A NEW SHOCK-TUBE FACILITY FOR STUDYING COMBUSTION PHENOMENA IN MIXTURES CONTAINING CONDENSED SPECIES

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ABSTRACT
Two shock tubes at The Aerospace Corporation have been refurbished for the study of fundamental processes related to the formation and reaction of solid and liquid aerosols at elevated temperatures. One shock tube is intended for the study of powdered aerosols and other condensed-phase species, while the second tube is designed for the study of gas-phase reactants. Recent upgrades and additions include a new high-vacuum system, an optimized velocity-detection scheme, a computer-based data acquisition system, and new techniques and procedures for handling experiments involving gas/powder mixtures. Diagnostic techniques include laser extinction for particle volume fraction and size, optical pyrometry for particle temperature, laser-light scattering for particle size and number density, temporally and spectrally resolved emission from gas-phase species, and a Scanning Mobility Particle Sizer. Details on the setup and operation of the shock tube and diagnostics for the study of heterogeneous combustion processes are given, and sample results are presented.

INTRODUCTION
Condensed-phase species are present in many combustion applications and reacting flow fields including, for example, solid-propellant particles, soot particles formed within the reaction zone, and liquid-propellant droplets. The general topic of heterogeneous combustion involving gas/aerosol mixtures covers a wide range of particle sizes from a few nanometers to several millimeters. In most cases, the volume fraction of condensed species within the gas mixture is relatively low. One application of present interest is the flame synthesis of materials, wherein condensed-phase species are the desired product of a gaseous combustion process (Wooldridge, 1998). Other topical applications include the study of soot formation from hydrocarbon flames (Brown et al., 1998) and the ignition of powdered propellants (Roberts et al., 1993).

For many years, shock tubes have been utilized for the study of heterogeneous combustion processes and the propagation of shock and detonation waves through aerosol-laden gas mixtures. Shock tubes are useful for such measurements because the shock wave can be used to heat the mixture nearly instantaneously to temperatures on the order of 1000 to 4000 K (or higher) in a controlled environment. However, shock-tube measurements in mixtures containing condensed species are generally more difficult to perform than similar measurements in purely gas-phase mixtures for several reasons, including nonideal gas-dynamic effects, optical interference from the particles, and mixture nonuniformities. A comprehensive review on the use of shock tubes for studying heterogeneous mixtures is provided by Petersen (2000a). In general, shock-tube applications for such measurements fall into one of six basic categories: 1) particle heating and vaporization; 2) particle formation from the gas phase; 3) gas/particle mixture aerodynamics; 4) droplet breakup; 5) spray combustion; and 6) solid-propellant combustion. A related approach is the use of shock tubes and similar apparatus for the study of detonation-wave propagation in gas/aerosol mixtures.

At The Aerospace Corporation, the current approach is to use a shock tube to study the fundamental processes related to the combustion synthesis of materials and the reaction of advanced propellants. Present and future experiments in the Aerospace facility include the measurement of soot formation, the formation of Ti- and Si-based condensed species from...
gaseous and liquid precursors, the decomposition and ignition of powdered metals and metallic oxides, the application and development of optical diagnostics for high-temperature gas/particle mixtures, and the study of the chemical kinetics and spectroscopy of related gas-phase species. This paper presents an overview of the experimental apparatus and newly implemented measurement procedures. A summary of the current and planned diagnostic techniques and some typical experimental results are given.

