GEORGIA INSTITUTE OF TECHNOLOGY — OFFICE OF CONTRACT ADMINISTRATION

PROJECT ADMINISTRATION DATA SHEET

[X] ORIGINAL [ ] REVISION NO. ____

Project No. G-35-684 (R6232-0A0) GTRC DATE 11 / 3 / 86

Project Director: E. Patterson School Geo Sci

Sponsor: US Defense Nuclear Agency, Washington, D.C.

Type Agreement: Contract No. DNA001-86-C-0310

Award Period: From 9/30/86 To 3/31/88 (Performance) 3/31/88 (Reports)

Sponsor Amount:	This Change	Total to Date
Estimated: $		$ 340,876
Funded: $		$ 50,000

Cost Sharing Amount: $ ____ Cost Sharing No: N/A

Title: Smoke Source Experiment

ADMINISTRATIVE DATA OCA Contact John B. Schonk X-4820

1) Sponsor Technical Contact:

Flo Lagergren
~~Dr. Michael H. Frankel~~

Headquarters, DNA
Shock Physics Directorate (SPAS)
Washington, DC 20305

2) Sponsor Admin/Contractual Matters:

Thomas Cox
~~Renee Greye~~

Headquarters
Defense Nuclear Agency
Washington, D.C. 20305-1000
202/325-1197

Defense Priority Rating: DPAS; DO-S1 Military Security Classification: Unclassified

(or) Company/Industrial Proprietary: N/A

RESTRICTIONS

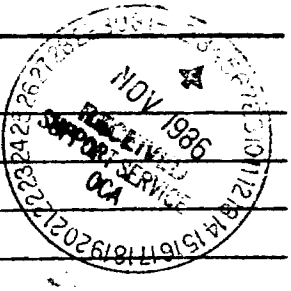
See Attached Government Supplemental Information Sheet for Additional Requirements.

Travel: Foreign travel must have prior approval – Contact OCA in each case. Domestic travel requires sponsor approval where total will exceed greater of $500 or 125% of approved proposal budget category.

Equipment: Title vests with GIT for equipment less than $5,000.

COMMENTS:

Current funding is expected to support work until 12/31/86.



COPIES TO: SPONSOR'S I. D. NO. 101.013

Project Director	Procurement/GTRI Supply Services	GTRC
Research Administrative Network	Research Security Services	Library
Research Property Management	~~Reports Coordinator (OCA)~~	Project File
Accounting	Research Communications (2)	Other A. Jones

FORM OCA 65-395

GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION

NOTICE OF PROJECT CLOSEOUT

Closeout Notice Date 03/27/91

Project No. G-35-684 Center No. R6232-0A0

Project Director PATTERSON E M JR** School/Lab E & A SCI

Sponsor US DEPT OF DEFENSE/DEFENSE NUCLEAR AGENCY

Contract/Grant No. DNA001-86-C-0310 Contract Entity GTRC

Prime Contract No. _____

Title A SMOKE SOURCE EXPERIMENT

Effective Completion Date 890915 (Performance) 890915 (Reports)

Closeout Actions Required:	Y/N	Date Submitted
Final Invoice or Copy of Final Invoice	Y	
Final Report of Inventions and/or Subcontracts	Y	
Government Property Inventory & Related Certificate	Y	
Classified Material Certificate	N	
Release and Assignment	Y	
Other _____	N	

Comments_____

Subproject Under Main Project No. _____

Continues Project No. _____

Distribution Required:

Project Director	Y
Administrative Network Representative	Y
GTRI Accounting/Grants and Contracts	Y
Procurement/Supply Services	Y
Research Property Managment	Y
Research Security Services	N
Reports Coordinator (OCA)	Y
GTRC	Y
Project File	Y
Other _____	N
_____	N

NOTE: Final Patent Questionnaire sent to PDPI.

GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION

NOTICE OF PROJECT CLOSEOUT (SUBPROJECTS)

Closeout Notice Date 03/27/91

Project No. G-35-684 Center No. R6232-0A0

Project Director PATTERSON E M JR** School/Lab E & A SCI

Sponsor US DEPT OF DEFENSE/DEFENSE NUCLEAR AGENCY

Project # A-4677 PD GOOCH J W Unit 01.021.363 T
CONT # DNA001-86-C-0310 MOD# MSTL *
Ctr # R6232-000 Main proj # G-35-684 OCA CO DSH
Sponsor-US DEPT OF DEFENSE /DEFENSE NUCLEAR AGEN 101/013
A SMOKE SOURCE EXPER
Start 860930 End 881230 Funded 35,183.40 Contract 35,183.40

Project # E-16-698 PD POWELL E A Unit 02.010.110 T
CONT # DNA001-86-C-0310 MOD# AERO ENGR *
Ctr # R6232-0A1 Main proj # G-35-684 OCA CO DSH
Sponsor-US DEPT OF DEFENSE /DEFENSE NUCLEAR AGEN 101/013
A SMOKE SOURCE EXPER
Start 860930 End 880331 Funded 33,287.40 Contract 33,287.40

LEGEND
1. * indicates the project is a subproject.
2. I indicates the project is active and being updated.
3. A indicates the project is currently active.
4. T indicates the project has been terminated.
5. R indicates a terminated project that is being modified.

Georgia Institute of Technology
A UNIT OF THE UNIVERSITY SYSTEM OF GEORGIA
ATLANTA, GEORGIA 30332
SCHOOL OF GEOPHYSICAL SCIENCES
404/894-3893

October 31, 1986

Ref: DNA001-86-C-0301
Progress Report 01

Ms. Renee Graye
Headquarters
Defense Nuclear Agency (AM)
Washington, DC 20305-1000

Dear Ms Graye:

This letter represents the first monthly progress report of work sponsored by the Defense Nuclear Agency under RDT&E RMSS CODE B 4662 D RB RB 00095 RAAE 3220 A under Contract DNA001-86-C-0301. This report covers the period 30 September 1986 to 31 October 1986.

This first reporting period has been devoted to activities involved in the initiation of the program, including the following:

1. Initiation of the process of ordering the equipment required for carrying out the planned work, including requesting sponsor and institutional approval and preparation of purchase requests.

2. Beginning detailed design work on the extinction/scattering cell and defining the requirements for the optical measurements.

3. Initiating some modifications to the existing burn chamber that will be needed to carry out these experiments.

4. Determination of the plastic and polymer materials to be used in the initial measurements.

We have also begun a review of previous measurements of related optical parameters that will enable us to place our measurements in the appropriate contex and provide a comparison and verification of our results. This will include previous measurements of the Georgia Tech group.

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DNA001-86-C-0301
Progress Report 01

During the next month we plan to place our initial equipment orders, to complete the design work on the scattering/extinction cell, and to begin the fabrication of the cell and the modifications to the burn chamber.

Should there be any question please contact me at 404-894-3898.

Sincerely,

Edward Patterson
Senior Research Scientist

cc: Dr. Michael Frankel (CTM)

Georgia Institute of Technology
A UNIT OF THE UNIVERSITY SYSTEM OF GEORGIA
ATLANTA, GEORGIA 30332
SCHOOL OF GEOPHYSICAL SCIENCES
404/894-3893

Ref: DNA001-86-C-0301
Progress Report 02

Ms. Renee Graye
Headquarters
Defense Nuclear Agency (AM)
Washington, DC 20305-1000

Dear Ms Graye:

This letter represents the second monthly progress report of work sponsored by the Defense Nuclear Agency under RDT&E RMSS CODE B 4662 D RB 00095 RAAE 3220 A under Contract DNA001-86-C-0301. This report covers the period 1 November, 1986 to 30 November, 1986.

This second reporting period was devoted to planning activities, ordering of equipment and experimental design. Some specific activities include:

1. A collation of some of the thermal properties of the plastic and polymeric materials to be used in this project.

2. Ordering of equipment needed to set up a small scale combustion apparatus utilizing a tube furnace as a heat source.

3. Continued design work on the extinction-scattering cell.

4. Continuation of the review of previous measurements.

It is planned to continue these activities during the next month's efforts.

Sincerely,

Edward Patterson
Senior Research Scientist

cc: Dr. David Auton (CTM)

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(4-35

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ATLANTA, GEORGIA 30332
SCHOOL OF GEOPHYSICAL SCIENCES
404/894-3893

Ref: DNA001-86-C-0301
Progress Report 03

Ms. Renee Graye
Headquarters
Defense Nuclear Agency (AM)
Washington, DC 20305-1000

Dear Ms Graye:

This letter represents the third monthly progress report of work sponsored by the Defense Nuclear Agency under RDT&E RMSS CODE B 4662 D RB 00095 RAAE 3220 A under Contract DNA001-86-C-0301. This report covers the period 1 December, 1986 to 31 December, 1986.

During this third reporting period we continued the activities of the earlier periods. In the area of thermal characterization, we began a series of tests for the thermal characterization of some polymeric materials by means of thermogravimetric analysis in a normal atmosphere. This technique allows the determination of reaction rate constants, activation energies, and orders of reaction of decomposition, which differ for non-oxidizing and oxidizing atmospheres. In the area of combustion measurements we began some tests of small scale combustion of polypropylene, polystyrene, and Polyvinyl chloride.

During this third reporting period, we also produced a report "Optical and Chemical Properties of Smoke Emissions" for a workshop at the National Bureau of Standards discussing Nuclear Winter issues. The emissions report is attached to this progress report as an attachment.

We plan to continue these activities in the next reporting period.

Sincerely,

Edward Patterson
Senior Research Scientist

cc:Dr. David Auton(CTM)

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DRAFT REPORT (prepared 12/86)

OPTICAL AND CHEMICAL PROPERTIES OF SMOKE EMISSIONS

Edward M. Patterson
Georgia Institute of Technology

ASSESSMENTS OF SMOKE OPTICAL PARAMETERS

Studies of the climatic effects of smoke following a nuclear exchange (NRC,1984; Turco et al, 1983; Crutzen et al, 1984) have assessed the effects considering the following factors: the amount of fuel of each type subject to burning, the amount of smoke that would be produced for a given amount of each fuel type consumed (the emission factor for the fuel), the relative amount of soot carbon present in the smoke, and the effectiveness of the soot carbon in producing optical extinction or absorption at visible and at infrared wavelengths. Average smoke optical properties were determined and were then input to radiative transfer models or large scale dynamics models of varying sophistication.

There are uncertainties in each of the estimates; and it is to be expected that there will continue to be large uncertainties. The goal of current research is to narrow these uncertainties and to better define the ranges of the variables. This review will assess our present understanding of the critical optical properties of the smoke.

OPTICAL PARAMETERS OF IMPORTANCE

The radiative effects of the smoke cloud will be determined by the extinction, scattering, and absorption of the cloud, as well as the details of the angular dependence of the scattering. Ideally, these parameters should be known as a function of wavelength from about 300 nm to about 15 um. For purposes of modeling, the effectiveness of a given mass of smoke in producing the optical effect should be known; and specific extinction, scattering, and absorption coefficients (B_e, B_s, and B_a) are defined in terms of the ratio of the optical component of interest to the mass concentration of the smoke. For example B_e is defined as

$$B_e = \sigma_e / M_v$$

with

$$\sigma_e = - \ln(I/I_o)$$

and with M_v the mass concentration of the aerosol. Similar ratios of optical quantities to fuel consumed (B_e^f, B_s^f, B_e^f) can be made as a measure of the effectiveness of the fuel in producing the optical effects. The fuel and the smoke emission factors are related by means of the the smoke emission factor EF for the fuel

$$B_a \cdot EF = B_a^f.$$

The absorption of the smoke is due primarily to the absorbing elemental carbon component of the smoke which can be termed black carbon, elemental carbon, or graphitic carbon. The variety of names reflects the difficulty of measuring the absorbing carbon component and differentiating between the organic and the elemental carbon components in a consistent fashion. The various methods for determining the graphitic carbon concentration in smoke can give quite different results and great care must be exercised in specifying the methodology used to determine the graphitic carbon.

If a given amount of elemental carbon in the smoke plume will produce a constant value of absorption, then the measurement of B_a with a determination of the total particulate mass concentration and the determination of elemental carbon concentrations will give equivalent information. The assumption is often made that a constant value of B_a is appropriate. Although this assumption may be approximately correct in many cases, the range of its applicability is not definitely known. The calculations of Chylek et al (1981) suggest that there can be significant differences in B_a that depend on the morphology of the carbon; but the range of variation for B_a has not been definitely established.

Some comparisons between optical inferences and measurements by the thermal-optical method of elemental carbon determination do suggest reasonable agreement for the cases considered. As such, an emission factor for elemental carbon for a given fuel and fire condition appears to be a useful parameter for describing the effectiveness of the material in producing optical absorption.

Elemental carbon measurements are, then, useful in describing the optics of the smoke. Additional microphysical measurements from which calculations of radiative effects can be made or which help interpret the radiative measurements are also

useful. These microphysical measurements focus on the physical or chemical properties of the smoke cloud or of the specific particles that make up the cloud. These measurements include chemical composition, size distribution, particle optical constants, and particle morphology.

This review will consider mainly the measurements of the specific extinction B_e, and the specific absorption, B_a, as well as measurements of the relative carbon concentration. The data on graphitic carbon concentration and specific absorption are of particular importance in determining the effects of the smoke. As yet, there are relatively few data available for these quantities; and, particularly for the absorption measurements, there is a considerable scatter in the data in the literature.

MEASUREMENTS OF OPTICAL PARAMETERS

Although there is certainly a large variation in the actual absorption properties of the smoke, there is also a variation in the data that is due to variation in the techniques of measurement. This problem arises because, unlike a transmission measurement which provides a direct measure of extinction, there is no single recognized widely used measurement for absorption. The two most fundamental measurement techniques are probably the photoacoustic method and the method reported by Gerber(1982) of measuring extinction and scattering and determining the absorption by means of a difference technique.

An example of the effect of measurement technique variation on a data set is seen in Table I from Gerber and Hindman (1982). The data in this table are results of an absorption measurement intercomparison at Fort Collins, CO in which the separate measurements were made using a common aerosol source. A propane flame was the source of the soot aerosol. The absorption was expressed as a specific absorption, single scattering albedo, and imaginary index of refraction. Although the measurements were made on a common aerosol population, B_a values range from 3.8 to 11.4 m^2/g, a variation of a factor of 3.

We can ask the question "What is the right answer?", but we can not give a definitive answer at this time. A critical consideration of the different measurements suggests that the best value will be near 7 m^2/g at a wavelength of 633 nm. with a single scattering albedo of 0.15. Direct B_e measurements were not reported for the Fort Collins data but use of the average value of the absorption and the simultaneous scattering data imply a B_e value near 8 m^2/g at 633 nm.

B_e Measurements for Smoke

Seader and Einhorn (1976) reported correlations between optical density per meter(base 10) and the particulate

concentration for a wide variety of materials for both flaming and nonflaming combustion. The Seader and Einhorn data can be expressed in terms of the B_e values defined above. Their data correspond to average B_e values of 4.4 m^2/g for non-flaming combustion (with a range from 1.8 to 7.4 m^2/g) and 7.6 m^2/g for flaming combustion (with a range from 6.0 to 9.7 m^2/g) for a wavelength band with a peak intensity near 550 nm. At this time we do not know whether this range of values is due to differences in the materials or to other experimental differences.

Rasbash and Drysdale (1982) have also discussed data of Ou and Seader (1977) which show correlations between absorption expressed in terms of a unit called the obscura and the smoke mass concentration for plastics, wood, and smoke from domestic heaters. The constant of proportionality for their data is approximately 3.3 m^2/g. While there is some question of the exact definitions, it appears that the Rasbash and Drysdale ratio

$$\frac{OK}{MJ} = B_e$$

In more recent work, Mulholland and associates at NBS (Mulholland, 1987) have measured K_s which is the same as the B_e defined here for various materials and have found that K_s values are generally in the range of 8 m^2/g at a wavelength of 632.8 nm. The Mulholland data are in substantial agreement with that of Seader and Einhorn.

Sutherland has also inferred B_e values from measurements of outdoor burn of diesel fuel. He found an average value of 5.6 m^2/g over the visible region and 1 m^2/g over the 10 μm window region. The Fort Collins data for propane soot show a B_e value near 8 m^2/g for a wavelength of 632.8 nm.

Although B_e values were not measured directly by Patterson and McMahon (1984), an analysis performed as part of that study and previous data allow an estimation of B_e values of approximately 5 m^2/g for flaming combustion of vegetative fuel and of approximately 4 m^2/g for smoldering combustion.

B_a values and C_e concentrations

The data on B_a show a much greater range of variation than the data on B_e. As discussed above, this is due in part to variation in the measurement techniques as well as to intrinsic variation in the fires. Unlike the data for B_e, the B_a data do show some systematic variation among the different fuel types which can be considered separately.

Oil and Gas Fuels

The Fort Collins data set provides the best characterized B_a measurements for oil and gas fires; B_a values of 7 m^2/g were inferred for propane soot. Nolan's (Nolan, 1977) absorption data can be analyzed to determine B_a values for residual oil and

natural gas burned in a normal oil or natural gas furnace. His data imply that B_a for the residual oil was 6.5 m^2/g on initial ignition and warmup and 3.9 m^2/g under steady state conditions; comparable values for the natural gas were 10 m^2/g on warmup and 2.5 m^2/g under steady state conditions. All of these data were for a wavelength of 530 nm. Possible reasons for these differences were not discussed.

Mulholland et al (this document package) have measured the elemental carbon fraction of smoke from burning propane and heptane. Values of the elemental carbon fraction were 0.74 for the propane and 0.80 for the heptane, data that are consistent with the Fort Collins data. Other values reported in the Crutzen study show values of the elemental carbon fraction that range from 30 to 100%, but there is apparently a considerable diversity in the definitions of elemental carbon.

Plastic and Polymer Fuels

The Crutzen study shows a range of values of absorption and relative elemental carbon concentration that is wider than the range for oil and gas fuels, but with a "best estimate" value for the relative elemental carbon concentration that is quite similar to the other case. For plastics, however, there is a need to differentiate between the smoke from smoldering combustion and that from flaming combustion. It is to be expected that the optical properties of the flaming combustion smoke and those of smoldering combustion smoke will be quite different, with the smoldering smoke having much less absorption than the flaming smoke. Experimental efforts are underway at this time to better define the absorption properties of smoke from these fuels.

Urban Wood Fuels

Crutzen et al surveyed several sets of wood burn data to estimate the effect of urban wood fuel loadings. His data showed a wide range of emission factors and of elemental carbon concentration ratios. Elemental carbon ratios, for example ranged from 8% to 50% in the data considered. More recent data suggests considerably higher elemental carbon ratios. Measurements at NBS for a wood crib of sugar pine yielded an elemental carbon fraction of 0.93; while measurements by Williamson for burning wood also suggest values for the elemental carbon fraction of greater than 0.8. This is a significant difference from the earlier values, but the reasons for the differences are not known.

Vegetative Forest Fuels

Laboratory measurements of Patterson and McMahon (1984) for burning pine needles show B_a values that range from approximately 2 to 0.04 m^2/g. Other data from Patterson, McMahon, and Ward (1986) determined for field burns show B_a values clustered

between 0.1 and 1 m^2/g. In general, flaming combustion B_a's will be near 1, while smoldering B_a's will be much lower, 0.04 and less. The data indicates that there is an approximate inverse relation between the magnitude of the B_a values and the emission factors, which for the Patterson and McMahon data range from 2g/kg to slightly more than 100 g/kg. Other Data of McMahon (private communication) suggest that under certain laboratory conditions, the emission factor for wood products can be as high as 200 g/kg.

The data of Patterson, McMahon, and Ward (see attached paper) show a range of variation of roughly a factor of 100 for the measured B_a values and for the total particulate emission factors. A calculation of graphitic carbon emission factors from the B_a data and the particulate emission factor data shows a range of only a factor of 20. There appears to be less variation in the emission factors for graphitic or elemental carbon than in either the total particle emission factors or the B_a values. Consequently the elemental carbon emission factor should be a useful parameter for modeling fire effects.

NAS ESTIMATES OF OPTICAL PARAMETERS

The National Academy panel presented its estimates of smoke optical parameters in terms of an average smoke composition with uniform optical properties for the resulting emissions. The smoke composition was assumed to be graphitic carbon (20% by mass) and oils (80% by mass), with a range of variation of graphitic carbon concentration between 5 and 50%. The specific absorption of the graphitic carbon at visible wavelengths was assumed to be 10 m^2/g, and the baseline value for B_a, the mid-visible specific absorption, was 2.0 m^2/g, with a range of 1 to 6 m^2/g. B_e, the mid-visible specific extinction, was assumed to be 5.5 m^2/g, with a range of 2 to 9 m^2/g; and B_a(IR), the infrared specific absorption, was assumed to be 0.5 m^2/g, with a range of 0.2 to 5 m^2/g.

These assumed values represent a wide range of data for the different fuels under varying conditions. The average values assumed for the optical parameters are well within the range of plausible values, but a more precise assessment requires knowledge of emission factors and fuel loadings as well as optical parameters.

DISCUSSION OF DATA AND PLANNED WORK

Measurements of B_a and graphitic carbon emission factors for a wide range of fuels and fire intensities are planned for the next six to twelve months. The results of these measurements should provide significant new information on the optical properties of interest. These measurements will also allow the

testing of our ideas of scaling of smoke properties with fire size--data for which little data is now available.

In planning these experiments, I think the following questions should be kept in mind:

1. What is the range of variation for the extinction and absorption parameters?

2. What is the best value to use for the specific absorption of pure elemental carbon?

3. Can we define the reasons for the apparent differences in the properties of urban lumber and forest vegetative fuels?

4. Can parameters, such as elemental carbon emission factors, be defined that have a minimum variation and that will be useful in parameterizing models?

It is also important for the various groups making measurements to define quantities and make measurements in a consistent way. Differences in measurement and analysis techniques should be minimized, and intercomparisons between measurement groups should be made as often as possible.

REFERENCES

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National Research Council/National Academy of Sciences, The Effects on the Atmospher of a Major Nuclear Exchange, National Academy Press, Washington, DC, 1985.

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Seader, J. D., and I. N. Einhorn, Some physical, chemical, toxicological, and physiological aspects of fire smokes, 16th Symposium (International) on Combustion, The Combustion Institute, Pittsburg, PA, pp 1423-1445.

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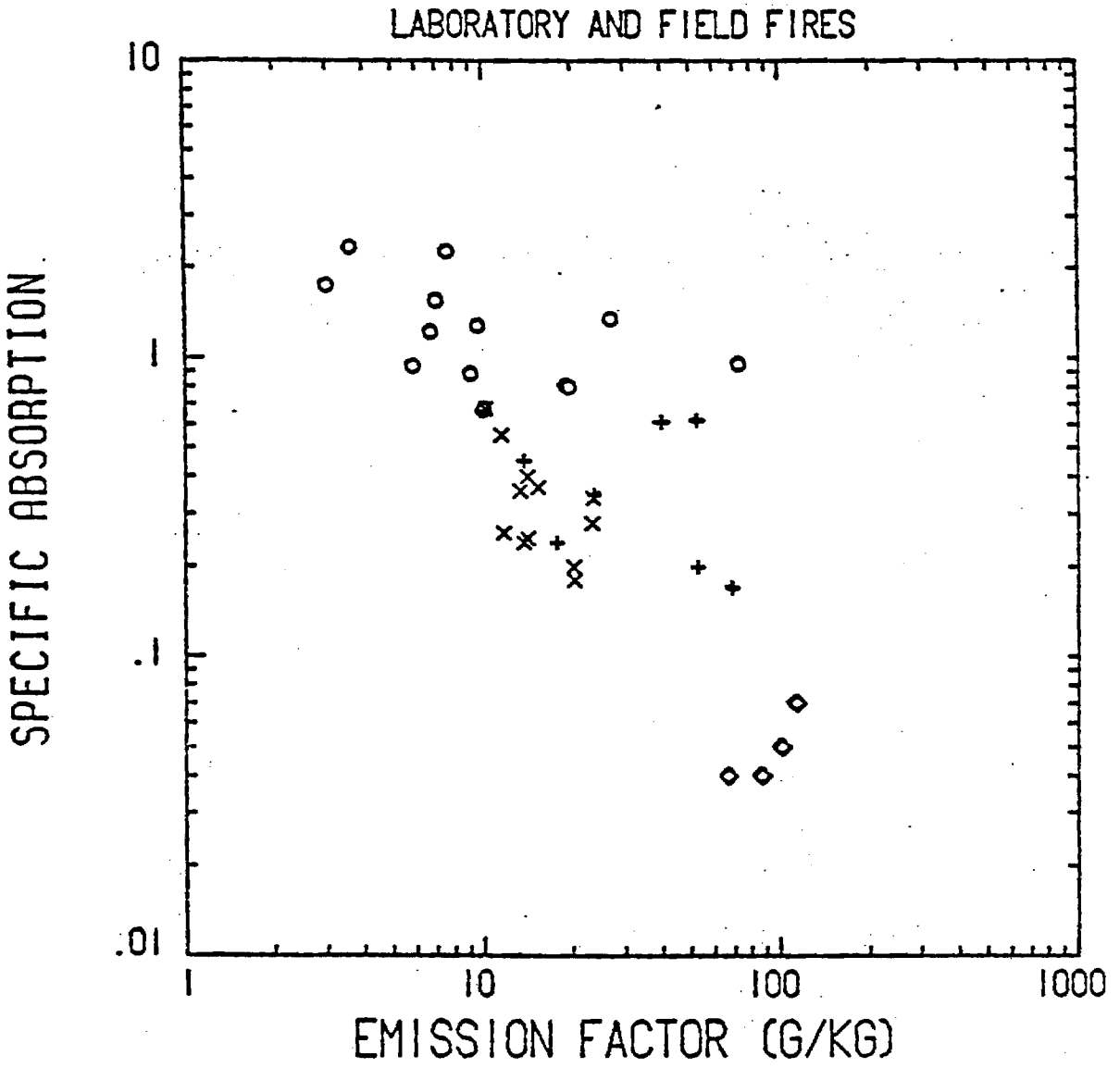
TABLE 2. Values of B_a, $\tilde{\omega}$, and n_2 averaged for all dates for each particle type. The last row gives an overall average.

