

Abstract

Plume Particle Collection and Sizing from Static Firing
of Solid Rocket Motors

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Thermal radiation from the plume of any solid rocket motor, containing aluminum as one of the propellant ingredients, is mainly from the microscopic, hot aluminum oxide particles in the plume. The plume radiation to the base components of the flight vehicle is primarily determined by the plume flowfield properties, the size distribution of the plume particles, and their optical properties. The optimum design of a vehicle base thermal protection system is dependent on the ability to accurately predict this intense thermal radiation using validated theoretical models.

Currently, the design thermal radiation to the base region of the shuttle components from the RSRM plumes is predicted using a simple empirical model (ref. 1) developed based on flight measured data. However, a more advanced reverse monte-carlo method (ref. 2) has been developed in the recent past for the Advanced Solid Rocket Motor (ASRM) program. This model is currently being validated using measured radiation data from flight motors as well as static firing of the full-scale motors at the Thiokol Space Operations Facility at Utah and the 18.3% scaled MNASA motors at NASA/Marshall Space Flight Center. Such validations enable one to gain confidence in this model. Application of this model to the RSRM design thermal radiation environments is expected to improve the current design environments and reduce the thermal protection system (TPS) requirements in the base region of the shuttle.

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One of the major unknowns in the inputs to the theoretical monte-carlo radiation model is the size distribution of the aluminum oxide particles in the plume. In the absence of any experimental results for the plume particle size distribution from the full-scale RSRM, a theoretical distribution is currently used in the model consisting of five equal mass fractions based on a normal distribution about a mass averaged mean diameter, d_{43} (ref. 3). However, radiation predictions made on such a theoretical particle size distribution tend to be conservative compared with measured data. It is widely believed that such conservatism will be reduced if the actual particle size distribution in the plume can be determined experimentally.

Plume particles characterizations have been done extensively in the past for motors of different sizes and an excellent summary has been presented by Hermesen (Ref.4). However, these analyses have been primarily to predict a mean mass averaged diameter, d_{43} , in the nozzle to accurately account for the two phase flow losses in the motor performance calculation and did not include any full-scale motors of the RSRM size. Salita (Ref. 5) employing a corrected version of OD3P code and an improved model of particles collision/coalescence in the nozzle flow has predicted a log normal monomodal particle size distribution for the full scale RSRM motor at the nozzle exit plane.

This article describes a successful effort to collect reasonably clean plume particle samples from the static firing of the flight simulation motor (FSM-4) on March 10, 1994 at the T-24 test bed at the Thiokol space operations facility at Wasatch, Utah as well as three 18.3% scaled MNASA motors tested at NASA/MSFC. Prior attempts to collect plume particles from the full-scale motor firings have been unsuccessful due to the extremely hostile thermal and acoustic environment in the vicinity of the motor nozzle.

A picture and a plumbing schematic of the plume particle collection system are presented in figures 1 and 2. The principle behind this particle collection technique is to launch darts through the plume during the motor firing and collect the plume particle samples on sticky copper tapes mounted at different locations on the dart. The dart system consisted of a launcher with a bank of four accumulators and an electronic control box. The accumulators are loaded with high pressure nitrogen to 800 psi and the darts are launched instantaneously by opening the high flow rate valves using the solenoids. The solenoids are triggered by a time

sequencer in the control box. The control box receives a trigger signal for the dart sequencer from the motor firing sequencer at ignition.

A simple 40-inch long projectile was utilized in MNASA tests to collect the plume particles by hurling it through the plume with the high pressure nitrogen launcher. Two different types of darts were launched in the FSM-4 test. One of them was a control dart and was basically a scaled version of the dart employed in the MNASA program. However, the full-scale RSRM motor is test fired horizontally compared to the vertical firing of the MNASA motor. A large recirculating cloud is created when the plume impacts the hill about 800 feet aft of the nozzle. The copper tapes affixed to control darts would be exposed to the dusty environment after their traverse through the plume and upon ground impact and could possibly result in severe contamination of the plume sample. Consequently, a new dart as shown in figure 3 was designed for the full-scale test to minimize the contamination of the samples collected by the copper tapes. A cylindrical sleeve, activated by a plate-pulley mechanism attached to a 240 feet long tether, slid over the sample area to protect the sample. The tail end of the tether was attached to a hook on the launcher and the head end to the plate/pulley mechanism on the dart.