**NOMENCLATURE**

\[
\begin{align*}
C_1 & = 0.595522 \times 10^2 \text{ W} \mu \text{m}^2/\text{m}^2 \cdot \text{sr} \\
C_2 & = 14,388 \text{ um-K} \\
I & = \text{Radiation intensity (W/um-m^2-sr)} \\
I_0 & = \text{Incident radiation intensity} \\
K_x & = \text{Optical extinction coefficient, cm}^{-1} \\
L & = \text{Optical pathlength} \\
N & = \text{Number density (molecules/cm}^3\text{)} \\
P_t & = \text{Shock-tube test section fill pressure} \\
T & = \text{Temperature} \\
Y & = \text{Soot yield, } [c]/[c]_{\text{total}} \\
[c] & = \text{Number density of carbon particles (#/cm}^3\text{)} \\
[c]_{\text{total}} & = \text{Total number density of c atoms (#/cm}^3\text{)} \\
\beta & = \text{Correction for detector solid-angle and area} \\
\epsilon_\lambda & = \text{Wavelength-dependent emissivity} \\
\phi & = \text{Correction for } \lambda \text{ sensitivity of detector} \\
\eta & = \text{Ideal intensity ratio, } I_1/I_2 \\
\eta' & = \text{Measured intensity ratio, } \eta' = \beta \phi \eta \\
\lambda & = \text{Wavelength of light} \\
\sigma_\lambda & = \text{Extinction cross section (cm}^2\text{)} \\
\psi & = \text{Correction factor for filter transmission}
\end{align*}
\]

**EXPERIMENTAL APPARATUS**

The experimental setup consists of the shock-tube hardware, the vacuum system, and the velocity-detection electronics. Figure 1 provides a layout of the facility and a schematic diagram of the vacuum and gas-handling systems. Each of the main components is described in the following paragraphs.

**Shock-Tube Facility**

As shown in Fig. 1, the facility has two horizontally mounted shock tubes that are identical in size, design, and operation. The shock tubes are situated with one tube approximately 1 m from the floor; the second tube is mounted parallel to but above the lower one, approximately 2 m from the floor. In general, the primary shock-tube hardware is the same as that used in earlier chemical kinetics experiments described, for example, in Bott and Jacobs (1969) and Bott and Cohen (1971, 1984). However, only the lower tube was employed for these earlier experiments, and the second, upper shock tube has until now never been utilized. Everything else on the facility such as the electronics, diagnostics, and vacuum system is new. Provided herein are details on the shock-tube hardware and the recent facility upgrades.

![Figure 1. Aerospace Shock Tube Facility for gas-phase and heterogeneous combustion measurements.](image-url)
Each shock tube is pressure-driven with helium and has the option of using either a single or a double diaphragm in the breech-loaded assembly (Fig. 1). Pre-scored aluminum diaphragms of thickness ranging from 2 to 10 mm are employed, as are Lexan diaphragms ranging in thickness from 0.4 to 2 mm. A recently designed cutter located slightly downstream aids the bursting of the Lexan diaphragms. The driver section is 3.5 m (10 ft) long and has an internal diameter of 7.62 cm (3 in). The driven section has a length of approximately 10.7 m (35 ft) with an internal diameter of 16.2 cm (6.38 in). A novel high-pressure flange design is employed in the driven part and allows for the easy removal and addition of the segmented tube section(s) near the downstream end.

Optical and instrumentation access to the shock-heated mixture is provided by ports located at 2.36-cm (6-in) intervals on the downstream section (Fig. 1). The distance between the furthest downstream port and the endwall can be varied from 1 cm up to 7.6 cm by using different end caps. In the present configuration, the distance from the reflected-shock test port to the endwall in the lower tube is 5.84 cm (2.3 in). The distance from the test port to the endwall in the upper tube is 1 cm.

Two MKS Baratron model PDR-C-1B pressure transducers with 0-10 and 0-1000 torr pressure ranges are used to measure the driven-section fill pressure (Pf). Post-shock test pressures are monitored by a Kistler 603B1 piezoelectric pressure transducer using a Kistler 5010 amplifier/signal conditioner box. We found that this transducer is sensitive to heat transfer from the shocked gas, causing an artificial decay in the pressure signal with time. This problem was eliminated by placing a single layer of standard black electrical tape on the surface of the sensor. Each shock tube is equipped with a computer-based data acquisition unit consisting of a Pentium computer and two computer oscilloscope boards from Gage Applied Sciences (one CS512 pair and one CS1602 pair). Each data acquisition unit has four channels (2 per board) with a speed of at least 5 MHz per channel and 12-bit resolution. Additional data-acquisition capability is available from a 2-channel, 8-bit digital oscilloscope (Tektronix TDS210).

