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NOVEL MASS SPECTROMETRIC INSTRUMENT FOR GASEOUS AND PARTICULATE CHARACTERIZATION AND MONITORING

Covering the period from January 1, 1993 through March 31, 1993

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EXECUTIVE SUMMARY

Under contract DE-AC21-92MC29116, SRI International will develop a unique new instrument that will be capable of providing real-time (<1 minute), quantitative, chemical characterization of gaseous and particulate pollutants generated from DOE waste cleanup activities. The instrument will be capable of detecting and identifying volatile organic compounds, polynuclear aromatic hydrocarbons, heavy metals, and transuranic species released during waste cleanup activities. The instrument will be unique in its ability to detect and quantify in real-time these diverse pollutants in both vapor and particulate form.

The instrument to be developed under this program will consist of several major components: (1) an isokinetic sampler capable of operating over a wide range of temperatures (up to 500 K) and flow rates; (2) a high pressure to low pressure transition and sampling region that efficiently separates particles from vapor-phase components for separate, parallel analyses; (3) two small mass spectrometers, one optimized for organic analysis using a unique field ionization source and one optimized for particulate characterization using thermal pyrolysis and electron-impact ionization (EI); and (4) a powerful personal computer for control and data acquisition.

The function of the sampler is to obtain a sufficient and representative quantity of air pollutants from a wide range of waste cleanup activities, both vapor and particulate. In addition, the sampler must deliver the vapors and particles to the detection instrument with minimal material loss. The pressure transition region serves multiple functions: (1) it focuses the particles into a "beam" toward the center of the gas flow by momentum separation, (2) it efficiently separates the particulate beam from the vapor stream, allowing independent chemical analyses of particles and vapors, and (3) it provides the first stage of pressure reduction between the ambient atmosphere and the lower pressure (1-2 Pa) region of an ion trap mass spectrometer.

Chemical analysis of the volatile organic species and the polynuclear aromatic hydrocarbons is typically accomplished by first enriching their concentration using a dimethylsilicone rubber membrane separator and then analyzing their composition with field ionization mass spectrometry (FIMS). FIMS is a soft ionization method that is ideally suited to the chemical characterization of complex mixtures of organic compounds. Also available will be an alternative direct inlet of vapors bypassing the membrane and use of EI, for comparisons with the membrane inlet and field ionization. Use of EI will permit monitoring of various small inorganic molecules as well, such as NO_x and SO_x .

Use of a direct sampling method and differential vacuum pumping allows particulate pollutants to be readily introduced into another ion trap mass spectrometer. Volatilization of particles on a heated surface within the volume of the ion trap followed by the complete and quantitative mass spectrometric analysis of the resulting vapors will yield the detailed information required to monitor waste cleanup activity. Based on conservative estimates of the instrument design and performance parameters, a single 0.1- μm -diameter particle will provide a signal level sufficient for complete analysis. All these operations are under the control of the data acquisition computer.

The overall goal of this effort is to develop and demonstrate an instrument that can provide real-time, part-per-billion detection sensitivity for important pollutant species generated by DOE waste cleanup activities. Initially, the instrument will be developed for targeted use in conjunction with the K-1435 Toxic Substances Control Act (TSCA) incinerator at the Oak Ridge National Laboratory K-25 site. Ultimately, the instrument will be designed to operate in the field at any cleanup site, located close to the stack or process vent, providing the plant operations personnel with real-time information and alarm capabilities. In addition, this instrument will be very broadly applicable for cleanup or sampling, for example, any time contaminated soil is moved or disturbed. Because of the versatility and analytical power of this instrument, commercialization for a wide variety of applications in monitoring and control will be important.

The instrument relies on both commercially available technology, including a simple laser scattering particle detector, an ion trap mass spectrometer and a membrane permeator, and unique technologies developed by our organization in the area of field ionization mass spectrometry, and high-temperature sampling. These technologies are now at a Maturity Level of II. The instrument is projected to be easily transportable with minimal utility requirements, making it ideal for deployment at a wide variety of DOE waste sites. Moreover, the straightforward design and use of proven technologies will result in an instrument of very high reliability and sensitivity that can be ready for actual field testing and use within two to three years.