Participant*	Soot (7/31,8/1,8/4, 8/6,8/7)			MB (8/1,8/4,8/8)			Salt (7/29,7/30,8/8)		
	B_a	$\tilde{\omega}$	n_2	B_a	$\tilde{\omega}$	n_2	B_a	$\tilde{\omega}$	n_2
1			0.56						
2									
3	6.45	0.180	0.883	2.11	0.442	0.163	0.065	0.988	
4	11.03	0.115		2.07	0.441	0.11	0.160	0.996	
5			0.0675			0.153			8.1×10^{-6}
6	7.00	0.180	1.04	0.976	0.626	0.03			
7						0.10			
8									
9	7.98	0.146		2.67	0.389		0.450	0.905	
10a	4.31	0.204	0.435	1.62	0.503	0.046	1.8×10^{-4}	1.00	1.6×10^{-5}
10b	5.37	0.180		1.28	0.561		0.159	0.966	
11	6.91	0.150	0.660						
12	11.37	0.090		4.46	0.290		~ 0	~ 1	~ 0
13									
14			0.422			0.203			5×10^{-3}
15	3.83	0.292		0.668	0.710				
Averages									
	7.14	0.171	0.581	1.98	0.495	0.115	0.139	0.971	1.26×10^{-3}

**Keyed to Table 1 in the preceding section (Section 7, Data Summary).*


LABORATORY AND FIELD FIRES
10
1
.1
.01
SPECIFIC ABSORPTION
1
10
100
1000
EMISSION FACTOR (G/KG)

6-35

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Ref: DNA001-86-C-0301
Progress Report 04

Mr. Lawrence Bates
Headquarters
Defense Nuclear Agency (AM)
Washington, DC 20305-1000

Dear Mr Bates:

This letter represents the fourth monthly progress report of work sponsored by the Defense Nuclear Agency under RDT&E RMSS CODE B 4662 D RB 00095 RAAE 3220 A under Contract DNA001-86-C-0301. This report covers the period 1 January, 1987 to 31 January, 1987.

Activities during this reporting period included work in thermal characterization, small scale combustion testing, and program assessment.

The thermal characterization work included analysis of thermogravimetric measurements of three polymer materials, polypropylene, polyethylene, and polystyrene for heat decomposition in both nitrogen and an oxidizing atmosphere. Differences in the behavior of the three plastics were seen, although a more complete analysis will await the optical and microphysical measurements on the actual combustion emissions.

The small scale combustion work included some modifications to the tube furnace that was purchased for this effort and development of filter holders and filtttings for the collection of samples for the small scale combustion tests. Testing of burn procedures was accomplished.

In program assessment, E. M Patterson took part in a National Academy of Sciences meeting assessing the status of the research effort in Nuclear Winter studies. In this program, Dr. Patterson presented data from various sources on characterization of smoke emissions from a variety of fuels.

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It is planned to continue these efforts in the following month.

Sincerely,

Edward Patterson
Senior Research Scientist

cc: Dr. David Auton(CTM)

Georgia Institute of Technology
A UNIT OF THE UNIVERSITY SYSTEM OF GEORGIA
ATLANTA, GEORGIA 30332
SCHOOL OF GEOPHYSICAL SCIENCES 404/894-3893

Ref: DNA001-86-C-0301
Progress Report 05

Mr. Lawrence Bates
Headquarters
Defense Nuclear Agency (AM)
Washington, DC 20305-1000

Dear Mr Bates:

This letter represents the fifth monthly progress report of work sponsored by the Defense Nuclear Agency under RDT&E RMSS CODE B 4662 D RB 00095 RAAE 3220 A under Contract DNA001-86-C-0301. This report covers the period 1 February, 1987 to 28 February,1987.

During this reporting period, work was accomplished in the areas of thermal analysis, and small scale combustion.

In the area of thermal analysis measurements by means of thermogravimetric analysis were done for mixtures of kaolinite and polyethylene to investigate the possibilities of affect jon the decomposition rates. These studies showed that the major differences were due to differing amounts of polymer and the inert clay material. There appeared to be little differneces in the thermal properties of the polymer as seen in the shape and the temperature dependence of the weight vs temperature curve due to the admixture of the clay. Some further work on different polymers is planned later in the project.

In the area of small scale combustion we were able to successfully burn several small samples of polystyrene, polypropylene, and polyvinyl chloride and to collect the material. Due to problems with overloading the filter and changing the filter flow, we were not able to make quantitative determinations of mass emission factors, a goal of the work.

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Further thermal analysis measurements are not planned for the following months, although work in each of the other areas is planned to continue.

Sincerely,

Edward Patterson
Senior Research Scientist

cc: Dr. David Auton

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404/894-3893

Ref: DNA001-86-C-0301
Progress Report 06

Mr. Lawrence Bates
Headquarters
Defense Nuclear Agency (AM)
Washington, DC 20305-1000

Dear Mr Bates:

This letter represents the sixth monthly progress report of work sponsored by the Defense Nuclear Agency under RDT&E RMSS CODE B 4662 D RB 00095 RAAE 3220 A under Contract DNA001-86-C-0301. This report covers the period 1 March, 1987 to 31 March, 1987.

During this reporting period, work continued on the small scale combustion tests, and work was begun on preparations for the larger scale combustion tests using the Combustion Products Test Facility.

For the small scale tests, we completed the analysis of the specific absorption values for smoldering and for flaming combustion for the three plastic material investigated. These measurements showed a range of B_a values for all of the materials. Polystyrene showed the smallest variation with values clustering near 5 m^2/gm. PVC data showed a range of values from nearly 1 to 9 with a mean near 5 and polypropylene smoke showed a range of values near 3. Smoldering B_a values were in general much less than the flaming B_a values as expected. These small scale tests indicated that plastics in flaming combustion exhibit a range of B_a values, that the range can be from near 1 to more than 10 m^2/gm, that the variation appears to be related to fire conditions, and that the variation is related to the particulate matter emission factor variation as in the case of the burning cellulosic materials.

The small scale combustion facilities were not as well instrumented as the larger scale combustion facilities, so as a result of the variation in the small scale processes we turned our attention to the larger scale fires that could be conducted in the Combustion Products Test Chamber. Investigation of needs for a computerized data acquaisition system for this chamber were continued.

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It is expected that work in the following months focus more on work with the larger scale combustion facility.

Sincerely,

Edward Patterson

cc: Dr David Auton

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SCHOOL OF GEOPHYSICAL SCIENCES 404/894-3893

Ref: DNA001-86-C-0310
Progress Report 07

Mr. Lawrence Bates
Headquarters
Defense Nuclear Agency (AM)
Washington, DC 20305-1000

Dear Mr Bates:

This letter represents the seventh monthly progress report of work sponsored by the Defense Nuclear Agency under RDT&E RMSS CODE B 4662 D RB 00095 RAAE 3220 A under Contract DNA001-86-C-0301. This report covers the period 1 April, 1987 to 30 April, 1987.

During this reporting period, efforts were focused on preparation of the combustion products test chamber (CPTC), the combustion products sampling system, and the in situ optical particulate monitoring system for testing new samples.

Most of this work centered on the modifications of the upper stack section which connects the CPTC sampling section to a larger diameter refractory pipe leading to the roof. The CPTC and the sampling section are shown in the attached Figure 1, while the original upper stack is shown in the attached Figure 2. The modifications of the upper stack were necessary to accomodate the sampling requirements of this DNA project, while maintaining the ability to use the CPTC for additional work. One requirement was for the upper section to be easily interchangable, thus the upper stack was cut into three sections, each of which was fitted with flanges for bolting the sections together. The three sections are shown in the attached Fig. 3. The lowest section is a fixed six-inch long spacer of 8 5/8-inch diameter pipe needed to raise the upper sections above the 90^{o}-scattering optical systems which were bracketed to the lower flange of the original upper stack. Otherwise the 90^{o} scattering system would have to be removed and replaced each time a different upper system was installed, requiring tedious realignment. The next section is a removable eleven inch long pipe which comprises the additional test section. The upper section provides an improved connection to the 11 1/4-inch diameter refractory pipe leading to the roof. This was accomplished by attaching a 12-inch O.D. collar (11.5 inch I.D.) concentric to the original pipe just above the sampling exhaust line. This allows the

refractory pipe to fit between the collar and the 8-5/8 diameter pipe, thus providing a much better seal. The gap between the collar and the refractory pipe is only about 1/8 inch wide and is easily sealed with duct tape. The shop drawing of the transition section is shown in the attached Figure 4.

In order to facilitate the interchanging of the sections, the upper transition section, which weighs 51 lbs, must be supported. A system of pulleys and counterweights was installed (Fig. 3) which keeps the transition section pulled up against the refractory pipe during removal or installation of the test section, but allows it to be easily lowered for bolting the sections together. This system will allow interchanging the two test sections by one person without disturbing the alignment of the laser systems.

Also during this period, Dr. Edward Patterson presented an overview of the results to date at the Global Effects review meeting in Santa Barbara, California. He also presented some results of cooperative measurements with the US Forest Service on the Lodi Canyon burns.

Sincerely,

Edward Patterson

cc: Dr David Auton

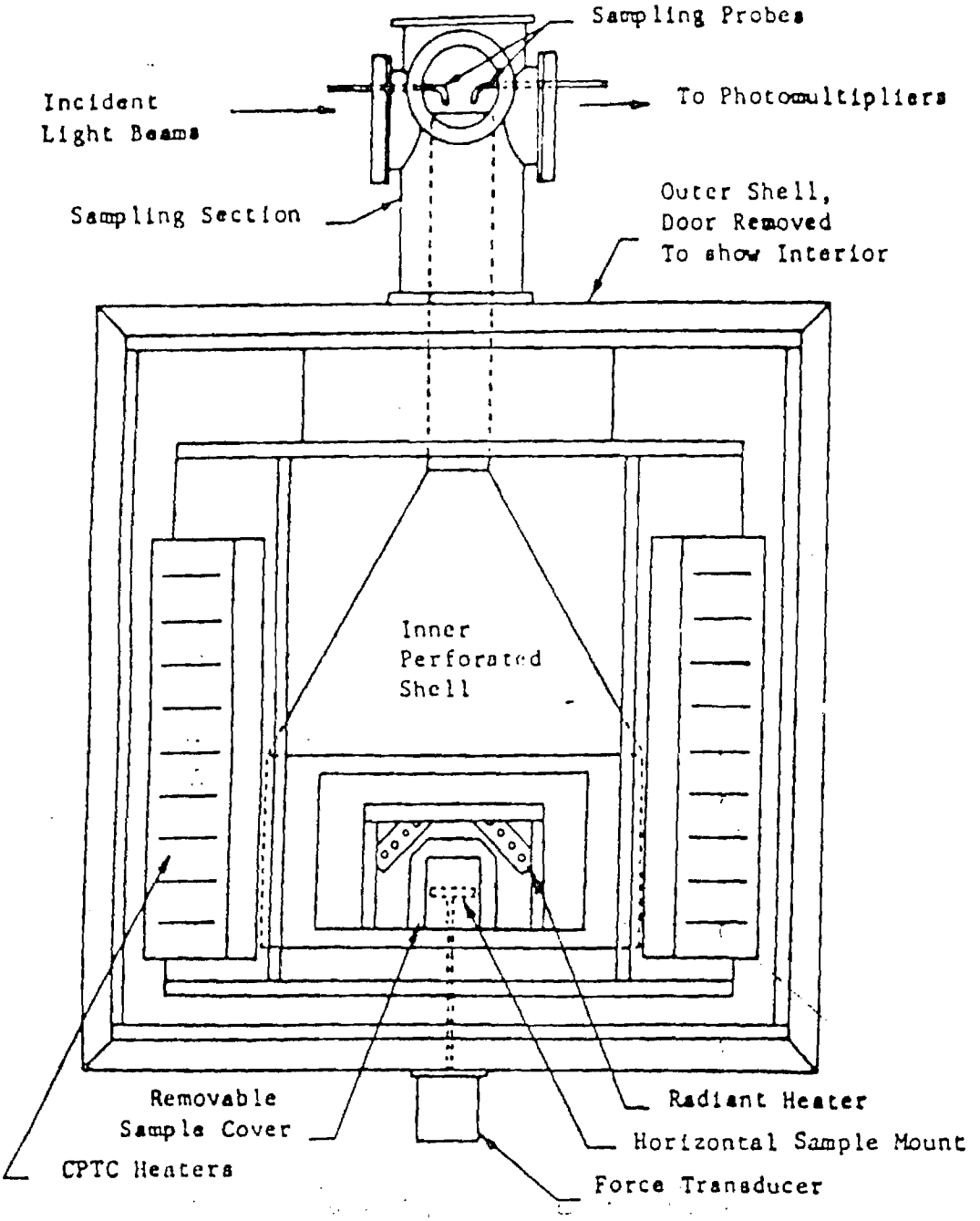

Figure 1. Combustion Products Test Chamber.

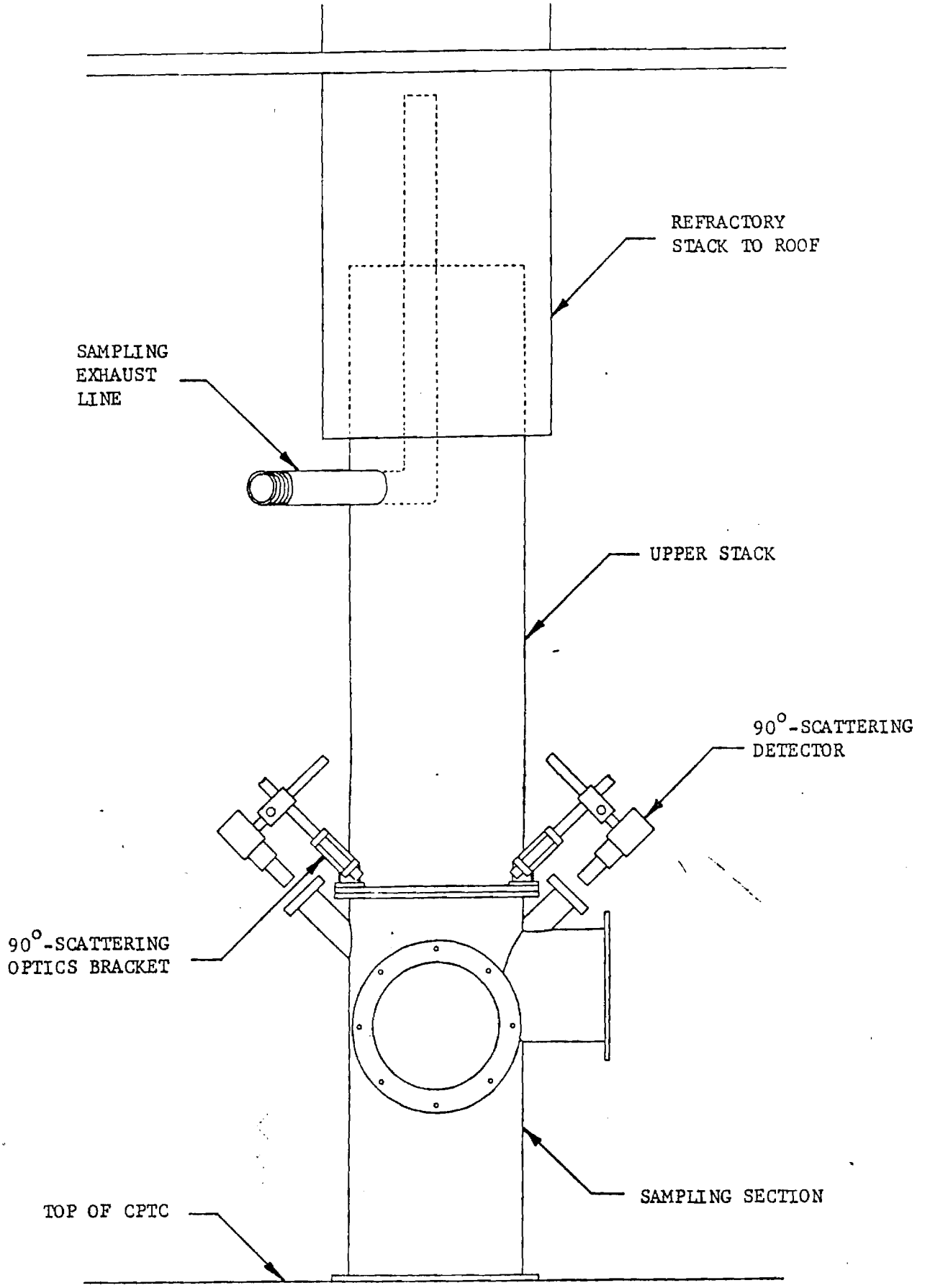

Figure 2. Original CPTC Upper Stack Assembly.

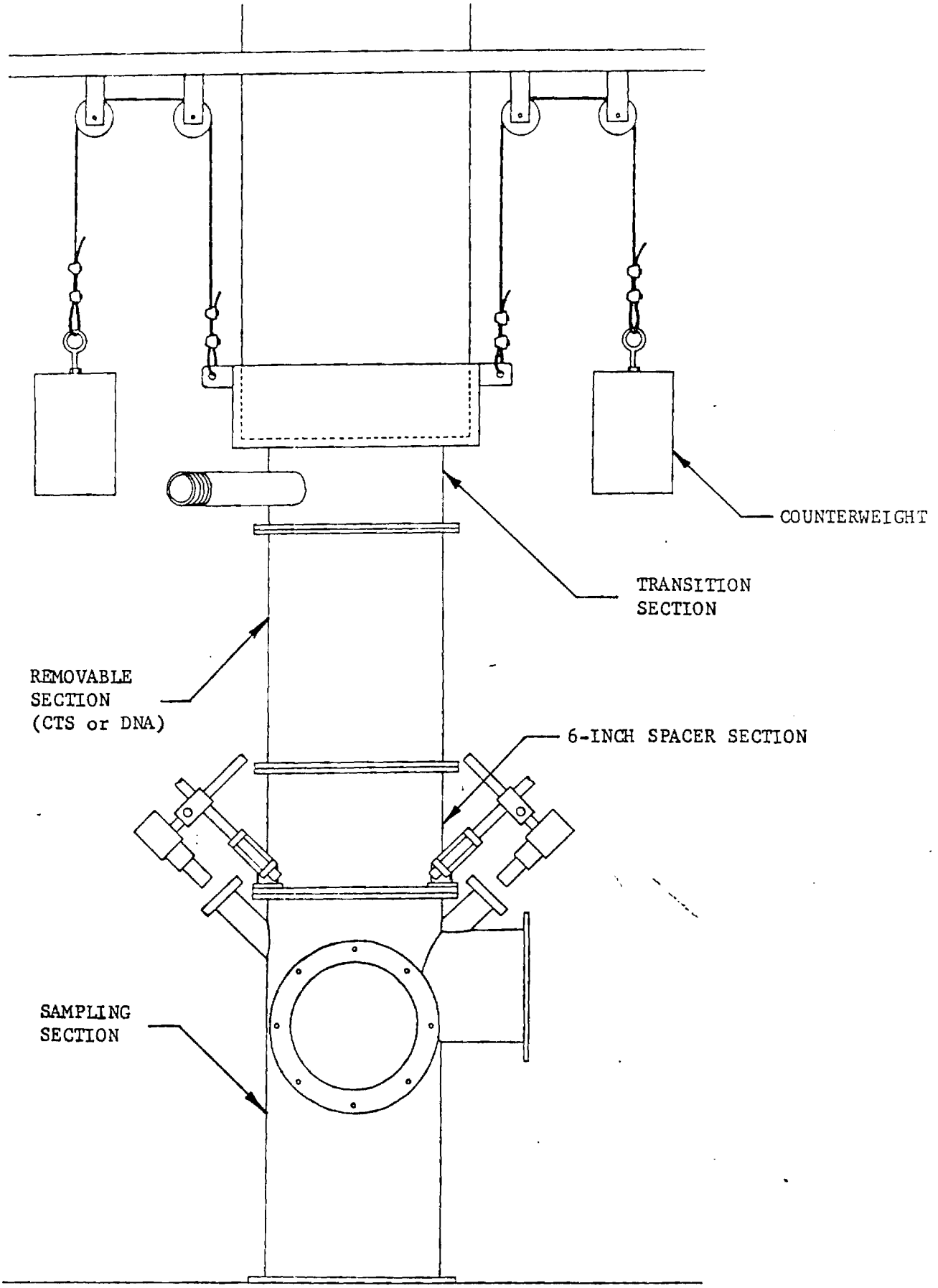

Figure 3. Modified CPTC Upper Stack Assembly.

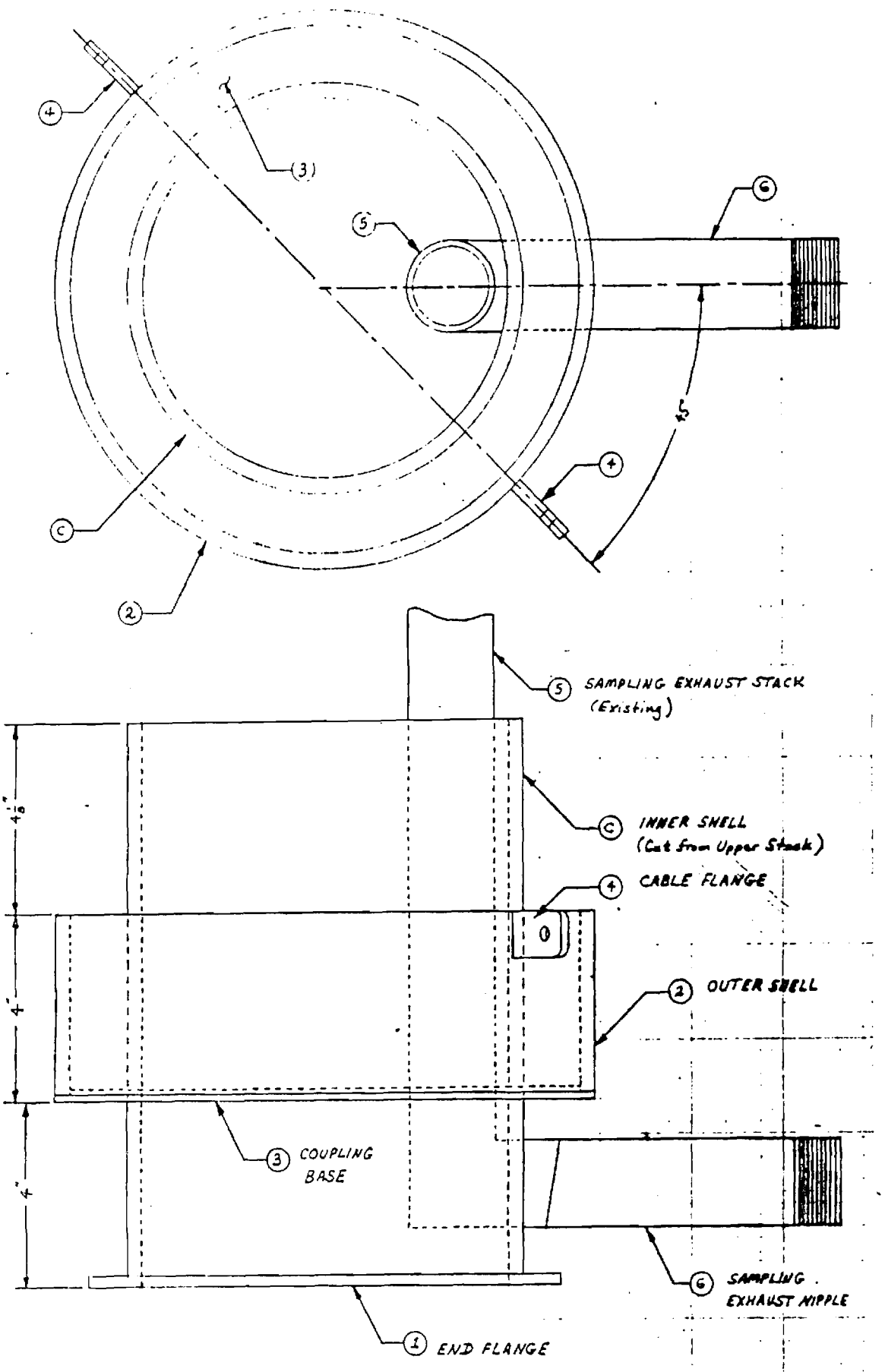

Figure 4. Transition Section.

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Ref: DNA001-86-C-0310
Progress Report 08

Mr. Lawrence Bates
Headquarters
Defense Nuclear Agency (AM)
Washington, DC 20305-1000

Dear Mr Bates:

This letter represents the eighth monthly progress report of work sponsored by the Defense Nuclear Agency under RDT&E RMSS CODE B 4662 D RB 00095 RAAE 3220 A under Contract DNA001-86-C-0301. This report covers the period 1 May, 1987 to 31 May, 1987.

During this reporting period, work continued on the preparation of the Combustion Products Test Chamber (CPTC) and ancillary equipment for test burns. Installation of the test section above the CPTC required for this project was done. In addition, work continued on the preparation of the computerized data acquisition system (CDAS), the combustion products sampling system, and the in situ optical particulate measuring system for testing the new samples.

In preparing the CPTC for testing, the inner shell door asssembly was found to be in poor condition; the insulation material was deteriorating and was structurally unstable. Thus a new improved inner shell door assembly was designed, and the shop drawings were completed. This door assembly is to be fabricated from 1/8 " thick stainless steel instead of the structurally weak insulation material used previously.