Presently, the upper shock tube is primarily intended for clean combustion-chemistry measurements using gas-phase mixtures. These experiments include traditional reaction-rate and ignition-time measurements as well as measurements related to gas-phase kinetics important in the early stages of the combustion synthesis of glasses and other materials. The lower shock tube is used for heterogeneous experiments involving condensed species (solid or liquid). Carbon-based soot-formation experiments are also performed in this shock tube (Petersen, 2000b). Further details are provided in the appropriate sections below. Additionally, the lower shock tube can also be used as a shock tunnel by adding a test section and connecting the exhaust to an evacuated, 14.7-m³ dump tank as in Petersen and Welle (1999).

Vacuum System

A new vacuum system has been implemented on the Aerospace Shock Tube Facility. This system allows for the operation and evacuation of both shock tubes to pressures of 10⁻⁶ torr or better before each experiment. In addition to bringing the second tube on line, the new system design: 1) increased vacuum quality, 2) improved dependability, 3) secured modular construction, and 4) incorporated flexibility and the independent, simultaneous use of both shock tubes. Figure 1 contains a schematic of the vacuum system.

The new system was built around two Leybold TMP1000C (1000 L/s) turbomolecular pumps, one for each tube. A Leybold D16B (450 L/min) roughing pump backs the upper turbomolecular pump, and a Leybold D16A (400 L/min) roughing pump backs the lower turbopump. An interface gate valve connects the lower vacuum system to the upper system so that either turbomolecular pump can be used to evacuate either shock tube if needed. The upper and lower vacuum systems also share a large-capacity Kinney roughing pump with the requisite isolation and interface plumbing. Not shown in Fig. 1 is additional plumbing that allows the primary Kinney roughing pump to serve as the backing pump for either turbomolecular pump if the need for such a configuration were to arise.

Velocity Detection

Measurement of the incident-shock velocity is performed using pressure sensors to detect the arrival of the shock wave and time-interval counters to clock the speed of the wave. Five PCB P113A piezoelectric pressure transducers are used to detect the arrival of the shock wave; specially manufactured charge-to-voltage amplifiers are utilized to enhance the sub-microsecond rise-time characteristics of the transducers. Signal conditioning and amplification come from a PCB 482A18 amplifier/signal conditioner box, and the outputs are sent to the gate channels of four Fluke PM6666 programmable timer/counters. The total timer error for the present configuration comes from four sources: trigger error, time-base error, systematic error, and resolution error. The resulting total trigger error was determined to be 400 ns per velocity interval.

These timer error estimates were part of a larger effort to optimize the placement and settings of the velocity-detection transducers and time-interval counters (Abbey and Petersen, 2001). The study took into account the error sources due to uncertainties in the transducer positions, the transducer calibration, the trigger level of the counters, and the estimated precision of the counter/timers. The analysis also considered the impact on the incident-shock axial velocity profile as determined from the four velocity measurements, since this (usually linear) profile is extrapolated to the endwall to determine the incident- and reflected-shock velocities there. As a result of the study, the best spacing for the transducers is approximately 4.72 cm (12 in) apart, and it was determined that the counter trigger level should be set as low as possible (i.e., to trigger early on the incident-shock pressure increase). Further details can be found in Abbey and Petersen (2001).
At a shock Mach number giving a reflected-shock test temperature of 2000 K, the uncertainty in the measurement of $T_S$ is estimated to be less than 8 K for the present configuration. At 3000 K, the uncertainty is near 15 K. Typical attenuation rates for both shock tubes are near or below 1%/m at the endwall. The shock-tube gas conditions are determined from the incident-shock velocity using the traditional one-dimensional shock relations and the Sandia thermodynamic database.

**EXPERIMENTAL TECHNIQUE**

In most aspects, the shock-tube facility operates in the traditional manner, particularly the upper shock tube since it is intended for gas-phase chemistry measurements. However, the lower shock tube is used for heterogeneous measurements where a solid-phase powder is mixed with the shock-tube driven gas. Future heterogeneous tests will include endwall injection of liquid precursors and condensed-species formation from gas-phase reactants. The heterogeneous application involving gas/powder mixtures is the primary focus of this section and the remainder of this paper.

