small diameter (approximately 0.25-inch) high speed gas jet and caused to impinge on a test specimen as illustrated in Figure 1. Since the diameter of the dust jet is smaller than the test specimen area, the specimen holder and jet are articulated so that the test specimen is moved through the dust jet in a uniform manner. This articulation provides a uniform particle loading (dust mass intercepted per unit surface area) over a square area of approximately 310 cm$^2$ (i.e. 6.9-inch square).

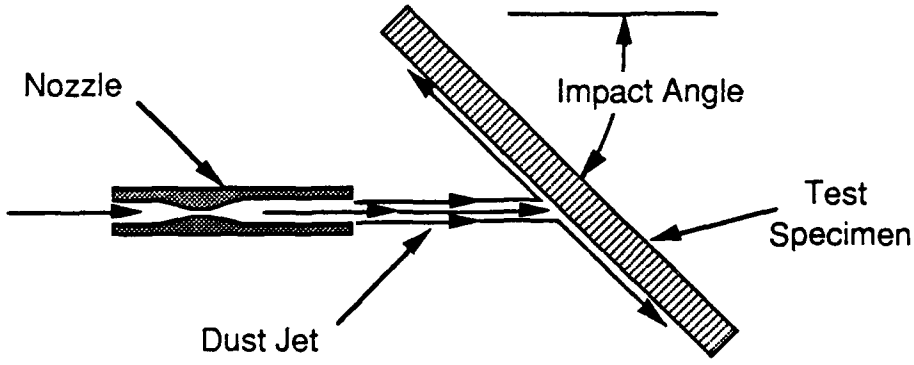


Figure 1. Test configuration.

The transport gas stream is provided by either compressed air or pure nitrogen (GN2) with regulators and pressure transducers to measure and control the pressure at the nozzle inlet. Dust particles are metered into the transport gas stream from a low concentration dust source created by a spouting fluidized bed. The dust mass flow is measured continuously by monitoring and recording the weight of the fluidized bed assembly. Dust velocity is determined as a function of the nozzle inlet pressure and the particle size by prior calibration. Thus, for a given test with a specified particle size, a specific test velocity can be selected from this velocity versus pressure calibration. Four independent nozzles and fluidized bed feed systems are integrated into the test

facility in order to provide greater flexibility in achieving the desired particle concentration, size distribution, and spatial uniformity.

Particle size, velocity and impact angle can be controlled independently. This provides an excellent capability to parametrically evaluate the response of critical aircraft materials to solid particle impact effects. Materials from such components as leading edges, windscreens, radomes, paints and any special coatings can be evaluated in a well controlled laboratory environment under realistic particle impact conditions.

Although the basic test equipment has been operational since early 1984, significant additions and/or modifications were required to create a reliable multi-user test facility. These upgrades were accomplished under the subject DNA program. They included a new and greatly expanded physical layout, an automated velocity calibration system, a continuous flow particle sizing system, post-test measurement instrumentation, improved control and reliability, specimen temperature control and improved test procedures. These and other upgrades are described in this section.

## 2.2 PHYSICAL LAYOUT.

During the first year of this DNA program, the dust erosion facility was moved to new and expanded PDA laboratory facilities. The original test facility consisted of a single air conditioned room containing the test equipment, fixtures, parts, tools, supplies and work space for specimen preparation and examination. Being contained in a single room, this space was subject to high noise levels and any dust fallout generated during testing.

The current facility layout was established in August 1987 and includes an expanded work area consisting of three separate rooms and a high bay area as illustrated in Figure 2. The floor space is divided into four primary areas. These include (1) the dust erosion laboratory which houses the test equipment, (2) a specimen preparation room which is also used for both pre and post-test activities; (3) an office area (available to users) with desk, telephone, and storage; and (4) an open bay area for storage of consumables, particle sizing and dust collection hardware. A basic machine shop is also available on the premises for specimen or fixture modifications that may be required to support testing. All areas except the open bay area are air conditioned. The specimen preparation room and office are dust free areas. Even the dust erosion laboratory experiences very little dust fallout since the actual test apparatus has been completely enclosed and a dust collection system installed. In addition, the high bay area has fork lift access for delivery and storage of bulk sand and compressed nitrogen bottles.

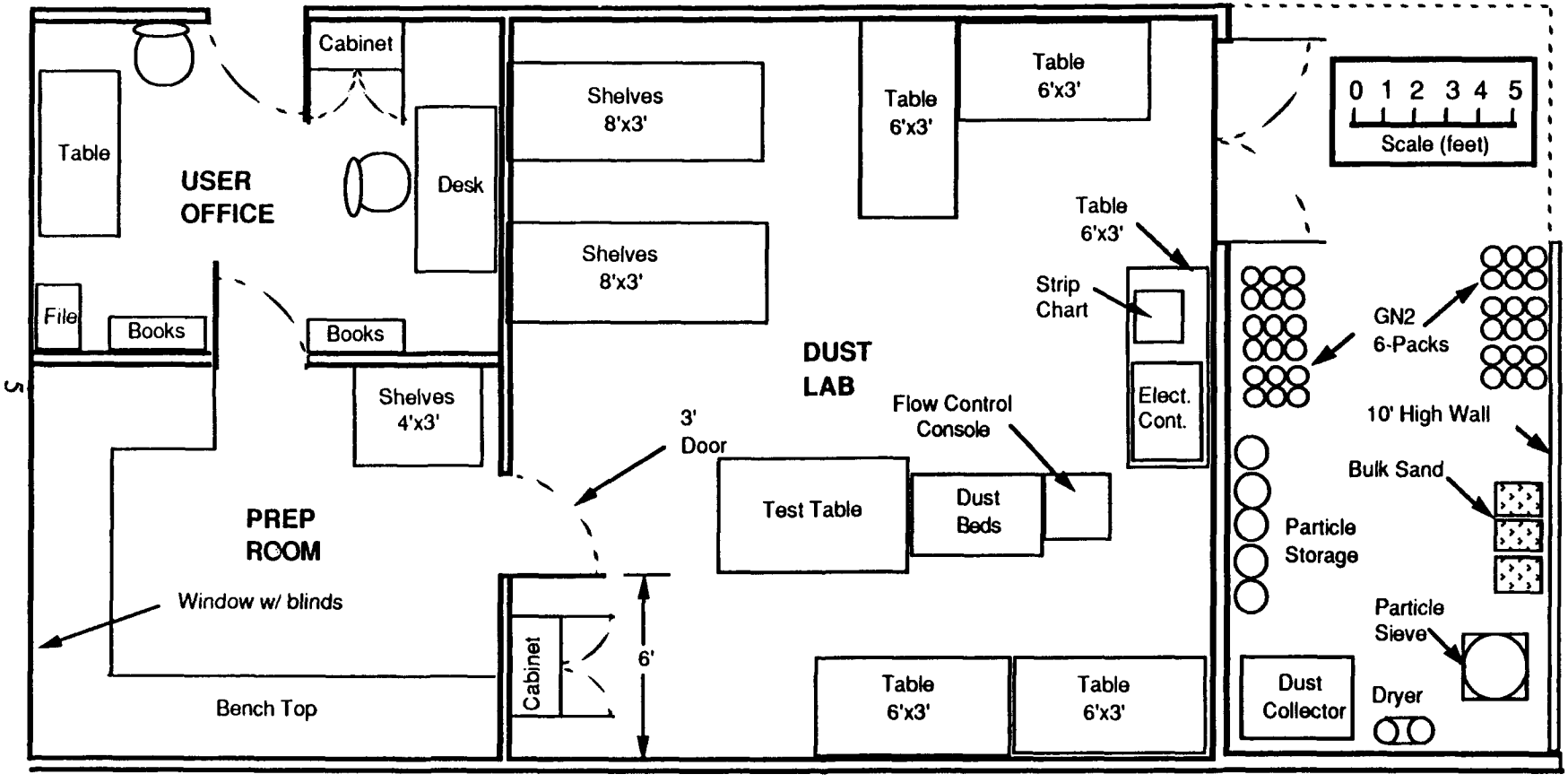


Figure 2. DNA dust erosion test facility layout.

## 2.3 PARTICLE CHARACTERISTICS.

Dust erosion effects are simulated with crushed silica particles since silica is a major component in anticipate lofted dust clouds, is a hard material and is readily available. Test results have shown that particle shape has a significant effect on the erosion of brittle materials. Irregular shaped particles produce more damage than spherical particles and are more representative of lofted dust. Crushed silica is obtained in bulk quantities and on-site particle classification is performed using sieves in order to obtain specific particle sizes for testing . Different sources of the bulk crushed silica have been used including pure white silica sand and several grades of foundry sand. The primary quality required in a bulk material is a broad distribution of particle sizes so that reasonable particle yields can be obtained in all of the particle size ranges.

Particle sizing capabilities were greatly enhanced as part of the facility upgrade effort. Particle sizing was initially performed using 8" diameter Tyler sieves and a small portable sieve shaker. However, this system had serious limitations. It was a batch mode process using small quantities on bulk material; therefore, throughput was low and continuous technician support was required to empty, clean and refill the sieves. Also, the sieves would tend to clog with the irregularly shaped particles thereby blocking the flow of material, further reducing particle yield and increasing sieving time.

Particle sizing capabilities were upgraded with the installation of an 18-inch diameter continuous flow sieve system (SWECO Model LS18S33333) as shown in Figure 3. The particles flow through a series of vibrating screens of specified size with particles larger than a screen size flowing off and being collected. Each screen has a unique "self-cleaning" system which dislodges embedded particles and maintains a high percentage of open area. The system holds four screens at a time; thus, two passes are normally required to obtain particles in seven size ranges. The stainless steel hopper will hold several hundred pounds of sand making frequent filling unnecessary. Also, the shaker system is controlled by a timer so that technician support is not required to turn it on or off.

The source of crushed silica particles is a foundry sand which is purchased in bulk. This material has a broad range of particle sizes with good yields in the 38 to 75 μm range. A total of 10 screens are available with openings that range in size from 38μm to 250μm. These are identified by Tyler Sieve Numbers in Table 1. Particle sizes between any two screen sizes can be generated for use in erosion tests. Seven specific size ranges are maintained in stock and are always available. These size ranges are as follows: (a) 38 - 44 μm, (b) 44 - 74 μm, (c) 74 - 88 μm, (d) 88 - 105 μm, (e) 105 - 125 μm, (f) 125 - 149 μm and (g) 149 - 177 μm.