INTRODUCTION

The goals of the Office of Technology Development as outlined by the director of the Environmental Restoration and Waste Management Program (EM), Leo Duffy, in 1991 appropriations hearings include conducting an aggressive technology development program for waste management, waste minimization, waste treatment, storage and disposal of waste. This will be done through the development of more effective remediation technology to reduce occupational and public exposure. We are developing a method to monitor airborne emissions from the TSCA plant at Oak Ridge which will provide real-time, accurate, and inexpensive data on the emission of hazardous organic and inorganic chemicals in both gaseous and particulate form, and to assist DOE in maintaining its ambitious schedules and overcoming significant scientific limitations of its current monitoring technologies.

In May 1988 under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), Oak Ridge National Laboratory (ORNL) established a timetable remedial investigation/feasibility study, and a Federal Facility Agreement is being negotiated with the Environmental Protection Agency and the Tennessee Department of Health and Environment. As a result, work has begun on inactive waste sites at ORNL to excavate and isolate wastes in compliance with current standards. In addition, ORNL must comply with the Resource Conservation and Recovery Act (RCRA), which regulates generation, transportation, treatment, storage, and disposal of hazardous wastes and corrective action of releases to the environment of hazardous wastes from active facilities.

Environmental restoration activities at DOE-ORO sites and facilities, such as K-25 and Y-12, are conducted to meet location, contaminant, and action-specific requirements imposed by statutes and regulations and to implement guidance and agreements. These activities typically follow a phased approach with public involvement throughout the process.

A key responsibility of the Oak Ridge Operations Office is for the environmental remediation and restoration activities at the Oak Ridge, Y-12 and K-25 facilities. Support of both the Department of Energy's and the State of Tennessee's commitment to environmental issues is a vital concern of the Oak Ridge site's workforce and management structure. Through advances in technology, the environmental remediation and restoration efforts may be accomplished at less cost, and with a decreased impact on the surrounding communities.

BACKGROUND

The Oak Ridge K-25 site is located 13 miles west of Oak Ridge. Until the summer of 1985, when the gaseous diffusion process was shut down, the mission of the K-25 site was ^{235}U enrichment of uranium hexafluoride (UF_6) for eventual use as a fuel in nuclear reactors. Typical facilities included the feed system and separate systems for collecting the product and the waste (tails) stream. The purging of contaminants from the product stream required the use of large amounts of alumina and sodium fluoride. A number of compounds were used for the clarification of coolant water, and hexavalent chromium, zinc, and phosphate were used to inhibit corrosion of heat transfer equipment. Support facilities produced solutions that required concentration and recovery with some residual that was discarded and buried. Laboratory sample residues and obsolete chemical reagents, spent chemicals, and contaminated equipment were candidates for discard. Sludges from chemical wastes contain hazardous materials, including chromium, copper, lead, mercury, naphthalene, and zinc. Wastes buried at the K-25 site include low-level radioactive solid waste, mixed chemical waste, and radioactive and nonradioactive classified materials. Uranium was released into the air, surface water, and on-site land disposal.

Waste management activities at the K-25 site are increasing. Low-level radioactive waste from other DOE-Oak Ridge Operations (ORO) sites are now being placed in interim storage facilities in the K-25 site building vaults until final disposition strategy is identified. Also, polychlorinated biphenyl (PCB) wastes began arriving from other DOE-ORO sites in 1987 for future incineration in the new K-1435 Toxic Substances Control Act incinerator.