Over the past four decades, several techniques have been utilized to uniformly disperse a solid powder into the driven section of a shock tube. A thorough review of these techniques is provided in Petersen (2000a). Among the most popular methods are: 1) those which utilize the induced gas flow behind the incident shock wave to disperse a sample of powder placed within the shock tube; 2) those which premix the powder with the gas and quickly fill the shock tube a few seconds prior to running a test; and, 3) those which employ a steady flow system that blows the gas/particle mixture through the test section prior to an experiment.

The technique chosen for the present work is one that involves incident-shock dispersion of a powder sample. This method was selected for the first experiments for several reasons, including its ease of use, short setup time, and reasonably established dispersion characteristics (Seeker et al., 1980). Figure 2 presents a conceptual view of the powder-dispersion technique. A sample of the powder is placed in the center of a thin (3-mm), steel plate that spans the shock-tube internal diameter. This plate is located 15.2 cm (6 in) upstream of the primary test port and, subsequently, 21.0 cm upstream of the endwall. As seen in Fig. 2, the relative locations of the powder sample, endwall, and test port are critical to the timing of the experiment. The particles accelerate nearly instantaneously to the flow speed behind the incident shock wave and must reach the test section before the reflected shock wave arrives.

Although the present dispersion method is relatively simple to employ, inevitable spatial and temporal nonuniformities exist in the gas/particle mixture due to the nonideal nature of the mixing. At the time of this writing, alternative methods are being considered for combining a solid powder with the shock-tube test-gas mixture (Traum and Petersen, 2001).

**MEASUREMENT TECHNIQUES**

Several non-intrusive optical diagnostic techniques are either currently employed or are being set up for making measurements in shock-heated gas/particle mixtures. Figure 3 details the diagnostics currently in use on the shock-tube facility. Among these are 2-color pyrometry, temporally resolved emission at a single wavelength, multi-wavelength emission using a spectrometer, and laser extinction. An additional particle-sensing diagnostic based on laser-light scattering is presently under development. Each of these techniques is an established method for making measurements in heterogeneous reacting flows and is briefly described below in the context of the present shock-tube application. Also presented is a separate system for measuring the particle size distribution of powder samples. Representative results are provided as well.

**Two-Color Pyrometry**

One way to determine the average particle surface temperature and, therefore, infer the surrounding gas temperature is to monitor the emitted radiation from the particles at multiple wavelengths. Similar techniques have been employed in other shock-tube experiments containing particles (Nettleton and Stirling, 1971; Seeker et al., 1980). The details of the present procedure for inferring the particle temperature from the particle radiation is provided as follows. From Planck's radiation law, the gray-body radiation intensity is related to the blackbody intensity by the emissivity, $\varepsilon_A$ (Siegel and Howell, 1992):
If the radiation intensity is monitored at two different wavelengths, one can take the ratio of the two intensities. Using Eqn. 1, this ratio gives

\[ \frac{I_{\lambda_1}}{I_{\lambda_2}} = \frac{2\varepsilon_{\lambda_1} C_1}{\lambda^5 \left( e^{C_1/\lambda T} - 1 \right) } \]

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\[ \frac{I_{\lambda_1}}{I_{\lambda_2}} = \frac{e_{\lambda_1} \left( \frac{\lambda_2}{\lambda_1} \right)^5 \left( e^{C_1/\lambda_2 T} - 1 \right) }{e_{\lambda_2} \left( \frac{\lambda_2}{\lambda_1} \right)^5 \left( e^{C_1/\lambda_1 T} - 1 \right) } \]