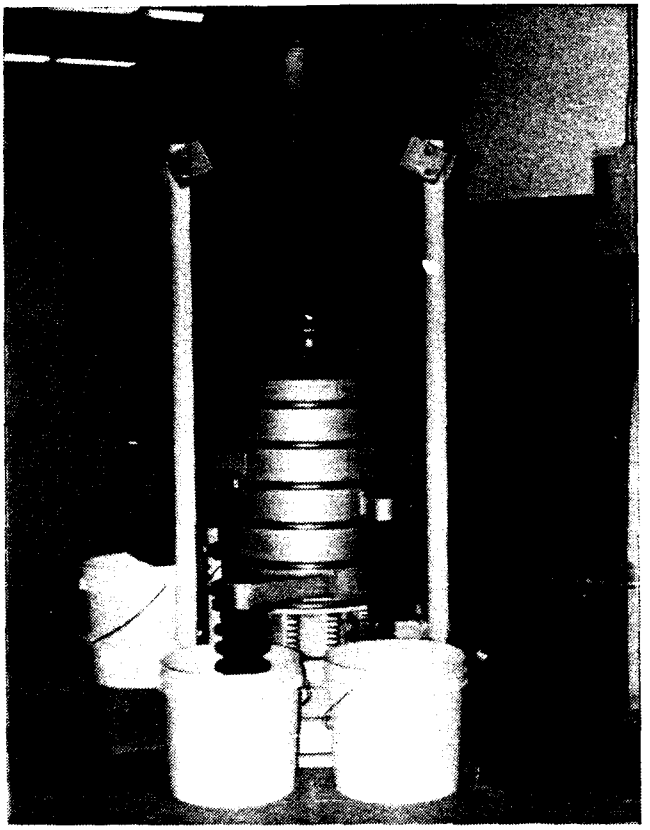

Figure 3 Particle sizing system.

Table 1. Available sieve sizes.

| TYLER SIEVE NO. | SCREEN MATERIAL | HOLE SIZE (μm) |
|---|---|---|
| 60 | 74 Mesh Tensile Bolting Cloth | 250 |
| 80 | 94 Mesh Tensile Bolting Cloth | 177 |
| 100 | 120 Mesh Tensile Bolting Cloth | 149 |
| 120 | 145 Mesh Tensile Bolting Cloth | 125 |
| 140 | 165 Mesh Tensile Bolting Cloth | 105 |
| 170 | 200 Mesh Tensile Bolting Cloth | 88 |
| 200 | 230 Mesh Tensile Bolting Cloth | 74 |
| 270 | Stainless Steel Market Grade Cloth | 53 |
| 325 | Stainless Steel Market Grade Cloth | 44 |
| 400 | Stainless Steel Market Grade Cloth | 38 |

## 2.4 VELOCITY CALIBRATION.

Particle velocity is one of the key erosion simulation parameters and the most difficult to measure. By the nature of the test method, particle velocity measurement techniques are best applied to a free jet without the interference of the test specimen, holder and translation hardware. This approach requires that velocity be determined by pre and/or post-test calibration. For a specific particle size range, the particle velocity is controlled by the expansion of the dusty gas flow through the nozzle where the gas pressure at the nozzle entrance is the controlling parameter. Thus, particle velocity can be correlated as a function of nozzle inlet pressure for a specific nozzle and particle size range. As long as the inlet pressure and nozzle dimensions are maintained at the determined value, the specified particle velocity will be obtained. However, since nozzle erosion can change nozzle dimensions, it is necessary in practice to recalibrate periodically to insure accurate particle velocity.

Significant improvements in the particle velocity calibration capabilities were made as part the facility upgrade efforts. When this effort was initiated, particle velocity measurements were accomplished using double flash photography. However, this approach has serious limitations for smaller particles sizes (<100 μm) and higher velocities (>120 m/s). The double flash technique utilizes two high intensity, high speed light sources (i.e. flash lamps with a 0.5 μsec pulse duration) to capture, through double exposure, two highly magnified images of dust particles. Particle velocity is then determined from the known distance traveled by the particle between flashes and the measured flash separation time. The particle travel is determine from photographs using known magnification factors. Flash separation is obtained from the output of a high speed photodiode as analyzed on a digital oscilloscope. A mean velocity and standard deviation is determined based on a sample size of ≥50 particles.

Although double flash photography has been used to measured velocities up to 240 m/s (800 fps) with particles as small as 75 μm, difficulties are encountered in " catching" particles in the camera's depth-of-field and in determining the image and pulse separations. One valid measurement in five or ten photographs was not uncommon. With such low data rates, a significant amount of facility run time, technician labor, photographic supplies and analysis effort was required for each calibration condition. To obtain a 50-particle sample using double flash photography could take several days. For the difficult conditions (e.g. small particles and high velocities) valid measurements may not be possible with this technique. Based on experience, it became obvious that photography could not provide the necessary quality or timeliness required of a facility calibration tool.

The requirements of high sample rate, rapid processing and good velocity resolution drove the measurement methodology toward electo-optic techniques. Specifically, Laser Doppler Velocimetry (LDV) was identified as the most promising approach to measure particle velocity in the high speed dust jet. LDV is a non-intrusive technique which can provide an accurate and rapid measurement of velocity for small particles (one to several hundred microns). Reference 2 discusses laser diagnostic techniques including LDV. Conventional fringe laser LDV utilizes an optical probe volume which is an ellipsoid of fringes formed by the interference of two intersecting coherent (laser) light beams having plane wave fronts. The transmitting optics used to create this probe volume consists of a HeNe laser, lens and beam splitter (grating) as shown in Figure 4 where the particle path is along the y-axis. Dust particles that pass through the optical probe volume scatter light which is collected with optics (not shown in Figure 4) and focused on a photomultiplier tube (PMT). The PMT converts the scattered light from the fringes into an AC voltage signal. A computer based signal processor measures the frequency of the signal, determines the time of flight between fringes, and stores the data for analysis. This processing is done for each valid signal at rates of several thousand samples per second.

The particle velocity is obtained by dividing a known distance (the fringe separation) by a measured time-of-flight. The flight time is derived via the processing of scattered light signals from the small dust particles as noted above. The fringe spacing and probe volume size are controlled by the intersection angle of the two laser beams and by the laser light frequency as shown in the figure. For typical dust particle calibration measurements, a fringe spacing of 30μm and a probe diameter of the order of 0.5 mm are used. With this optical configuration the instrument can measure velocities ranging from 0 to 470 m/s (1540 ft/sec) which is well beyond the capabilities of the erosion facility. Figure 5 presents a typical velocity histogram generated by one measurement consisting of 2000 samples (particles). Analysis of the histogram by the data processing software provides the mean velocity and standard deviation indicated on the figure.

Photographs of the LDV system including both the optical system and data processor are presented in Figure 6. The optics are located on a rail that can be quickly installed for velocity calibration The data processor/computer is mounted on a cart that can be easily moved into place with the optical system. All data are reduced, displayed and stored by the processing computer. Key results can be displayed graphically as illustrated by the velocity histogram displayed on the computer monitor shown in Figure 6. Also, the relatively small optical probe (~500 μm diameter) associated with the LDV setup provides sufficient spatial resolution to obtain radial velocity distributions. Since particle velocity in not constant across the dust jet, both mean velocity and sample rate (particle flow rate) distributions are useful in characterizing particle flow.

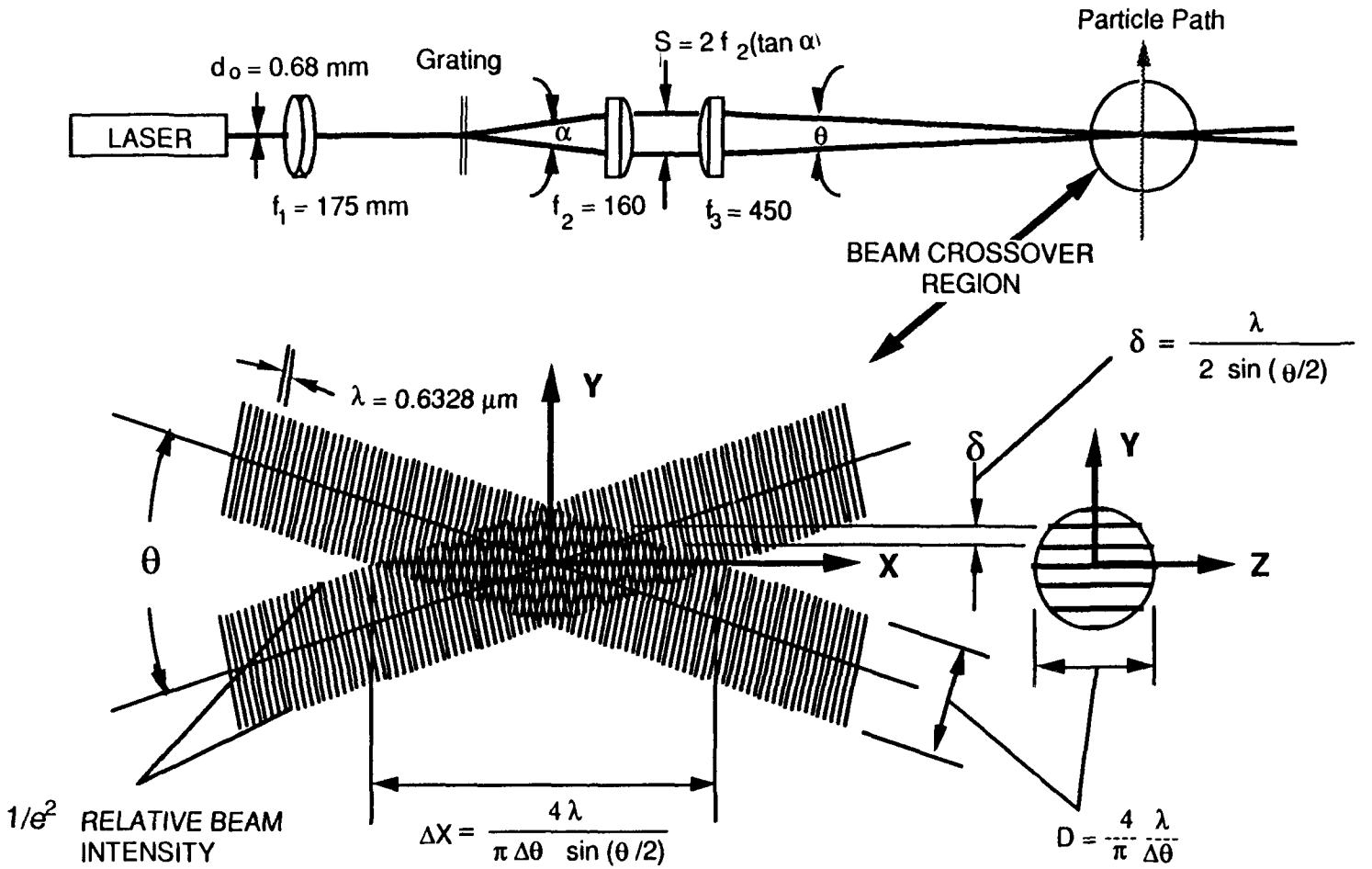


Figure 4. LDV transmitting optics.