The installation of CDAS was begun. This system is based on an IBM PC compatible computer with a Metrabyte data acquistion board. The Metrabyte system will acquire up to 16 chanels of analog data, will digitize the data, and provide for the transfer to the computer memory. Plans are for the voltage output of the optical scattering channels, the optical attenuation channels, and the mass of the fuel to be recorded by the CDAS.

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Connections between the CDAS and the amplifiers outputting the CPTC data were designed and initial testing was begun.

Sincerely yours,

Edward Patterson

cc: Dr David Auton

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Ref: DNA001-86-C-0310
Progress Report 09

Mr. Lawrence Bates
Headquarters
Defense Nuclear Agency (AM)
Washington, DC 20305-1000

Dear Mr Bates:

This letter represents the ninth monthly progress report of work sponsored by the Defense Nuclear Agency under RDT&E RMSS CODE B 4662 D RB 00095 RAAE 3220 A under Contract DNA001-86-C-0301. This report covers the period 1 June, 1987 to 30 June, 1987.

During this reporting period, work on refurbishing the Combustion Products Test Facility continued. In addition, several improvements were made in preparing the optical systems and their signal handling systems. the laser system was modified to make alignment adjustments easier and more accurate. Fine tuning of the argon-ion laser increased its power from 9 mw to 22 mw. The plane of polarization of the incident laser beam was aligned at an angle of 45^{o} to the vertical axis of the CPTC stack as required by the 90 scattering optics system.

In this procedure, it was discovered that the thick quartz incident beam window caused a 5 rotation and an unacceptable depolarization of the incident laser beam. Thus the quartz window was replaced by a thin optical glass window. Fine alignment adjustmnets were made on the forward scattering receiving optics and detectors so that both the 5 and the 15 detectors receive scattered light form the same optical sampling volume in the smoke plume. A new rack and new input and output cables for the DC amplifiers that process the photomultiplier signals were obtained and installed.

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Installation of the Computerized Data Acquisition System was completed and testing of the system was begun.

Sincerely yours,

Edward Patterson

cc: Dr David Auton

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Ref: DNA001-86-C-0310
Progress Report 10

Mr. Lawrence Bates
Headquarters
Defense Nuclear Agency (AM)
Washington, DC 20305-1000

Dear Mr Bates:

This letter represents the tenth monthly progress report of work sponsored by the Defense Nuclear Agency under RDT&E RMSS CODE B 4662 D RB 00095 RAAE 3220 A under Contract DNA001-86-C-0301. This report covers the period 1 July, 1987 to 31 July, 1987.

Work continued at a reduced level in this month due to contract difficulties. The major accomplishment was a continuation of the work testing the computer data acquisition system and the initiation of the development of programs to control the data acquisition. This programming is necessary to set the acquisition parameters and to acomplish the transfer of the individual data into appropriate memory locations.

This effort is to be continued in the following reporting period.

Sincerely yours,

Edward Patterson

cc: Dr. David Auton

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rm 62

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Ref: DNA001-86-C-0310
Progress Report 11

Mr. Lawrence Bates
Headquarters
Defense Nuclear Agency (AM)
Washington, DC 20305-1000

Dear Mr Bates:

This letter represents the eleventh monthly progress report of work sponsored by the Defense Nuclear Agency under RDT&E RMSS CODE B 4662 D RB 00095 RAAE 3220 A under Contract DNA001-86-C-0301. This report covers the period 1 August, 1987 to 31 August, 1987.

Work continued at a reduced level in this month due to the contract difficulties of the previous month. The major accomplishment was a completion of the testing of the computer data acquisition system and the successful tying together of the optical sensors and the data acquisition system. In addition, the development of programs to control the data acquisition process continued. Initial testing of these program modules began.

This effort is to be continued in the following reporting period.

Sincerely yours,

Edward Patterson

cc: Dr. David Auton

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Ref: DNA001-86-C-0310
Progress Report 12

Mr. Lawrence Bates
Headquarters
Defense Nuclear Agency (AM)
Washington, DC 20305-1000

Dear Mr Bates:

This letter represents the twelfth monthly progress report of work sponsored by the Defense Nuclear Agency under RDT&E RMSS CODE B 4662 D RB 00095 RAAE 3220 A under Contract DNA001-86-C-0301. This report covers the period 1 September, 1987 to 30 September, 1987.

Work continued at a reduced level in this month due to the contract difficulties of the previous months. The major accomplishment of this reporting system was the completion of the program development and testing for the control of the data acquisition process.

The data acquisition capabilities that have been developed provide for sampling input voltages from a maximum of 16 channels at sampling rates of more than 10 hz. These voltages are read as integers with 12 bit resolution and stored as binary numbers in the individual arrays. These binary integers are converted to decimal integers and are averaged to provide lower temporal resolution, lower noise data which are then stored in averaged data arrays. The operator has the capability to modify the number of different channels sampled, the time of the run, and the number of channels for each averaging calculation.

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The development of the program modules for the reduction of these data will be emphasized in the following reporting period.

Sincerely yours,

Edward Patterson
Senior Research Scientist

cc: Dr. David Auton

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Ref: DNA001-86-C-0310
Progress Report 13

Mr. Lawrence Bates
Headquarters
Defense Nuclear Agency (AM)
Washington, DC 20305-1000

Dear Mr Bates:

This letter represents the thirteenth monthly progress report of work sponsored by the Defense Nuclear Agency under RDT&E RMSS CODE B 4662 D RB 00095 RAAE 3220 A under Contract DNA001-86-C-0301. This report covers the period 1 October, 1987 to 31 October, 1987.

Work continued at a reduced level in this month due to the contract difficulties of the previous months. The work during this reporting period emphasized the continuation of the development of procedures for the reduction of the data from the Combustion Products Test Chamber. The major accomplishment of this reporting period was the completion of program modules for converting the raw integer output arrays of the data acquisition programs to data suitable for analysis of the desired scientific parameters.

This data reduction module combines the separate arrays for each channel of averaged input and converts the individual voltages to transmission values and attenuation parameters for the two optical wavelengths and relative scattering values and scattering ratios for the measured scattering at the two angles of 5 and 15 degrees. These data are combined with a time value calculated from the known sample acquisition rate and averaging parameter so that two combined arrays are produced in which the calculated quantities are output with associated time values. These combined arrays are output as ASCII values for use by plotting programs and other analysis programs.

A copy of the source code for this data analysis module is attached to this report.

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The continuation of the development of other program modules for the analysis of these data will be emphasized in the following reporting period.

Sincerely yours,

Edward Patterson
Senior Research Scientist

cc: Dr. David Auton

```
      program dnadt1


C     Program takes raw integer files and converts to real, analyzed
C     numbers for plotting  --5 files are read in --2 ext, 2 sca, 1 wt

      character*30 runid
      dimension ifld1a(400),ifld2a(400),ifld3a(400),ifld4a(400)
      dimension ifld5a(400),time(400),awt(400)
      dimension transr(400),transb(400),attr(400),attb(400)
      dimension sca5(400),sca15(400),rat(400)
      open(21,file = ' ',status = 'old')
      open(22,file = ' ',status = 'old')
      open(23,file = ' ',status = 'old')
      open(24,file = ' ',status = 'old')
      open(25,file = ' ',status = 'old')
      write(*,'(a\)')'   enter ID for data'
      read(*,'(a)')runid
      write(*,'(a\)')'   enter number of points to process '
      read(*,'(i5)')numpts

 0    read(21,*,end=30)ifld1a

 0    write(*,'(i5)')numpts
      write(*,'(i10)')ifld1a
      read(22,*,end=40)ifld2a
 0    read(23,*,end=50)ifld3a
 0    read(24,*,end=55)ifld4a
 5    read(25,*,end=60)ifld5a
 0    continue
      do 70 i=1,numpts
      time(i) = 2.5 + 5.0*(i-1)
 0    continue

      do 120 i= 1, numpts
      ifld1a(i)= -ifld1a(i)
      ifld2a(i)= - ifld2a(i)
      ifld3a(i)= -ifld3a(i)
      ifld4a(i)= -ifld4a(i)
 0    continue

      write(*,'(a\)')' enter begin and end pts for 100% trans avg '
      read (*,*)it1,it2
      write(*,'(a\)')' enter begin and end pts for end of run mass '
      read(*,*)ifm1,ifm2
      write(*,'(a\)')' enter amount of material burned (in gms): '
      read(*,*)afuel
      isum1= 0
      isum2 = 0
      isum5 = 0
      do 140 i=it1,it2
      isum1 = isum1 +ifld1a(i)
      isum2 = isum2 +ifld2a(i)
      isum5 = isum5 +ifld5a(i)
 0 continue
      idif = it2-it1+1
      asum1 = isum1/idif
      asum2 = isum2/idif
      asum5 = isum5/idif
```

```
    ifsum5 = 0
    do 160 i = ifm1,ifm2
    ifsum5 = ifsum5 + ifld5a(i)
160 continue
    afsum5 = ifsum5/(ifm2-ifm1+1)

    open(31, file ='tratt', status = 'new')
    open(32, file = 'srat', status = 'new')

    write(31,'(a30)')runid
    write(32,'(a30)')runid

    do 180 i=41,numpts
    transr(i) = ifld1a(i)/asum1
    transb(i) = ifld2a(i)/asum2
    if(transr(i).le.0.) transr(i) = 0.001
    if(transb(i).le.0.) transb(i) = 0.001

    attr(i) = -alog(transr(i))/0.114
    attb(i) = -alog(transb(i))/0.114
    awt(i) = afuel*(1-((ifld5a(i)-asum5)/(afsum5-asum5)))
    write(31,1020)time(i),transr(i),transb(i),attr(i),attb(i),awt(i)

 calculate and write to second file

    sca5(i) = ifld3a(i)/2048.
    sca15(i) = ifld4a(i)/2048.
    rat(i) = (sca15(i)/(sca5(i)+.0001))*0.6

    write(32,1021)time(i),sca5(i),sca15(i),rat(i)
 80 continue
 20 format(f7.1,2f6.3,3f6.2)
 21 format(f7.1,3f7.3)
    end
```

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Ref: DNA001-86-C-0310
Progress Report 14

Mr. Lawrence Bates
Headquarters
Defense Nuclear Agency (AM)
Washington, DC 20305-1000

Dear Mr Bates:

This letter represents the fourteenth monthly progress report of work sponsored by the Defense Nuclear Agency under RDT&E RMSS CODE B 4662 D RB 00095 RAAE 3220 A under Contract DNA001-86-C-0301. This report covers the period 1 November, 1987 to 30 November, 1987.

Work continued at a reduced level in this month due to the contract difficulties of the previous months. The work during this reporting period emphasized the continuation of the development and testing of procedures for the use of the Combustion Products Test Chamber and the collection and analysis of data from the Chamber. The major accomplishment of this reporting period was the initiation of testing of the Chamber and its Data Acquisition System and the development of additional program modules needed for the data analysis.

The initial tests were generally successful, although there were some deficiencies in the collection of the filter samples, and a modification of the sampling lines was begun.

As a part of this effort a program module DNAAVG1 was developed to calculate average values of the optical quantities, the attenuation coefficients and the scattering values, for comparison with the collected samples as well as with the fuel consumption data.

A copy of the source code for this data analysis module is attached to this report.

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The continuation of the development of procedures for the test burns will be continued in the following reporting period.

Sincerely yours,

Edward Patterson
Senior Research Scientist

cc: Dr. David Auton

```
      program dnaavg1

      character*30 runid
      dimension time(400),awt(400)
      dimension transr(400),transb(400),attr(400),attb(400)
      dimension sca5(400),sca15(400),rat(400)
      open(21,file = ' ',status = 'old')
      open(22,file = ' ',status = 'old')
      read(21,'(a)')runid
      read(22,'(a)')runid
      write(*,'(a\)')'   enter number of points to read in '
      read(*,'(i5)')numpts
      do 120 i=1,numpts
      read(21,1020)time(i),transr(i),transb(i),attr(i),attb(i),awt(i)
      read(22,1021)time(i),sca5(i),sca15(i),rat(i)
20    continue
      write(*,'(a\)')' enter begin and end pt nums for calc of avg '
      read (*,*)iavg1,iavg2

      sumr = 0.
      sumb = 0.
      sum5 = 0.
      sum15 = 0.
      sumrt = 0.

      do 140 i=iavg1,iavg2
      sumr = sumr + attr(i)
      sumb = sumb + attb(i)
      sum5 = sum5 + sca5(i)
      sum15 = sum15 + sca15(i)
      sumrt = sumrt +rat(i)*sca15(i)
40    continue
      idif = iavg2-iavg1+1
      asumr = sumr/idif
      asumb = sumb/idif
      asum5 = sum5/idif
      asum15 = sum15/idif
      asumrt = sumrt/sum15

      write(*,1025) iavg1,iavg2, asumr, asumb,asum5,asum15,asumrt

20    format(f7.1,2f6.3,3f6.2)
21    format(f7.1,3f7.3)
25    format('  first point for average is ',i3,/
     &'  Last point for average is ',i3,//
     &'  average red extinction is  ',f6.3,/
     &'  average blue extinction is ',f6.3,//
     &'  average  5 scatter is  ',f7.3/
     &'  average 15 scatter is  ',f7.3//
     &'  average ratio is ',f5.3)
      end
```

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MONTHLY PROGRESS REPORT: 15

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Ref: DNA001-86-C-0310
Progress Report 16

Mr. Lawrence Bates
Headquarters
Defense Nuclear Agency (AM)
Washington, DC 20305-1000

Dear Mr Bates:

This letter represents the sixteenth monthly progress report of work sponsored by the Defense Nuclear Agency under RDT&E RMSS CODE B 4662 D RB 00095 RAAE 3220 A under Contract DNA001-86-C-0301. This report covers the period 1 January, 1988 to 31 January, 1988.

The effort in this time period was in two different areas, continuation of development of test procedures and data analysis methodologies and conducting test burns.

Development during this time period included tests of different procedures for the collection of data using the Combustion Products Test Chamber. The filter absorption apparatus was also brought on line, and the flows through the filter and the cascade impactor sampling systems were calibrated during this time period. The flow calibration was necessary because of the need to determine quantitative values of concentrations as part of the data analysis. Graphics analysis capabilities were enhanced with the development of a system for the preparation of presentation quality graphics from the data sets generated in our test burns.

Various test burns were done during this reporting period with high density polyethylene (HDPE) and polyvinyl chloride (PVC) as the fuels. We successfully acquired optical and physical data on the emisssions from the combustion of these fuels for several burn conditions. This data included specific extinction at two wavelengths, specific absorption at 633 nm, size distributions measured with the cascade impactor, and emission factors for total particulate emisssions and for elemental carbon. The optical data also provided the capability for the determination of optically effective sizes.

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We will continue to develop procedures and data collection capabilities for the test burns in the following reporting period. In particular we plan to add an optical particle counter for size analysis in the 1 micron size range to enhance our capabilities for these measurements.

Sincerely yours,

Edward Patterson
Senior Research Scientist

cc: Dr. David Auton

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MONTHLY PROGRESS REPORT: 17 & 18

Ref: DNA001-86-C-0310
Progress Report 19

Mr. Lawrence Bates
Headquarters
Defense Nuclear Agency (AM)
Washington, DC 20305-1000

Dear Mr. Bates:

This letter represents the nineteenth monthly progress report of work sponsored by the Defense Nuclear Agency under RDT&E RMSS CODE B 4662 D RB 00095 RAAE 3220 A under Contract DNA001-86-C-0301. This report covers the period 1 April, 1988 to 30 April, 1988.

During this time period, a series of data measurements were made on PVC, PMMA, and HDPE plastic materials. Optical measurements were made at a wavelength of 633 nm because of problems with the Argon laser. Measurements of the specific attenuation, emission factors and other optical properties was made. A listing of the data measurement runs is attached.

We will continue the measurements for the test burns in the following reporting period.

Sincerely yours,

Edward Patterson
Senior Research Scientist

cc: Major Richard Hartley

Test Burn Matrix --April, 1988

Material	Burn Conditions
PVC	High Flow (Air Only); Low Irradiance
PVC	High Flow (Mixed Air and N2); High Irradiance
PVC	Low Flow (Mixed Air and N2); High Irradiance
PVC	High Flow (Mixed Air and N2); High Irradiance
PVC	Low Flow (Mixed Air and N2); High Irradiance
PMMA	High Flow (Air Only); Low Irradiance
Polystyrene	High flow (Air Only); Low Irradiance

Ref: DNA001-86-C-0310
Progress Report 20

Mr. Lawrence Bates
Headquarters
Defense Nuclear Agency (AM)
Washington, DC 20305-1000

Dear Mr. Bates:

This letter represents the twentieth monthly progress report of work sponsored by the Defense Nuclear Agency under RDT&E RMSS CODE B 4662 D RB 00095 RAAE 3220 A under Contract DNA001-86-C-0301. This report covers the period 1 May, 1988 to 31 May, 1988.

During this time period, a series of data measurements were made on combinations of PVC, and HDPE plastic materials and sand to investigate the effect of such mixtures on the emissions properties of the smokes. Measurements were made for a series of wood burnes also, including one with a mixed wood and plastic fuel loading. Optical measurements were made at a wavelength of 633 nm only. as in the previous month.

Measurements of the specific attenuation, emission factors and other optical properties was made. A listing of the data measurement runs is attached.

We will continue the measurements for the test burns in the following reporting period.

Sincerely yours,

Edward Patterson
Senior Research Scientist

cc: Major Richard Hartley

Test Burn Matrix -- May, 1988

Material	Burn Conditions
PVC+Sand	High Flow (Air Only); Low Irradiance
HDPE+Sand	High Flow (Air Only); Low Irradiance
Red Oak	High Flow (Air Only); High Irradiance
Red Oak	Low Flow (Mixe Air and N2); High Irradiance
Red Oak	Low Flow (Mixed Air and N2); High Irradiance
Red Oak+HDPE	High flow (Air Only); High Irradiance

Ref: DNA001-86-C-0310
Progress Report 21

Mr. Lawrence Bates
Headquarters
Defense Nuclear Agency (AM)
Washington, DC 20305-1000

Dear Mr. Bates:

This letter represents the twenty first monthly progress report of work sponsored by the Defense Nuclear Agency under RDT&E RMSS CODE B 4662 D RB 00095 RAAE 3220 A under Contract DNA001-86-C-0301. This report covers the period 1 June, 1988 to 30 June, 1988.

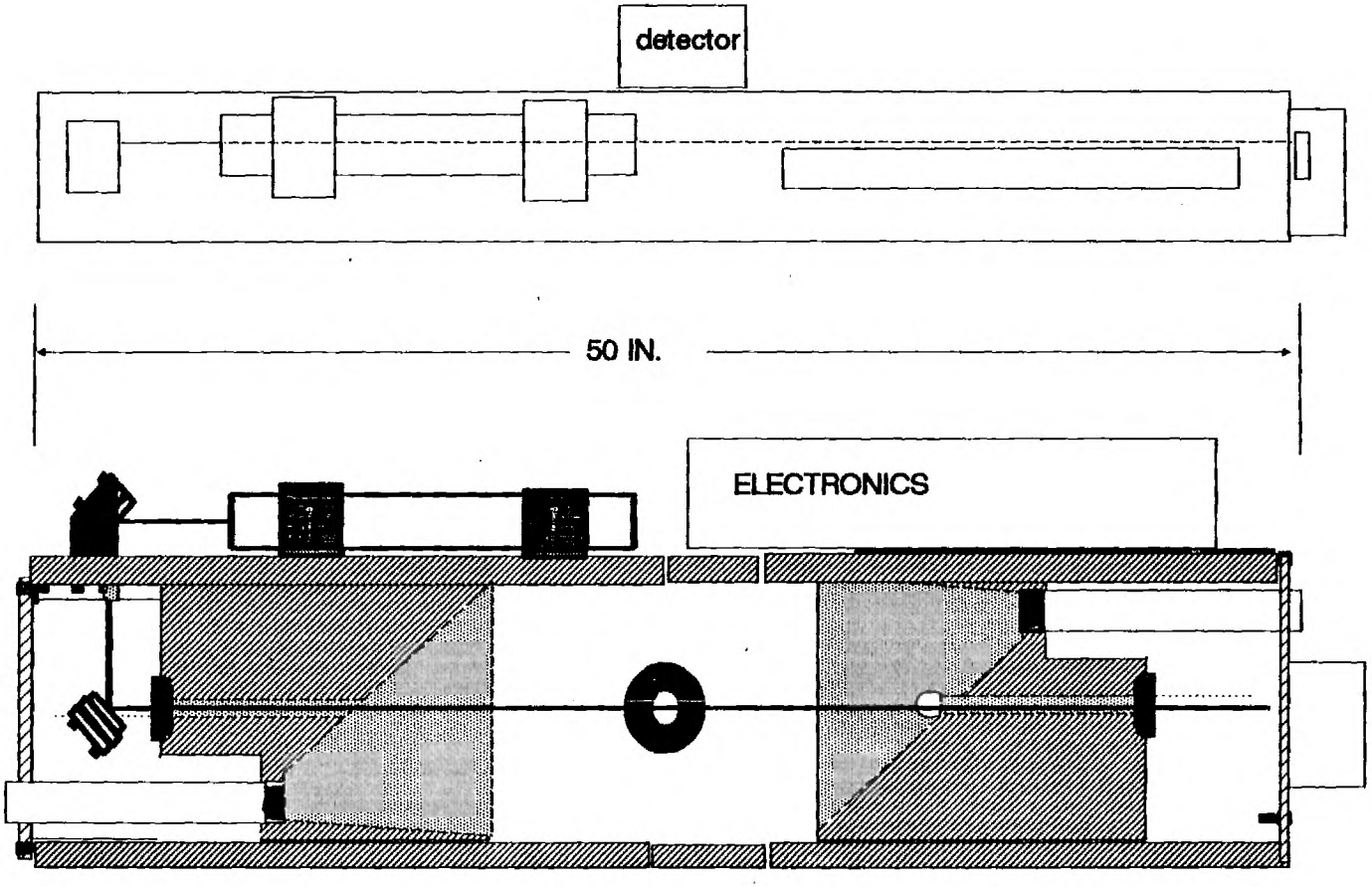
During this time period, effort was directed to the development of the instrument for the direct measurement of single scatter albedo. This transmissometer-nephelometer operates by the simultaneous measurement of aerosol scattering and transmission from which attenuation is determined. The single scatter albedo, which is a measure of the importance of the smoke in producing absorption effects, is a quantity of direct importance in possible global effects scenarios. A diagram of the instrument is shown in the attached figure.

We will continue the development of the single scatter albedo measurement instrument in the following reporting period.

Sincerely yours,

Edward Patterson
Senior Research Scientist

cc: Major Richard Hartley


detector
50 IN.
ELECTRONICS

Ref: DNA001-86-C-0310
Progress Report 22

Mr. Lawrence Bates
Headquarters
Defense Nuclear Agency (AM)
Washington, DC 20305-1000

Dear Mr. Bates:

This letter represents the twenty second monthly progress report of work sponsored by the Defense Nuclear Agency under RDT&E RMSS CODE B 4662 D RB 00095 RAAE 3220 A under Contract DNA001-86-C-0301. This report covers the period 1 July, 1988 to 30 July, 1988.

During this time period, effort was directed to the continued development of the instrument for the direct measurement of single scatter albedo. The construction of the unit was completed and a series of calibration tests were done. Two approaches to calibration were taken. In the first, measurements the scattering of a freon gas were done and the calibration was determined from the known scattering properties of the freon gas. In the other method, an aerosol was generated and introduced into the instrument and the calibration determined directly from the measured attenuation of the laser beam. For consistency the two methods should agree. Our results indicate that the two methods are in agreement within a few percent.

We will continue the development of the single scatter albedo measurement instrument and will begin the integration of the instrument into the other burn chamber integration in the following reporting period.

Sincerely yours,

Edward Patterson
Senior Research Scientist

cc: Major Richard Hartley

Ref: DNA001-86-C-0310
Progress Report 23

Mr. Lawrence Bates
Headquarters
Defense Nuclear Agency (AM)
Washington, DC 20305-1000

Dear Mr. Bates:

This letter represents the twenty third monthly progress report of work sponsored by the Defense Nuclear Agency under RDT&E RMSS CODE B 4662 D RB 00095 RAAE 3220 A under Contract DNA001-86-C-0301. This report covers the period 1 August, 1988 to 31 August, 1988.

During this time period, effort was directed to the continued development of the instrument for the direct measurement of single scatter albedo and to the integration of this instrument into our measurement procedures. Test runs were made and procedures for the use of the instrument were developed. As a part of this development the sampling lines used for the collection of the aerosol samples were modified to accommodate the scattering-transmission nephelometer.

We will continue the instrument development and integration in the following reporting period.

Sincerely yours,

Edward Patterson
Senior Research Scientist

cc: Major Richard Hartley

Ref: DNA001-86-C-0310
Progress Report 24

Mr. Lawrence Bates
Headquarters
Defense Nuclear Agency (AM)
Washington, DC 20305-1000

Dear Mr. Bates:

This letter represents the twenty fourth monthly progress report of work sponsored by the Defense Nuclear Agency under RDT&E RMSS CODE B 4662 D RB 00095 RAAE 3220 A under Contract DNA001-86-C-0301. This report covers the period 1 September, 1988 to 30 September, 1988.

During this time period, effort was directed to the measurements of the smoke aerosol optical properties with the total system, including the instrument for the direct measurement of single scatter albedo. Test runs using HDPE fuel were made and analysis of the data was made. In addition a comparison of the measurements made with the nephelometer and the earlier measurements was made to as a way of investigation consistency of measurements. A dilution system was added to the nephelometer air sampling system to produce measurements that were consistent in form with the original system attenuation measurements. Development of this dilution system resulted in further modification in the sampling lines leading to the nephelometer.

We will continue the measurements and tests in the following reporting period.