Making an analogy, it is well established that heavy metals are present in the stack emissions of coal-fired power plants. Considerable research in this area has identified every naturally occurring element in coal fly ash, with concentrations ranging from percents to parts-per-million and below. In the case of coal combustion, these heavy metals are present in the feedstock, whereas in the process stream of a waste cleanup facility, many heavy metals will be present at high concentrations as part of the original waste material. Although a number of the naturally occurring elements are of minor concern, many of the heavy metals, such as mercury, lead, cadmium, arsenic, chromium, and uranium, pose significant health risks to humans. Additionally, the transuranic elements such as plutonium, are of particular concern due to their extreme toxicity as respirable particles. Many other elements, both radioactive and nonradioactive, also pose health and safety risks. Included in this category are particles containing beryllium, iodine, and cesium.

By analogy with the known distribution of heavy metals within airborne particles generated by coal-fired power plants, it is reasonable to conclude that significant levels of heavy metals and hazardous inorganic contamination can be unknowingly discharged from process vent stacks in the particulate form. To maintain a high degree of safety and control over cleanup activities at waste sites containing these materials, a monitoring instrument is required that can provide real-time, quantitative measurements of levels of important elements at any point within the process. Particular attention must be given to effluent discharge to the atmosphere via vents and stacks to prevent any release of hazardous by-products of the cleanup activities.

In addition to the heavy metal and inorganic emissions, a very wide range of VOCs will be produced and emitted from any waste cleanup plants, including PAHs, heterocyclic nitrogen and sulfur species, and polychlorinated biphenyls (PCBs). Many of these VOCs are known or suspected carcinogens whose levels must also be controlled. Unlike the metals and inorganic species, many of the organic compounds found in the gaseous effluent of waste cleanup facilities will include materials not initially present in the waste stream. For example, many PAHs are formed during the incomplete combustion of simple organic wastes. As with metals and inorganics, the organic pollutants can be released in both the vapor and particulate forms. Thus, a versatile real-time instrument for determining VOC levels is required to allow plant operators to monitor and regulate stack emissions of these hazardous species.

Any real-time waste cleanup process monitor should be capable of simultaneously measuring numerous important chemical species, both organic and inorganic, present as vapors and particles. Although very sophisticated monitoring technologies are currently under development that make use of optical, electrochemical, and microsensor methods, none yet offers quantitative chemical characterization of both vapor phase and particulate air pollutants. Moreover, most of these sophisticated sensors are capable of detecting only one or two specific chemical species, thereby requiring that many separate sensors be integrated to perform the necessary monitoring and control functions. Such multisensor systems will often be technologically more complex and less reliable than a single, multifunctional instrument, as well as more costly to develop, manufacture, operate, and maintain.

The most universal analytical technique available for monitoring a broad range of chemical species is mass spectrometry. If mass spectrometry is to be used, however, the sampled materials must be vaporized and ionized before analysis. The ionization method must be carefully chosen to prevent preferential, or nonstatistical, ionization while providing adequate and stable signal levels. Even before the effluent can be ionized, it must be sampled and transported from the stack or process stream to the ionizer. In the case of a waste cleanup plant such as the K-1435 TSCA incinerator at the DOE-Oak Ridge Operations site, the sampled effluent will consist of vapors and

particles. Thus, the development of an appropriate sampler will be a critical aspect of this effort. Most of the heavy metals, for example, will not appear in vapor form, but will be incorporated into particles of varying sizes. Not only must these particles be efficiently sampled, they must also be separated from the vapor component and then completely vaporized to provide the requisite composition information. At the same time, the sampled vapors, including the organic species of interest, must be isolated and efficiently detected. No single *instrumental* technique (FTIR, ICP-AES, ICP-MS, GC, GC-MS, LIF) is capable of simultaneously detecting both organic and inorganic species in vapor and particulate forms. However, a single *instrument* consisting of two closely integrated detectors that share a common sampler can provide this critical analytical capability.