Scanning Electron Microscope (SEM) analysis of the copper tapes recovered from the darts of both the MNASA and FSM-4 tests revealed a large collection of mostly spherical plume particles as shown in figure 4. Majority of the particles had a smooth surface and appeared dark brown under an optical microscope. The diameter of the particles varied from one micron to 40 microns (μm). Electron microprobe analysis of the copper tapes revealed the composition of these particles to be primarily Al_2O_3 except the very large particles in the FSM-4 test. These large particles were significantly contaminated with calcium and silicon. The size distribution for a given sample is determined by measuring individual particles on enlarged SEM photographs using a scanner and a MacIntosh personal computer.

Currently, the d_{43} for solid rocket motor plume Al_2O_3 particles at the nozzle exit plane is calculated using the industry standard Hermesen's correlation (Ref. 4) given by

$$d_{43} = 3.6304 \cdot D_t^{0.2932} [1.0 - \exp(-0.0008163 \times P_c t)] \text{ mm}$$

where D_t is the throat diameter in inches (53.86 inches for the RSRM motor), x_c is the Al_2O_3 concentration inside the chamber in gm-mole/100 gm (0.262 for the RSRM propellant formulation), P_c is the chamber pressure in psia (880 psi at 12.3 seconds) and t is the average residence time in the chamber in msec (estimated to be about 350 msec for the RSRM motor). The Hermesen d_{43} for the RSRM motor is calculated to be 11.68 μm and is primarily dictated by the throat diameter.

Figure 5 shows the cumulative mass distribution for the plume particle sample collected by the tethered dart in the FSM-4 test. In this plot, all particles above 23 microns were deleted due to the results of the electron microprobe analysis of the particles. The test derived mean mass averaged diameter, d_{43} , is calculated to be 11.2 μm . Also, shown in this figure is the best fit of the data; a monomodal log-normal distribution with a standard deviation of 0.13. This distribution agrees extremely well with that predicted by Salita (Ref.5) at the exit plane of the full-scale RSRM using the OD3P code.

Figure 6 shows the cumulative mass fraction plotted against the particle size for one of the MNASA samples analyzed. Also, shown in the figure is the best fit of the data, a log-normal distribution with a standard deviation of 0.15. In fact, the size distribution of each MNASA sample analyzed is best curve fitted by a log-normal monomodal distribution with the standard deviation varying from 0.13 to 0.17. These results indicate that a monomodal log-normal distribution about a mean mass averaged diameter d_{43} with a standard deviation of 0.13 - 0.17 best describes the plume particle size distribution in large scale solid rocket motors.

It has been demonstrated that the dart system developed in-house for the MNASA program can be adapted for collecting reasonably clean plume particle samples from static firings of the full-scale RSRM motor. This is the first time that clean plume particle samples have been obtained during the static firing of such large motors. The mean mass averaged diameter, d_{43} , measured from these samples agree with that calculated using the industry standard Hermesen's correlation within the standard deviation of the correlation. The cumulative mass fraction of the aluminum oxide plume particles as a function of the particle diameter measured from these large scale motors agree well with the theoretically predicted distribution by Salita and is best represented by a monomodal log-normal distribution with a standard deviation of 0.13 - 0.17.