Sincerely yours,

Edward Patterson
Senior Research Scientist

cc: Major Richard Hartley

Ref: DNA001-86-C-0310
Progress Report 25

Mr. Lawrence Bates
Headquarters
Defense Nuclear Agency (AM)
Washington, DC 20305-1000

Dear Mr. Bates:

This letter represents the twenty fifth monthly progress report of work sponsored by the Defense Nuclear Agency under RDT&E RMSS CODE B 4662 D RB 00095 RAAE 3220 A under Contract DNA001-86-C-0301. This report covers the period 1 October, 1988 to 31 October, 1988.

During this time period, effort was directed to the an analysis and interpretation of data from the tests and data collection burns performed in the preceding month. A paper describing the results of the project to date was presented at the Annual meeting of the American Association for Aerosol Science in Chapel Hill North Carolina. An Abstract of the paper is attached to this report.

We will continue the instrument development and integration in the following reporting period.

Sincerely yours,

Edward Patterson

Edward Patterson
Senior Research Scientist

cc: Major Richard Hartley

RELATIONSHIPS BETWEEN THE EMISSIONS PROPERTIES OF BURNING PLASTIC MATERIALS AND FUEL AND FIRE CONDITIONS DETERMINED FROM A LABORATORY STUDY--APPLICABILITY FOR NUCLEAR WINTER STUDIES.

E. M. Patterson, R. M. Duckworth, E. A. Powell, and J. W. Gooch, Georgia Institute of Technology, Atlanta, GA 30332.

The smoke emissions from burning plastic fuels would be a major component of urban fires started as a result of a nuclear exchange and, as such, would be important in determining climatic effects of these fires. We have used the results of a series of measurements of the optical and microphysical characteristics of these smokes to determine mean values of parameters to use in source term models and to investigate the relationships between smoke properties and fuel and fire conditions.

The measurements are laboratory scale measurements that have included measurements of mass emission factors, particle size distributions and effective optical sizes, specific extinction at two wavelengths, and specific absorption. The absorption measurements have been made using filter techniques as well as by simultaneous measurements of extinction and scattering.

Our studies have confirmed that the smoke emissions from plastic fuels have large absorption coefficients with particle sizes that are approximately one micron in diameter, but with significant differences in emission properties for the different plastic materials. The range of variation will be discussed and will be related to variation in the thermal and the chemical properties of the different plastic materials or fuel combinations and the different fire scales.

G-35-684

GEORGIA TECH RESEARCH CORPORATION

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April 30, 1990

Ref: DNA001-86-C-0310
Progress Report 25 26

Mr. Lawrence Bates
Headquarters
Defense Nuclear Agency (AM)
Washington, DC 20305-1000

Dear Mr. Bates:

This letter represents the final progress report for work sponsored by the Defense Nuclear Agency under RDT&E RMSS CODE B 4662 D RB 00095 RAAE 3220 A under Contract DNA001-86-C-0301. This report covers the period 1 November, 1988 to 30 April, 1990 and incorporates monthly progress reports 26 through 43.

During this time period, effort was directed to the measurement, analysis, and interpretation of data from test fires in the Georgia Tech Combustion products Test Chamber. A summary of activities by month follows:

November, 1988-- Measurements were made in the Georgia Tech combustion products test chamber on PMMA and PVC fuels. These and following measurements were made with the full complement of instrumentation. Measurements were made under a variety of fire conditions.

December, 1988-- Measurements were made in the combustion products test chamber on PVC and fibreglas fuels.

January, 1989-- Measurements were made in the combustion products test chamber on PMMA and mixtures of PMMA with sand.

February, 1989-- Measurements were made in the combustion producst test chamber on PMMA.

March, 1989-- Analysis of earlier measurements was done during this month and some additional calibrations were made on the aerosol scattering and absorption measurement instrument.

April, 1989-- Measurements of #2 and #5 fuel oil were begun in the combustion products test chamber.

May, 1989-- Measurements of K1 kerosene and asphalt were made

in the combustion products test chamber.

June, 1989-- A set of test runs with PMMA fuel were run to resolve problems that developed with respect to the combustion products test chamber. Additional test burns were made with PMMA, PVC, and rubber fuels.

July, 1989-- Test burn measurements were made with polycarbonate, polystyrene, oak, and mixtures of wood with the plastic fuels.

August, 1989-- The measurement phase of the program concluded during this month. Final test burns were conducted on mixtures of fuels with sand and with ambient aerosols.

September, 1989-- Analysis of the test burn data from the preceeding months was begun.

October, 1989-- The analysis of the test burn data continued.

November, 1980-- The analysis of the test burn data continued.

December, 1989-- The analysis of the test burn data continued. Some problems with the data set were resolved during this analysis.

January, 1990-- The analysis of the test burn data continued during this month.

February, 1990-- The analysis of the test burn data continued during this month.

March, 1990-- The analysis of the test burn data continued during this month.

April, 1990-- During this month, the analysis of the data was concluded and a paper presenting this work was prepared for Atmospheric Environment. This paper, which has been submitted, is attached to this report as an appendix. The draft Final Report has also been prepared for submission to the Defense Nuclear Agency.

Sincerely yours,

Edward Patterson
Senior Research Scientist

cc: Major Richard Hartley

SUBMITTED TO
ATMOSPHERIC ENVIRONMENT

Measurements of the Emissions Properties of Burning Plastic Material for Nuclear Winter Studies

by

E. M. Patterson, R. M. Duckworth, C. M. Wyman
E. A. Powell, and J. W. Gooch

Georgia Institute of Technology
Atlanta, Georgia 30332

April, 1990

ABSTRACT

We have measured the optical and microphysical properties of smoke from burning plastic materials and other components of the urban fuel mix, including hydrocarbons, rubber, and wood, to provide information on the source term for possible aerosol clouds injected into the atmosphere following large scale urban fires. Our measurements included measurements of emission factors; in-situ optical measurements of aerosol absorption, scattering, and attenuation; and collection of particles using both filters and cascade impactors for size and mass concentration determinations.

These measurements were made under a variety of conditions to investigate the range of variation of these optical parameters and to relate observed differences in smoke properties to differences in fuel composition and fire conditions.

INTRODUCTION

We have measured the optical and microphysical properties of smoke from burning plastic materials and other components of the urban fuel mix, including hydrocarbons, rubber, and wood, to provide information on the source term for possible aerosol clouds injected into the atmosphere following large scale urban fires. Our measurements included measurements of emission factors; in-situ optical measurements of aerosol absorption, scattering, and attenuation; and collection of particles using both filters and cascade impactors for size and mass concentration determinations.

These measurements were made under a variety of conditions of radiant heating, ventilation, and smoke concentration to investigate the range of variation of these optical parameters, to relate observed differences in smoke properties to differences in fuel composition and fire conditions, and to investigate the effect of scaling.

Measurement techniques were developed as a part of this program to improve our ability to make real time, accurate measurement of smoke optical properties. As a part of this development activity, we produced a compact instrument for the measurement of the scattering, attenuation, and single scattering albedo of the smoke

emissions from the fuels.

SMOKE PARAMETERS DETERMINING OPTICAL EFFECTS

The optical effects of a smoke aerosol will be determined by the optical properties of the aerosol and by the amount of the smoke produced by a given amount of fuel, the emission factor for the fuel. Aerosol optical properties can be described by several quantities. The optical depth δ as a function of wavelength is a measure of the total optical effect of the aerosol layer. The optical depth of an atmospheric aerosol layer is defined by the equation

$$\delta = - \ln (I/I_o)$$

in which I is the intensity of a direct beam of light after passing vertically through the layer and I_o is the initial intensity. The extinction coefficient, σ_e, is a measure of the amount of light removed from a beam of light per unit length. For a given path, δ and σ_e are related by the equation

$$\delta = \int \sigma_e(x)\,dx$$

The extinction of light is due to both scattering, in which the light is removed from the incident beam and

redirected, and absorption, in which the light is absorbed by the particles. The coefficients are related by the equation

$$\sigma_e = \sigma_s + \sigma_a$$

To relate these quantities to the microphysical properties of the aerosol, we can define specific attenuation, scattering and absorption coefficients by ratioing the optical quantity to the mass concentration of the aerosol. These specific extinction or absorption coefficients are measures of the effectivness of a given amount of aerosol material in producing an optical effect. These specific coefficients are defined according to the equations

$$B_e = \sigma_e / M_c,$$

$$B_s = \sigma_s / M_c,$$

and

$$B_a = \sigma_a / M_c$$

with B_e the specific extinction, B_s the specific scattering, B_a the specific absorption, and M_c the mass concentration of the aerosol. As before, B_e is the sum of B_s and B_a.

In addition to the specific coefficients of the

aerosol discussed above, the material of the aerosol may be described by a refractive index m, with m = n - ik. n is the real component of the refractive index and k is the absorption index. The bulk refractive indices for the soot material are approximately 2 - i1 (Janzen, 1979); the soot particles consist of chainlike aggregates and the average or effective refractive index will be given by a mixing rule that takes account of the relative fraction of solids in the soot particle.

Given the refractive indices and the size distributions of the particles, the extinction, scattering and absorption coefficients can be calculated as a function of wavelength.

The single scattering albedo, ω_o, is defined as the ratio of the scattering coefficient to the extinction coefficient. For non-absorbing aerosols, the ω_o will be equal to 1 and the aerosol will be a white aerosol; for highly absorbing aerosols ω_o will be near 0 and the aerosol will be a black aerosol.

The angular distribution of the scattered light is given by the phase function of the aerosol, which can be calculated from the size distribution and the measured optical constants of the aerosol. For radiative transfer calculations, the phase function is often parameterized in terms of the asymmetry parameter, which is defined as the average cosine of the scattered light.

The emission factor is defined as the amount (mass)

of smoke produced for a given amount of fuel burned. The emission factor measurement can be combined with the specific attenuation and related measurements to define new quantities B_e',B_s', and B_a', which we call the fuel specific attenuation , scattering, and absorption coefficients. These quantities are defined by the equations

$$B_e' = B_e \times EF$$

$$B_s' = B_s \times EF$$

$$B_a' = B_a \times EF$$

The fuel specific quantities are of interest because, even though we have defined them in terms of the specific quantities and the emission factors, operationally, they depend only on the integrated optical measurements and the amount of fuel burned. Filter measurements to determine aerosol mass concentration are intermediate measuremnts that are not needed for final calculations, and any questions associated with the size range represented by the filter measurements are avoided. Conceptually the fuel specific quantities are a direct measure of the optical effectiveness of a given amount of fuel consumed since the definitions of the fuel specific attenuation are

equivalent to the average optical depth of the smoke cloud times the area of the cloud divided by the mass of the fuel burned.

In this experimental program we have treated the specific attenuation, scattering, and absorption coefficients, the fuel specific coefficients, and the emission factors as the basic measurements describing the optical effects of the aerosol. Data are presented for emission factors, specific attenuation coefficients, and w_o values. We have also calculated the wavelength dependence of the attenuation for comparison with earlier models as well as aerosol sizes, expressed as optically effective sizes and as size distributions.

DEVELOPMENT OF AN INSTRUMENT FOR THE MEASUREMENT OF SINGLE SCATTER ALBEDO

Although the absorption properties of the smoke particles are a major determinant of the climatic effects of the aerosol, the accurate measurement of absorption is difficult; and one of the goals of this study was the development of an instrument for direct in-situ measurements of aerosol absorption. Some of the uncertainties associated with absorption measurements were demonstrated in a comparative study of absorption measurement methodologies during a 1980 workshop at Fort Collins, CO (Gerber and Hindman, 1982). Simultaneous

measurements of absorption of soot from burning propane resulted in major differencesin the measured absorption. B_a values ranged from 3.8 to 11.4 m^2/g, while single scattering albedo values ranged from 0.09 to 0.29.

Traditionally, the most common method of measuring absorption involved the collection of the material and the measurement of the decrease in transmission or reflectance due to the presence of the aerosol material on a filter or mixed with some other material. The collection of material and the subsequent handling of the material can cause changes in both physical and optical properties. In addition, Patterson and Marshall (1983) demonstrated that the filter measurements were dependent on such factors as filter material and measurement geometry.

An in-situ method of measuring absorption avoids the problems associated with filter collection methods and a way of avoiding these problems. Two in-situ techniques have been used, photoacoustic techniques and measurements of the difference between attenuation and scattering. We chose to develop a laboratory instrument for determining absorption by means of this difference measurement that is based on an earlier design of Gerber (1979). As such the instrument provides a direct determination of the attenuation, the scattering, the absorption, and the single scattering albedo for the smoke particles. Since the measurement is an in-situ measurement that minimizes any effect on the aerosol, the new instrument should

provide credible values of absorption without the problems associated with the collection of particles.

A schematic diagram of this aerosol scattering and attenuation measurement instrument (ASAM), is shown in Fig. 1. Conceptually, the instrument is a combination of an inverse nephelometer in which the diffuser is associated with the detector rather than with the source, and a transmissometer. It consists of a rectangular chamber approximately 75 cm in length with tapered ends to ensure smooth aerosol flow through the chamber. A HeNe laser beam at a wavelength of 632.8 nm passes through the chamber longitudinally. Detection of the light is by means of silicon PIN diodes. Two detectors are used in the ASAM instrument, one to measure the direct beam and the other to measure the light scattered by the aerosol.

The direct beam detector measures the transmission of the light, from which the attenuation of the aerosol can be calculated, given the length of the light path through the instrument. The other detector, the scattered light detector, is placed behind a plastic diffuser midway along the beam approximately 2 cm away from the laser beam. This detector measures the scattered light that is transmitted through the diffuser plate. With this geometry, the detector views the beam over nearly the complete range of angles from 0 to 180 (The actual viewing angle range is from 3^{o} to 177^{o}). The plastic diffuser has an approximate cosine response--that is the intensity of

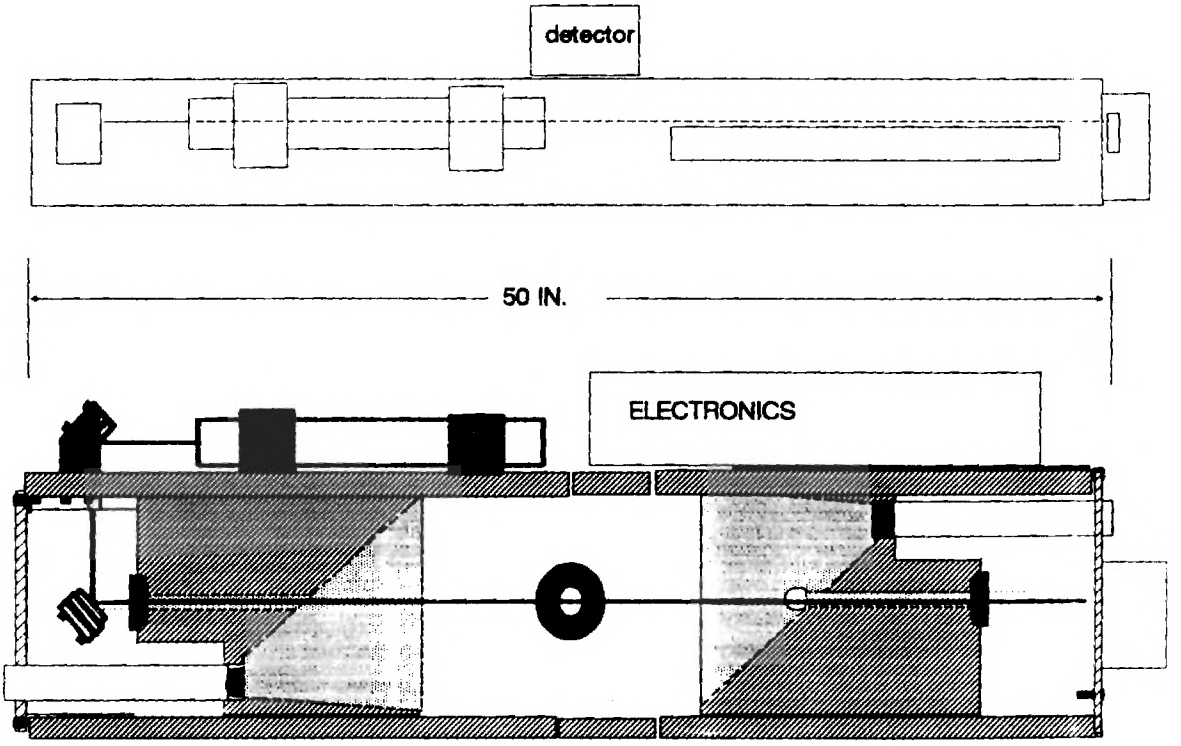

Fig. 1

the transmitted light is proportional to the cosine of the angle (measured from the perpendicular) of the incident light. The diffuser plate is mounted in a stepped outer plate to produce a more exact cosine response. This cosine response of the detector, together with the beam geometry, produces a scattered light signal that is proportional to the total light scattered from the main beam within the angular acceptance angles of the diffuser, assuming that the light not measured is small relative to that within the acceptance angle of the scattered light detector.

The signals from the scattered light detector and the direct beam detector are amplified, converted to an output voltage, and measured with a voltage to frequency converter. The output from the voltage to frequency converter is a series of pulses whose frequency at any time is proportional to the instantaneous voltage. The use of a voltage to frequency converter allows us to integrate the signal over the counting time by counting the number of pulses in the time period. The count number is stored for both the diffuse and the direct beams. The relative intensity of the laser beam is measured at the laser output; this intensity is used to normalize the direct and the scattered light data. Data acquisition and control for the ASAM are provided by a PC compatible computer.

The measurement of the aerosol attenuation is done by

calculating the ratio of the direct beam intensity with the aerosol present in the instrument to the direct beam intensity in clean air. Since the signal is normalized to the laser output power no other calibration is required. For the scattering signal, however, a calibration is required to convert the output signal to a scattering value.

Two different calibration procedures were used to determine scattering values. In the first the scattering of two gases, air and Freon 12, is measured and the calibration constant k is determined from the equation:

$$k = (\sigma_{sF} - \sigma_{sa}) / (S_F - S_a)$$

with σ_s the scattering coefficient of Freon (F) and of air (a) and with S_F and S_a the measured signals for Freon and for air. In the second method, a non-absorbing aerosol is introduced into the ASAM instrument and the extinction coefficient, σ_e is calculated from the direct beam attenuation. σ_s is equal to σ_e and the calibration constant k is determined from the equation

$$k = (\sigma_e) / (S_{aero} - S_a)$$

with S_{aero} the scattering signal from the aerosol. Calibration values determined by each of these methods were close to each other, verifying the consistency in the

two methods.

The calibrations described above were done under conditions for which the transmittance is approximately 1. For conditions in which the transmittance is significantly less than 1, there will be a significant decrease in beam intensity along the beam path; and the scattered light signal will be less than expected from the low concentration data. All of the measurements were made in conditions in which the transmittance was significantly less than 1, and so an additional calibration was necessary to account for the decrease in beam intensity along the beam path.

These additional calibration measurements were made using a non-absorbing ammonium sulfate aerosol in varying concentrations with measured transmission values between 1 and 0.8. Measured scattering and attenuation values were used to determine an empirical adjustment factor for conversion of the measured scattering coefficient to the actual scattering coefficient. This adjustment factor was defined so that the single scattering albedo was equal to 1 (the measured scattering coefficient was equal to the measured attenuation coefficient) for the range of measured transmissions. The best adjustment factor was found to be given by the equation

$$\sigma_s = \sigma_{s,init} / T^{**}.45$$

in which T is the transmission measured along the total path in the instrument. This empirical adjustment factor worked quite well for measurements of absorbing smokes for transmission values as low as 0.10.

We would note that this empirical adjustment factor is approximately that which would be determined if the adjustment were made in terms of beam intensity at the closest point to the detector. Since the scattered light detector is at the midpoint of the beam, the intensity of the beam at its midpoint is given by the initial intensity multiplied by the square root of the transmission.

EXPERIMENTAL MEASUREMENTS AND PROCEDURES

The measurement program consisted of a series of burns on the different fuel samples shown in Table 1. The measurements were conducted using the combustion characterization facililties on the campus of the Georgia Institute of Technology (Zinn, et al, 1977, Perry et al, 1977). These facilities consist of a combustion products test chamber (CPTC) and associated in-situ and aerosol sampling instrumentation. The CPTC is a ventilated chamber that was designed to provide capabilities for control of air flow to the combustion volume, control of

TABLE 1

MATERIALS AND FIRE CONDITION MATRIX FUELS

- Polyethylene (HDPE)
- Polyvinylchloride (PVC)
- PMMA
- Polystyrene
- Polypropyline
- Polycarbonate
- Kl Kerosene
- #2 Oil
- #5 Oil
- Asphalt
- Oak

FIRE CONDITIONS

- Ventilation
- Radiance
- Smoke Concentration

the temperature of air entering the combustion volume, and control of radiance on the sample. Provision was made for both optical measurements and collection of samples for microphysical measurements.

The chamber consists of an outer shell approximately 1.4 m on a side. Within this outer shell there are a series of heaters to control the temperature of the air as it enters the combustion volume. There is an inner conical shell to channel the air and combustion products from the chamber to the exhaust line. This inner cone is perforated to improve air flow within the chamber. The exhaust line passes through a measurement chamber and is then ducted out of the building. The measurement chamber contains the in-situ optical measurement system as well as an inlet for the aerosol sampling system. Airflow through the system is produced using positive pressure from compressed air or from a mixture of air and another gas. This arrangement insures that the flow through the system will not be affected by changes in exhaust air temperature. Air flow during our series of measurements ranged from 2 cfm to 20 cfm; flow was measured using calibrated rotometers.

The sample holder consists of an approximately 6 x 10 cm tray that is suspended on top of a force transducer that provides a continuous measurement of the weight of sample from which the rate of weight loss of the sample can be determined. The sample heater produces a radiant

flux which can be varied between 0 and 8 W/cm^2.

The in-situ optical measurement system provides for attenuation measurements at two wavelengths (red light at 632.8 nm produced by a HeNe laser and blue light at 488 nm produced by an Argon ion laser) and angular scattering measurements of blue light at 5^o and 15^o. The arrangement of the optical system has been described in detail by Zinn et al. The ratios of the scattered light intensities at 5^o and at 15^o are calculated and used to determine a volume-surface mean diameter D_{32} (Powell et al, 1976) which can be thought of as an effective optical diameter for the particles. At the near forward scattering angles of 5 and 15^o, the ratio of the scattered light at the two angles is not highly sensitive to variations in particle refractive indices or shape. The measurement of this ratio is applicable for the calculation of D_{32} in the range of 0.15 to 2.0 microns.

The aerosol sampling system drew a small volume of air from the exhaust line. This air was used to provide sample air to an optical particle counter (PMS LAS-X), a cascade impactor (Anderson 1-CFM), a single stage filter, and the ASAM instrument. The PMS optical particle counter and the two aerosol collection devices were provided with undiluted air. The ASAM air was diluted so that the instrument signal would be within its range of validity. Consequently, the ASAM extinction and scattering measurements must be normalized to the in-situ

measurements.

The data system for the CPTC was modified for this program to provide for computer controlled data acquisition using a PC compatible system. The voltage outputs from the optical detectors (two attenuation and two scattering), the detector voltage setting, and the force transducer are converted to digital readings with a Metrabyte data acquisition board for PC compatible computers. The computer acquires data at a rate of 5 samples per second for each of the six data channels. This high speed data is then processed to produce 5 second averages for each channel. These 5 second averages are then used to calculate attenuation values, relative scattering values, and sample weight values as a function of time during the burn. The nephelometer and ASAM instrument data were acquired by the individual instruments rather than by the CPTC data acquisition system.

Similar experimental procedures were followed for each of the burns. A given mass of fuel was placed in the sample tray and the sample was covered. The radiant heaters were turned on and allowed to equilibrate to the final radiance. Airflow into the chamber was adjusted to the desired flow, and the sample was then uncovered. There was, in general, a period of smoldering combustion followed by flaming combustion.

The <u>in-situ</u> optical data, ASAM data, and force

transducer data were recorded continuously. Optical particle counter data were recorded on a one minute average basis. Several filter samples were collected during each combustion test. One sample was collected during any smoldering and one or more samples during the flaming phase. The filter sampling arrangement was set up so that no sample was lost during filter changes. The cascade impactor was used to collect one sample only during each fire; in general, the cascade impactor sampling was started at the beginning of the flaming phase of the fire and ended at the conclusion of the fire.

The airflow through the chamber could be varied between approximately 2 and 20 cfm. The measurements were generally at 10 and 20 cfm. Variation in atmospheric composition was obtained by ventilating the chamber with a mixture of nitrogen and compressed air. Various mixtures were used; air/N_2 ratios are shown in the individual data sheets. The measurements used two values of radiant flux, a low value of 5.0 w/cm^2 and a high value of 8.0 w/cm^2. a small pilot propane flame was used to initiate the flaming phase of the combustion.

In the analysis of the data from each test fire, the <u>in-situ</u> optical data is averaged to provide integrated data that corresponds to filter sample time intervals. The fuel weight loss for the time period is calculated from the force transducer data. The mass emission factor is calculated using the filter mass data, the fuel mass

loss data and the relative air flow for the filter sample and the CPTC. Where possible, emission factors were calculated for the different phases of the test burn. The attenuation coeficient was calculated from the average transmisssion for the blue and the red light and the path length through the smoke. The specific attenuation B_e was then calculated for both the blue and the red beams by dividing the average attenuation by the average mass concentration. In addition, the fuel specific attenuation coefficient was then calculated by multiplication of B_e values by the mass emission factors. The ratio of blue to red attenuation was calculated from the two attenuation measurements. Detailed size distributions were measured, but only the optically effective sizes are discussed here

MEASUREMENT RESULTS

Results of measurements for the plastic fuels, rubber, wood, and hydrocarbon fuels are given in the following sections. The results are presented in Tables 2 through 9. In these Tables we list the data by sample or fuel type; for the individual samples the mass of fuel consumed is given. Emission factors (EF), B_e and B_e'for blue and red wavelengths, attenuation ratios of blue to red extinction, and ω_o are also given. Fire conditions list the chamber air flow in cfm and the radiant heating in Watts per cm^2.