RESULTS AND DISCUSSION

The goals of this research program are to develop, demonstrate, and field test a real-time monitoring instrument capable of providing quantitative chemical information on the vapor and particulate emissions produced during the incineration of toxic waste. The Phase I effort is divided into five main tasks and subtasks as follows:

Task 1: NEPA Documentation

Task 2: Instrument Development

Task 2.1: Sampler Development

Task 2.2: Vapor Instrument Development

Task 2.3: Particulate Instrument Development

Task 3: Instrument Testing

Task 3.1: Single Metal Species Testing

Task 3.2: Multiple Metal Species Testing

Task 4: System Design

Task 5: Project Management

Work was started on tasks 2.1, 2.2, and 2.3 during the month of January, following the project initiation meeting held at METC in December. Under task 2.1, the primary effort was devoted to initiating the design for a particulate sampler. Previously used particulate samplers were examined for their adaptability to this project, and some details regarding the specific sampling conditions that will prevail at the ORNL test site were obtained. Based upon this clearer picture of the sampling requirements (particle size, gas flows, temperatures, physical sizes and limitations, etc.), a preliminary sampler design was started. This design is also being integrated with the instrument design to ensure proper sample transport, to minimize losses, and to satisfy the mass spectrometers vacuum and gas load restrictions.

Development of the vapor instrument under task 2.2 is actually broader in scope because it involves adapting the ion trap mass spectrometer to operate in larger, more accessible vacuum system that will be used for both vapor and particulate testing. Using many existing vacuum components, including turbomolecular pumped vacuum chambers and suitable vacuum feedthrus

for electrical and sample connections, one of our laboratory ion trap detectors is being modified and installed in the test chamber. Initially, the ion trap will be tested using directly introduced vapor samples and conventional electron impact ionization to verify that it operates correctly in the new vacuum housing. Following those tests, modifications will begin to incorporate one of SRI's volcano field ionization devices as an external ionization source.

Development of the vapor instrument under task 2.2 and the particulate instrument under task 2.3 both proceeded jointly since the first step was the design of a common vacuum system. We have made extensive calculations of the gas loads, pumping requirements, and resultant operating pressures. These detailed calculations are included below, including estimates of particle light scattering signal levels. Using available vacuum pumps and components to the extent possible, and purchasing some commercially available specialty items such as the skimmer cones, we have arrived at a workable design for the laboratory prototype system. We are currently awaiting fabrication of one of the main vacuum housings, while continuing with the remaining design details for component mounting and aligning. Fabrication and delivery of the vacuum housing is scheduled for the end of March. By that time, the existing vacuum components will be mounted on a small laboratory cabinet with space for the electronics and pumps, as well as the particle beam sampler and interface.

Vacuum System Pumping Calculations

Assumptions:

1. Inlet pressure = $P_1 = 50$ torr (Region I).
2. Main chamber gas load of $\lesssim 10^{-6}$ torr (requires 2 differential pumping stages).
3. Use available pumps:

Region II: 5.6 l/s Leybold D16A trivac mechanical pump

Region III: 170 l/s turbopump (effective speed w/particle shield ≈ 135 l/s).

Region IV: 270 l/s turbopump (effective speed w/particle shield ≈ 220 l/s).

4. Orifice diameters:

Nozzle (A_{12}) = 250 μm

Skimmer (A_{23}) = 400 μm (commercially available skimmer)

Skimmer (A_{34}) = 600 μm (1.5 times skimmer A_{23} diameter)

Region I $P_I = 50$ torr (assumed)

Region II Mass flow through $A_{12} = \dot{m} = (14.3)(D_o)^2 P_I$, where $D_o = A_{12}$ diameter (cm)
 $= 14.3 (0.0250 \text{ cm})^2 (50 \text{ torr})$
 $= 0.45 \text{ torr l/s}$

With a 5.6 l/s mechanical pump, the estimated pressure in Region II is:

$$P_{II} = \frac{0.45 \text{ torr l/s}}{5.6 \text{ l/s}} \approx \boxed{0.80 \text{ torr}}$$

Region III Distance between nozzle A_{12} and skimmer A_{23} is governed by the position of the mach disk, assuming continuous free jet expansion. Skimmer A_{23} should be placed in the zone of silence before the mach disk.

$$\text{Mach disk location} = X_M = (0.67) \left(\frac{P_o}{P_b} \right)^{\frac{1}{2}} (d) \quad \text{where } d = \text{nozzle diameter} = 0.250 \text{ mm}$$

$$= (0.67) \left(\frac{50}{0.8} \right)^{\frac{1}{2}} (0.250 \text{ mm}) \quad P_o = \text{nozzle stagnation pressure} = P_I$$

$$X_M = 1.3 \text{ mm}$$

$$P_b = \text{background pressure} = P_{II}$$

Therefore, place A_{23} at a distance of ~ 1.0 mm from nozzle A_{12} .