References

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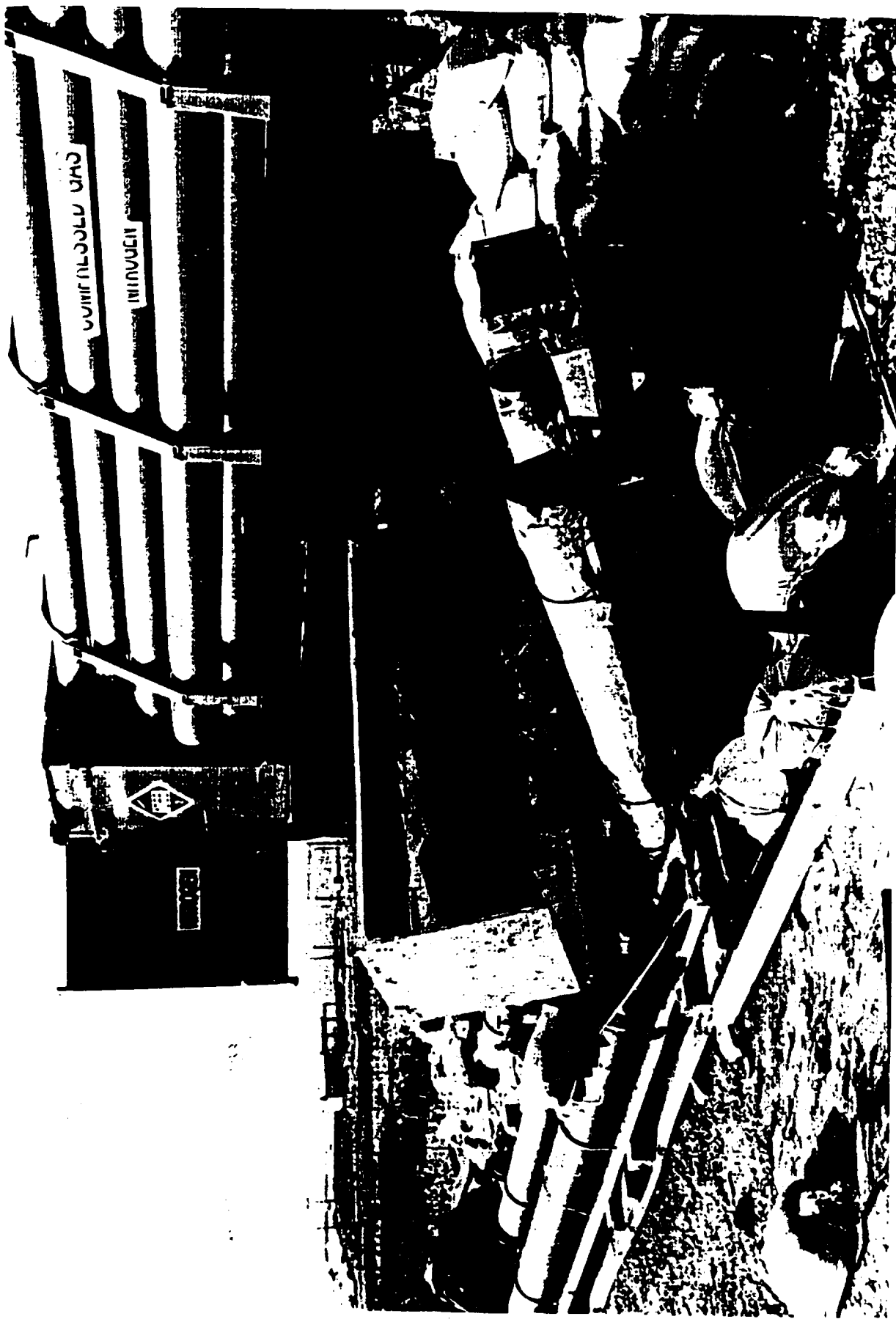


Figure 1 Plume Particle Collection System Employed in the FSM-4 Test. The darts are located inside the Cylindrical Silver tape insulated Housing to protect them from dirt and heat during the motor burn.