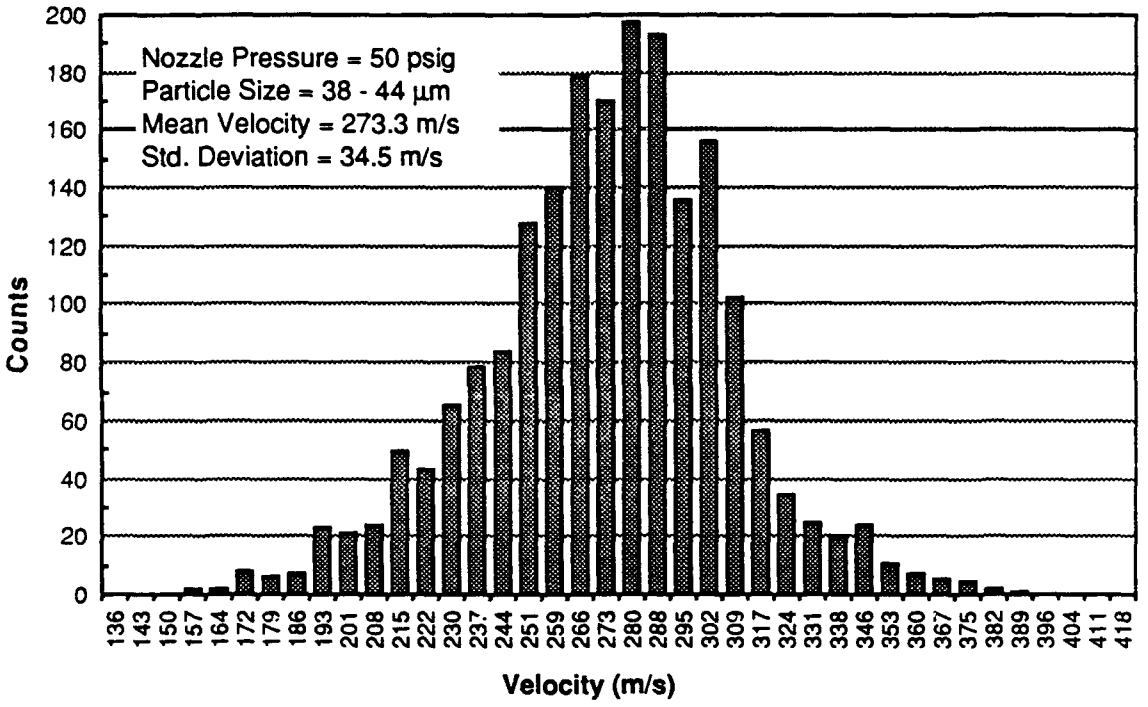


Figure 5. Velocity histogram generated with LDV system.

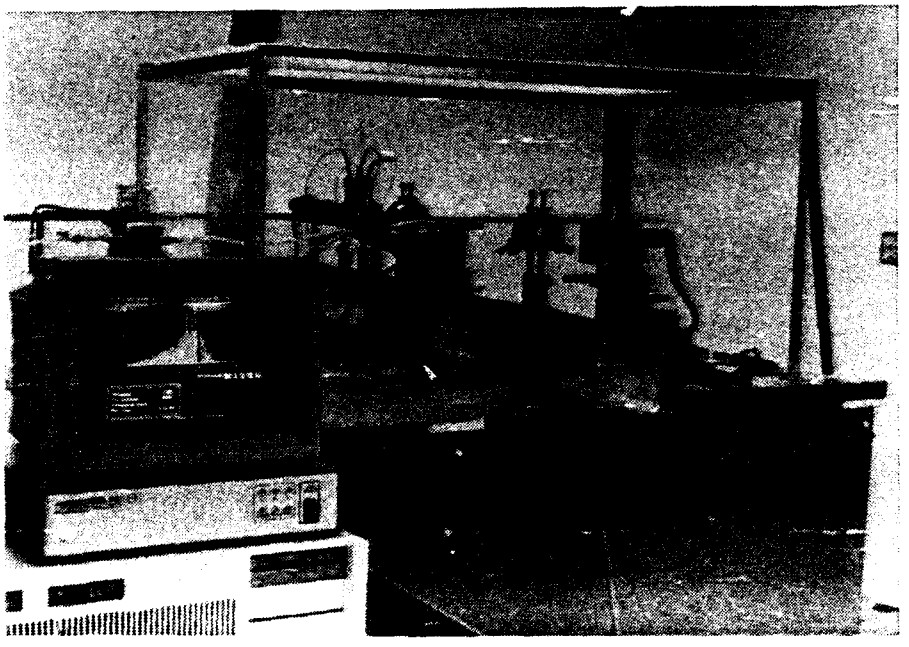

Figure 6. Laser doppler velocimeter system.

## 2.5 TEST CAPABILITIES.

Expanding the performance capabilities of the dust erosion facility was an important phase of the facility upgrade efforts. Specific performance enhancements were developed to meet user needs. Key upgrades were accomplished in the areas of (1) expanded particle flow rate capability, (2) increased particle velocity, (3) specimen temperature control and (4) test procedure development. The need to quantify the erosion response of composite materials, paints and transparencies was the primary basis for expanding test capabilities. Efforts in each of these areas are described in this subsection.

### 2.5.1 Particle Flow Rate.

One of the critical challenges in the design of the erosion facility was the particle injection technique. Specifically, this means both the method of metering particles into the transport flow and the control of their flow rate. The approach used is to metered dust particles into the transport gas flow by maintaining a suitable pressure differential between the transport flow and a low density dust plume created in the upper section of a spouting fluidized bed. The fluidized bed design is shown in Figure 7. The diameter and position of the dust pickoff tube in the fluidized bed is selected in conjunction with the pressure differential to establish the proper dust flow rate. Suitable pressure regulators, flowmeters, and adjustable valves are utilized to provide a stable and constant fluidized bed pressures and flow rates. The particle flow system has been operated successfully at nozzle inlet pressures as low as 2 psig and as high as 70 psig. Figure 8 shows a closeup view of the fluidized bed configuration including the four independent fluidized beds with their pedestal mounted load cells, support frame and particle feed lines. Up to four particle feed systems (containing either same of different particle sizes) can be operated simultaneously in order to simulate a specific dust environment. The available particle types and sizes are discussed above in Section 2.3 as part of the description of the particle classification system.

Enhancements in the particle flow rate capabilities and control were centered primarily in the areas of improved fluidized bed components (both component design and materials) and mass measurement accuracy. Hardware improvements were directed at the central pump or spout tube shown in Figure 7 which sustained a significant amount of erosion damage in use. Not only did this damage make periodic replacement of the pump tube and elbow necessary, but it also introduced metallic fragments (or flakes) into the dust beds. These fragments were large enough to block the pump tube inlet slot and to cause observed particle mass flow rate fluctuations.

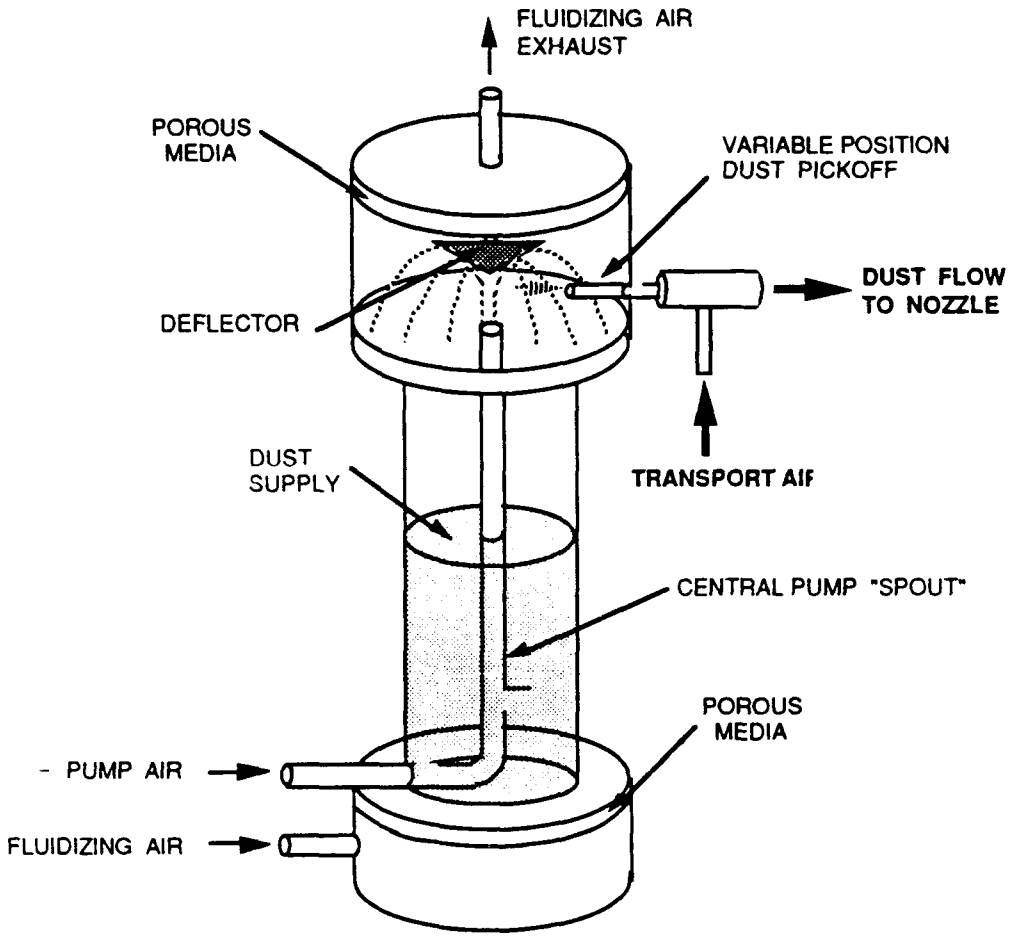


Figure 7. Fluidized bed design.

A significant improvement in flow rate control was realized through the redesign of the pump tube elbow and replacement of both the pump tube and elbow with harder materials. An elbow redesign eliminated a forward facing step which was the key source of erosion while introduction of a much harder steel alloy greatly reduced erosion in other areas. Also, the stainless steel pump tube was replaced with a harder ceramic tube to further reduce erosion and eliminate metallic flakes. Also, any erosion of the ceramic would tend to produce very fine particulates that would be less of a threat to the flow system than the larger metallic flakes. With these modifications, steady mass flow rates of 0.5 g/min or less have been achieved This represents a 50% reduction in the previous minimum flow rate capability of the facility and is particularly important in evaluating the damage threshold of very sensitive transparency materials.