Mach disk reference: D. R. Milier in *Atomic and Molecular Beam Methods*, ed. by G. Scoles (NY: Oxford University Press, 1988) p.15.

Using this distance and the Region I pressure, the number density at the skimmer location can be calculated as follows:

$$\begin{aligned} \text{Number density at skimmer } A_{23} &= n = (0.161) (3.24 \times 10^{16} \frac{\text{atoms}}{\text{cm}^3 \cdot \text{torr}}) (P_I) \left(\frac{A_{12} \text{ nozzle diameter}}{A_{12} \rightarrow A_{23} \text{ distance}} \right)^2 \\ n &= (0.161) (3.24 \times 10^{16} \frac{\text{atoms}}{\text{cm}^3 \cdot \text{torr}}) (50 \text{ torr}) \left(\frac{0.250 \text{ mm}}{1.0 \text{ mm}} \right)^2 \\ &= 1.63 \times 10^{16} \text{ atoms/cm}^3 \end{aligned}$$

At a velocity of $v \approx 4 \times 10^4 \text{ cm/s}$, the flux at skimmer $A_{23} = nv$

$$\approx (4 \times 10^4 \frac{\text{cm}}{\text{s}}) (1.63 \times 10^{16} \frac{\text{atoms}}{\text{cm}^3}) \approx 6.5 \times 10^{20} \text{ atoms/cm}^2 \cdot \text{s}$$

The numbers of atoms passing through A_{23} into Region III is given by:

$$\begin{aligned} (6.5 \times 10^{20} \text{ atoms/cm}^2 \cdot \text{s}) \left(\frac{\pi}{4} \times (A_{23}, \text{ in cm, diameter})^2 \right) &= (6.5 \times 10^{20}) (\pi/4) (0.0400)^2 \\ &\approx 8.2 \times 10^{17} \text{ atoms/s} = Q_{\text{III, MB}} \end{aligned}$$

The gas load entering region III is comprised of two contributions, one associated with the molecular beam formed by the gas dynamic expansion through A_{23} , and the other arising from the normal gas diffusion from the higher ambient pressure in Region II.

Throughput (molecular beam) = $Q_{\text{III, MB}}$

$$= \frac{8.2 \times 10^{17} \text{ atoms/s}}{3.24 \times 10^{19} \text{ atoms/l} \cdot \text{torr}} \approx 2.5 \times 10^{-2} \text{ torr} \cdot \text{l/s}$$

Throughput (diffusion across A_{23}) = $Q_{\text{III, D}} = P_{\text{II}} \times \text{aperture } A_{23} \text{ conductance}$

$$= (0.80 \text{ torr}) (9.15) (0.0400 \text{ cm})^2 \approx 1.2 \times 10^{-2} \text{ torr} \cdot \text{l/s}$$

Combined throughput $Q_{\text{III}} \approx 3.7 \times 10^{-2} \text{ torr l/s}$, therefore, the estimated pressure in Region III is:

$$P_{\text{III}} \approx \frac{3.7 \times 10^{-2} \text{ torr l/s}}{135 \text{ l/s}} \approx \boxed{2.7 \times 10^{-4} \text{ torr}}$$

Region IV Assume distance between skimmers A_{23} and $A_{34} \approx 1.3$ inches (~ 33 mm), due to use of miniconflat (1.33" O.D.) flanges in mounting lenses for collecting scattered light.