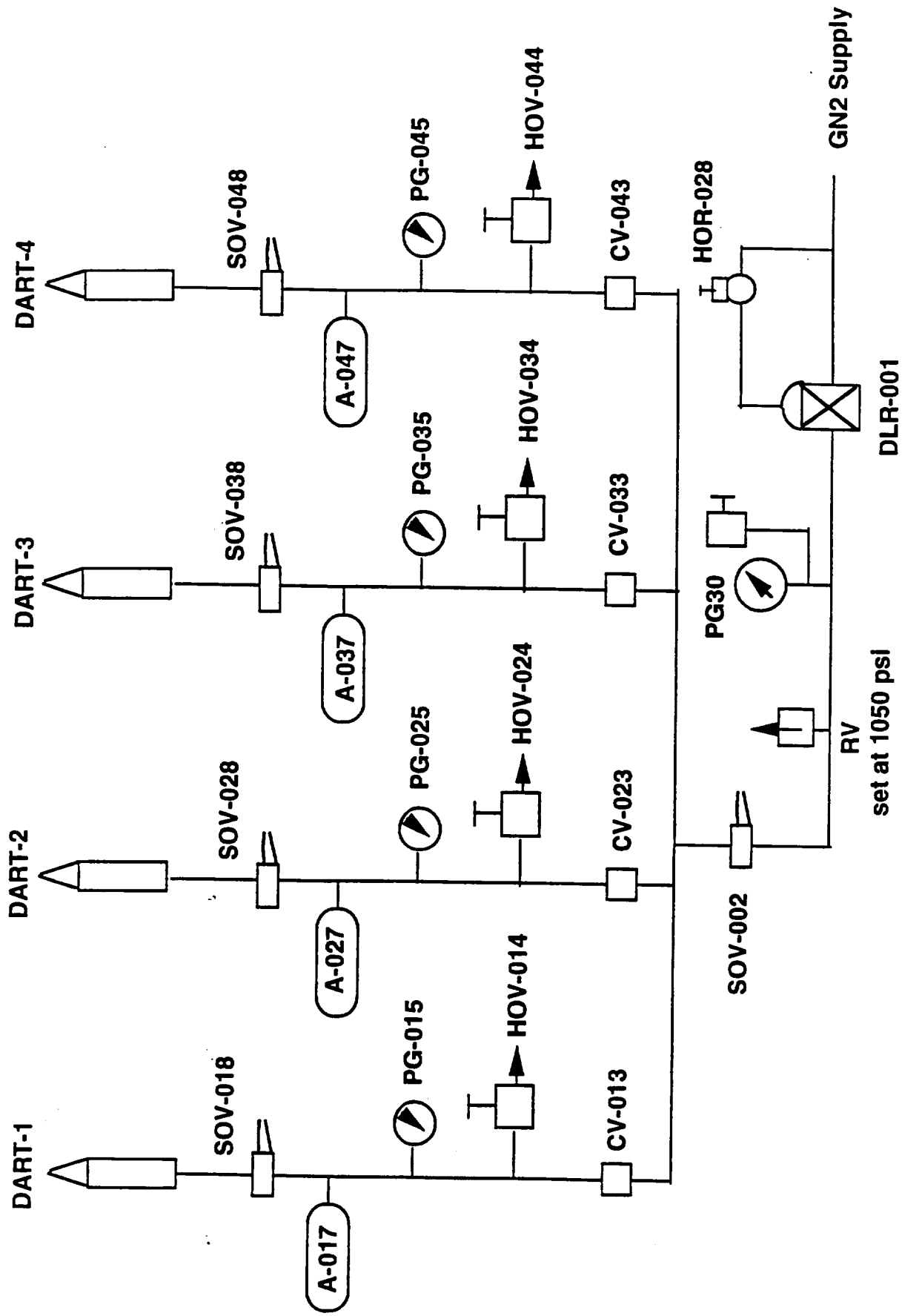


Figure 2. High Pressure Plumbing