However, the assumption in Eqn. 2 is that the detection area, solid angle, and detector sensitivity are the same for both intensity measurements. The actual measurement includes differences in these parameters, so Eqn. 2 is modified by a factor \( \beta \) that accounts for differences in solid angle and detection area, a factor \( \phi \) that accounts for differences in detector sensitivity with wavelength, and a factor \( \psi \) that accounts for differences in the transmission of the narrow-band filters, or:

\[ \eta' = \beta \phi \psi = \frac{I_{\lambda_1}/I_{\lambda_2}}{\text{meas}} \]

For a wide range of wavelengths and temperatures, the approximation that \( \exp(C_1/\lambda T) - 1 = \exp(C_1/\lambda T) \) holds for \( \lambda T < 3000 \mu\text{m-K} \). Invoking this approximation in conjunction with Eqn. 3, the average particle temperature can be solved from Eqn. 2:

\[ T = \frac{C_2 \left( 1/\lambda_2 - 1/\lambda_1 \right) }{\ln \left( \frac{\eta' \beta \phi \psi (e_{\lambda_2} / e_{\lambda_1}) (\lambda_1 / \lambda_2)^5}{} \right) } \]

Figure 3 shows the optical configuration for measuring the emission at two different wavelengths. The emitted light from the center of the shock tube is focused via a parabolic mirror onto two different detectors. Mirrors and beamsplitters are used to steer the light. Although the path lengths and detectors are designed to be identical, any actual differences are built into the factor \( \beta \), which is determined prior to an experimental series by performing an experiment with \( \lambda_1 = \lambda_2 \) and invoking Eqn. 3. Wavelength discrimination is obtained by narrow-band (10-nm FWHM) optical filters placed in front of each detector. If the emissivity is not known for the particle under investigation as a function of wavelength and temperature (which is often the case), the usual assumption is made that the emissivities are equal. This approximation is valid when \( \lambda_1 \) and \( \lambda_2 \) are close in value. Similar arguments can be made for the correction factor \( \phi \) when the detector sensitivity as a function of wavelength is not known.

When the emitted radiation is in the visible or ultraviolet, the emission detectors in Fig. 3 consist of photomultiplier tubes (PMTs). The PMT detectors are either 1P21 or 1P28 tubes from Hamamatsu mounted in homemade housings, powered by a Hamamatsu C3830 HV power supply. Great care was taken to optimize the signal-to-noise (S/N) ratio, time response (< 2 \( \mu \text{s} \)), and linearity of these PMT detectors (Rickard and Petersen, 2001). When the emitted radiation is in the infrared, a pair of Judson InSb detectors, model J10D-M204-R01M-60, with matched amplifiers (model PA-9), a 1-mm element, and a 900-kHz bandwidth are employed.

**Time-Resolved Emission**

While particle emission can lead to the average particle temperature, important information can also be obtained from monitoring the time-dependent emission from essential gas-phase species. Since the total emission is proportional to the number density of the emitting molecules, the emission time histories are an indication of when a species is formed or depleted and how much is present. Discrimination between species can be obtained by monitoring the emission at wavelengths corresponding to characteristic electronic or rotational-vibrational transition.

In most respects, the gas-phase emission measurements are performed with the Fig. 3 setup using the equipment described.
average particle diameter is much smaller than the wavelength of the light \( d \ll \lambda \), the Rayleigh approximation to the Mie theory can be applied (Lester et al., 1975; Kellerer et al., 1996).

By utilizing two wavelengths simultaneously, both the particle size and number density can be measured via the dispersion quotient method (Wittig et al., 1981).

The present setup, shown in Fig. 3, utilizes two HeNe laser beams of different wavelength (633, 1152 nm) as in an earlier study on soot formation (Petersen, 2000b). Photodiode detectors are used to measure the incident and transmitted light. Detectors employed for this purpose include the New Focus 2031 and/or 2032 and the Electro-Optics Technology, Inc. (EOT) ET-2040 Si-photodiode models for the uv and visible laser wavelengths; the ir wavelengths are monitored with InGaAs detectors from EOT, model ET-3020. The differential extinction signals are obtained using an SRS SR560 differential preamplifier.