Skimmer A_{23} forms a molecular beam source with a solid angle of:

$$\text{Solid angle of skimmer } A_{23} = \frac{\pi/4 (0.400 \text{ mm})^2}{(1 \text{ mm})^2} = 0.126 \text{ steradians (viewed from nozzle)}$$

$$\text{The beam flux exiting skimmer } A_{23} = \frac{8.2 \times 10^{17} \text{ atoms/s}}{0.126 \text{ steradians}} = 6.5 \times 10^{18} \text{ atoms/steradian}\cdot\text{s}$$

The amount of gas reaching skimmer A_{34} depends on its relative solid angle as:

$$\text{Solid angle of skimmer } A_{34} = \frac{\pi/4 (0.600 \text{ mm})^2}{((1.3 \text{ in.} \times 25.4 \text{ mm/in.}) + 1 \text{ mm})^2} \approx 2.4 \times 10^{-4} \text{ steradians (viewed from nozzle)}$$

$$\begin{aligned} \text{The flux through skimmer } A_{34} &= (6.5 \times 10^{18} \text{ atoms/s steradian}) (2.4 \times 10^{-4} \text{ steradians}) \\ &= 1.6 \times 10^{15} \text{ atoms/s} = Q_{IV,MB} \end{aligned}$$

Assuming a gas velocity $v = 4 \times 10^4$ cm/s,

$$\begin{aligned} \text{the number density at skimmer } A_{34} &= \frac{1.6 \times 10^{15} \text{ atoms/s}}{(4 \times 10^4 \text{ cm/s}) (2.8 \times 10^{-3} \text{ cm}^2)} \\ &= 1.4 \times 10^{13}/\text{cm}^3 (\sim 0.43 \text{ torr at } 300 \text{ K}). \end{aligned}$$

The gas load entering region IV is also comprised of two contributions, one associated with the molecular beam formed by the gas dynamic expansion through A_{34} , and the other arising from the normal gas diffusion from the higher ambient pressure in Region III.

$$\text{Throughput (molecular beam)} = Q_{IV,MB} = \frac{1.6 \times 10^{15} \text{ atoms}}{3.24 \times 10^{19} \text{ atoms/l torr}} \approx 4.9 \times 10^{-5} \text{ torr l/s}$$

$$\begin{aligned} \text{Throughput (diffusion across } A_{34}) &= Q_{IV,D} = (2.7 \times 10^{-4} \text{ torr}) (9.15) (0.06 \text{ cm})^2 \\ &\approx 8.9 \times 10^{-6} \text{ torr l/s} \end{aligned}$$

Combined throughput $Q_{IV} \approx 5.8 \times 10^{-5}$ torr l/s, therefore, the estimated pressure in Region IV is:

$$\text{Pressure in Region IV: } P_{IV} \approx \frac{5.8 \times 10^{-5} \text{ torr l/s}}{220 \text{ l/s}} \approx \boxed{2.6 \times 10^{-7} \text{ torr}}$$

Collection of scattered HeNe Light:

Desired lens diameter: ~ 20 mm (to fit miniconflat flange)

Standard size lens available: ~20 mm diameter; 22 mm focal length

Thin lens formula: $\frac{1}{s_o} + \frac{1}{s_i} = \frac{1}{f}$ where s_o = object distance
 s_i = image distance = location of pinhole
 f = lens focal length

Try a range of object distances:

Let $s_o = 2.5 \text{ cm}$, $\frac{1}{2.5} + \frac{1}{s_i} = \frac{1}{2.2}$; $s_i = 18.3 \text{ cm}$ (~7.2") Too long

Let $s_o = 3.0 \text{ cm}$, $s_i = 8.25 \text{ cm}$ (3.2"); Magnification $M = \frac{s_i}{s_o} = 2.75$ Acceptable

Let $s_o = 3.5 \text{ cm}$, $s_i = 5.92 \text{ cm}$ (2.3"); $M = 1.7$.