Schematic for the Dart System

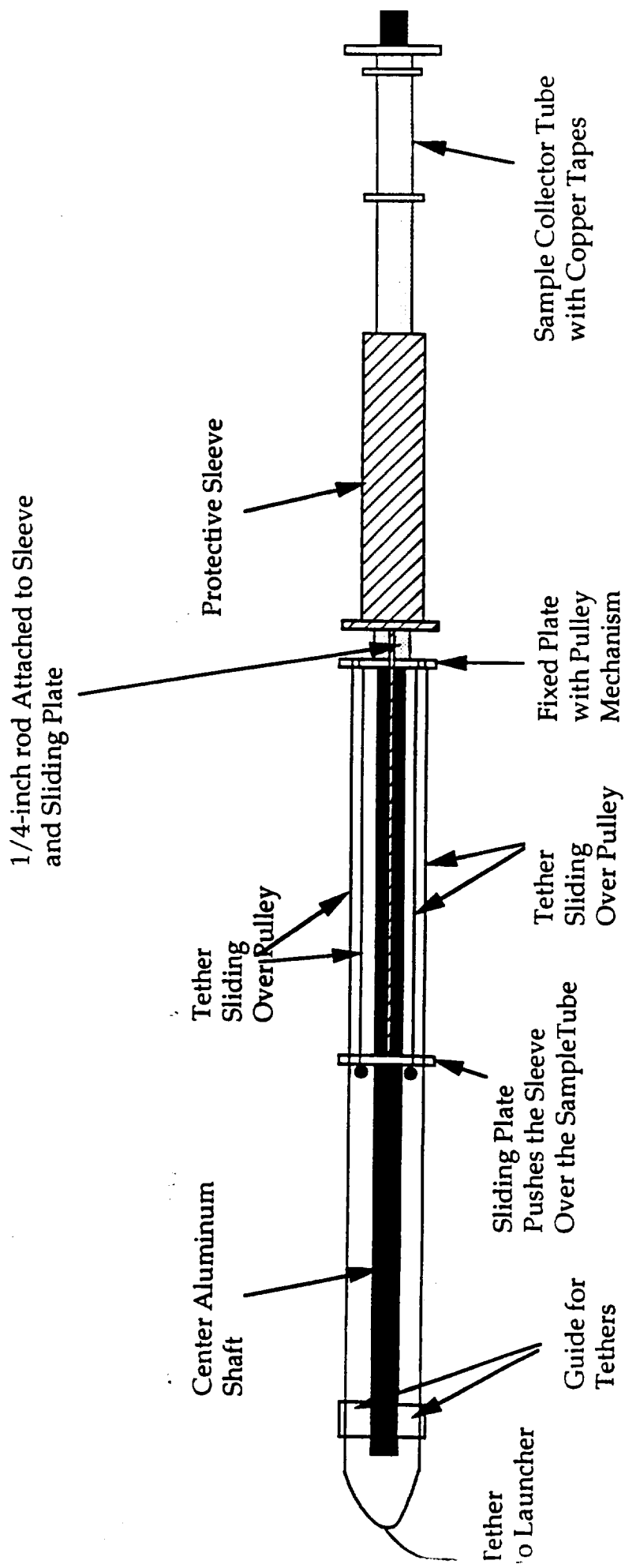