In addition to improvements to the fluidized bed components, modifications to the mass measurement system were also introduced which reduced noise and drift in the load cell output and

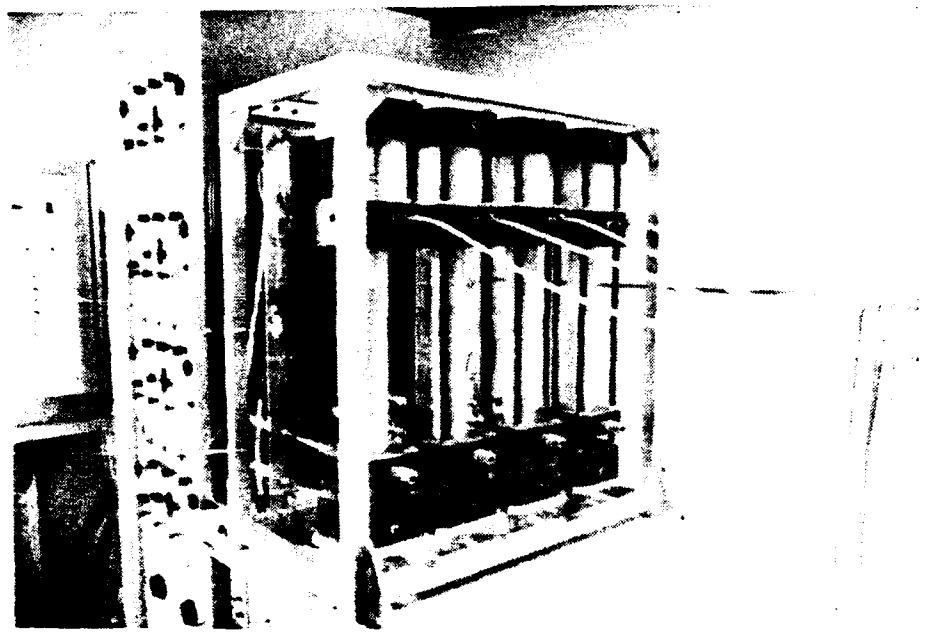

Figure 8. Fluidized bed configuration.

signal amplifier. As noted above in the facility overview, the dust particle mass is determined by measuring the change in weight of the fluidized bed assembly. This is accomplished by mounting the complete bed assembly on a calibrated load cell and measuring weight change as a function of time. The load cell output is displayed on a digital meter and logged on a strip chart recorder. Under certain conditions noise and/or drift had been observed which reduced the precision of the mass measurements.

As part of the facility upgrade effort, noise was reduced through a redesign of the output circuit and better electrical isolation. The drift in the output readings was a longer term phenomenon which was due primarily to temperature changes in the load cell and/or signal amplifier as a result of ambient temperature cycles. Although efforts had been made to insulate the key components of the system, improving both the temperature control within the laboratory and the thermal insulation on the load cell components significantly reduced drift. Temperature stability for periods of at least two hours is now typical.

### 2.5.2 Particle Velocity.

As noted in the introduction, particle velocity is achieved by accelerating particles via aerodynamic drag in an expanding gas jet. Thus, the final particle velocity is dependent on the particle properties (e.g. size, mass and drag coefficient) as well as the nozzle expansion

characteristics. Since particle properties are fixed by the test conditions (i.e. dust environment), the primary design variables are the expansion characteristics of the nozzle (e.g. expansion rate and length). Not only is the achievement of high gas velocities important, but providing sufficient residence time to allow the particle to accelerate is also critical.

The nozzle design that was originally developed for the facility consisted of (1) a converging-diverging section to produce a supersonic gas flow at sufficient inlet pressures and (2) a constant diameter extension to provide necessary resident time for particle acceleration. The nozzle diameter was determined by the overall facility design including (1) the available gas flow rate which can be supported by the laboratory compressor or the bottled gas supply system and (2) the transport flow line size. The diameter of the transport flow line not only sizes the maximum flow rate, but determines the maximum diameter of the nozzle throat. While it is important to have a rapid and efficient expansion in the converging-diverging section of the nozzle, the key variable in determining particle velocity in this design is the length of the constant diameter nozzle extension.

Efforts to enhance particle velocity capabilities were directed at (1) optimizing nozzle extension length, (2) redesigning nozzle components for improved fit and simplified fabrication, (3) selecting materials to improve nozzle hardness and reduce wear and (4) characterizing particle velocity for a variety of dust sizes and nozzle operating pressures. The nozzle extension length was originally determined based on limited velocity measurements using the double flash photography technique described in Section 2.4. The effect on nozzle length on particle velocity was re-evaluated as part of the facility upgrade efforts using the newly developed laser based LDV system to measure particle velocity. The re-evaluation was conducted with an intermediate particle size range of 105-125 μm and at a nozzle pressure of 65 psig which is typical for high velocity conditions. The testing included eight different nozzle extension lengths which ranged from zero to four inches. Results are shown in Figure 9 which presents mean velocity (on the jet centerline) as a function of nozzle extension length. The original photography-based data are also included for reference. Although there is scatter in the data, results indicate that particle velocity increases up to a length of 2 inches, remains relatively constant to a length of 3.5 inches and then decreases rapidly as extension length is further increased. Based on these results, the current two inch nozzle extension was retained as the primary nozzle design. The data scatter appears to be due to the condition of the available nozzle extensions which had slightly varying degrees of wear.

Although increasing the particle velocity capabilities of the facility is important goal, maintaining those capabilities during an extended period of use was an issue that needed to be addressed first. The original nozzle design was difficult to machine, susceptible to high pressure

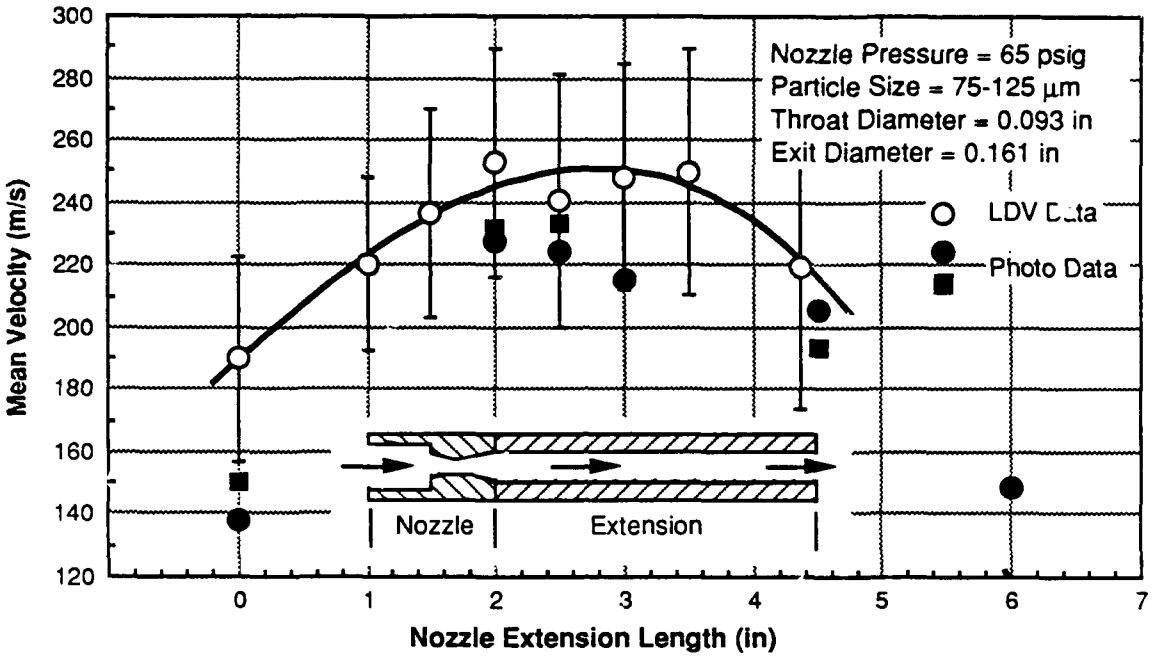


Figure 9. Effect of nozzle extension length on particle velocity.

gas leaks and had a relatively short service life due to internal erosion or wear. Nozzle wear was a key concern since both particle velocity and flow rate performance degenerated with the increase in internal nozzle dimensions. In some cases, velocity performance would change during the period of calibration which made it difficult to maintain accuracy without frequent recalibration.

Several constructive nozzle design changes were identified and implemented. The exterior shape of the converging-diverging nozzle section (and associated holder) were redesigned to have circular ends which simplified fabrication and led to improved fit. Also, the interface between the converging-diverging nozzle section and the nozzle extension block was modified to accept O-rings which provide a seal against leaks. The primary approach taken to reduce nozzle wear, which was most noticeable in the throat and exit regions, was to substitute a harder material for the original steel nozzle components. Initial replacement nozzles were fabricated from a tool steel and hardened with either an air or oil quench. Although these hardened nozzles had a significantly greater service life than the unhardened ones, they still did not provide the stability and repeatability desired. Frequent velocity recalibration was still necessary so that the deterioration in performance could be compensated by increasing nozzle pressure or switching to a less worn nozzle. A significant improvement in hardness was achieved with a special tool steel (CPM-10V) which undergoes a triple tempering process. Nozzle service life appears to be several times that of the previous nozzles.

The plan at the beginning of this program was to map the particle velocity as a function of nozzle inlet pressure for all frequently used particle sizes. Figure 10 presents a plot of such data for a specific nozzle and four commonly used particle size ranges. As expected the smaller particles achieve higher velocities. Also, the jump in velocity seen between 40 and 45 psig appears to be due to the establishment of sonic flow conditions in the nozzle extension. The purpose behind this calibration approach was to be able to set particle velocity by simply dialing-in the correct nozzle pressure. However, it was discovered in practice that particle velocity is also a function of the specific nozzle used. Although performance is similar, each nozzle due to fabrication tolerances, wear and the condition of other feed system components may produce different particle velocities for the same particle size and nozzle pressure. Thus, periodic velocity calibration is necessary to insure good velocity accuracy. In fact, pre and post-test calibrations are obtained as a routine matter. For tests series involving long run times (large dust loads) intermediate calibrations will also be completed after several hours of operation to insure that no changes in the facility have occurred which affect particle velocity.