Plastic Fuel Results

PMMA

PMMA data are shown in Table 2. A total of nine test burns of PMMA were analyzed in detail, three with a complete data set and six with a partial data set, in which only the fuel specific attenuation coefficients (B' values) were measured. The range of fire conditions is also shown in Table 2; air flow was either 10 or 20 cfm and the radiant intensity onto the fuel was either 5 W/cm^2 or 8 W/cm^2. In all cases, including those in which the ventilation was with a mixture of air and nitrogen, the fires consisted almost entirely of flaming combustion. Very little fuel consumption or smoke emissions occurred in the smoldering phase; and smoldering aerosol emissions were not sufficient for accurate measurements.

The data appeared consistent for this material. The average emission factor for the PMMA was 0.015 g/g. Average fuel specific attenuation, B_e', values were 0.153 for the blue and 0.12 for the red with an attenuation ratio of 1.28 and an α value of 0.95. B_e values showed more variation, averages calculated for the PMMA data were 10.2 for the blue and 8.0 for the red. ω_o values were in the range of 0.18 to 0.23. In general, most of the values were between .21 and 0.23. We estimate that a value of 0.22 is the most probable value for ω_o, with a resulting

PMMA SUMMARY

SAMPLE	FUEL BURNED	EF	BLUE Be	BLUE Be'	RED Be	RED Be'	ATTN RATIO	ω_o (RED)	CONDITION
PMMA-1	24.5	.015			10.1	.15			20(AIR)/5W/cm^2
PMMA-2 TOTAL	21.9	.018	8.1	.14	6.2	.11	1.31	.23	10(AIR)/8W/cm^2
PMMA-3 TOTAL	22.4	.018	6.9	.12	5.5	.10	1.25	.22	10(6A/4N)8W/cm^2
PMMA-4 TOTAL	19.4	.008	14.0	.12	9.8	.08	1.43	.18-.21	10(6A/4N)5W/cm^2
PMMA-5 TOTAL	20.9			.15		.12	1.20		10(AIR)8W/cm^2
PMMA-6	20.6			.16		.11	1.37		10(AIR)8W/cm^2
PMMA-7 TOTAL	20.3			.21		.15	1.36		20CFM(AIR)8W/cm^2
PMMA-8 TOTAL	18.7			.16		.13	1.30		
PMMA-9 TOTAL	18.8			.16		.13	1.24		

B_a value of 6.2 in the red. Although not shown individually in the table for the different runs, the average D_{32} value for the PMMA was 1.3 microns.

Little variation in the emission properties was observed for the variation in fire conditions.

Polycarbonate

Polycarbonate data is shown in Table 3. For the polycarbonate, unlike the PMMA, the combustion included a significant smoldering component. In addition, there were some differences in the results for the air and for the air/nitrogen mixture combustion.

Considering flaming combustion only, the air-only measurements resulted in emission factors of approximately 0.1, B_e values of 11 in the blue and 9 in the red, B_e' values of 1.1 in the blue and 0.95 in the red, and ω_o values of 0.3. Those air-nitrogen mixture measurements resulted in emission factors of 0.07, B_e values of 8 to 9 in the blue and 6 to 7 in the red, B_e' values of approximately 0.6 in the blue and 0.5 in the red, and ω_o values of 0.4 and higher. The high ω_o values are of particular interest because they indicate that B_a values for these cases would be only of the order of 4 to 5 m^2/g. Optically effective diameters were approximately 1.0 micron.

Smoldering combustion measurements resulted in lower B_e values and ω_o values ofapproximtely 0.9.

POLYCARBONATE SUMMARY

SAMPLE	FUEL BURNED	EF	BLUE Be	BLUE Be'	RED Be	RED Be'	ATTN RATIO	ω_o (RED)	CONDITION
PC-1									20CFM(AIR)5W/cm^2
A	.2	.32	2.38	.76	3.6	1.13	.67	.88	SMOLDERING
B	13.5	.104	10.74	1.12	9.0	.94	1.19	.29	FLAMING
TOTAL	13.7	.107	10.38	1.11	8.8	.94	1.19		
PC-2									20CFM(AIR)8W/cm^2
A	.1	.35	1.88	1.64	1.4	.56	1.18	.70	SMOLDERING
B	13.9	.102	11.23	1.15	7.4	.95	1.21	.30	FLAMING
TOTAL	14.0	.104	10.95	1.14	9.1	.95	1.20		
PC-3									10CFM(6A/4N)8W/cm^2
A	.2	.13	6.40	.82	5.8	.75	1.10	.91	SMOLDERING
B	11.9	.079	9.01	.71	7.4	.58	1.22	.48	FLAMING
TOTAL	12.1	.079	8.94	.71	7.3	.58	1.22		
PC-4									20CFM(6A/4N)8W/cm^2
A	3.4	.057	5.5	.32	5.0	.28	1.11	.90	SMOLDERING
B	8.9	.056	8.8	.49	6.6	.37	1.33	.41	FLAMING
TOTAL	12.3	.056	7.9	.44	6.2	.35	1.28		

The effects of variation of fire parameters discussed above may be summarized as follows: The changes in radiance had little effect; as the percent oxygen in the air decreased ω_o increases, the emission factos decrease and B_e' decreases.

PVC

The PVC data was collected in two series, one, Series A, in which the measurements were made prior to the completion of the aerosol scattering and attenuation instrument and the other, Series B, in which the measurements included the ASAM data. The Series A runs data were not separated by combustion phase; series B data, which was separated by fire phase is the only data set considered here. This data is shown in Table 4.

The PVC also burned with an appreciable smoldering component which was characterized by low B_e values and high ω_o values, indicating essentially no absorption. For the flaming phases of the fires, there were some apparent differences between the runs in which there was air only and those in which there was a mixture of air and nitrogen for a reduced oxygen atmosphere. For the normal air-only runs, the B_e values were 10.4 for the blue and 8.8 for the red and the B_e' values were 1.8 for the blue and 1.5 for the red. ω_o values were 0.42. Measurements with 80% air and 20% Nitrogen showed little difference in optical properties, with ω_o values slightly

PVC SUMMARY
Series B

SAMPLE	FUEL BURNED	EF	BLUE Be	BLUE Be'	RED Be	RED Be'	ATTN RATIO	ω (RED)	CONDITION
PCV-B1									20CFM(AIR)5W/cm^2
A	10.6	.037	3.2	.12	2.8	.10	1.15	.98	Smoldering
B	5.7	.185	11.3	2.09	9.6	1.8	1.18	.44	Flaming
TOTAL	16.3	.087	9.1	.79	7.7	.67	1.17		
PCV-B2									10CFM(AIR)5W/cm^2
A	10.5	.017	5.8	.10	3.9	.07	1.48	1.0	SMOLDERING
B	6.0	.144	9.4	1.4	8.0	1.15	1.18	.40	FLAMING
TOTAL	16.5	.063	8.8	.56	7.3	.48	1.20		
PCV-B3									10CFM(6A/4N)8W/cm^2
A	6.0	.028	4.5	.13	3.6	.10	1.25	.98	
B	8.8	.148	5.0	.74	4.3	.63	1.17	.50	
TOTAL	14.8	.099	4.9	.49	4.2	.41	1.18		
PCV-B4									10CFM(8A/2N)8W/cm^2
A	10.2	.082	3.7	.30	3.4	.28	1.07	1.00	SMOLDERING
B	5.1	.105	10.2	1.1	8.6	.90	1.19	.45	
TOTAL	15.3	.084	6.2	.52	5.4	.46	1.15		
PCV-B5									10CFM(8A/2N)
A	2.8	.036	3.7	.13	3.2	.12	1.14	1.00	SMOLDERING
B	13.8	.065	11.0	.72	9.6	.62	1.15	.45	FLAMING & SMOLDERING
TOTAL	16.6	.060	10.3	.62	8.9	.54	1.15		

higher. A run with 60% air and 40% Nitrogen showed higher ω_o values of 0.50 with B_e values that are comparable to those in smoldering combustion.

The variation in our PVC data may be summarized as follows: PVC shows more sample to sample variation than some other plastics; with reduced air there is more smoldering, but in the flaming phase there is little variation in $_o$ and B_e. Overall, ω_o will be higher, B_e somewhat lower, B_a significantly lower, and emission factors significantly higher. Higher radiant heating flux reduces smoldering--this can be important under reduced oxygen conditions.

HDPE

A high density polyethylene (HDPE) was used as the fuel for the polyethylene burns. This HDPE data is shown in Table 5 for Series A and B as in the PVC case. The data in Series A were more variable; the Series B data were, in general, more consistent with a greater contribution from flaming. Of particular interest are the ω_o data for Series B which show quite consistent values of 0.26. Average B_e' values (from Series B) were 0.19 for the blue and 0.14 for the red. The D_{32} diameters for the HDPE were approximately 1.2 microns. The HDPE showed no systematic variation with either heating or ventilation variation

HDPE SUMMARY

Series A

SAMPLE	FUEL	EF	BLUE Be	BLUE Be'	RED Be	RED Be'	ATTN RATIO	W_o (RED)	CONDITION
HDPE-A1	10.3	.029	9.21	.26	7.2	.21	1.28		10/8W/cm^2
HDPE-A2 TOT FL	10.0	.021	11.6	.24	9.4	.19	1.23	.075*	10/8W/cm^2
HDPE-A3	10.1	.028	15.9	.41	12.5	.35	1.28	.25*	20/5W/cm^2 FLAMING
HDPE-A4	10.1	.028	-	-	-	-	-		10/5W/cm^2 SMOL & FLAMING
HDPE-A5	9.9	.021	14.4	.30	11.9	.25	1.21	.32*	10/44 FLAMING
HDPE-A6	2.6	.047	10.6	.50	8.3	.39	1.28	.11*	20/8W/cm^2 SMOLDER
HDPE-A7	10.2			.51	.49				MIX SMOLDER & FLAMING

Series B

HDPE-B1		.020	10.3	.21	7.6	.15	1.36	.26	10/5W/cm^2
HDPE-B2		.018	8.4	.15	6.7	.12	1.25	.26	10/8W/cm^2 <2% MASS NOT INCLUDED
HDPE-B3		.023	8.2	.19	6.5	.15	1.26	.25	10/8W/cm^2
HDPE-B4		.020	9.3	.19	6.6	.13	1.41	.26	10(6A/4N)8W/cm^2 .3 OF 11.95 M

*Data based on filter absorption measurements

Summary of Plastic Fuel Results

The plastic fuel data discussed above, with additional data from polystyrene and polypropylene, are shown in Table 6. There is a wide range of values of emission factors, with a much narrower range of values for B_e values. Because of the different emission factors, B_e' values also show a large variation. Attenuation ratio values are approximately 1.2 indicating consistancy in particle size; ω_o values range from 0.22 for the PMMA to 0.45 for the PVC.

Wood Emissions Study

As part of the study of the urban fuel mix we wanted to investigate the effect of wood materials in combination with plastic and alone. Consequently, several burns were made to investigated the optical properties of the smoke emissions from a wood fuel (red oak). The data for these burns are shown in Table 7.

The data indicate the B_e and ω_o values for the flaming combustion of this dried wood fuel material are close to the values measured for the plastic materials, unlike the earlier measurements of Patterson and McMahon (1980) on natural vegetative fuels. Emission factors for the flaming combustion are much lower than for the plastic

PLASTICS SUMMARY
(Flaming Combustion Only)

MATERIAL	EF	BLUE		RED		ATTN	ω_o
		Be	Be'	Be	Be'	RATIO	(RED)
PMMA	.015	10.3	.15	7.9	.12	1.30	.22
HDPE	.023	10.9	.25	8.5	.20	1.28	.26
PVC	.129	9.4	1.21	8.0	1.03	1.17	.45
POLYCARBONATE	.085	9.9	.84	8.0	.68	1.24	.29
POLYSTYRENE	.041			9.6	.39		
POLYPROPYLENE	.042			7.4	.31		

OAK SUMMARY
Series B

SAMPLE	FUEL BURNED	EF	BLUE Be	BLUE Be'	RED Be	RED Be'	ATTN RATIO	W_o (RED)	CONDITION
OAK-B1									20(AIR)8W/cm^2
A	0.6	.053	4.8	.26	2.5	.13	1.75	.8	
B	26.2	.0026	14.6	.038	11.6	.030	1.27	.15	
TOTAL	26.8	.0038	11.4	.043	8.5	.032	1.33		
OAK-B2									10(5/5)8W/cm^2 SMOLDER
TOTAL	24.5	.183	3.9	.71	3.8	.69	1.03	.9	
OAK-B3									10(6A/4N)8W/cm^2
A	12.5	.113	3.0	.34	2.8	.32	1.08	.86	SMOLDER
B	12.6	.017	7.1	.12	6.0	.10	1.18	.2-.3	FLAMING
TOTAL	25.1	.065	3.3	.22	3.0	.20	1.10		
OAK-B4									10(6A/4N)
A	2.2	.12	1.5	.17	1.5	.18	.98	.85	SMOLDER
B	24.1	.009	7.6	.008	5.8	.053	1.32	.17	FLAMING
TOTAL	26.3	.033	2.8	.095	2.4	.080	1.17		
OAK-B5									10(AIR)8W/cm^2
A	.5	.029	-					.87	
B	24.7	.0041	10.1	.041	7.5	.031	1.35	.14-.16	
TOTAL	25.2	.0046	8.9	.041	6.6	.031	1.34		
OAK-B6									10(AIR)8W/cm^2
TOTAL	26.3	.0046	7.6	.035	14.8	.026	1.36	.16-.17	

materials. D_{32} values for the flaming combustion are approximately 1.4 microns.

We also attempted to simulate the effect of reduced ventilation on the combustion products by burning the wood in an oxygen poor environment. For oxygen concentrations of 50% or less the wood fuel would not sustain flaming combustion at chamber flows of 10 cfm. In other cases of air nitrogen mixtures, the relative contribution of the smoldering phase to the total fire emissions was increased relative to the air only cases. In all of the cases in which the emissions factors were significantly increased over the lowest purely flaming values, the single scattering albedo also showed an increase over the lowest values. This suggests that high emission factors under reduced oxygen fuel consumption are not accompanied by correspondingly low single scatter albedos or high absorption.

Rubber Emissions Study

Data for several burns with rubber as a fuel are shown in Table 8. Two representative types of rubber were burned, a plain rubber and tire rubber. The tire rubber differs from the plain rubber because it contains a large amount of carbon black to improve its strength properties for tire applications. Although the ω_o values are about the same for the flaming combustion for both types of

RUBBER SUMMARY

SAMPLE	FUEL BURNED	EF	BLUE Be	BLUE Be'	RED Be	RED Be'	ATTN RATIO	w_o (RED)	CONDITION
RUBB-1 (CLEAR)									10CFM(AIR)5W/cm^2
A	.2	.12	15.5	1.86	5.8	.69	2.6	.9	SMOLDERING
B	10.7	.045	11.9	.53	9.4	.42	1.27	.28	FLAMING
TOTAL	10.9	.047	12.0	.56	9.2	.43	1.31		
RUBB-2 (CLEAR)									20CFM(AIR)8W/cm^2
A	.1	-						.93	SMOLDERING
B	10.5	-						.29	FLAMING
TOTAL	10.6	.064	12.2	.78	9.7	.62	1.26		
RUBB-3 (CLEAR)									10CFM(6A/4N)8W/cm^2
A	0.1	-						.9	SMOLDERING
B	12.4	-						.29	FLAMING
TOTAL	12.5	.045	8.2	.37	6.6	.30	1.25		
RUBB-4 (TIRE)									20CFM(AIR)5W/cm^2
A	0.3	.107	-	.91	-	.93	.98	.80	SMOLDERING
B	10.9	.082	17.2	1.41	15.0	1.22	1.15	.30	FLAMING
TOTAL	11.2	.083	17.0	.83	14.8	1.22	1.15		
RUBB-5 (TIRE)									20CFM(AIR)8W/cm^2
A	.2	.136	-	3.7	-	2.8	1.32	-	SMOLDERING
B	13.7	.089	14.0	1.24	10.8	.96	1.29	.30	FLAMING
TOTAL	13.9	.090	15.0	1.35	11.7	1.05	1.29		

rubber, the emission factors are different (0.05 for the plain and 0.08 for the tire) as are the B_e values ($11 m^2/g$ for the plain and 16 m^2/g for the tire). Resulting B_e' values are larger for the tire material than for the plain rubber.

Petroleum Products Study

A series of measurements were made on four petroleum products, kerosene, two diesel oil products, and asphalt. The kerosene was a K1 grade; the Diesel fuels were #2 and # 5 grades. The four fuel types spanned a range of viscosities, boiling points and molecular weights, with K1 the lightest and asphalt the heaviest. The purpose of the test series was to determine whether there were any consistent differences in the optical properties that are related to the differences in the physical properties of the fuels. A summary of the results for the petroleum products emissions is shown in Table 9.

In general, each of the data sets used to generate Table 8 appear to be internally consistent, with no major differences in the different fire conditions. The summary data show some interesting trends. The emission factor data show an increase with the increasing molecular weight fractionsfrom 0.029 g/g for the kerosene to 0.092 for the asphalt. The B_e values show little variation with

TABLE 9

PETROLEUM PRODUCTS SUMMARY
(Flaming Combustion Only)

MATERIAL	EF	BLUE		RED		ATTN	$L_1/_0$
		Be	Be'	Be	Be'	RATIO	(RED)
K1	.029	11.6	.33	9.2	.25	1.27	.24
#2 OIL	.033	9.7	.32	7.5	.25	1.28	.26
#5 OIL	.053	11.3	.60	9.5	.50	1.19	.30
ASPHALT	.092	10.8	.99	8.9	.82	1.21	.31

plastics; values which are also comparable to the earlier Seader and Ou data

B_e values for the rubber appear to be somewhat higher, particularly for the tire rubber; petroleum product fuel values are comparable to the plastic fuel values. Oak smoke emissions B_e values for flaming combustion range from 6 m^2/g to 12 m^2/g with an average value of approximatly 7 m^2/g at 633 nm; thes values are slightly lower than the plastic values.

Inferred B_a values at 633 nm for the plastic fuel emissions range from 4.4 for the PVC to 6.5 for the HDPE. If we assume a 1/ dependence the comparable midvisible B_a values would range from 5.1 to 7.5. Similarly the B_a values range from 6 to $7m^2/g$ for the petroleum products, from 5 m^2/g to 11 m^2/g for the rubber, and from 6 m^2/g to 12 m^2/g for the oak at 633 nm. Conversion to average values at mid-visible gives values of 7 m^2/g for the petroleum products, 8 m^2/g for the rubber and 11 for the wood. These numbers for B_a are in general less than assumed in the earlier models of climatic effects from urban fires, primarily due to the higher values of single scatter albedo that we measured relative to that assumed in the earlier models.

SUMMARY AND CONCLUSIONS

We have measured the optical properties of the smoke

emissions from the combustion of a series of plastics, wood, and petroleum products. The plastic data show average B_e values near 10 m^2/g for the blue and 8 m^2 for the red. Values of B_e measured during smoldering combustion are significantly less than in flaming combustion and appear to be in the range of 3 to 5 m^2/g for these plastics. B_e values for the rubber appear to be somewhat higher, particularly for the tire rubber; petroleum product fuel values are comparable to the plastic fuel values. Oak smoke emissions B_e values for flaming combustion range from 6 m^2/g to 12 m^2/g nm with an average value of approximatly 7 m^2/g at 633 nm; thes values are slightly lower than the plastic values.

Conversion of measured B_a values to average values at mid-visible gives values of 7 m^2/g for the petroleum products, 8 m^2/g for the rubber and 11 for the wood. These numbers for B_a are in general less than assumed in the earlier models of climatic effects from urban fires, primarily due to the higher values of single scatter albedo that we measured relative to that assumed in the earlier models.

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Cost and Performance Report

for

Contract DNA-001-86-C-0310.

Presented to the Defense Nuclear Agency

by

E. M. Patterson

School of Earth and Atmospheric Sciences
Georgia Institute of Technology
Atlanta, Georgia 30332

This report incorporates cost and performance reports for the time period from 9-30-86 to 4-30 90.

The total contract amount was $340,876. This money was sufficient to meet the objectives of the contract; and all objectives were met. Because of problems and delays in the transfer of funds to GTRC, the contract objectives were not completed in the originally allocated time; and no-cost extensions to the original preformance and reporting periods were required.

The contracted funds were allocated as follows:

School of Earth and
Atmospheric Sciences

Personal Services:	$ 113,922.93
Fringe Benefits	$ 25,694.05
Materials and Supplies	$ 15,469.43
Travel	$ 5,615.23
Capital Equipment	$ 9,345.70
Indirect Costs	$ 99,357.56
Total Costs	$ 272,405.20

Georgia Tech Research Institute

Personal Services:	$ 18,141.30
Fringe Benefits	$ 4,196.12
Materials and Supplies	$ 536.36
Computer Charges	$ 59.00
Capital Equipment	$ 0.00
Indirect Costs	$ 12,250.62
Total Costs	$ 35,183.40

School of Aerospace Engineering

Personal Services:	$ 16,424.00
Fringe Benefits	$ 3,876.07
Materials and Supplies	$ 59.20
Capital Equipment	$ 0.00
Indirect Costs	$ 12,928.13
Total Costs	$ 33287.40

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Measurements of the Emissions Properties of Burning Plastic Material for Nuclear Winter Studies"

RSONAL AUTHOR(S)

.M.Patterson, R.M.Duckworth, E.A.Powell, and J.W.Gooch

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STRACT (Continue on reverse if necessary and identify by block number)

We have measured the optical and microphysical properties of smoke from burning plastic materials and other components of the urban fuel mix, including hydrocarbons, rubber, and wood, to provide information on the source term for possible aerosol clouds injected into the atmosphere following large scale urban fires. Our measurements included measurements of emission factors; in-situ optical measurements of aerosol absorption, scattering, and attenuation; and collection of particles using both filters and cascade impactors for size and mass concentration determinations.

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These measurements were made under a variety of conditions to investigate the range of variation of these optical parameters and to relate observed differences in smoke properties to differences in fuel composition and fire conditions. to investigate the effect of scaling, and to investigate effects of mixtures of combustible and non-combustible materials. Accordingly, fuels were burned as a single component and in combinations to determine effects of mixtures of fuels and of fuels with non-fuel components.

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Measurements of the Emissions Properties of Burning Plastic Material for Nuclear Winter Studies

Draft Final Report

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by

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ABSTRACT

We have measured the optical and microphysical properties of smoke from burning plastic materials and other components of the urban fuel mix, including hydrocarbons, rubber, and wood, to provide information on the source term for possible aerosol clouds injected into the atmosphere following large scale urban fires. Our measurements included measurements of emission factors; in-situ optical measurements of aerosol absorption, scattering, and attenuation; and collection of particles using both filters and cascade impactors for size and mass concentration determinations.

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Wood emission factors were lower than for the plastics, and the highest absorption cases were those in which the emission factors were lowest.

INTRODUCTION

We have measured the optical and microphysical properties of smoke from burning plastic materials and other components of the urban fuel mix, including hydrocarbons, rubber, and wood, to provide information on the source term for possible aerosol clouds injected into the atmosphere following large scale urban fires. Our measurements included measurements of emission factors; in-situ optical measurements of aerosol absorption, scattering, and attenuation; and collection of particles using both filters and cascade impactors for size and mass concentration determinations.

These measurements were made under a variety of conditions of radiant heating, ventilation, and smoke concentration to investigate the range of variation of these optical parameters, to relate observed differences in smoke properties to differences in fuel composition and fire conditions, to investigate the effect of scaling, and to investigate possible changes in the properties of the emissions when non-combustible material is mixed with the fuel.

Measurement techniques were developed as a part of this program to improve our ability to make real time, accurate measurement of smoke optical properties. As a part of this development activity, we produced a compact instrument for the measurement of the scattering, attenuation, and single scattering albedo of the smoke emissions from the fuels.

SMOKE PARAMETERS DETERMINING OPTICAL EFFECTS

The optical effects of a smoke aerosol will be determined by the optical properties of the aerosol and by the amount of the smoke produced by a given amount of fuel, the emission factor for the fuel. Aerosol optical properties can be described by several quantities. The optical depth δ as a function of wavelength is a measure of the total optical effect of the aerosol layer. The optical depth of an atmospheric aerosol layer is defined by the equation

$$\delta = - \ln (I/I_o)$$

in which I is the intensity of a direct beam of light after passing vertically through the layer and I_o is the initial intensity. The extinction coefficient, σ_e, is a measure of the amount of light removed from a beam of

light per unit length. For a given path δ and σ_e are related by the equation

$$\delta = \int \sigma_e(x)dx$$

the extinction of light is due to both scattering, in which the light is removed from the incident beam and redirected, and absorption, in which the light is absorbed by the particles. The coefficients are related by the equation

$$\sigma_e = \sigma_s + \sigma_a$$

To relate these quantities to the microphysical properties of the aerosol, we can define specific attenuation, scattering and absorption coefficients by ratioing the optical quantity to the mass concentration of the aerosol. These specific extinction or absorption coefficients are measures of the effectiveness of a given amount of aerosol material in producing an optical effect. These specific coefficients are defined according to the equations

$$B_e = \sigma_e/M_c$$

$$B_s = \sigma_s/M_c$$

and

$$B_a = \sigma_a/M_c$$

with B_e the specific extinction, B_a the specific absorption, and M_c the mass concentration of the aerosol. As before, B_e is the sum of B_s and B_a.