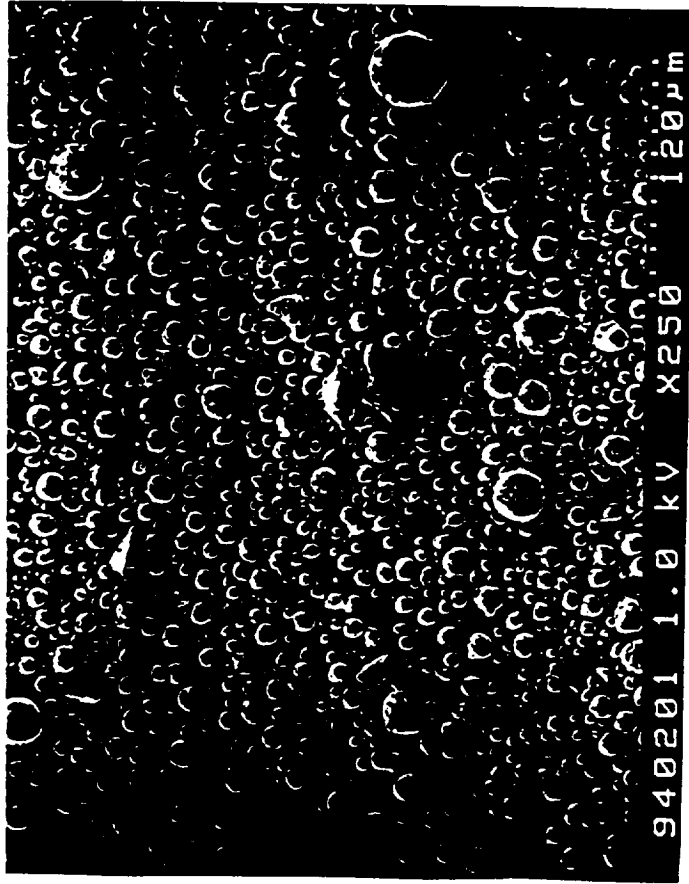
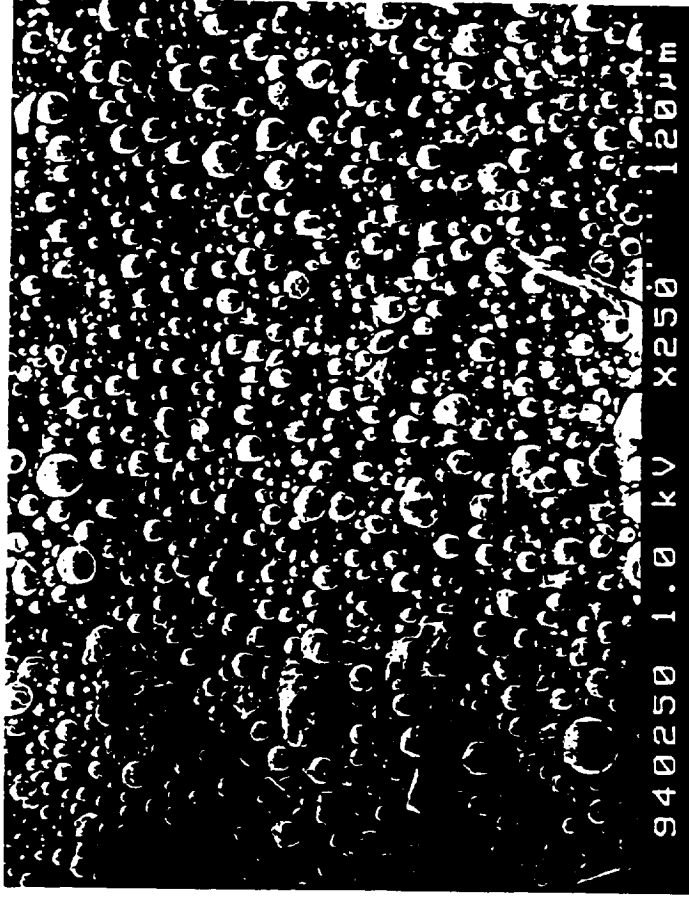