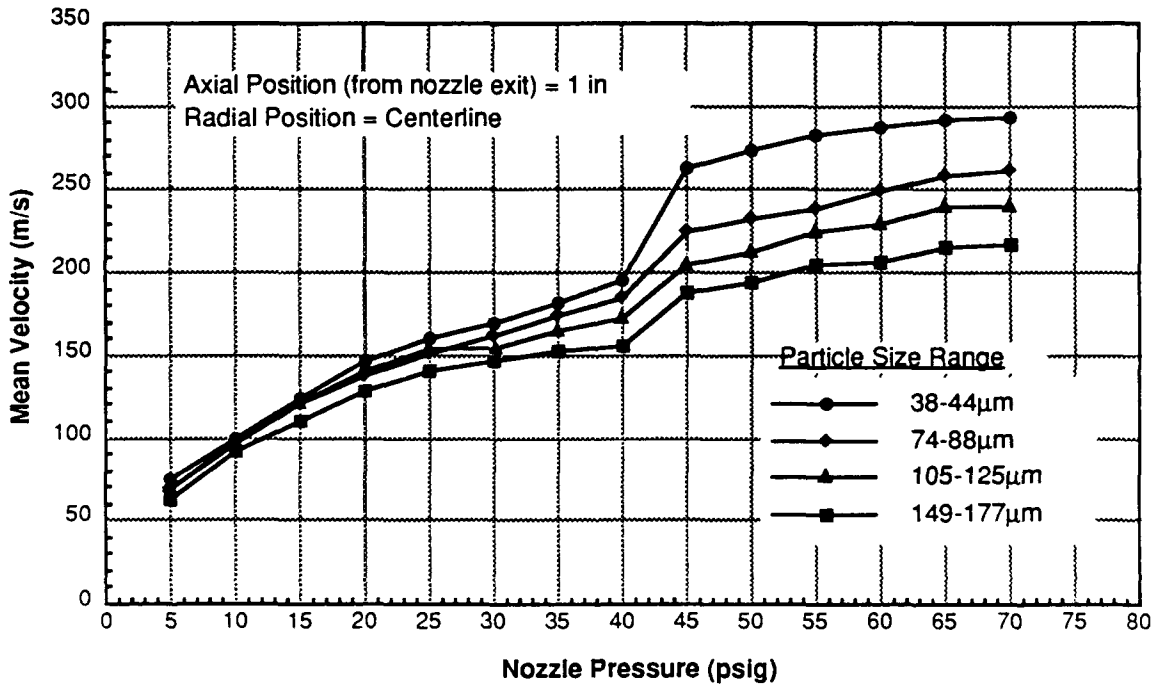


Figure 10. Velocity calibration results.

2.5.3 Specimen Temperature Control.

The original design of the facility did not provide for control of the test specimen temperature. All testing was conducted at laboratory "room temperature" which is nominally 75°F. For materials such as glass or aluminum, erosion response is not sensitive to variation about room

temperature and the simulation of actual aircraft flight temperatures is not an important issue. However, the physical properties (specifically hardness) of some materials (e.g. certain plastics) do vary with temperature for conditions near room temperature. In order to characterize erosion performance at operational temperatures or to evaluate temperature sensitivity, specimen temperature control is required. The capability to conduct erosion tests at both elevated and reduced temperatures was developed and implemented in order to meet customer testing needs. The actual design and installation of the temperature control systems were funded by outside users with the understanding that these modifications would become a permanent part of the facility. Calibration and maintenance of the these systems has been conducted as part of this program support.

Temperature conditions of interest for aircraft erosion evaluations are the external flight temperatures of the components. For the skin and transparency surfaces, these are the ambient temperatures at altitude less aerodynamic heating and any internal heat transfer such as provided by a de-icing system. Except for aircraft on the ground in warm climates or at high supersonic velocities, operational temperatures will be below room temperature. In order to provide realistic temperature conditions, the temperature control systems were designed to provide temperatures ranging from -50°F to +150°F. Thus, systems to both heat and chill the test specimens were developed.

Specimen temperature control involves two components, the test specimen and the dust jet. Since the specimen surface (at the time particle erosion is occurring) is exposed to a impinging jet, the surface heat transfer will vary as the dust jet sweeps across the specimen surface. Thus, the temperature of the specimen, as well as, the dust jet must be set and controlled so that the resulting surface temperature during jet impingement is within a specified tolerance of the design point. To achieve this end, both the test specimen and the jet transport gas (GN2) temperatures are controlled by separate heaters and programmable controllers.

Figure 11 presents a schematic of the temperature control system for erosion testing at elevated surface temperatures. The dust jet is electrically heated with a 1kw line heater controlled by thermocouple at the nozzle inlet. The test specimen is heated by an electrical heating element in the specimen holder and controlled by a thermocouple mounted on the specimen surface. The jet temperature is adjusted via the line heater until the measured jet stagnation temperature matches the specified test specimen surface temperature. This determines the setpoint for the jet temperature controller. The temperature of the specimen holder is adjusted until the measured surface temperature (with dust jet impingement) matches the specified test specimen surface temperature. This determines the setpoint for the specimen temperature controller. During the erosion test, the

two programmable controller units maintain the jet and specimen temperatures at the setpoint values while a surface mounted thermocouple monitors actual surface temperature at one location on the test specimen. Surface temperatures within ±5°F of the specified test condition are achievable with this system based on temperature measurements over the specimen surface.

The low temperature test condition requires a more complex temperature control system than does the warm flow condition since both heating and cooling capabilities are necessary. A chilling system is needed to provide the low (jet and specimen) temperatures; however, the heating system is also required to provide the necessary temperature control. Thus, the cold flow system consists of the warm flow system with the addition of (1) a liquid nitrogen (LN2) chiller on the transport gas stream forward of the in-line heater and (2) a low temperature GN2 chiller on the back side of the specimen holder and behind the electrical heater element. The chiller plate mounted on the specimen holder is cooled by a GN2 flow which has been chilled in a LN2 bath. The same LN2 bath is used to cool both the jet transport flow and the specimen cooling flow. A liquid level controller is used to maintain a constant LN2 level in the chiller bath. The bath is automatically filled from a large LN2 dewar. A schematic of this cold flow temperature control system is shown in Figure 12.

In addition to the difficulties in achieving well controlled low temperature test conditions, other problems associated with sub-freezing temperatures had to be over come. The primary difficulty was condensation on the surface the test specimen. This condensate formed a thin ice

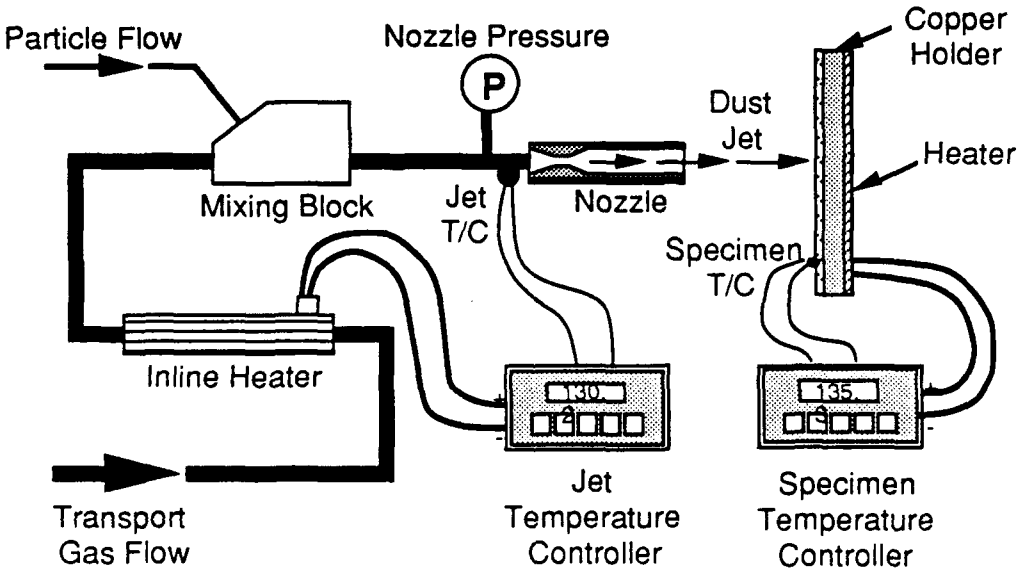


Figure 11. Warm flow temperature control system.

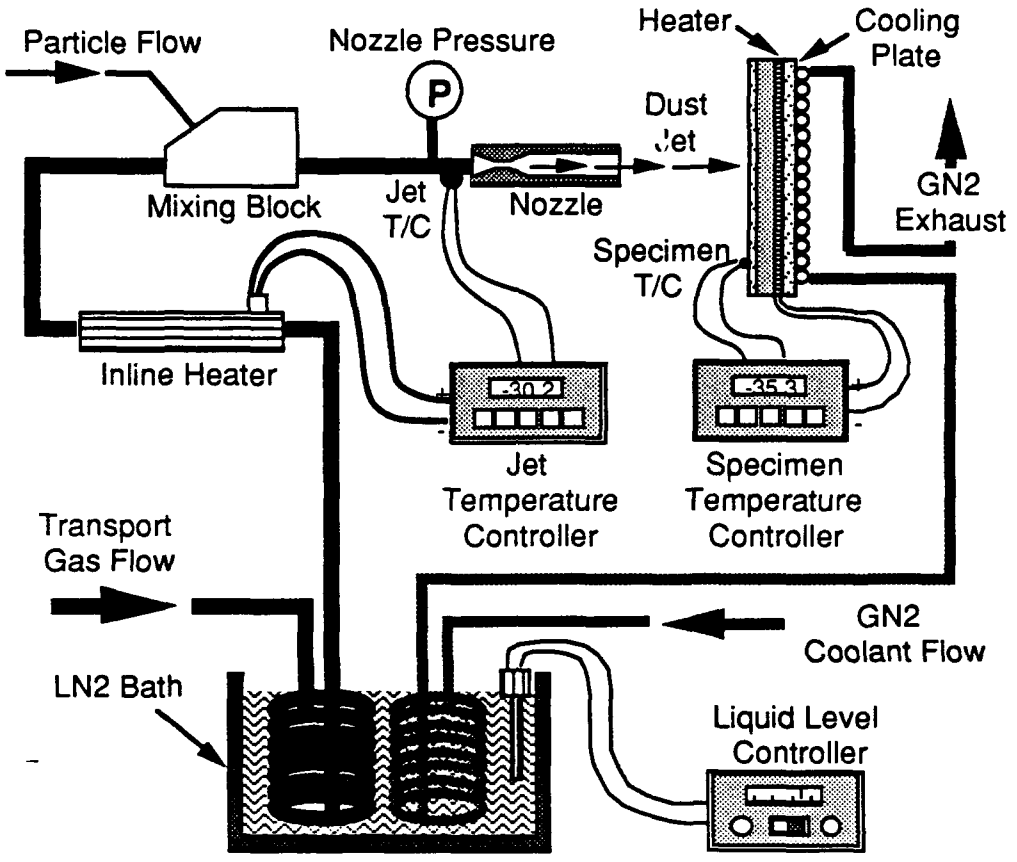


Figure 12. Cold flow temperature control system.

layer and altered the erosion response of the specimen. In order to prevent condensation, all water vapor must be removed from the test cell. This involves purging the test cell for several minutes with dry GN2 before the specimen is chilled, maintaining a purge flow during the test is initiated and ensuring a positive seal from air entering the cell.