Spectrometer

Spectrally resolved information can also be obtained from the gas-phase species emission by collecting the radiation with a spectrometer. Light emitted from the gas/particle reaction zone is taken from the endwall of the shock tube and directed onto the collimating mirror of the spectrometer (Fig. 3). The present spectrometer is a 1-meter GCA/McPherson model 2051. The grating is replaceable and is chosen to optimize the wavelength range/species of interest. In general, the light is collected by a ccd camera, the output of which returns an integrated signal that corresponds to the total light collected for the entire experiment. The camera employed is either a Princeton Instruments liquid-N\(_2\) cooled 298x1151 array or a newer Princeton Instrument/Roper Scientific IMAX512 with a uv-sensitive, 512x512 array. The later camera is intensified and controlled by a ST-133 DMA controller and SRS DG535 digital delay generator, so some discrimination can be made as to the time interval the camera records data by controlling the intensifier gate.

Presented in Fig. 4 is a typical emission measurement using the spectrometer diagnostic in a TiO\(_2\) decomposition experiment at a reflected-shock temperature of 4440 K and pressure of 0.5 atm. The key intermediate species TiO was being monitored in this experiment, so the grating was chosen to coincide with prominent features of the TiO C-X spectroscopic transition near 330 nm.

Laser Extinction

Another established method for monitoring the presence of particles is laser extinction. By passing a laser beam through a gas/particle mixture, the ratio of the transmitted to incident radiation is related to the average number density of the particles and the optical characteristics of the particles via the Bouger-Lambert law (Siegel and Howell, 1992):

\[
\frac{I}{I_0} = \exp(-K_c L) = \exp(-N \sigma_c L)
\]

(5)

If the extinction properties of the particles are known at the wavelength and temperature of the experiment, the volume fraction of the particles can be measured as a function of time. Typically, Mie theory is applied in the calculations, and if the average particle diameter is much smaller than the wavelength of the light \( d \ll \lambda \), the Rayleigh approximation to the Mie theory can be applied (Lester et al., 1975; Kellerer et al., 1996).

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Figure 4. Sample spectrometer data for TiO C-X emission. Test conditions: TiO\(_2\) powder in Argon; 4440 K, 0.5 atm.

Figure 5 presents a representative laser extinction measurement of soot formation in a fuel-rich toluene/O\(_2\)/Ar mixture (Petersen, 2000b). The results are displayed in the form of the soot yield, \( Y \), as a function of time. Using Eqn. 5, the yield was calculated from the extinction measurement via

\[
Y = \frac{[c]}{[c]_{total}} = \frac{\ln(I_0/I)}{\sigma_c L[c]_{total}}
\]

(6)
The value used for the extinction cross section was \( \sigma_e = 6.6 \times 10^{-19} \text{ cm}^2 \) per the data of Rawlins et al. (1984). The Fig. 5 extinction measurement was obtained using only the 633-nm laser wavelength.

![Graph showing soot yield vs. time](Image)

**Figure 5.** Laser extinction measurement of the soot yield in a 0.67\% C\(_6\)H\(_6\)/1.18\% O\(_2\)/Ar mixture. Fuel/O\(_2\) equivalence ratio = 5.09; 1850 K, 1.5 atm; \( \lambda = 633 \text{ nm} \).

Extinction measurements performed to date on TiO\(_2\) and SiO\(_2\) powders with the Fig. 3 setup have been used only to gain qualitative information on the powder-dispersion technique by detecting the absence or presence of particles. Further work is required to extend the current setup to quantitative measurements of the particle number density and diameter as a function of time. Alternate laser wavelengths and additional data on the extinction properties of the SiO\(_2\) and TiO\(_2\) powders are anticipated from the ongoing efforts.

### Scattering

Another ongoing effort involves the development of a laser-light scattering diagnostic to monitor the time-dependent particle diameter and volume fraction. This method is a common particle-detection method in shock-tube experiments (Graham, 1977; Kellerer et al., 1996) wherein a laser beam is focused in the test section of the shock tube. Scattered light from the interaction of the laser beam with the particles is collected at off-angles to the incident beam. The intensity of the scattered light is proportional to the scattering coefficient of the particles. By utilizing the Mie theory for scattered radiation, information on the average particle diameter and volume fraction can be obtained. Upon measuring the light at multiple angles, certain assumptions regarding the average particle size and size distribution can be relaxed (Roth and Fischer, 1985).