Figure 3. Tethered Dart Employed in the FSM-4 Test to Collect Reasonably Clean Plume Aluminum Oxide Particle Samples



Tethered Dart, t (launch) =12.3 sec after Ignition



Control Dart, t (launch) =68.3 sec after Ignition

Figure 4 Typical SEM Micro Graphs of the Plume Aluminum Oxide Particle Samples Collected by the Copper Tapes on the Darts Launched Through the Plume During the FSM-4 Test.

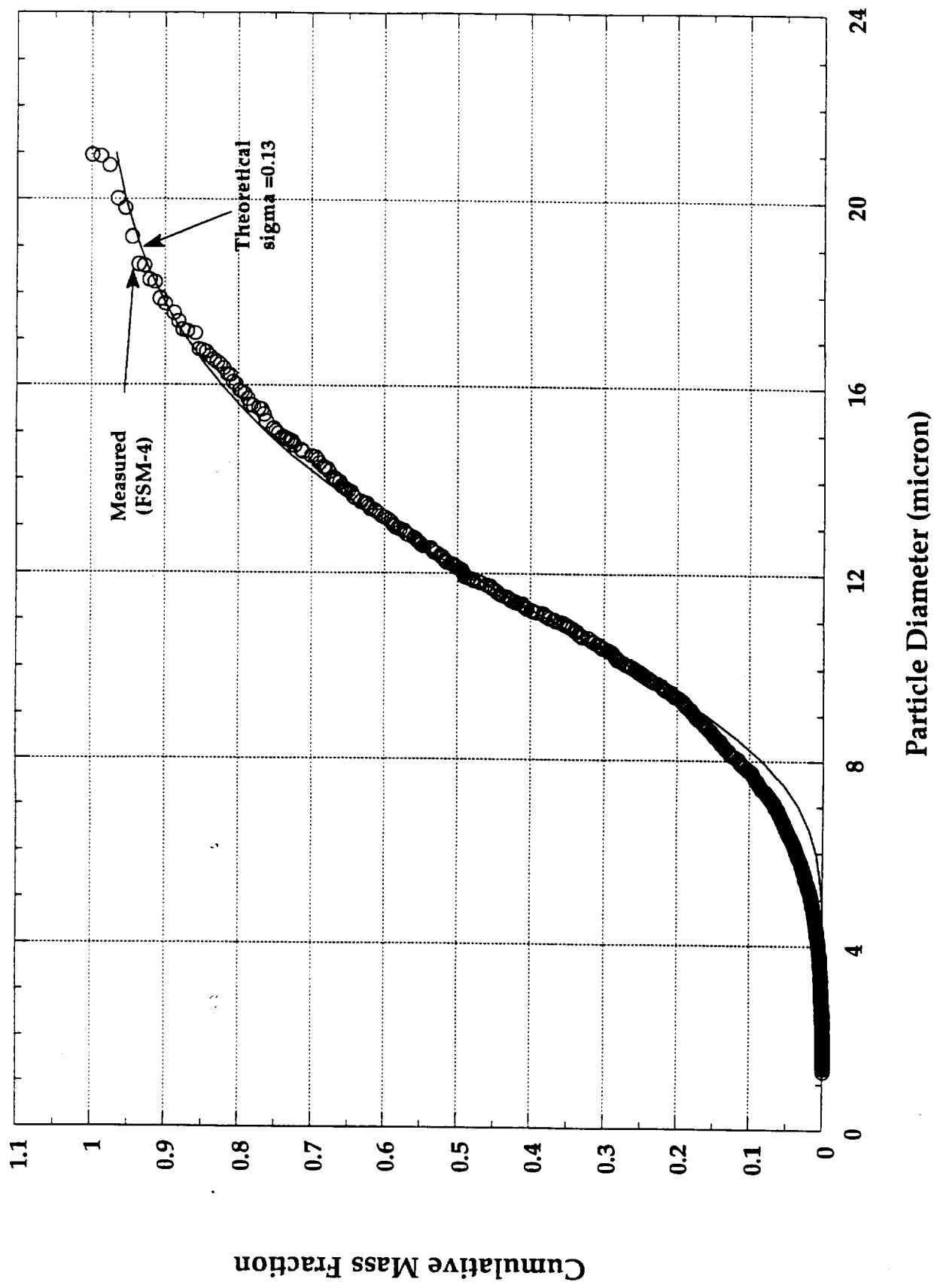


Figure 5. Cumulative Mass Fraction of all Plume Particles Below 23 micron Measured from Dart 1. The Best Fit of the Measured Data is Given By a Monomodal Log-normal Curve with a Standard Deviation of 0.13