The particle velocity is not only a function of nozzle inlet pressure but also depends on the temperature of the transport gas flow. Since the temperature of the jet transport flow (GN2) is adjusted in order to produce a specified specimen surface temperature, the particle velocity in the dust jet will not correspond to the room temperature calibration. For a given nozzle inlet pressure, particle velocity increases with increasing gas flow temperature. For example, a room temperature particle velocity of 280 m/s (918 fps) will increase to approximately 300 m/s (984 fps) at a nozzle inlet temperature of 176 °F. If the nozzle inlet temperature is then reset at -76 °F, particle velocity will drop to approximately 270 m/s (885 fps). Thus, particle velocity must be calibrated at the specific jet set-point temperature to ensure accurate impact velocities.

2.5.4 Test Procedure Development.

In addition to the standard mode of testing where a specimen is exposed to a specified dust load ($g/cm^2$), removed and examined, new test techniques were developed as part of the upgrade efforts. These techniques were directed towards (1) providing data on the transient erosion response of materials, (2) exposing multiple small specimens and (3) evaluating materials at elevated and reduced temperatures. Specifically, procedures for evaluating the transient erosion response were developed in order to determine the mass loss history of opaque materials (i.e. paints, coatings and skin materials) and the degradation history of transparencies.

The standard measure of solid particle erosion is the erosion rate which is defined as the ratio of the mass removed from the test specimen to the mass of impacting particles (Reference 3). Mass loss histories of most materials exhibit a short incubation period (nonlinear response) followed by a steady state (linear) rate of material removal. The erosion rate is usually determined for steady state conditions where the mass removed is the same for equal increments of impacting particle mass. The erosion rate is dependent on a number of parameters including the size and type of particles, impact angle and impact velocity. Since all of these parameters can be controlled in the dust erosion facility, the facility is a natural site for evaluating erosion response of materials.

In order to evaluate and model the erosion performance of materials, the specimen mass loss must be measured as a function of dust loading for specific test conditions. A procedure was developed which utilizes an array of small test specimens and a series of short dust exposures with mass loss measurements conducted between exposures. The erosion rate test procedure consists of the following:

(1) Cleaning, weighing and mounting the test specimens
(2) Exposing the test specimen array to the dust environment for a short period and noting the applied total dust load (dust mass per unit area).
(3) Removing, cleaning, weighing and remounting test specimens
(4) Repeating steps 2 and 3 until a steady state rate of mass removal is achieved or until a prescribed total dust load has been applied.
(5) Compute the mean mass loss for the specimen array and the mass impacted per unit area (dust load) for each incremental dust loading.
(6) Compute the erosion rate from the results of step 5 ( Rate = mass loss / mass impacted) for each increment of dust.

In order to improve mass measurement accuracy a number of small specimens are exposed at the same time. The technique for mounting an array of 2-in x 2-in specimens was developed

which allows up to nine specimens to be tested in a nominal 6-in x 6-in fixture. The specimens are butted together and held in place by a sticky backing which is part of the holder and by compression from the holder sides. A photograph is presented in Figure 13 showing coated metallic samples mounted for testing. The nine small samples not only provide better mass measurement accuracy but also allow several samples to be removed for detailed characterization at specified dust loadings

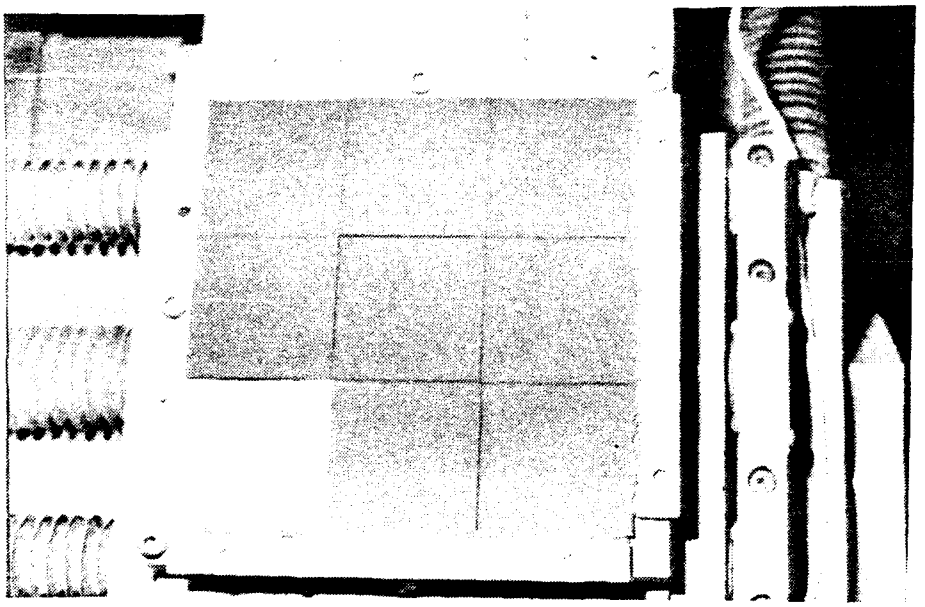

Figure 13. Specimen holder with 2-in. x 2-in. sample array.

Mass loss data obtained using the erosion rate test procedure is presented in Figure 14. The figure shows a plot of mass loss per unit specimen area (milligrams/cm$^2$) versus mass impacted per unit area (grams/cm$^2$). The data were obtained using six incremental dust loadings. In this case, the mass loss data were curvefit with a fifth degree polynomial. This allows the erosion rate to be obtained by differentiation of the curvefit equation, if desired.

A procedure similar to that for erosion rate was developed to evaluate the optical degradation observed in transparencies which are exposed to particle impacts. In the case of transparent specimens including glass and plastics, surface cratering affects visibility through the material. Convenient measures of optical quality are luminous transmittance and haze. These are determined by a standard test method (Reference 4) which utilizes a device call a hazemeter. Haze is defined as the ratio of the diffuse (scattered) component of the transmitted light to the total light transmitted. Typically, haze value over a few percent result in a loss of contrast when viewing a scene through the transparent part. Haze is a very sensitive measure of erosion damage and

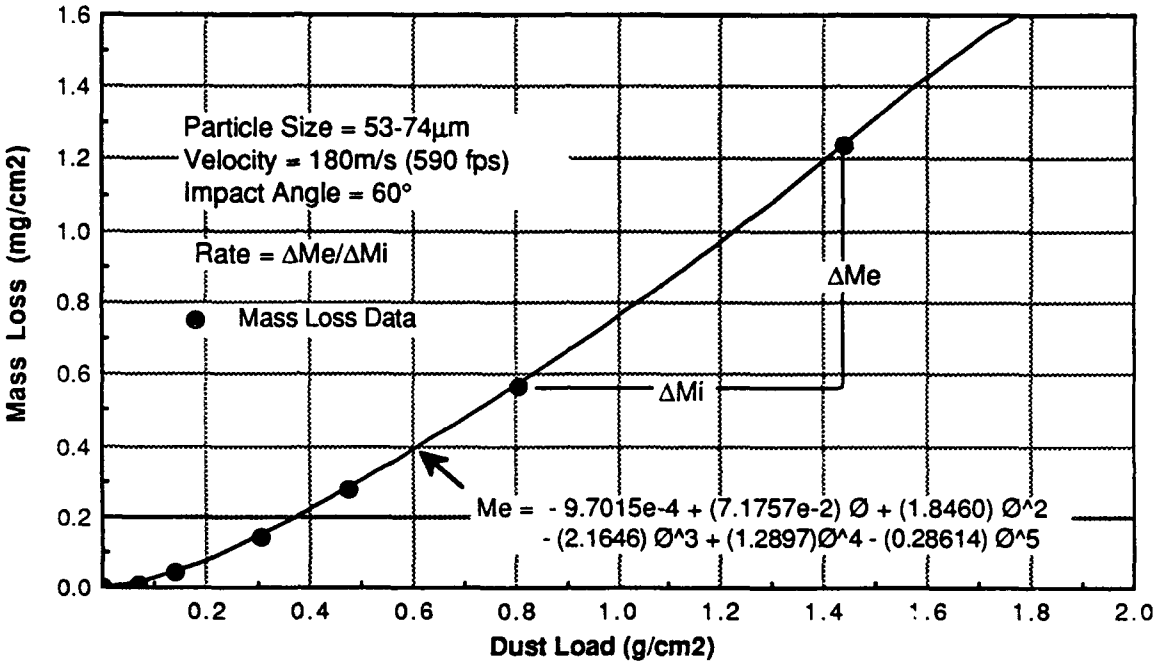


Figure 14. Sample of mass loss data for determining erosion rate.

evaluating the change in haze level with dust loading requires that the dust exposures be very short (e.g. of the order of 0.001 g/cm$^2$) compared to those required for mass loss (e.g. of the order of 0.1 g/cm$^2$). Except for very light incremental dust loadings and optical measurements between exposures, the procedure for evaluating the development of haze in transparent specimens is identical to that developed for evaluating erosion rate. Haze data obtained for two types of plastic transparencies using this procedure are presented in Figure 15.

New procedures were also developed for conducting erosion tests at reduced and elevated temperatures. The key issues associated with the development of a specimen temperature control system were reviewed above in Section 2.5.3. Although detailed test procedures are quite involved for conditions other than room temperature and will not be listed here, the general approach is to utilize the basic room temperature techniques with the addition of start-up procedures necessary to establish steady state specimen temperatures. This involves bringing the dust jet and the test specimen to their previously determined set point temperatures. In the case of low temperature conditions, a separate procedure is also required to purge the test chamber of water vapor and prevent frost build-up on the specimen surface. Once steady state temperature conditions are established, the actual dust exposure follows the room temperature procedures with the surface temperature being monitored on a recorder.

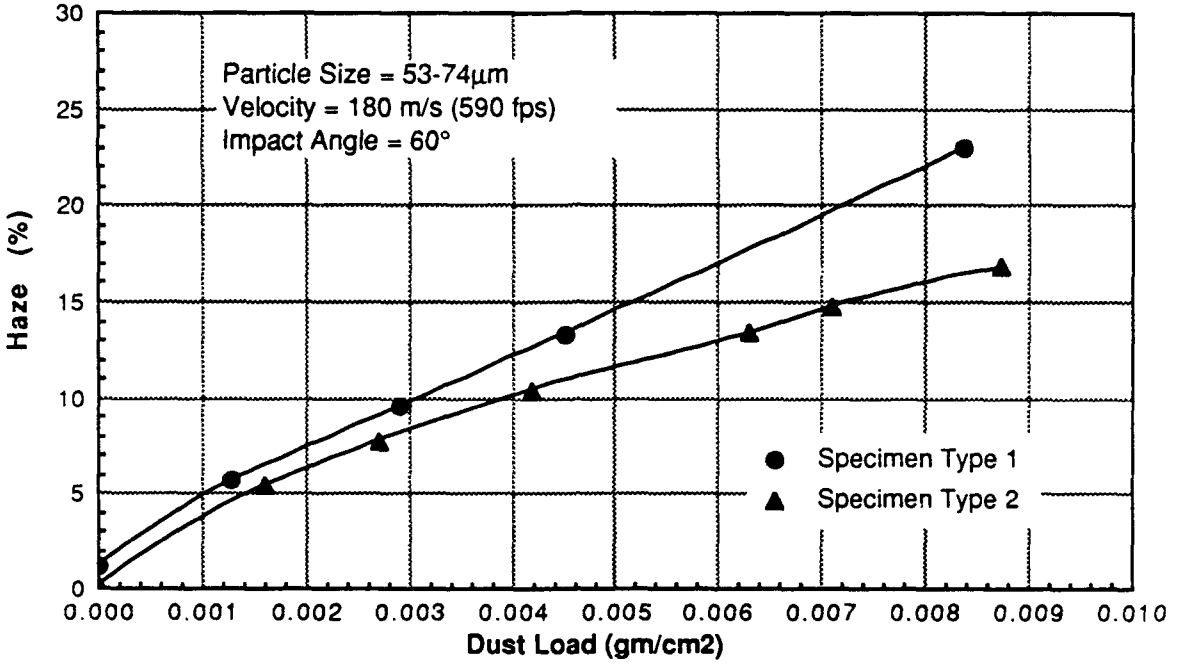


Figure 15. Sample of haze data for evaluating optical degradation in transparencies.