In addition to the specific coefficients of the aerosol discussed above, the material of the aerosol may be described by a refractive index m, with m = n - ik. n is the real component of the refractive index and k is the absorption index. The bulk refractive indices for the soot material are approximately 2 - i1 (Janzen, 1979); the soot particles consist of chainlike aggregates and the average or effective refractive index will be given by a mixing rule that takes account of the relative fraction of solids in the soot particle.

Given the refractive indices and the size distribution of the particles, the extinction, scattering

and absorption coefficients can be calculated as a function of wavelength.

The single scattering albedo, ω_o, is defined as the ratio of the scattering coefficient to the extinction coefficient. For non-absorbing aerosols, the ω_o will be equal to 1 and the aerosol will be a white aerosol; for highly absorbing aerosols SSA will be near 0 and the aerosol will be a black aerosol.

The angular distribution of the scattered light is given by the phase function of the aerosol that can be calculated from the size distribution and the measured optical constants of the aerosol. For radiative transfer calculations, the phase function is often parameterized in terms of the asymmetry parameter, which is defined as the average cosine of the scattered light.

The emission factor is defined as the amount (mass) of smoke produced for a given amount of fuel burned. The emission factor measurement can be combined with the specific attenuation and related measurements to define new quantities B_e', B_s', and B_a', which we call the fuel specific attenuation, scattering, and absorption coefficients. These quantities are defined by the equations

$$B_e' = B_e \times EF$$

$$B_s' = B_s \times EF$$

$$B_a' = B_a \times EF$$

The fuel specific quantities are of use because, even though we have defined them in terms of the specific quantities and the emission factors, operationally they depend only on the integrated optical measurements and the amount of fuel burned; filter measurements to determine aerosol mass concentration are intermediate measurements that are not needed for final calculations and any questions associated with the size range represented by the filter measurements are avoided. Conceptually the fuel specific quantities are a direct measure of the optical effectiveness of a given amount of fuel consumed since the definition of the fuel specific attenuation is equivalent to the average optical depth of the smoke cloud times the area of the cloud divided by the mass of the fuel burned.

In this experimental program we have treated the specific attenuation, scattering, and absorption coefficients, the fuel specific coefficients, and the

emission factors as the basic measurements describing the optical effects of the aerosol. Data are presented for emission factors, specific attenuation coefficients, and σ_o values. We have also calculated the wavelength dependence of the attenuation for comparison with earlier models as well as aerosol sizes, expressed as optically effective sizes and as size distributions.

DEVELOPMENT OF AN INSTRUMENT FOR THE MEASUREMENT OF SINGLE SCATTER ALBEDO

Although the absorption properties of the smoke particles are a major determinant of the climatic effects of the aerosol, the accurate measurement of absorption is difficult; and one of the goals of this study was the development of an instrument for direct in-situ measurements of aerosol absorption. Some of the uncertainties associated with absorption measurements were demonstrated in a comparative study of absorption measurement methodologies during a 1980 workshop at Fort Collins, CO (Gerber and Hindman, 1982). Simultaneous measurements of absorption of soot from burning propane resulted in major differences in the measured absorption. B_a values ranged from 3.8 to 11.4 m^2/g, while single scattering albedo values ranged from 0.09 to 0.29.

Traditionally, the most common method of measuring absorption involved the collection of the material and the measurement of the decrease in transmission or reflectance due to the presence of the aerosol material on a filter or mixed with some other material. The collection of material and the subsequent handling of the material can cause changes in both physical and optical properties. In addition, Patterson and Marshall (1983) demonstrated that the filter measurements were dependent on such factors as filter material and measurement geometry.

An in-situ method of measuring absorption avoids the problems associated with filter collection methods and a way of avoiding these problems. Two in-situ techniques have been used, photoacoustic techniques and measurements of the difference between attenuation and scattering. We chose to develop a laboratory instrument for determining absorption by means of this difference measurement that is based on an earlier design of Gerber (1979). As such the instrument provides a direct determination of the attenuation, the scattering, the absorption, and the single scattering albedo for the smoke particles. Since the measurement is an in-situ measurement that minimizes any effect on the aerosol, the new instrument should provide credible values of absorption without the problems associated with the collection of particles.

A schematic diagram of this aerosol scattering and attenuation measurement instrument (ASAM), is shown in Fig. 1. Conceptually, the instrument is a combination of an inverse nephelometer in which the diffuser is associated with the detector rather than with the source, and a transmissometer. It consists of a rectangular chamber approximately 75 cm in length with tapered ends to ensure smooth aerosol flow through the chamber. A HeNe laser beam at a wavelength of 632.8 nm passes through the chamber longitudinally. Detection of the light is by means of silicon PIN diodes. Two detectors are used in the ASAM instrument, one to measure the direct beam and the other to measure the light scattered by the aerosol.

The direct beam detector measures the transmission of the light, from which the attenuation of the aerosol can be calculated, given the length of the light path through the instrument. The other detector, the scattered light detector, is placed behind a plastic diffuser midway along the beam approximately 2 cm away from the laser beam. This detector measures the scattered light that is transmitted through the diffuser plate. With this geometry, the detector views the beam over nearly the complete range of angles from 0 to 180 (The actual viewing angle range is from 3^{o} to 177^{o}). The plastic diffuser has an approximate cosine response--that is the intensity of the transmitted light is proportional to the cosine of the angle (measured from the perpendicular) of the incident light. The diffuser plate is mounted in a stepped outer plate to produce a more exact cosine response. This cosine response of the detector, together with the beam geometry, produces a scattered light signal that is proportional to the total light scattered from the main beam within the angular acceptance angles of the diffuser, assuming that the light not measured is small relative to that within the acceptance angle of the scattered light detector.

The signals from the scattered light detector and the direct beam detector are amplified, converted to an output voltage, and measured with a voltage to frequency converter. The output from the voltage to frequency converter is a series of pulses whose frequency at any time is proportional to the instantaneous voltage. The use of a voltage to frequency converter allows us to integrate the signal over the counting time by counting the number of pulses in the time period. The count number is stored for both the diffuse and the direct beams. The relative intensity of the laser beam is measured at the laser output; this intensity is used to normalize the direct and the scattered light data. Data acquisition and control for the ASAM are provided by a PC compatible

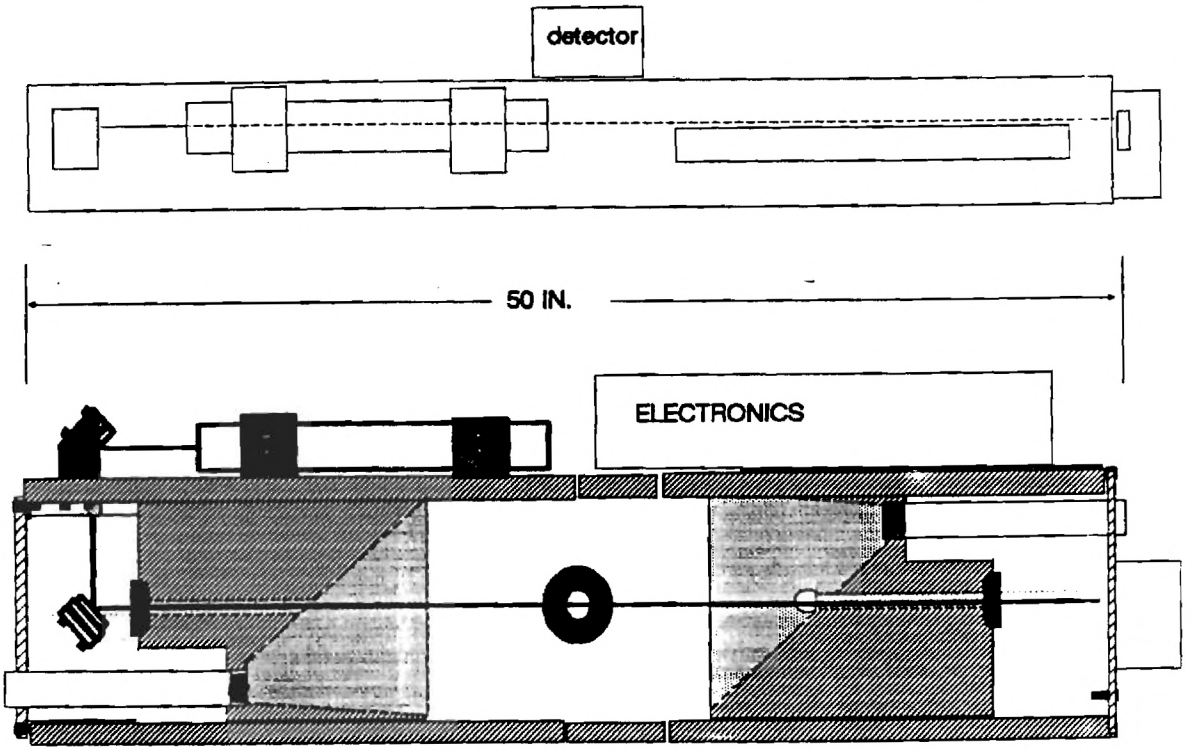


Fig. 1 Aerosol Scattering and Absorption Instrument

computer.

The measurement of the aerosol attenuation is done by calculating the ratio of the direct beam intensity with the aerosol present in the instrument to the direct beam intensity in clean air. Since the signal is normalized to the laser output power no other calibration is required. For the scattering signal, however, a calibration is required to convert the output signal to a scattering value.

Two different calibration procedures were used to determine scattering values. In the first the scattering of two gases, air and Freon 12, is measured and the calibration constant k is determined from the equation:

$$k = (\sigma_{sF} - \sigma_{sa}) / (S_F - S_a)$$

with σ_s the scattering coefficient of Freon (F) and of air (a) and with S_F and S_a the measured signals for Freon and for air. In the second method, a non-absorbing aerosol is introduced into the ASAM instrument and the extinction coefficient, σ_e is calculated from the direct beam attenuation. σ_s is equal to σ_e and the calibration constant k is determined from the equation -

$$k = (\sigma_e) / (S_{aero} - S_a)$$

with S_{aero} the scattering signal from the aerosol. Calibration values determined by each of these methods were close to each other, verifying the consistency in the two methods.

The calibrations described above were done under conditions for which the transmittance is approximately 1. For conditions in which the transmittance is significantly less than 1, there will be a significant decrease in beam intensity along the beam path; and the scattered light signal will be less than expected from the low concentration data. All of the measurements were made in conditions in which the transmittance was significantly less than 1, and so an additional calibration was necessary to account for the decrease in beam intensity along the beam path.

These additional calibration measurements were made using a non-absorbing ammonium sulfate aerosol in varying concentrations with measured transmission values between 1 and 0.8. Measured scattering and attenuation values were used to determine an empirical adjustment factor for conversion of the measured scattering coefficient to the actual scattering coefficient. This adjustment factor was defined so that the single scattering albedo was equal to

1 (the measured scattering coefficient was equal to the measured attenuation coefficient) for the range of measured transmissions. The best adjustment factor was found to be given by the equation

$$\sigma_s = \sigma_{s,init} / T^{**}.45$$

in which T is the transmission measured along the total path in the instrument. This empirical adjustment factor worked quite well for measurements of absorbing smokes for transmission values as low as 0.10.

We would note that this empirical adjustment factor is approximately that which would be determined if the adjustment were made in terms of beam intensity at the closest point to the detector. Since the scattered light detector is at the midpoint of the beam, the intensity of the beam at its midpoint is given by the initial intensity multiplied by the square root of the transmission.

EXPERIMENTAL MEASUREMENTS AND PROCEDURES

The measurement program consisted of a series of burns on the different fuel samples shown in Table 1. The measurements were conducted using the combustion characterization facilities on the campus of the Georgia Institute of Technology (Zinn, et al, 1977, Perry et al, 1977). These facilities consist of a combustion products test chamber (CPTC) and associated in-situ and aerosol sampling instrumentation. The CPTC is a ventilated chamber that was designed to provide capabilities for control of air flow to the combustion volume, control of the temperature of air entering the combustion volume, and control of radiance on the sample. Provision was made for both optical measurements and collection of samples for microphysical measurements.

The chamber, shown in schematic form in Fig. 2 from Zinn et al, consists of an outer shell approximately 1.4 m on a side. Within this outer shell there are a series of heaters to control the temperature of the air as it enters the combustion volume. There is an inner conical shell to channel the air and combustion products from the chamber to the exhaust line. This inner cone is perforated to improve air flow within the chamber. The exhaust line passes through a measurement chamber and is then ducted out of the building. The measurement chamber contains the in-situ optical measurement system as well as an inlet for the aerosol sampling system. Airflow through the system is produced using positive pressure from compressed air or from a mixture of air and another gas. This arrangement insures that the flow through the system

TABLE 1

MATERIALS AND FIRE CONDITION MATRIX FUELS

- Polyethylene (HDPE)
- Polyvinylchloride (PVC)
- PMMA
- Polystyrene
- Polypropyline
- Polycarbonate
- Kl Kerosene
- #2 Oil
- #5 Oil
- Asphalt
- Oak

FIRE CONDITIONS

- Ventilation
- Radiance
- Smoke Concentration

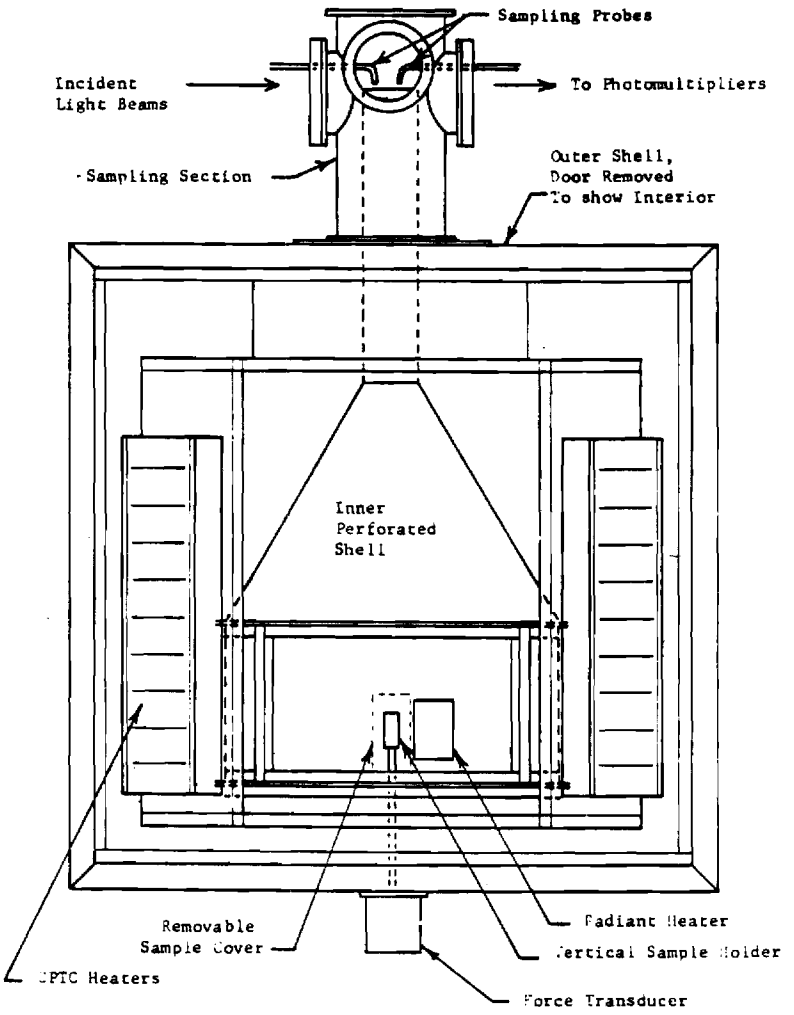


Fig. 1. Combustion products test chamber.

Fig. 2 Combustion Products Test Chamber

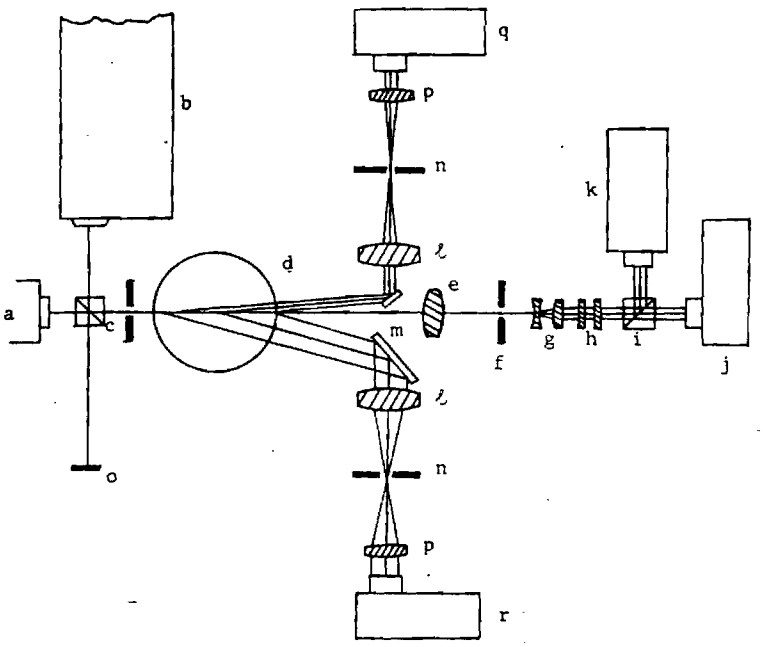
will not be affected by changes in exhaust air temperature. Air flow during our series of measurements ranged from 2 cfm to 20 cfm; flow was measured using calibrated rotometers.

The sample holder consists of an approximately 6 x 10 cm tray that is suspended on top of a force transducer that provides a continuous measurement of the weight of sample from which the rate of weight loss of the sample can be determined. The sample heater produces a radiant flux which can be varied between 0 and 8 W/cm^2.

The in-situ optical measurement system, shown in Fig. 3, provides for attenuation measurements at two wavelengths (red light at 632.8 nm produced by a HeNe laser and blue light at 488 nm produced by an Argon ion laser) and angular scattering measurements of blue light at 5^o and 15^o. The arrangement of the optical system has been described in detail by Zinn et al. The ratios of the scattered light intensities at 5^o and at 15^o are calculated and used to determine a volume-surface mean diameter D_{32} (Powell et al, 1976) which can be thought of as an effective optical diameter for the particles. At the near forward scattering angles of 5 and 15^o, the ratio of the scattered light at the two angles is not highly sensitive to variations in particle refractive indices or shape. The measurement of this ratio is applicable for the calculation of D_{32} in the range of 0.15 to 2.0 microns.

The aerosol sampling system drew a small volume of air from the exhaust line. This air was used to provide sample air to an optical particle counter (PMS LAS-X), a cascade impactor (Anderson 1-CFM), a single stage filter, and the ASAM instrument. The PMS optical particle counter and the two aerosol collection devices were provided with undiluted air. The ASAM air was diluted so that the instrument signal would be within its range of validity. Consequently, the ASAM extinction and scattering measurements must be normalized to the in-situ measurements.

The data system for the CPTC was modified for this program to provide for computer controlled data acquisition using a PC compatible system. The voltage outputs from the optical detectors (two attenuation and two scattering), the detector voltage setting, and the force transducer are converted to digital readings with a Metrabyte data acquisition board for PC compatible computers. The computer acquires data at a rate of 5 samples per second for each of the six data channels. This high speed data is then processed to produce 5 second averages for each channel. These 5 second averages are



a. Helium - Neon Laser
b. Argon - Ion Laser
c. Beam Combining Cube
d. 4" Diameter Stack from CPTC
e. Objective Lens
f. Pinhole Aperture
g. Beam Expander
h. Neutral Density Filters
i. Beam Splitter Cube
j. Transmitted Blue Light Detector
k. Transmitted Red Light Detector
l. Objective Lenses
m. Mirrors
n. Pinhole Apertures
o. Light Stop
p. Collimating Lenses
q. 5^{o} - Scattering Detector
r. 15^{o} - Scattering Detector

Fig. 3 In-Situ Optical Measurements

then used to calculate attenuation values, relative scattering values, and sample weight values as a function of time during the burn. The nephelometer and ASAM instrument data were acquired by the individual instruments rather than by the CPTC data acquisition system.

Similar experimental procedures were followed for each of the burns. A given mass of fuel was placed in the sample tray and the sample was covered. The radiant heaters were turned on and allowed to equilibrate to the final radiance. Airflow into the chamber was adjusted to the desired flow, and the sample was then uncovered. There was, in general, a period of smoldering combustion followed by flaming combustion.

The in-situ optical data, ASAM data, and force transducer data were recorded continuously. Optical particle counter data were recorded on a one minute average basis. Several filter samples were collected during each combustion test. One sample was collected during any smoldering and one or more samples during the flaming phase. The filter sampling arrangement was set up so that no sample was lost during filter changes. The cascade impactor was used to collect one sample only during each fire; in general, the cascade impactor sampling was started at the beginning of the flaming phase of the fire and ended at the conclusion of the fire.

The airflow through the chamber could be varied between approximately 2 and 20 cfm. The measurements were generally at 10 and 20 cfm. Variation in atmospheric composition was obtained by ventilating the chamber with a mixture of nitrogen and compressed air. Various mixtures were used; air/N_2 ratios are shown in the individual data sheets. The measurements used two values of radiant flux, a low value of 5.0 w/cm^2 and a high value of 8.0 w/cm^2. a small pilot propane flame was used to initiate the flaming phase of the combustion.

In the analysis of the data from each test fire, the in-situ optical data is averaged to provide integrated data that corresponds to filter sample time intervals. The fuel weight loss for the time period is calculated from the force transducer data. The mass emission factor is calculated using the filter mass data, the fuel mass loss data and the relative air flow for the filter sample and the CPTC. Where possible, emission factors were calculated for the different phases of the test burn. The attenuation coefficient was calculated from the average transmission for the blue and the red light and the path length through the smoke. The specific attenuation B_e was then calculated for both the blue and the red beams by

dividing the average attenuation by the average mass concentration. In addition, the fuel specific attenuation coefficient was then calculated by multiplication of B_e values by the mass emission factors. The ratio of blue to red attenuation was calculated from the two attenuation measurements. Detailed size distributions were measured, as well as the D_{32} parameter which is an optically effective mean size.

MEASUREMENT RESULTS

Results of measurements for the plastic fuels, rubber, wood, and hydrocarbon fuels are given in the following sections. The results are presented in Tables 2 through 9. In these Tables we list the data by sample or fuel type; for the individual samples the mass of fuel consumed is given. Emission factors (EF), B_e and B_e'for blue and red wavelengths, attenuation ratios of blue to red extinction, and ω_o are also given. Fire conditions list the chamber air flow in cfm and the radiant heating in Watts per cm^2.

Plastic Fuel Results

PMMA

PMMA data are shown in Table 2. A total of nine test burns of PMMA were analyzed in detail, three with a complete data set and six with a partial data set, in which only the fuel specific attenuation coefficients (B' values) were measured. The range of fire conditions is also shown in Table 2; air flow was either 10 or 20 cfm and the radiant intensity onto the fuel was either 5 W/cm^2 or 8 W/cm^2. In all cases, including those in which the ventilation was with a mixture of air and nitrogen, the fires consisted almost entirely of flaming combustion. Very little fuel consumption or smoke emissions occurred in the smoldering phase; and smoldering aerosol emissions were not sufficient for accurate measurements.

The data appeared consistent for this material. The average emission factor for the PMMA was 0.015 g/g. Average fuel specific attenuation, B_e , values were 0.153 for the blue and 0.12 for the red with an attenuation ratio of 1.28 and an α value of 0.95. B_e values showed more variation, averages calculated for the PMMA data were 10.2 for the blue and 8.0 for the red. ω_o values were in the range of 0.18 to 0.23. In general, most of the values were between .21 and 0.23. We estimate that a value of 0.22 is the most probable value for ω_o, with a resulting B_a value of 6.2 in the red. Although not shown individually in the table for the different runs, the average D_{32} value for the PMMA was 1.3 microns.

PMMA SUMMARY

SAMPLE	FUEL BURNED	EF	BLUE Be	BLUE Be'	RED Be	RED Be'	ATTN RATIO	w_o (RED)	CONDITION
PMMA-1	24.5	.015			10.1	.15			20(AIR)/5W/cm^2
PMMA-2 TOTAL	21.9	.018	8.1	.14	6.2	.11	1.31	.23	10(AIR)/8W/cm^2
PMMA-3 TOTAL	22.4	.018	6.9	.12	5.5	.10	1.25	.22	10(6A/4N)8W/cm^2
PMMA-4 TOTAL	19.4	.008	14.0	.12	9.8	.08	1.43	.18-.21	10(6A/4N)5W/cm^2
PMMA-5 TOTAL	20.9			.15		.12	1.20		10(AIR)8W/cm^2
PMMA-6	20.6			.16		.11	1.37		10(AIR)8W/cm^2
PMMA-7 TOTAL	20.3			.21		.15	1.36		20CFM(AIR)8W/cm^2
PMMA-8 TOTAL	18.7			.16		.13	1.30		
PMMA-9 TOTAL	18.8			.16		.13	1.24		

Little variation in the emission properties was observed for the variation in fire conditions.

Polycarbonate

Polycarbonate data is shown in Table 3. For the polycarbonate, unlike the PMMA, the combustion included a significant smoldering component. In addition, there were some differences in the results for the air and for the air/nitrogen mixture combustion.

Considering flaming combustion only, the air-only measurements resulted in emission factors of approximately 0.1, B_e values of 11 in the blue and 9 in the red, B_e' values of 1.1 in the blue and 0.95 in the red, and ω_o values of 0.3. Those air-nitrogen mixture measurements resulted in emission factors of 0.07, B_e values of 8 to 9 in the blue and 6 to 7 in the red, B_e' values of approximately 0.6 in the blue and 0.5 in the red, and ω_o values of 0.4 and higher. The high ω_o values are of particular interest because they indicate that B_a values for these cases would be only of the order of 4 to 5 m^2/g. Optically effective diameters were approximately 1.0 micron.