If $s_o = 3.0 \text{ cm}$ and assume ~ 15 mm (3/4) of 20 mm lens gathers light:

$$\text{collection lens solid angle } \Delta\Omega \approx \frac{\pi(1.5 \text{ cm})^2}{4(3.0 \text{ cm})^2} = 0.20 \text{ sr}$$

Pinhole aperture diameter $\geq$ magnification (M) $\times$ diameter of particle beam sample

Light scattering calculations

Calculate is the number of photons per steradian for a 0.2 μm and 0.5 μm particle, respectively.

Assume a 1 mW HeNe laser focused to 1 a mm diameter spot size, and a particle velocity of $4 \times 10^4 \text{ cm/s}$. The number of scattered photons, N_{ph} , is given by:

$$N_{ph} = I_L \left(\frac{d\sigma}{d\Omega} \right) (d\Omega)t \quad \text{where} \quad I_L = \text{intensity of laser light}$$

$t = \text{time}$

$\frac{d\sigma}{d\Omega} = \text{differential scattering cross section}$

The differential cross section for light scattering is calculated as:

$$\frac{d\sigma}{d\Omega} = \frac{2\pi a^2}{4\pi} = \frac{1}{2} a^2 \quad \text{where } a = \text{particle radius}$$

The time element is associated with particle transit:

$$t = \frac{10^{-3}\text{m}}{4 \times 10^2 \text{cm/s}} = 2.5 \times 10^{-6}\text{s}$$

For a 0.2 μm particle:

$$a = 0.1 \times 10^{-4}\text{cm} \text{ and } \frac{d\sigma}{d\Omega} = 5 \times 10^{-11} \text{ cm}^2/\text{sr}$$

hence,

$$\begin{aligned} N_{ph} &= \frac{10^{-3}\text{J/s}}{10^{-2} \text{ cm}^2} \times 5 \times 10^{-11} \frac{\text{cm}^2}{\text{sr}} \times d\Omega \times 2.5 \times 10^{-6}\text{s} \times \frac{1 \text{ eV}}{1.6 \times 10^{-19}\text{J/eV}} \times \frac{1 \text{ photon}}{2 \text{ eV}} \\ &= 39 \text{ photons/sr} \times d\Omega \end{aligned}$$

In a solid angle of 0.20 sr (see above) for the collection lens:

$$N_{ph} \text{ collected} \simeq (0.20 \text{ sr}) (39 \text{ photons/sr}) \simeq \boxed{8 \text{ photons}}$$

For a 0.5 mm particle:

$$a = 0.25 \times 10^{-4}\text{cm} \text{ and } \frac{d\sigma}{d\Omega} = 3.1 \times 10^{-10} \text{ cm}^2/\text{sr}$$

$$N_{ph} = 242 \text{ photons/sr} \times d\Omega$$

In the solid angle of 0.20 sr:

$$N_{ph} \text{ collected} \simeq \boxed{50 \text{ photons}}$$

Given the typical quantum efficiency and dark count of photomultiplier tubes in the HeNe wavelength region, the number of *detected* photons is above background. Changes in the optics and additional calculations are needed, however, to increase the light scattering intensities to allow for uniformity in the light scattering cross section, optics losses, and high levels of scattered background light.

CONCLUSION

At the completion of the first six months of this research effort, progress is on schedule as proposed in both the original research proposal and the Management Plan. The main critical path milestone during the first quarter was the granting of a NEPA exclusion, thus allowing initiation of the laboratory research effort. SRI has allocated the appropriate technical staff to continue work on tasks 2.1, 2.2, and 2.3. Weekly staff meetings are attended by all personnel so that intertask communication and cooperation is maximized.

During the third quarter of this program, it is anticipated that final designs will be completed for the sampler and its vacuum interface with the ion trap detectors. In addition, both of the ion trap detectors will be installed in the vacuum test stand, and their operation verified. Considerable progress will also be made toward designing, fabrication, and testing of the pyrolysis filament required for particulate analysis. Additional light scattering calculations will also be made to increase the predicted signal levels.

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