2.5.5 Performance Summary.

As discussed in this report, a number upgrades and improvements that have been incorporated into the dust erosion facility during the course of this program. These have included improved particle flow control, increased particle velocity range, expanded stock of particle sizes, design of multi-sample specimen arrays and development of new test procedures. These upgrades have greatly enhanced erosion simulation capabilities of the facility. Current facility performance capabilities are summarized in Table 2. It is important to not only expand performance in terms of the facility parameters, but it is also necessary to relate that performance to the flight environment.

The DNA Dust Erosion Test Facility differs from the real flight environment in that the specimen is stationary and the dust field is moving at the specified impact velocity. Whereas the key parameters in the flight environment are the static dust cloud mass concentration (mass of particles per unit volume) and velocity, in the dust erosion facility the key parameters are the dust particle mass flow rate and velocity. The relationship between the particle flow rate in the test facility, impact velocity, and the dust cloud concentration in the flight environment is as follows:

Table 2. Facility performance summary.

| PARAMETER | RANGE |
|---|---|
| Particle Type | Crushed silica |
| Particle Size | 38 μm to 250 μm (in 9 increments) |
| Particle Velocity | 25 to 300 m/s (80 to 980 feet/sec) |
| Minimum Particle Mass Flow | 0.5 gm/min (1 nozzle operating) |
| Maximum Particle Mass Flow | 20 gm/min (4 nozzle operating) |
| Impact Angle | 15 to 90 degrees (continuously adjustable) |
| Recommended Specimen Size | ≤ 6-inches x 6-inches |
| Equivalent Cloud Concentration | 0.001 to 0.43 gm/m$^3$ |

$$\dot{m} = 0.006\, C_c\, U_p\, A_s \sin\alpha \qquad (1)$$

where $\dot{m}$ = particle mass flow rate (gm/min) in the test facility,

$C_c$ = ambient cloud concentration (gm/m$^3$)

$U_p$ = impact velocity (m/sec)

$A_s$ = specimen surface area (cm$^2$)

$\alpha$ = impact angle (normal impact = 90°)

In the test facility the particle mass flow rate (gm/min) is controlled by adjusting the number and operating conditions of the fluidized beds. For the current facility configuration, stable dust flow rates can be achieved between approximately 0.5 and 5 gm/min per nozzle. Thus, total flow rates between 0.5 gm/min (1 nozzle) and 20 gm/min (4 nozzles) represents the current operational limits. From a facility operation standpoint, the preferred particle flow rates for the current nozzle design are between 1 and 2 gm/min per nozzle.

For specific test conditions, the corresponding equivalent cloud concentration range that can be simulated in the dust erosion facility is determined from Equation (1). Solving for the cloud concentration, $C_c$, yields:

$$C_c = 166.7\, \frac{\dot{m}}{U_p\, A_s \sin\alpha} \qquad (2)$$

For typical particle test velocities and a normal particle impact angle ($\alpha = 90°$), the range of equivalent cloud concentrations corresponding to the maximum particle flow rate (20 gm/min) and the minimum flow rate (0.5 gm/min) is given in Table 3. For example, with normal particle impact at a velocity of 250 m/s (820 ft/sec), equivalent cloud concentrations between 0.001 and 0.0430 $gm/m^3$ can be simulated in the dust erosion facility.

## 2.6 SPECIMEN PREPARATION AND POST-TEST ANALYSIS.

A separate room was provided for the preparation and evaluation of test specimens as shown in the facility floor plan presented in Figure 2. The specimen preparation room includes counter-top work space and laboratory supplies for cleaning and preparing test specimens. Also, included are key instrumentation/equipment required to support facility operations and post-test evaluations.

Table 3. Equivalent dust cloud concentrations for typical test conditions.

| PARTICLE IMPACT VELOCITY (m/s) | EQUIVALENT CLOUD CONCENTRATION * ($gm/m^3$) | |
|---|---|---|
| | Minimum Flow Rate | Maximum Flow Rate |
| 25 | 0.0108 | 0.430 |
| 50 | 0.0054 | 0.215 |
| 100 | 0.0027 | 0.108 |
| 150 | 0.0018 | 0.072 |
| 200 | 0.0013 | 0.054 |
| 250 | 0.0011 | 0.043 |
| 300 | 0.0009 | 0.036 |

* Based on a normal particle impact angle and a 310 $cm^2$ surface area.

Instrumentation and equipment are listed in Table 4 and include: (1) an ultrasonic cleaner for removing dust and debris from test specimens prior to weight measurements, (2) an analytical balance for specimen mass loss measurements, (3) micrometers and calipers for basic size and thickness measurements, (4) a sensitive digital multimeter, (5) a high speed analog oscilloscope to support various calibration needs, (6) a 35-mm camera and macro-photography accessories for specimen documentation and (7) a PC/AT computer used as an LDV processor and for laboratory data acquisition. Figure 16 present photographs of some of the available instrumentation and equipment.

Table 4. Instruments and equipment for specimen preparation/evaluation.

| ITEM | No | MAKE / MODEL | APPLICATION |
|---|---|---|---|
| Electronic Balance | 1 | Sartorius, RD160D | Specimen mass loss |
| Ultrasonic Cleaner | 1 | Cole-Parmer, J-8851-00 | Specimen cleaning |
| Analog Oscilloscope | 1 | Tektronix, 2215A | LDV system/general diagnostics |
| Digital Multimeter | 1 | Fluke, 8062A | Basic laboratory diagnostics |
| Thermocouple Ice Point | 6 | Omega, MCJ-K | Specimen/laboratory temperature |
| Micrometer (1 in.) | 1 | Mitutoyo, RN1217-5446 | Thickness measurements |
| Calipers (8 in.) | 1 | Mitutoyo, RN2238-5100 | Size measurements |
| Macro-photo. Camera | 1 | Nikon, F-3 System | Lab/specimen documentation |
| Computer | 1 | AMT 286 | LDV Processor/Data acquisition |

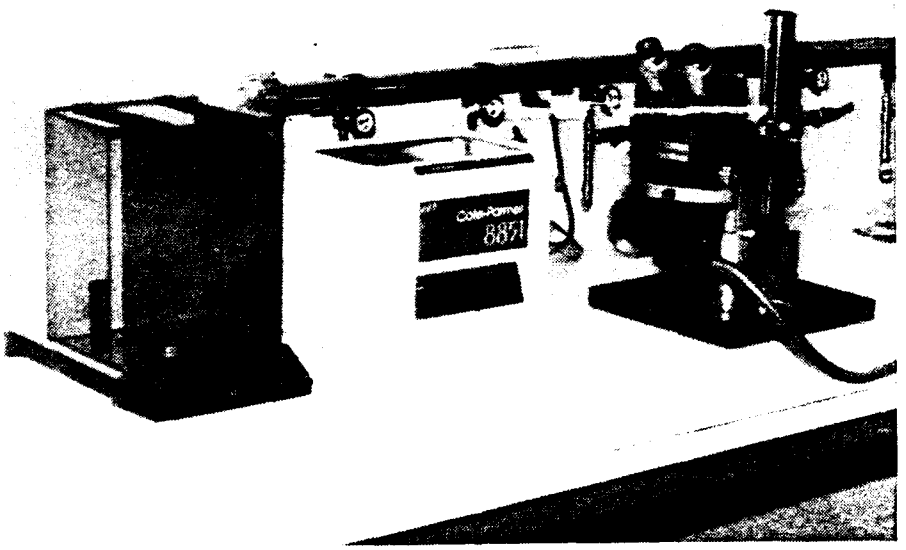

Figure 16. Instrumentation for post-test evaluations.

A 12-bit/16-channel data acquisition system was installed in PC/AT computer (which is part of the LDV system). This system provides the capability to monitor all of the critical pressure and mass measurements on all four nozzle/feed systems using the existing LDV computer. This data acquisition system consists of an electronic circuit board which is installed in the computer and terminal connection boxes for the analog inputs (i.e. pressure transducer, thermocouple and load cell voltage inputs). Software is provided which performs standard data acquisition tasks such as data logging, real time plotting and digital display. This capability supplements the strip chart recorder a provides the capability to support special measurement requirements.

In addition to these instruments which were procured for and dedicated to the dust erosion facility, PDA-owned instruments were also used for post-test evaluations on an "as available" basis. These instruments included a high magnification binocular microscope, a lower magnification stereo zoom microscope and a Pacific Scientific Model XL-211 Hazemeter. As noted in Section 2.5.4, hazemeter is used to measure both the luminous transmittance and haze for transparence specimens. Haze is a particularly sensitive and relevant measure of erosion damage for transparencies.

# SECTION 3
# FACILITY UTILIZATION

## 3.1 DOCUMENTATION.

The primary purpose of facility documentation is to notify potential users of the existence of the dust erosion facility and to provide detailed test capabilities. Documentation efforts were direct toward three main areas: (1) a facility brochure, (2) technical papers/publications and (3) a facility (users) report. A tri-fold facility brochure on 9-in. x 12-in. paper stock was assembled during the first six months of the program and was published by DNA in April 1987. The two-color brochure which incorporated photos and graphics included a brief description of the facility, test methods, available test support and test scheduling. The brochure was distributed with the DNA Nuclear Survivability newsletter in June of 1987 and has been distributed at meetings/briefings and to all facility visitors and interested parties.

Technical papers, briefings and publications were also used to advertise the facility. Table 5 lists key papers and publications which addressed the dust erosion facility. A DNA technical report (Reference 1) which is to be published concurrent with this final report is designed as a user guide. This report provides a detailed description of the dust erosion facility including performance capabilities, test procedures, pre and post-test support, sample results, and scheduling and planning direction. All pertinent facility upgrades and procedures developed during the course of this program are included.