Smoldering combustion measurements resulted in lower B_e values and ω_o values of approximately 0.9.

The effects of variation of fire parameters discussed above may be summarized as follows: The changes in radiance had little effect; as the percent oxygen in the air decreased ω_o increases, the emission factors decrease and B_e' decreases.

PVC

The PVC data was collected in two series, one, Series A, in which the measurements were made prior to the completion of the aerosol scattering and attenuation instrument and the other, Series B, in which the measurements included the ASAM data. The Series A runs data were not separated by combustion phase; series B data, which was separated by fire phase is the only data set considered here. This data is shown in Table 4.

The PVC also burned with an appreciable smoldering component which was characterized by low B_e values and high ω_o values, indicating essentially no absorption. For the flaming phases of the fires, there were some apparent differences between the runs in which there was air only and those in which there was a mixture of air and nitrogen for a reduced oxygen atmosphere. For the normal air-only runs, the B_e values were 10.4 for the blue and

POLYCARBONATE SUMMARY

SAMPLE	FUEL BURNED	EF	BLUE Be	BLUE Be'	RED Be	RED Be'	ATTN RATIO	W_o (RED)	CONDITION
PC-1									20CFM(AIR)5W/cm^2
A	.2	.32	2.38	.76	3.6	1.13	.67	.88	SMOLDERING
B	13.5	.104	10.74	1.12	9.0	.94	1.19	.29	FLAMING
TOTAL	13.7	.107	10.38	1.11	8.8	.94	1.19		
PC-2									20CFM(AIR)8W/cm^2
A	.1	.35	1.88	1.64	1.4	.56	1.18	.70	SMOLDERING
B	13.9	.102	11.23	1.15	7.4	.95	1.21	.30	FLAMING
TOTAL	14.0	.104	10.95	1.14	9.1	.95	1.20		
PC-3									10CFM(6A/4N)8W/cm^2
A	.2	.13	6.40	.82	5.8	.75	1.10	.91	SMOLDERING
B	11.9	.079	9.01	.71	7.4	.58	1.22	.48	FLAMING
TOTAL	12.1	.079	8.94	.71	7.3	.58	1.22		
PC-4									20CFM(6A/4N)8W/cm^2
A	3.4	.057	5.5	.32	5.0	.28	1.11	.90	SMOLDERING
B	8.9	.056	8.8	.49	6.6	.37	1.33	.41	FLAMING
TOTAL	12.3	.056	7.9	.44	6.2	.35	1.28		

PVC SUMMARY
Series A

SAMPLE	FUEL BURNED	EF	BLUE Be	BLUE Be'	RED Be	RED Be'	ATTN RATIO	ω_o (RED)	CONDITION
PVC-A1									
TOTAL	5.2	.094	11.1	1.04	9.4	.89	1.174		10/5W/cm^2 FLAMING
PVC-A2									
TOTAL	9.1			.87		.74	1.18		20/5W/cm^2 MIX FLAMING AND SMOLDERING
PVC-A3									20/5W/cm^2
TOTAL	7.7	.057	4.5	.25	4.5	.25			SMOLDERING ONLY
PVC-A4									SMOLDERING ONLY
TOTAL	22.7	.038	6.2	.46	6.2	.46	1.0		20(10A/10N)8W/cm^2
PVC-A5									
TOTAL	9.3	0.75	7.0	.53	7.0	.53	1.0		15(5A/10N)8W/cm^2
PVC-A6									15(5A/10N)8W/cm^2
TOTAL	9.8	0.62	-	-	6.1	.38			SMOLDERING
PVC-A7									
TOTAL	17.8					.43			
PVC-A8									
TOTAL	8.9	.018(Cl)				.49			
PVC-A9									
TOTAL	17.9	.034							
PVC-A10									10(8A/2N)8W/cm^2
A	5.4								SMOLDERING
B	13.7	.084	-	-	8.3	.70			FLAMING
TOTAL									

PVC SUMMARY
Series B

SAMPLE	FUEL BURNED	EF	BLUE Be	BLUE Be'	RED Be	RED Be'	ATTN RATIO	ω_s (RED)	CONDITION
PCV-B1									20CFM(AIR)5W/cm^2
A	10.6	.037	3.2	.12	2.8	.10	1.15	.98	Smoldering
B	5.7	.185	11.3	2.09	9.6	1.8	1.18	.44	Flaming
TOTAL	16.3	.087	9.1	.79	7.7	.67	1.17		
PCV-B2									10CFM(AIR)5W/cm^2
A	10.5	.017	5.8	.10	3.9	.07	1.48	1.0	SMOLDERING
B	6.0	.144	9.4	1.4	8.0	1.15	1.18	.40	FLAMING
TOTAL	16.5	.063	8.8	.56	7.3	.48	1.20		
PCV-B3									10CFM(6A/4N)8W/cm^2
A	6.0	.028	4.5	.13	3.6	.10	1.25	.98	
B	8.8	.148	5.0	.74	4.3	.63	1.17	.50	
TOTAL	14.8	.099	4.9	.49	4.2	.41	1.18		
PCV-B4									10CFM(8A/2N)8W/cm^2
A	10.2	.082	3.7	.30	3.4	.28	1.07	1.00	SMOLDERING
B	5.1	.105	10.2	1.1	8.6	.90	1.19	.45	
TOTAL	15.3	.084	6.2	.52	5.4	.46	1.15		
PCV-B5									10CFM(8A/2N)
A	2.8	.036	3.7	.13	3.2	.12	1.14	1.00	SMOLDERING
B	13.8	.065	11.0	.72	9.6	.62	1.15	.45	FLAMING & SMOLDERING
TOTAL	16.6	.060	10.3	.62	8.9	.54	1.15		

8.8 for the red and the B_e' values were 1.8 for the blue and 1.5 for the red. ω_o values were 0.42. Measurements with 80% air and 20% Nitrogen showed little difference in optical properties, with ω_o values slightly higher. A run with 60% air and 40% Nitrogen showed higher ω_o values of 0.50 with B_e values that are comparable to those in smoldering combustion.

The variation in our PVC data may be summarized as follows: PVC shows more sample to sample variation than some other plastics; with reduced air there is more smoldering, but in the flaming phase there is little variation in ω_o and B_e. Overall, ω_o will be higher, B_e somewhat lower, B_a significantly lower, and emission factors significantly higher. Higher radiant heating flux reduces smoldering--this can be important under reduced oxygen conditions.

HDPE

A high density polyethylene (HDPE) was used as the fuel for the polyethylene burns. This HDPE data is shown in Table 5 for Series A and B as in the PVC case. The data in Series A were more variable; the Series B data were, in general, more consistent with a greater contribution from flaming. Of particular interest are the ω_o data for Series B, which show quite consistent values of 0.26. Average B_e' values (from Series B) were 0.19 for the blue and 0.14 for the red. The D_{32} diameters for the HDPE were approximately 1.2 microns. The HDPE showed no systematic variation with either heating or ventilation variation

Summary of Plastic Fuel Results

The plastic fuel data discussed above, with additional data from polystyrene and polypropylene, are shown in Table 6. There is a wide range of values of emission factors, with a much narrower range of values for B_e values. Because of the different emission factors, B_e' values also show a large variation. Attenuation ratio values are approximately 1.2 indicating consistancy in particle size; ω_o values range from 0.22 for the PMMA to 0.45 for the PVC.

Wood Emissions Study

As part of the study of the urban fuel mix we wanted to investigate the effect of wood materials in combination with plastic and alone. Consequently, several burns were made to investigated the optical properties of the smoke emissions from a wood fuel (red oak). The data for these burns are shown in Table 7.

HDPE SUMMARY

Series A

SAMPLE	FUEL	EF	BLUE Be	BLUE Be'	RED Be	RED Be'	ATTN RATIO	ω_o (RED)	CONDITION
HDPE-A1	10.3	.029	9.21	.26	7.2	.21	1.28		10/8W/cm^2
HDPE-A2 TOT FL	10.0	.021	11.6	.24	9.4	.19	1.23	.075*	10/8W/cm^2
HDPE-A3	10.1	.028	15.9	.41	12.5	.35	1.28	.25*	20/5W/cm^2 FLAMING
HDPE-A4	10.1	.028	-	-	-	-	-		10/5W/cm^2 SMOL & FLAMING
HDPE-A5	9.9	.021	14.4	.30	11.9	.25	1.21	.32*	10/44 FLAMING
HDPE-A6	2.6	.047	10.6	.50	8.3	.39	1.28	.11*	20/8W/cm^2 SMOLDER
HDPE-A7	10.2			.51	.49				MIX SMOLDER & FLAMING

Series B

HDPE-B1	.020	10.3	.21	7.6	.15	1.36	.26	10/5W/cm^2
HDPE-B2	.018	8.4	.15	6.7	.12	1.25	.26	10/8W/cm^2 <2% MASS NOT INCLUDED
HDPE-B3	.023	8.2	.19	6.5	.15	1.26	.25	10/8W/cm^2
HDPE-B4	.020	9.3	.19	6.6	.13	1.41	.26	10(6A/4N)8W/cm^2 .3 OF 11.95 M

*Data based on filter absorption measurements

PLASTICS SUMMARY
(Flaming Combustion Only)

MATERIAL	EF	BLUE		RED		ATTN	W_o
		Be	Be'	Be	Be'	RATIO	(RED)
PMMA	.015	10.3	.15	7.9	.12	1.30	.22
HDPE	.023	10.9	.25	8.5	.20	1.28	.26
PVC	.129	9.4	1.21	8.0	1.03	1.17	.45
POLYCARBONATE	.085	9.9	.84	8.0	.68	1.24	.29
POLYSTYRENE	.041			9.6	.39		
POLYPROPYLENE	.042			7.4	.31		

OAK SUMMARY
Series A

SAMPLE	FUEL BURNED	EF	BLUE Be	BLUE Be'	RED Be	RED Be'	ATTN RATIO	ω_o (RED)	CONDITION
OAK-A1 TOTAL	21.5	.0036	-	-	11.9	.043	-	-	20(AIR)8W/cm^2
OAK-A2 TOTAL	22.8	.057	-	-	6.81	.376	-	-	10(3A/7N)8W/cm^2 Smoldering
OAK-A3	16.2	.0033			7.07	.023			10(5/5)8W/cm^2

OAK SUMMARY
Series B

SAMPLE	FUEL BURNED	EF	BLUE Be	BLUE Be'	RED Be	RED Be'	ATTN RATIO	ω_o (RED)	CONDITION
OAK-B1									20(AIR)8W/cm^2
A	0.6	.053	4.8	.26	2.5	.13	1.75	.8	
B	26.2	.0026	14.6	.038	11.6	.030	1.27	.15	
TOTAL	26.8	.0038	11.4	.043	8.5	.032	1.33		
OAK-B2									10(5/5)8W/cm^2 SMOLDER
TOTAL	24.5	.183	3.9	.71	3.8	.69	1.03	.9	
OAK-B3									10(6A/4N)8W/cm^2
A	12.5	.113	3.0	.34	2.8	.32	1.08	.86	SMOLDER
B	12.6	.017	7.1	.12	6.0	.10	1.18	.2-.3	FLAMING
TOTAL	25.1	.065	3.3	.22	3.0	.20	1.10		
OAK-B4									10(6A/4N)
A	2.2	.12	1.5	.17	1.5	.18	.98	.85	SMOLDER
B	24.1	.009	7.6	.008	5.8	.053	1.32	.17	FLAMING
TOTAL	26.3	.033	2.8	.095	2.4	.080	1.17		
OAK-B5									10(AIR)8W/cm^2
A	.5	.029	-					.87	
B	24.7	.0041	10.1	.041	7.5	.031	1.35	.14-.16	
TOTAL	25.2	.0046	8.9	.041	6.6	.031	1.34		
OAK-B6									10(AIR)8W/cm^2
TOTAL	26.3	.0046	7.6	.035	14.8	.026	1.36	.16-.17	

The data indicate the B_e and ω_o values for the flaming combustion of this dried wood fuel material are close to the values measured for the plastic materials, unlike the earlier measurements of Patterson and McMahon (1980) on natural vegetative fuels. Emission factors for the flaming combustion are much lower than for the plastic materials. D_{32} values for the flaming combustion are approximately 1.4 microns.

We also attempted to simulate the effect of reduced ventilation on the combustion products by burning the wood in an oxygen poor environment. For oxygen concentrations of 50% or less the wood fuel would not sustain flaming combustion at chamber flows of 10 cfm. In other cases of air nitrogen mixtures, the relative contribution of the smoldering phase to the total fire emissions was increased relative to the air only cases. In all of the cases in which the emissions factors were significantly increased over the lowest purely flaming values, the single scattering albedo also showed an increase over the lowest values. This suggests that high emission factors under reduced oxygen fuel consumption are not accompanied by correspondingly low single scatter albedos or high absorption. This inference is corroborated by Fig. 4 which is a plot of the single scatter albedo vs. the emission factor for the oak data of Table 7, omitting those data for which there was low fuel consumption.

Emissions from Combinations of Wood and Plastic

As part of the study of the urban fuel mix we measured the emissions from a combination of the oak and plastic fuels. These data are shown in Table 8. There do not appear to be any major variations in the data from the data that would be expected from a linear combination of the two components.

Rubber Emissions Study

Data for several burns with rubber as a fuel are shown in Table 9. Two representative types of rubber were burned, a plain rubber and tire rubber. The tire rubber differs from the plain rubber because it contains a large amount of carbon black to improve its strength properties for tire applications. Although the ω_o values are about the same for the flaming combustion for both types of rubber, the emission factors are different (0.05 for the plain and 0.08 for the tire) as are the B_e values ($11 m^2/g$ for the plain and 16 m^2/g for the tire). Resulting B_e' values are larger for the tire material than for the plain rubber.

MIXED WOOD AND PLASTIC

SAMPLE	FUEL	EF	BLUE		RED		ATTN	W_o	CONDITION
			Be	Be'	Be	Be'	RATIO	(RED)	
OAK & PMMA-1									10(AIR)8W/cm^2
A		.011	1.5	.016	1.3	.014	1.13	.85	
B		.008	14.4	.114	11.3	.090	1.27	.21	
TOTAL		.008	11.7	.100	9.5	.079	1.27		
OAK & PMMA-2									10(6A/4N)8W/cm^2
A		-	-					.86	
B		.005	8.0	.040	6.2	.031		.14	
TOTAL		.005	7.5	.038	5.8	.030			
OAK & HDPE-1		.018			10.7	.20			
OAK & PVC-1		.028							

RUBBER SUMMARY

SAMPLE	FUEL BURNED	EF	BLUE Be	BLUE Be'	RED Be	RED Be'	ATTN RATIO	W_o (RED)	CONDITION
RUBB-1 (CLEAR)									10CFM(AIR)5W/cm^2
A	.2	.12	15.5	1.86	5.8	.69	2.6	.9	SMOLDERING
B	10.7	.045	11.9	.53	9.4	.42	1.27	.28	FLAMING
TOTAL	10.9	.047	12.0	.56	9.2	.43	1.31		
RUBB-2 (CLEAR)									20CFM(AIR)8W/cm^2
A	.1	-						.93	SMOLDERING
B	10.5	-						.29	FLAMING
TOTAL	10.6	.064	12.2	.78	9.7	.62	1.26		
RUBB-3 (CLEAR)									10CFM(6A/4N)8W/cm^2
A	0.1	-						.9	SMOLDERING
B	12.4	-						.29	FLAMING
TOTAL	12.5	.045	8.2	.37	6.6	.30	1.25		
RUBB-4 (TIRE)									20CFM(AIR)5W/cm^2
A	0.3	.107	-	.91	-	.93	.98	.80	SMOLDERING
B	10.9	.082	17.2	1.41	15.0	1.22	1.15	.30	FLAMING
TOTAL	11.2	.083	17.0	.83	14.8	1.22	1.15		
RUBB-5 (TIRE)									20CFM(AIR)8W/cm^2
A	.2	.136	-	3.7	-	2.8	1.32	-	SMOLDERING
B	13.7	.089	14.0	1.24	10.8	.96	1.29	.30	FLAMING
TOTAL	13.9	.090	15.0	1.35	11.7	1.05	1.29		

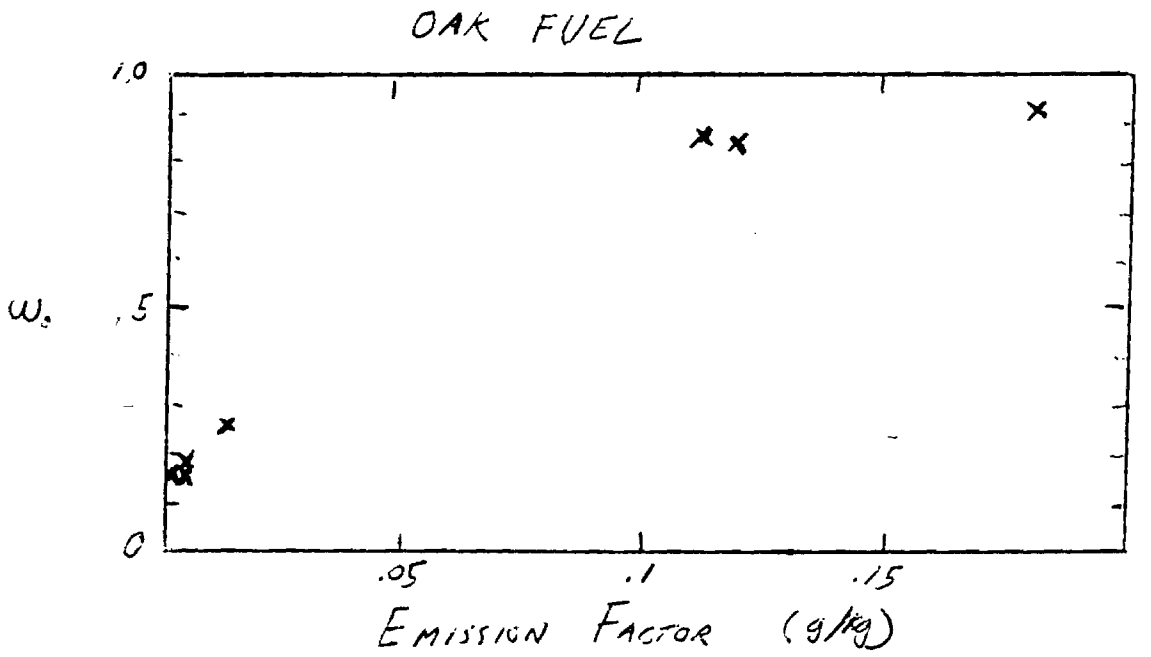


Fig. 4 Single Scatter Albedo as Function of Emission Factor

Petroleum Products Study

A series of measurements were made on four petroleum products, kerosene, two diesel oil products, and asphalt. The kerosene was a K1 grade; the Diesel fuels were #2 and # 5 grades. The four fuel types spanned a range of viscosities, boiling points and molecular weights, with K1 the lightest and asphalt the heaviest. The purpose of the test series was to determine whether there were any consistent differences in the optical properties that are related to the differences in the physical properties of the fuels. The data for the individual products are shown in Tables 10 through 13; a summary of the results for the petroleum products emissions is shown in Table 14.

In general, each of the data sets used to generate Table 14 appears to be internally consistent, with no major differences in the different fire conditions. The summary data show some interesting trends. The emission factor data show an increase with the increasing molecular weight fractions from 0.029 g/g for the kerosene to 0.092 for the asphalt. The B_e values show little variation with the increasing weight fractions. The average is approximately 10.9 m^2/g for the blue and 8.8 for the red. with a ratio of 1.24 which corresponds to an α of 0.8. B_e values show an increase from 0.33 to .99 for the blue and from 0.25 to 0.82 for the red. ω_o values range for 0.24 for the kerosene to 0.31 for the asphalt. This is of particular interest because, in the absence of other data, this data can be used to scale the behavior of other hydrocarbon fuels.

Additional Studies of Fire and Fuel Conditions

Three sets of additional studies of the effects of fire conditions on aerosol emissions were made. These included measurements of the effect of admixtures of sand with the plastic fuel, measurements of the effects of high concentrations of aerosols on the measured emissions, and measurements of the effects of variations in the amount of fuel.

Plastics in a Mixture with Sand

A series of burns were made in which the plastic fuel was mixed with sand. These were designed to simulate the effects of rubbleized fuel. The data from these mixed burns are shown in Table 15 and in summary form in Table 16; these data may be compared with the pure plastic data of Table 6. The most noticeable difference in the two tables is in the emission factor data. All of the plastic materials except for the PVC show an increase in emission

K1 SUMMARY

SAMPLE	EF	BLUE Be	BLUE Be'	RED Be	RED Be'	ATTN RATIO	(RED)	CONDITION
K1-1	.031	10.9	.34	9.1	.25	1.20	.24	10/5W/cm^2
K1-2	-							
K1-3	.027	12.3	.33	9.2	.25	1.34	.24	10/5W/cm^2
K1-4			.12		.09	1.33	.30	10(4A/6N)8W/cm^2
K1-5			.09		.14	.64	.9	10(6N/4A)8W/cm^2 SMOL

#2 OIL SUMMARY

SAMPLE	EF	BLUE Be	BLUE Be'	RED Be	RED Be'	ATTN RATIO	ω_o (RED)	CONDITION
20IL-1							.26	
20IL-2	0.35	11.0	.385	-	-	-	.26	10/5W/cm^2
20IL-3							.27	
20IL-4							.26	
20IL-5	.045	6.72	.303	5.29	.238	1.27	.25	10/5W/cm^2
20IL-6			.278		.280	.99	.75-.9	10(6N/4A)/65V SMOL
20IL-7	.028	9.9	.277	7.82	.219	1.27	.24	
20IL-8	.023	10.99	.241	8.38	.184	1.31	.25	10/5W/cm^2

#5 OIL SUMMARY

SAMPLE	EF	BLUE		RED		ATTN		CONDITION
		Be	Be'	Be	Be'	RATIO	(RED)	
5OIL-1							.32	10/
5OIL-2	.045	12.3	.56	-	-		.29	10/5W/cm^2
5OIL-3	.041	12.2	.50	9.8	.40	1.25	.32	10(7A/3N)8W/cm^2
5OIL-4	.071	9.2	.64	8.7	.61	1.14	.29	20/5W/cm^2
5OIL-5	.053	11.5	.61	9.7	.51	1.19	.30	10/5W/cm^2

TABLE 13

ASPHALT SUMMARY

SAMPLE		EF	BLUE Be	BLUE Be'	RED Be	RED Be'	ATTN RATIO	(RED)	CONDITION
ASP-1		.061						.31	10/5W/cm^2 MAIN FLAMING
ASP-2		.207	5.13	1.06	4.38	.91	1.17	.95-SMOL .5-.7-MIX	10(5/5)8W/cm^2 SMOL+MIX
ASP-3	A	.288	3.5	.94	2.8	.75	1.26	.9	SMOLDERING
	B	.097	12.6	1.22	10.5	1.01	1.20	.31	FLAMING
	TOT	.117	9.9	1.15	8.2	.96	1.20	-	20/5W/cm^2
ASP-4	TOT	.119	9.0	1.07	7.4	.88	1.22	.31	20/8W/cm^2 FLAMING

TABLE 14

PETROLEUM PRODUCTS SUMMARY
(Flaming Combustion Only)

MATERIAL	EF	BLUE		RED		ATTN	4/0
		Be	Be'	Be	Be'	RATIO	(RED)
K1	.029	11.6	.33	9.2	.25	1.27	.24
#2 OIL	.033	9.7	.32	7.5	.25	1.28	.26
#5 OIL	.053	11.3	.60	9.5	.50	1.19	.30
ASPHALT	.092	10.8	.99	8.9	.82	1.21	.31

SAMPLES & SAND

SAMPLE	FUEL	EF	BLUE		RED		ATTN		CONDITION
			Be	Be'	Be	Be'	RATIO	(RED)	
HDPE & SAND-1		.040	9.3	.37	8.1	.32	1.15	.22	20(AIR)8W/cm^2
HDPE & SAND-2									
A			4.5						
B			10.2		8.6		1.18	.23	20(AIR)8W/cm^2
TOTAL		.063	7.3	.54	7.9	.46	1.18		
HDPE & SAND-3		.073	5.7	.41	4.8	.35	1.18	.22	20(AIR)8W/cm^2
POLYCARB & SAND									
A								.85	
B			13.4		11.5			.28	
TOTAL		.106	12.9	1.37	11.1	1.18	1.17		
POLYSTYRENE & SAND		.124	10.4	1.29	9.3	1.16	1.11		
PVC & SAND-1	7.4	.063			9.9	.62			20(AIR)5W/cm^2
PVC & SAND-2									20(5A/5N)8W/cm^2
A	5.0	.058	2.4	.14	2.2	.13	1.07	.82	SMOLDERING
B	5.6	.118	9.8	1.16	8.3	.98	1.18	.34	FLAMING
TOTAL	10.6	.089	6.8	.61	5.8	.52	1.17		
PVC & SAND-3									20(AIR)8W/cm^2
A			5.8		4.7		1.23	.88	
B			10.7		9.6		1.11	.28	
TOTAL	11.5	.045	7.8	.35	6.7	.30	1.16		
PMMA & SAND-1		.021	8.3	.17	7.1	.21			20(AIR)8W/cm^2
PMMA & SAND-2		.020	10.1	.20	8.9	.18	1.14	.22	20(AIR)8W/cm^2

factor when mixed with sand: PMMA from .015 to .021, HDPE from .023 to .059, polycarbonate from .085 to .106 and polystyrene from .041 to .124. The decrease for PVC is small, from 0.129 to 0.118. ω_o values seem slightly less in the mixed case, and the B_e' values are generally higher. In general it appears that our data indicate the the effects of burning the plastic material in the presence of a material such as sand will increase emissions and decrease single scatter albedo, enhancing the absorption effects.