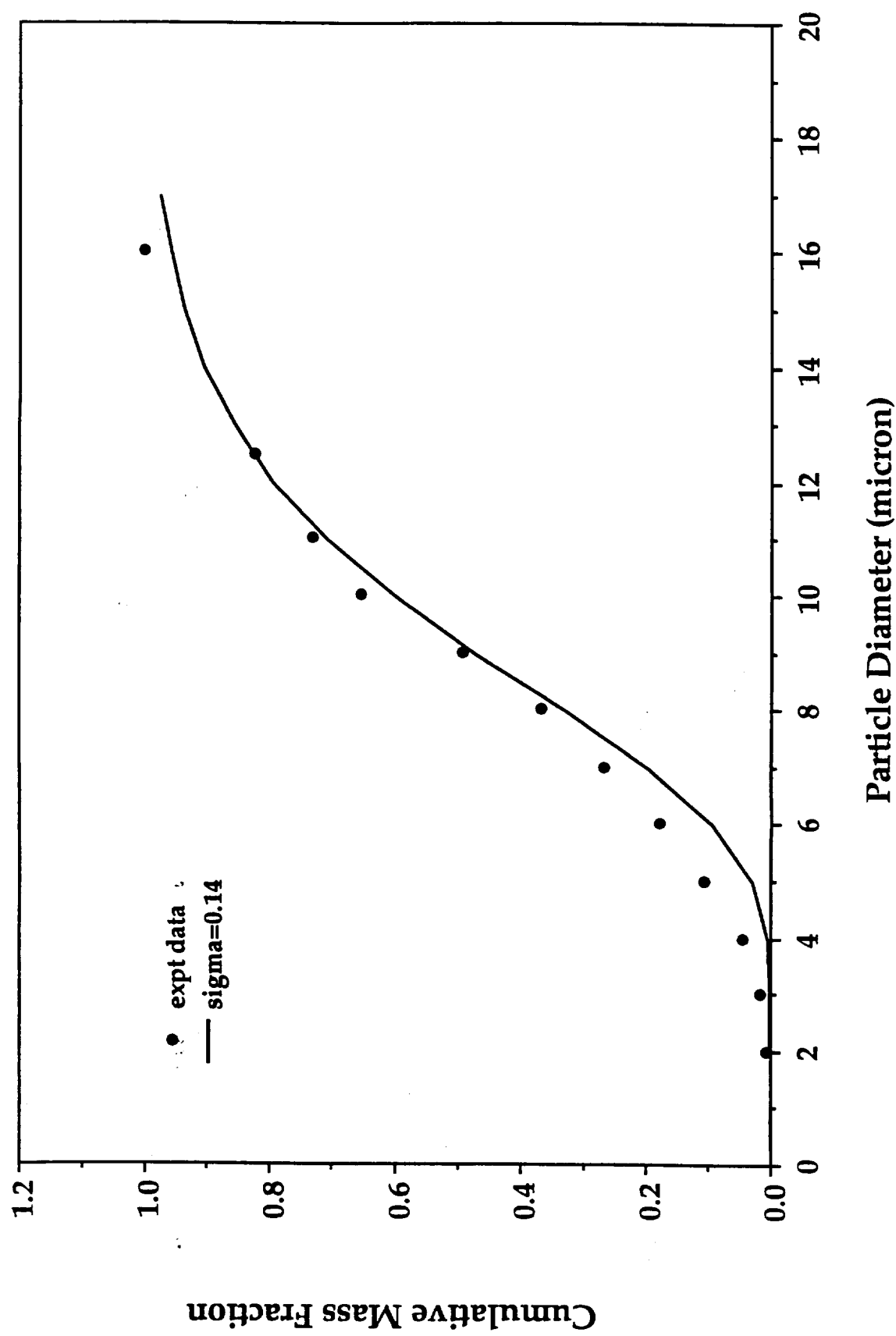


Figure 6. Cumulative Mass Fraction plotted Against the Particle Size for the Plume Particles Sample Collected From Dart 1 of MNASA 9 Test