Table 5. Technical papers, briefings and publications.

| TYPE | MEETING/PUBLICATION | LOCATION | DATE |
|---|---|---|---|
| Paper | DNA Dust Erosion and Particle Impact Damage Conference | Marina del Ray, CA | Nov 1986 |
| Publication | DNA Nuclear Survivability Newsletter | Alexandria, VA | June 1987 |
| Paper | ASTM Transparency Conference | Arlington, TX | Oct 1987 |
| Paper | JOWOG 36, Nuclear Hardening of Aircraft | Farnborough, UK | Oct 1988 |
| Publication | Guide to NWE Simulation Facilities and Techniques (DASIAC Report) | Santa Barbara, CA | 198_ - 1990 |

## 3.2 CUSTOMER SUPPORT.

The DNA Dust Erosion Test Facility is available to DNA sponsored contractors and other government agencies on a no-charge basis. Under these conditions the facility, labor and materials necessary to complete the user's test program are provided as part of this DNA program. For all other users, the facility is provided at no charge; however, charges will be assessed for operating labor and specific test materials. Test schedule priority is given in the following order to programs involving (1) past customers, (2) DNA sponsored programs, (3) other government agencies and (4) other users from industry. All test programs must be approved by DNA.

Facility users were classified as either past customers or new customers. Past customers included all users of the facility prior to the beginning of this program. These users had established requirements and test procedures which had to be maintained to meet their continuing testing needs. All users coming to the facility for the first time during this program were classified as new customers. Support provided new customers was basically the same as for past customers except that more effort was generally required to develop specific test procedures and expand test capabilities. Specific support provide each user group is outline in the following subsections.

### 3.2.1 Past Customer Support.

In order to satisfy the testing needs of past customers, test capabilities developed to meet previous test requirements were maintained during the course of this program. Support provided to past customers included the following:

(1) Test planning support to establish requirements and scheduling,

(2) Maintaining security arrangements when necessary,

(3) Reconfiguring and recalibrating the facility as required to meet previous test conditions, and

(4) Conducting tests, providing pre and post-test analysis support and documenting test results.

Past customer test support accounted for approximately 22% of the facility usage from December 1986 through December 1989. No significant problems were encountered in either scheduling or providing past customer support. Expanded test capabilities were required and developed to meet past customer test needs. These new capabilities included specimen temperature control which was discussed in Section 2.5.3.

### 3.2.2 New Customer Support.

The primary test support effort on this program was directed toward providing new customer test support. New customers included both DNA contractors and other agency/industry users. Test support was provided for a period of three years beginning in December 1986 and extending through December 1989. During this period, the facility was staffed on a half-time basis (i.e. the facility was operational at least half of the month less approximately 20 hrs. for routine maintenance). Specific periods of operation and periods of downtime were scheduled around the facility test load wherever possible. Downtime was used for major repairs, extended maintenance, upgrade installation and test documentation and reporting.

New customer support included the following:

(1) Planning, scheduling and development of test procedures,
(2) Providing test security as required,
(3) Defining specimen configuration and facility interface,
(4) Calibrating and maintaining the facility,
(5) Performing tests,
(6) Reducing and reporting test data, and
(7) Storing and shipping test specimens.

New customer test support accounted for approximately 64% of the facility usage during the three year period of operation. Of the new customer support, approximately 75% was for DNA sponsored programs where tests were conducted for DNA directly or for DNA contractors. Test objectives included (1) erosion rate determination (mass loss measurements) on various coatings and substrates, (2) visibility degradation on transparent materials, (3) parametric study of erosion effects on generic materials and (4) evaluation of dust detection techniques.

## 3.3 UTILIZATION DATA.

The DNA Dust Erosion Test Facility was operated under this program from September 1986 through December 1989, a period of 40 months. Except for the initial three months, the facility was available for customer testing during this entire period. The first three months of operation were devoted to facility checkout, upgrades and calibration. This included the installation and checkout of the LDV particle velocity calibration system as well as the initial velocity calibration mapping. Customer testing was initiated in December 1986 and continued through December 1989.

Utilization data were collected during this three year period of operation. Data consisted of (1) a test log listing each test specimen and each exposure to the dust environment, (2) the number of hours that the facility was in operation and (3) expendable materials used. During the 40 month period, the facility was operated for a total of 2,987 hours or an average of 74.7 hrs/month. This usage is slightly greater than the planned half-time minus 20 hrs per month for routine maintenance. A distribution of operating hours by month is presented in Figure 17. The figure indicates that usage tends to be periodic with usage generally light at the beginning of the calendar year and heavy at the end of the year.

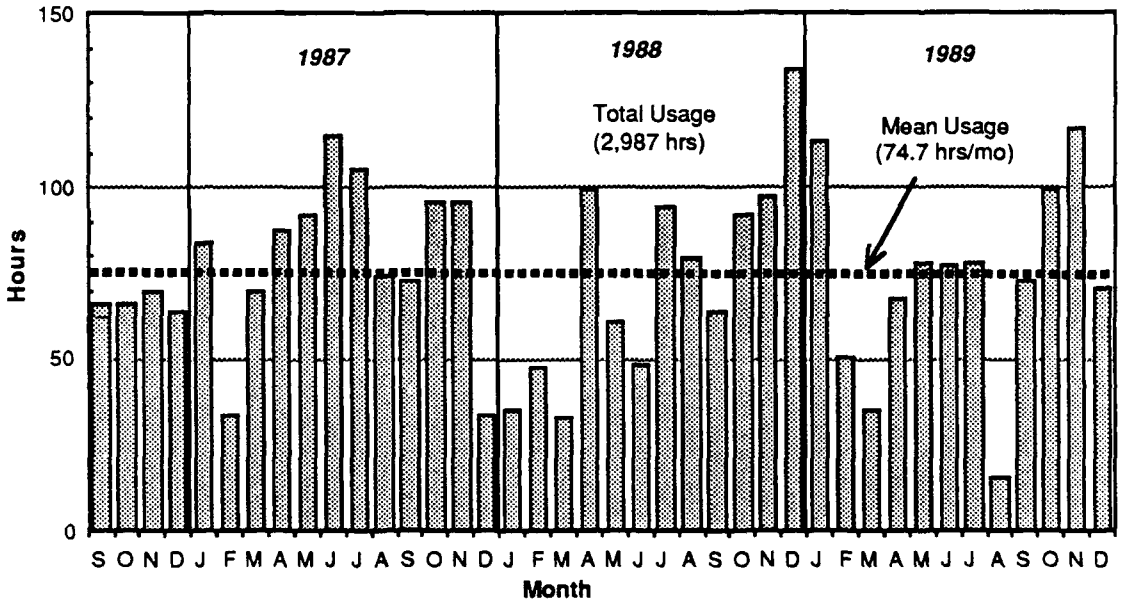


Figure 17. Facility usage by month.

Although not shown on the usage chart, a breakout of the type of usage was as follows; 64% for new customer testing, 22% for past customer testing and 14% for facility calibration and checkout. A review of the test log indicated that over 1500 separate dust exposures were conducted on over 500 specimens (or specimen arrays). The large number of exposures is due to the fact that a significant amount of testing was in conjunction with erosion rate evaluations where each specimen array was exposed to several incremental dust loadings.

# SECTION 4
# SUMMARY AND RECOMMENDATIONS

## 4.1 SUMMARY.

A laboratory scale facility has been established for the purpose of evaluating dust erosion effects of on critical aircraft surfaces and components. The DNA Dust Erosion Test Facility is located at the PDA Engineering laboratory facilities in Santa Ana, California and has been operated by PDA Engineering under DNA sponsorship since September 1986. During this period, the facility has logged approximately 3,000 hours of test time which includes over 1,500 dust exposures involving over 500 test specimen arrays. Test support has been provided to a variety of customers including government agencies, directed contractors and industry.

In addition to testing support provided since September 1986, a number of significant facility upgrades have been installed and new test procedures developed. Upgrades included the relocation of the facility and expansion of the laboratory floor space, the development and installation of a Laser Doppler Velocimeter (LDV) for particle velocity calibration, the expansion of post-test specimen analysis capabilities, extension of critical component service life, enhancement of facility performance capabilities, development of specimen temperature control system, installation of a computer based data acquisition system and the development of test procedures to measure specimen mass loss histories and haze build-up in transparencies.

The upgraded test facility provides a flexible and well-characterized dust environment, excellent low concentration simulation capabilities, high subsonic impact velocities, variable impact angle, specimen temperature control and modest operating costs. The facility design allows key erosion parameters to be varied independently including particle cloud properties (particle size and concentration) and impact conditions (velocity and angle). This make the facility an ideal tool for the parametric evaluation of erosion effects necessary for the assessment of materials hardness and development of response models.

## 4.2 RECOMMENDATIONS.

The improvements incorporated into the dust erosion facility as part of this program have created a flexible multi-user test facility well suited for evaluating dust erosion effects on aircraft materials and components. In order to benefit from this investment, continued operation of the facility is necessary. The consistent usage over the period of this program indicates that a need exists for such a facility.

Although the major upgrades to the facility have been accomplished and no serious operational problems exist, further development is recommended in several areas in order to fully utilize the present capabilities and to meet anticipated needs. These recommendations include the following:

(1) Utilization of the present computer capabilities to automate facility operations. This would include data acquisition and control of facility hardware. Exposure of test specimens would be initiated from the keyboard and controlled by a specific software procedure subject to operator over ride. This offers the potential for more precise timing and exposure controlled than can currently be accomplished in a manual operating mode.

(2) Development of high speed particle flow capability necessary to simulate dust erosion effects at supersonic flight conditions. This would require evaluation of alternate nozzle designs and gas flow systems which could produce sufficient supersonic flow length to accelerate particles beyond Mach 1.

(3) Improved particle flow control to allow testing a very low flow rates (e.g. 0.1 gm/min) necessary to study the damage thresholds for windscreens, sensor windows and other erosion sensitive components. The current particle feed system based on a fluidized bed design cannot achieve flow rates below the present 0.5 gm/min with good stability. Commercial screw drive systems are available which can achieve these very low flow rates at atmospheric conditions. Incorporating this screw drive technology into a pressurized system appears to offer the potential for an extremely accurate and versatile particle flow system.

## SECTION 5
## LIST OF REFERENCES


1. Oeding, R.G., "DNA Dust Erosion Test Facility", PDA Engineering Report No.. TR-1385-03-02 (to be published).

2. Trolinger, J. D., "Laser Instrumentation for Flow Field Diagnostics", AGARD Report AGARD-AG-186, 1977.

3. "Standard Test Method for Haze and Luminous Transmittance of Transparent Plastics", ANSI/ASTM D-1003, 1977.

4. Adler, W. F., "Analytical Modeling of Liquid and Solid Particle Erosion", Air Force Materials Laboratory Report, AFML-TR-73-174, September 1973.

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