Figure 6 presents a diagram of the proposed scattering setup on the Aerospace Shock Tube Facility. A new test section was fabricated with both forward- and back-scattering observation ports at 30 and 45 degrees in addition to the usual 90 and 180 degrees. The laser source is a Coherent Innova I-20 argon-ion laser operating at 488 nm, 514 nm, or any other prism-selectable visible wavelength. The scattered light is collected by the specially designed PMT detectors described above and in Rickard and Petersen (2001). Set up and optimization of the scattering diagnostic are in progress.

![Diagram of scattering setup](Image)

**Figure 6.** Laser-light scattering diagnostic currently under development for measuring time-dependent particle size and number density. Multiple scattering angles are available in the recently fabricated test section.

### Particle Sizer

An important aspect of the solid-phase measurements, particularly for data analysis and interpretation, is the size distribution of the powder introduced into the shock tube. Similar information is also important for analyzing the size characteristics of particles formed from gas-phase chemistry within the shock tube in other experiments. To satisfy these requirements, a Model 3936 scanning mobility particle sizer (SMPS) from TSI is utilized. The SMPS is capable of measuring the number of particles in discrete size ranges from 10 to 1000 nm. The net result is a histogram of the powder sample's particle-size distribution.

A schematic of the basic operation of the device is shown in Fig. 7. The SMPS consists of an electrostatic classifier, a differential mobility analyzer (DMA), and a condensation particle counter (CPC). A polydisperse stream of particles enters the classifier where the particles are exposed to a high concentration of bipolar ions from the Kr-85 Bipolar Charger. Since the particle charge is related to the size of the particles, the DMA succeeds in separating the particles into the desired monodisperse category by employing a high-voltage electric field to discriminate particles with different charges (i.e., sizes). The monodisperse particles are subsequently sent to the CPC for counting. Computer control via software is used to step through the entire range of particle sizes, hence building a size distribution.
one primarily for heterogeneous measurements of particle decomposition and early particle formation, and one for gas-phase chemistry measurements of precursor and intermediate species. Although the shock-tube hardware was originally built in the 1960's, many improvements and upgrades were made to the facility to meet the requirements of the present applications. Among these upgrades were a new vacuum system, updated electronics, new experimental techniques, new diagnostics, and operation of the second shock tube. The current diagnostics include an optical pyrometry technique for particle temperature, a laser-extinction setup for particle number density and size, spectrally and time-resolved emission of gas-phase species, and a scanning mobility particle sizer. Under development is a laser-light scattering diagnostic for temporally resolved particle-size and volume-fraction measurements. Current and future experiments will focus on time-dependent measurements of interest to the flame synthesis of glasses such as TiO₂ and SiO₂.

Figure 5. Schematic of the TSI Scanning Mobility Particle Sizer, Model 3936. A polydisperse aerosol enters the Electrostatic Classifier where it is charged by the Bipolar Charger; the charged particles enter the DMA where they are sorted and sent to the Condensation Particle Counter.

Perhaps the most difficult issue with measuring the size distribution of submicron, solid particles is breaking up the inevitable agglomerations into the fundamental particles. At present, a disperser similar to that of Rajathurai et al. (1990) is employed and is described in Petersen (2001). Figure 8 presents a typical size distribution taken with the SMPS for a silicon dioxide powder sample. The size-averaged diameter of the sample was measured as 74 nm. Further studies to identify the best powder-dispersion and -measurement techniques are planned.

Figure 8. Particle size distribution of SiO₂ powder taken with the TSI SMPS and the powder-dispersion technique described in Petersen (2001). The average diameter is 74 nm.

SUMMARY
A new shock-tube facility for performing fundamental measurements of heterogeneous combustion phenomena was described. The facility consists of two identical shock tubes:

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