Combustion of Plastic in the Presence of Ambient Aerosol

A series of burns were made to investigate possible effects of ambient non-combustible aerosols on the smoke emissions. These burns were made in the usual manner, except that an aerosol, either ammonium sulfate or titanium dioxide, was introduced into the CPTC in the ventilation air. The aerosol was introduced in a steady state condition so that the optical effects of the aerosol could be subtracted from the optical effects of the smoke. The subtraction was made, and the resulting data are shown in Table 17. No systematic changes in smoke properties are seen that could be attributed to the presence of the aerosol.

Measurements with Larger Fuel Volumes

A set of measurements of plastic fuel emissions were made with fuel weights approximately five times the usual values for the PMMA. HDPE, and PVC materials. These data are shown in Table 18. The only major change in the data from that in Table 6 is in the single scattering albedo data for the HDPE which is quite high for the larger fuel weight fire considered. The reasons for the different values are not known at this time; one future area of work should be measurements with fuel loadings in the range of a few kilograms to better explore the scaling questions.

Measurements of Size Distributions

As discussed in the experimental procedures section, detailed size distribution measurements were made during the test burns. A summary of the cascade impactor data is shown in Table 19. The mass mean diameter is a measure of the central tendency of the data and the standard deviation is a measure of the breadth of the distribution. The large standard deviation indicate that these size distributions are, in general, very broad. Optical particle counter measurements were made, but not completely analyzed. They indicate, smaller size distributions than measured by the cascade impactor. These differences may be due to reduced inlet efficiency for the larger particles in the optical particle counter

SUMMARY PLASTICS & SAND

MATERIAL	EF	BLUE		RED		ATTN	ω_o
		Be	Be'	Be	Be'	RATIO	(RED)
PMMA & SAND	.021	9.2	.19	8.0	.17	1.16	.22
HDPE & SAND	.059	8.1	.44	6.9	.22	1.17	.22
POLYCARBONATE & SAND	.106	12.9	1.37	11.1	1.18	1.17	.28
PVC & SAND	.118	9.8	1.16	8.3	.98	1.18	.30
POLYSTYRENE & SAND	.124	10.4	1.29	9.3	1.16	1.11	

TABLE 17

PLASTIC FUEL IN PRESENCE OF AEROSOL

MATERIAL	EF	BLUE		RED		ATTN	ω_o
		Be	Be'	Be	Be'	RATIO	(RED)
PMMA & AMS04							
TOTAL	.023	8.2	.19	7.0	.16	1.17	.20
PVC & AMS04							
A	.044	1.7	.072	1.5	.067	1.08	.78
B	.093	10.3	.96	9.2	.86	1.12	.38
TOTAL	.078	8.7	.68	7.8	.61	1.12	
PMMA & T102							
TOTAL	.021	9.1	.19	7.9	.17	1/15	.22

* CORRECTED FOR EFFECTS OF INTRODUCED AEROSOLS

TABLE 18

LARGER BURN VOLUMES

MATERIAL	FUEL x NOM	EF	BLUE Be	BLUE Be'	RED Be	RED Be'	ATTN RATIO	ω_o(RED)
PVC	5X	.080	10.9	.87	7.4	.75	1.16	.40
PMMA	5X	.013	11.6	.15	10.3	.13	1.12	.20
HDPE	4X	.028	13.5	.38	12.3	.34	1.10	.40

TABLE 19

SUMMARY OF CASCADE IMPACTOR DATA

Material	Mass Mean Diameter (Micron)	Std Dev
HDPE	0.17 - 0.4	3 - 6
PVC	0.4 - 3	2.5 - 7
PP	0.6	11
PS	1.0	4
PMMA	1.1	9

as well as to particle counter calibration effects.

DISCUSSION

The plastic data show average B_e values near 10 m^2/g for the blue and 8 m^2 for the red. This may be compared with earlier data of Seader and Ou (1977). The Seader and Ou data of particulate optical density are equivalent to our B_e data, except that the Seader and Ou definitions are in terms of logarithms to the base 10 rather than the base e. When converted to our B_e definition, the Seader and Ou data for flaming combustion of plastics are equivalent to a mean value of 7.6 m^2/g. are comparable to but slightly smaller than our measured values. A similar value of 10 m^2/g was measured by Roessler and Faxvog (1980) for acetylene smoke.

Values of B_e measured during smoldering combustion are significantly less than in flaming combustion and appear to be in the range of 3 to 5 m^2/g for these plastics; values which are also comparable to the earlier Seader and Ou data

B_e values for the rubber appear to be somewhat higher, particularly for the tire rubber; petroleum product fuel values are comparable to the plastic fuel values. Oak smoke emissions B_e values for flaming combustion range from 6 m^2/g to 12 m^2/g nm with an average value of approximately 7 m^2/g at 633 nm; these values are slightly lower than the plastic values.

Inferred B_a values at 633 nm for the plastic fuel emissions range from 4.4 for the PVC to 6.5 for the HDPE. If we assume a 1/ dependence the comparable midvisible B_a values would range from 5.1 to 7.5. Similarly the B_a values range from 6 to 7m^2/g for the petroleum products, from 5 m^2/g to 11 m^2/g for the rubber, and from 6 m^2/g to 12 m^2/g for the oak at 633 nm. Conversion to average values at mid-visible wavelengths gives values of 7 m^2/g for the petroleum products, 8 m^2/g for the rubber and 11 for the wood. These numbers for B_a are in general less than assumed in the earlier models of climatic effects from urban fires, primarily due to the higher values of single scatter albedo that we measured relative to that assumed in the earlier models.

SUMMARY AND CONCLUSIONS

We have measured the optical properties of the smoke emissions from the combustion of a series of plastics, wood, and petroleum products. The plastic data show average B_e values near 10 m^2/g for the blue and 8 m^2 for

the red. Values of B_e measured during smoldering combustion are significantly less than in flaming combustion and appear to be in the range of 3 to 5 m^2/g for these plastics. B_e values for the rubber appear to be somewhat higher, particularly for the tire rubber; petroleum product fuel values are comparable to the plastic fuel values. Oak smoke emissions B_e values for flaming combustion range from 6 m^2/g to 12 m^2/g nm with an average value of approximately 7 m^2/g at 633 nm; these values are slightly lower than the plastic values.

Conversion of measured B_a values to average values at mid-visible wavelengths (550 nm) gives values of 7 m^2/g for the petroleum products, 8 m^2/g for the rubber and 11 m^2/g for the wood. These numbers for B_a are in general less than assumed in the earlier models of climatic effects from urban fires, primarily due to the higher values of single scatter albedo that we measured relative to that assumed in the earlier models.

Emission factors for the plastics show a wide range of values, from 0.015 for the PMMA to 0.13 for the PVC. Emission factors and overall absorption effects appear to be enhanced by burning in the presence of sand, which has been used as an analog for rubbleized fuel. Little effect was seen for combustion in the presence of aerosols or for the larger fuel amounts that we tested.

Wood emission factors were lower than for the plastics, and the highest absorption cases were those in which the emission factors were lowest. There does appear to be a relationship between single scatter albedo and emission factor.

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Measurements of the Emissions Properties of Burning Plastic Material for Nuclear Winter Studies

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31 January 1991

Final Report

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We have measured optical and microphysical properties and emission factors of smoke from burning plastic materials and other components of the urban fuel mix, including hydrocarbons, rubber, and wood, to provide information on the source term for possible smoke aerosol clouds produced by large scale urban fires. These measurements were made under a variety of conditions to investigate the range of variation of these optical parameters, to relate observed differences in smoke properties to differences in fuel composition and fire conditions, to investigate the effect of scaling, and to investigate effects of mixtures of combustible and non-combustible materials.

B_e values for these fuels were close to expected values, while B_a values were somewhat less than expected; emission factors are quite variable. Emission factors and absorption effects appear to be enhanced when the fuel is mixed with non-combustible material. Little effect was seen for combustion in the presence of aerosols or for the larger fuel amounts that we tested.

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Conversion Table

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

Multiply ——————>	**By** ——————>	**To Get**
To Get <——————	**By** <——————	**Divide**
micron (μm)	1.00 x E -6	meter (m)
nanometer (nm)	1.00 x E -9	meter (m)
ft^3/min (cfm)	4.72 x E -4	m^3/sec

Table of Contents

Section		Page
	Conversion Table	iii
	List of Illustrations	v
	List of Tables	vi
1	Introduction	1
2	Smoke Parameters Determining Optical effects	2
3	Development of an Instrument for the Measurement of Single Scatter Albedo	5
4	Experimental Measurements and Procedures	10
5	Measurement Results	16
6	Discussion	44
7	Summary and Conclusions	45
8	List of References	46

List of Illustrations

Figure		Page
1	Aerosol Scattering and Absorption Instrument	7
2	Combustion Products Test chamber	12
3	In-Situ Optical Measurements	13
4	Single Scatter Albedo as Function of Emission Factor	28

List of Tables

Table		Page
1	Materials and Fire Condition Matrix	11
2	PMMA Summary	17
3	Polycarbonate Summary	19
4	PVC Summary Series A	20
5	PVC summary Series B	21
6	HDPE Summary	23
7	Plastics Summary	24
8	Oak Summary Series A	25
9	Oak Summary Series B	26
10	Mixed wood and Plastic	29
11	Rubber Summary	30
12	K1 Summary	32
13	#2 Oil Summary	33
14	#5 Oil Summary	34
15	Asphalt Summary	35
16	Petroleum Products Summary	36
17	Plastics and Sand	37
18	Summary Plastics and Sand	38
19	Plastic Fuel in Presence of Aerosol	40
20	Larger Burn Volumes	41
21	Summary of Cascade Impactor Data	42

SECTION 1

INTRODUCTION

We have measured the optical and microphysical properties of smoke from burning plastic materials and other components of the urban fuel mix, including hydrocarbons, rubber, and wood, to provide information on the source term for possible aerosol clouds injected into the atmosphere following large scale urban fires. Our measurements included measurements of emission factors; in-situ optical measurements of aerosol absorption, scattering, and attenuation; and collection of particles using both filters and cascade impactors for size and mass concentration determinations.

These measurements were made under a variety of conditions of radiant heating, ventilation, and smoke concentration to investigate the range of variation of these optical parameters, to relate observed differences in smoke properties to differences in fuel composition and fire conditions, to investigate the effect of scaling, and to investigate possible changes in the properties of the emissions when non-combustible material is mixed with the fuel.

Measurement techniques were developed as a part of this program to improve our ability to make real time, accurate measurement of smoke optical properties. As a part of this development activity, we produced a compact instrument for the measurement of the scattering, attenuation, and single scattering albedo of the smoke emissions from the fuels.

SECTION 2

SMOKE PARAMETERS DETERMINING OPTICAL EFFECTS

The optical effects of a smoke aerosol will be determined by the optical properties of the aerosol and by the amount of the smoke produced by a given amount of fuel, the emission factor for the fuel. Aerosol optical properties can be described by several quantities. The optical depth δ as a function of wavelength is a measure of the total optical effect of the aerosol layer. The optical depth of an atmospheric aerosol layer is defined by the equation

$$\delta = - \ln (I/I_o)$$

in which I is the intensity of a direct beam of light after passing vertically through the layer and I_o is the initial intensity. The extinction coefficient, σ_e, is a measure of the amount of light removed from a beam of light per unit length. For a given path δ and σ_e are related by the equation

$$\delta = \int \sigma_e(x)dx$$

the extinction of light is due to both scattering, in which the light is removed from the incident beam and redirected, and absorption, in which the light is absorbed by the particles. The coefficients are related by the equation

$$\sigma_e = \sigma_s + \sigma_a$$

To relate these quantities to the microphysical properties of the aerosol, we can define specific attenuation, scattering and absorption coefficients by ratioing the optical quantity to the mass concentration of the aerosol. These specific extinction or absorption coefficients are measures of the effectiveness of a given amount of aerosol material in producing an optical effect. These specific coefficients are defined according to the equations

$$B_e = \sigma_e/M_c$$

$$B_s = \sigma_s/M_c$$

and

$$B_a = \sigma_a / M_c$$

with B_e the specific extinction, B_a the specific absorption, and M_c the mass concentration of the aerosol. As before, B_e is the sum of B_s and B_a.

In addition to the specific coefficients of the aerosol discussed above, the material of the aerosol may be described by a refractive index m, with m = n - ik. n is the real component of the refractive index and k is the absorption index. The bulk refractive indices for the soot material are approximately 2 - i1 (Janzen, 1979); the soot particles consist of chainlike aggregates and the average or effective refractive index will be given by a mixing rule that takes account of the relative fraction of solids in the soot particle.

Given the refractive indices and the size distribution of the particles, the extinction, scattering and absorption coefficients can be calculated as a function of wavelength.

The single scattering albedo, ω_o, is defined as the ratio of the scattering coefficient to the extinction coefficient. For non-absorbing aerosols, the ω_o will be equal to 1 and the aerosol will be a white aerosol; for highly absorbing aerosols SSA will be near 0 and the aerosol will be a black aerosol.

The angular distribution of the scattered light is given by the phase function of the aerosol that can be calculated from the size distribution and the measured optical constants of the aerosol. For radiative transfer calculations, the phase function is often parameterized in terms of the asymmetry parameter, which is defined as the average cosine of the scattered light.

The emission factor is defined as the amount (mass) of smoke produced for a given amount of fuel burned. The emission factor measurement can be combined with the specific attenuation and related measurements to define new quantities B_e', B_s', and B_a', which we call the fuel specific attenuation, scattering, and absorption coefficients. These quantities are defined by the equations

$$B_e' = B_e \times EF$$

$$B_s' = B_s \times EF$$

$$B_a' = B_a \times EF$$

The fuel specific quantities are of use because, even though we have defined them in terms of the specific quantities and the emission factors, operationally they depend only on the integrated optical measurements and the amount of fuel burned; filter measurements to determine aerosol mass concentration are intermediate measurements that are not needed for final calculations and any questions associated with the size range represented by the filter measurements are avoided. Conceptually the fuel specific quantities are a direct measure of the optical effectiveness of a given amount of fuel consumed since the definition of the fuel specific attenuation is equivalent to the average optical depth of the smoke cloud times the area of the cloud divided by the mass of the fuel burned.

In this experimental program we have treated the specific attenuation, scattering, and absorption coefficients, the fuel specific coefficients, and the emission factors as the basic measurements describing the optical effects of the aerosol. Data are presented for emission factors, specific attenuation coefficients, and σ_o values. We have also calculated the wavelength dependence of the attenuation for comparison with earlier models as well as aerosol sizes, expressed as optically effective sizes and as size distributions.

SECTION 3

DEVELOPMENT OF AN INSTRUMENT FOR THE MEASUREMENT OF SINGLE SCATTER ALBEDO

Although the absorption properties of the smoke particles are a major determinant of the climatic effects of the aerosol, the accurate measurement of absorption is difficult; and one of the goals of this study was the development of an instrument for direct in-situ measurements of aerosol absorption. Some of the uncertainties associated with absorption measurements were demonstrated in a comparative study of absorption measurement methodologies during a 1980 workshop at Fort Collins, CO (Gerber and Hindman, 1982). Simultaneous measurements of absorption of soot from burning propane resulted in major differences in the measured absorption. B_a values ranged from 3.8 to 11.4 m^2/g, while single scattering albedo values ranged from 0.09 to 0.29.

Traditionally, the most common method of measuring absorption involved the collection of the material and the measurement of the decrease in transmission or reflectance due to the presence of the aerosol material on a filter or mixed with some other material. The collection of material and the subsequent handling of the material can cause changes in both physical and optical properties. In addition, Patterson and Marshall (1983) demonstrated that the filter measurements were dependent on such factors as filter material and measurement geometry.

An in-situ method of measuring absorption avoids the problems associated with filter collection methods and a way of avoiding these problems. Two in-situ techniques have been used, photoacoustic techniques and measurements of the difference between attenuation and scattering. We chose to develop a laboratory instrument for determining absorption by means of this difference measurement that is based on an earlier design of Gerber (1979). As such the instrument provides a direct determination of the attenuation, the scattering, the absorption, and the single scattering albedo for the smoke particles. Since the measurement is an in-situ measurement that minimizes any effect on the aerosol, the new instrument should provide credible values of absorption without the problems associated with the collection of particles.

A schematic diagram of this aerosol scattering and attenuation measurement instrument (ASAM), is shown in Fig. 1. Conceptually, the instrument is a combination of an inverse nephelometer in which the diffuser is

associated with the detector rather than with the source, and a transmissometer. It consists of a rectangular chamber approximately 75 cm in length with tapered ends to ensure smooth aerosol flow through the chamber. A HeNe laser beam at a wavelength of 632.8 nm passes through the chamber longitudinally. Detection of the light is by means of silicon PIN diodes. Two detectors are used in the ASAM instrument, one to measure the direct beam and the other to measure the light scattered by the aerosol.

The direct beam detector measures the transmission of the light, from which the attenuation of the aerosol can be calculated, given the length of the light path through the instrument. The other detector, the scattered light detector, is placed behind a plastic diffuser midway along the beam approximately 2 cm away from the laser beam. This detector measures the scattered light that is transmitted through the diffuser plate. With this geometry, the detector views the beam over nearly the complete range of angles from 0° to 180° (The actual viewing angle range is from 3° to 177°). The plastic diffuser has an approximate cosine response--that is the intensity of the transmitted light is proportional to the cosine of the angle (measured from the perpendicular) of the incident light. The diffuser plate is mounted in a stepped outer plate to produce a more exact cosine response. This cosine response of the detector, together with the beam geometry, produces a scattered light signal that is proportional to the total light scattered from the main beam within the angular acceptance angles of the diffuser, assuming that the light not measured is small relative to that within the acceptance angle of the scattered light detector.

The signals from the scattered light detector and the direct beam detector are amplified, converted to an output voltage, and measured with a voltage to frequency converter. The output from the voltage to frequency converter is a series of pulses whose frequency at any time is proportional to the instantaneous voltage. The use of a voltage to frequency converter allows us to integrate the signal over the counting time by counting the number of pulses in the time period. The count number is stored for both the diffuse and the direct beams. The relative intensity of the laser beam is measured at the laser output; this intensity is used to normalize the direct and the scattered light data. Data acquisition and control for the ASAM are provided by a PC compatible computer.

The measurement of the aerosol attenuation is done by calculating the ratio of the direct beam intensity with the aerosol present in the instrument to the direct beam

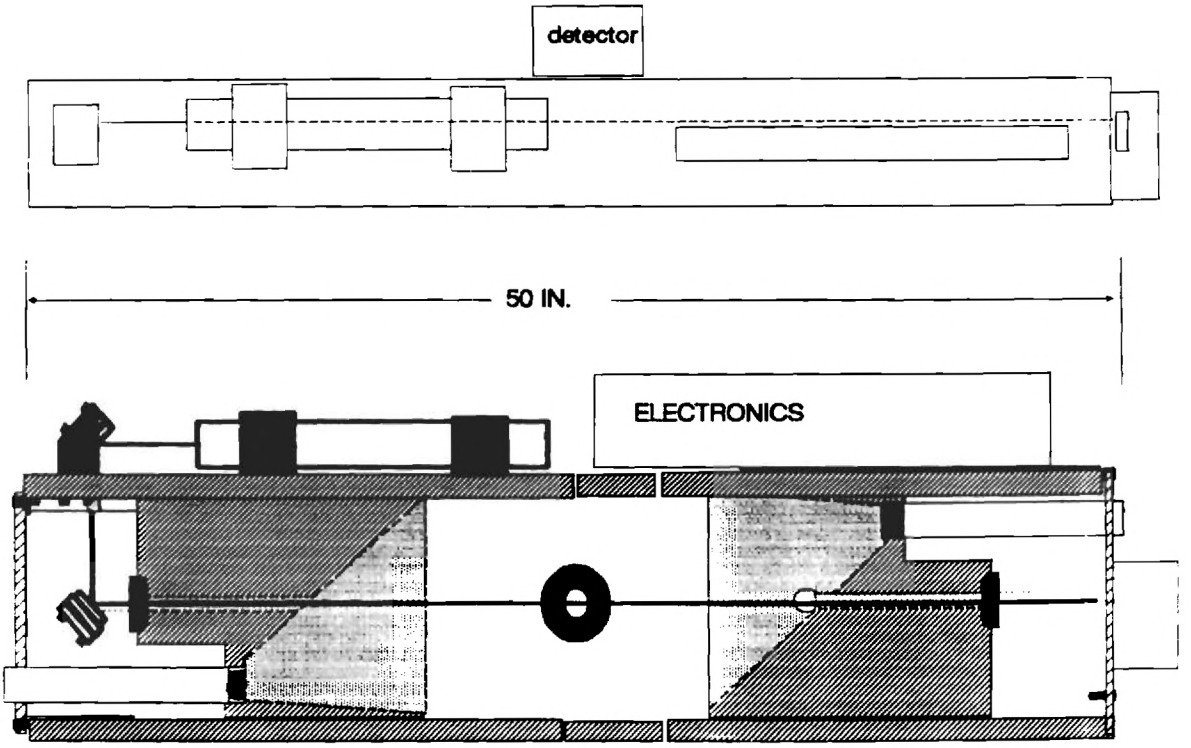


Figure 1. Aerosol Scattering and Absorption Instrument.

intensity in clean air. Since the signal is normalized to the laser output power no other calibration is required. For the scattering signal, however, a calibration is required to convert the output signal to a scattering value.

Two different calibration procedures were used to determine scattering values. In the first the scattering of two gases, air and Freon 12, is measured and the calibration constant k is determined from the equation:

$$k = (\sigma_{sF} - \sigma_{sa}) / (S_F - S_a)$$

with σ_s the scattering coefficient of Freon (F) and of air (a) and with S_F and S_a the measured signals for Freon and for air. In the second method, a non-absorbing aerosol is introduced into the ASAM instrument and the extinction coefficient, σ_e is calculated from the direct beam attenuation. σ_s is equal to σ_e and the calibration constant k is determined from the equation

$$k = (\sigma_e) / (S_{aero} - S_a)$$

with S_{aero} the scattering signal from the aerosol. Calibration values determined by each of these methods were close to each other, verifying the consistency in the two methods.

The calibrations described above were done under conditions for which the transmittance is approximately 1. For conditions in which the transmittance is significantly less than 1, there will be a significant decrease in beam intensity along the beam path; and the scattered light signal will be less than expected from the low concentration data. All of the measurements were made in conditions in which the transmittance was significantly less than 1, and so an additional calibration was necessary to account for the decrease in beam intensity along the beam path.

These additional calibration measurements were made using a non-absorbing ammonium sulfate aerosol in varying concentrations with measured transmission values between 1 and 0.8. Measured scattering and attenuation values were used to determine an empirical adjustment factor for conversion of the measured scattering coefficient to the actual scattering coefficient. This adjustment factor was defined so that the single scattering albedo was equal to 1 (the measured scattering coefficient was equal to the measured attenuation coefficient) for the range of measured transmissions. The best adjustment factor was found to be given by the equation

$$\sigma_s = \sigma_{s,init} / T^{**}.45$$

in which T is the transmission measured along the total path in the instrument. This empirical adjustment factor worked quite well for measurements of absorbing smokes for transmission values as low as 0.10.

We would note that this empirical adjustment factor is approximately that which would be determined if the adjustment were made in terms of beam intensity at the closest point to the detector. Since the scattered light detector is at the midpoint of the beam, the intensity of the beam at its midpoint is given by the initial intensity multiplied by the square root of the transmission.

SECTION 4

EXPERIMENTAL MEASUREMENTS AND PROCEDURES

The measurement program consisted of a series of burns on the different fuel samples shown in Table 1. The measurements were conducted using the combustion characterization facilities on the campus of the Georgia Institute of Technology (Zinn, et al, 1977, Perry et al, 1977). These facilities consist of a combustion products test chamber (CPTC) and associated in-situ and aerosol sampling instrumentation. The CPTC is a ventilated chamber that was designed to provide capabilities for control of air flow to the combustion volume, control of the temperature of air entering the combustion volume, and control of radiance on the sample. Provision was made for both optical measurements and collection of samples for microphysical measurements.

The chamber, shown in schematic form in Fig. 2 from Zinn et al, consists of an outer shell approximately 1.4 m on a side. Within this outer shell there are a series of heaters to control the temperature of the air as it enters the combustion volume. There is an inner conical shell to channel the air and combustion products from the chamber to the exhaust line. This inner cone is perforated to improve air flow within the chamber. The exhaust line passes through a measurement chamber and is then ducted out of the building. The measurement chamber contains the in-situ optical measurement system as well as an inlet for the aerosol sampling system. Airflow through the system is produced using positive pressure from compressed air or from a mixture of air and another gas. This arrangement insures that the flow through the system will not be affected by changes in exhaust air temperature. Air flow during our series of measurements ranged from 2 cfm to 20 cfm; flow was measured using calibrated rotometers.

The sample holder consists of an approximately 6 x 10 cm tray that is suspended on top of a force transducer that provides a continuous measurement of the weight of sample from which the rate of weight loss of the sample can be determined. The sample heater produces a radiant flux which can be varied between 0 and 8 W/cm^2.

The in-situ optical measurement system, shown in Fig. 3, provides for attenuation measurements at two wavelengths (red light at 632.8 nm produced by a HeNe laser and blue light at 488 nm produced by an Argon ion laser) and angular scattering measurements of blue light at 5^o and 15^o. The arrangement of the optical system has

Table 1. Materials and Fire Condition Matrix.

Materials:

- Polyethylene (HDPE)
- Polyvinylchloride (PVC)
- PMMA
- Polystyrene
- Polypropylene
- Polycarbonate
- K1 Kerosene
- #2 Oil
- #5 Oil
- Asphalt
- Oak

Fire Conditions:

- Ventilation
- Radiance
- Smoke Concentration

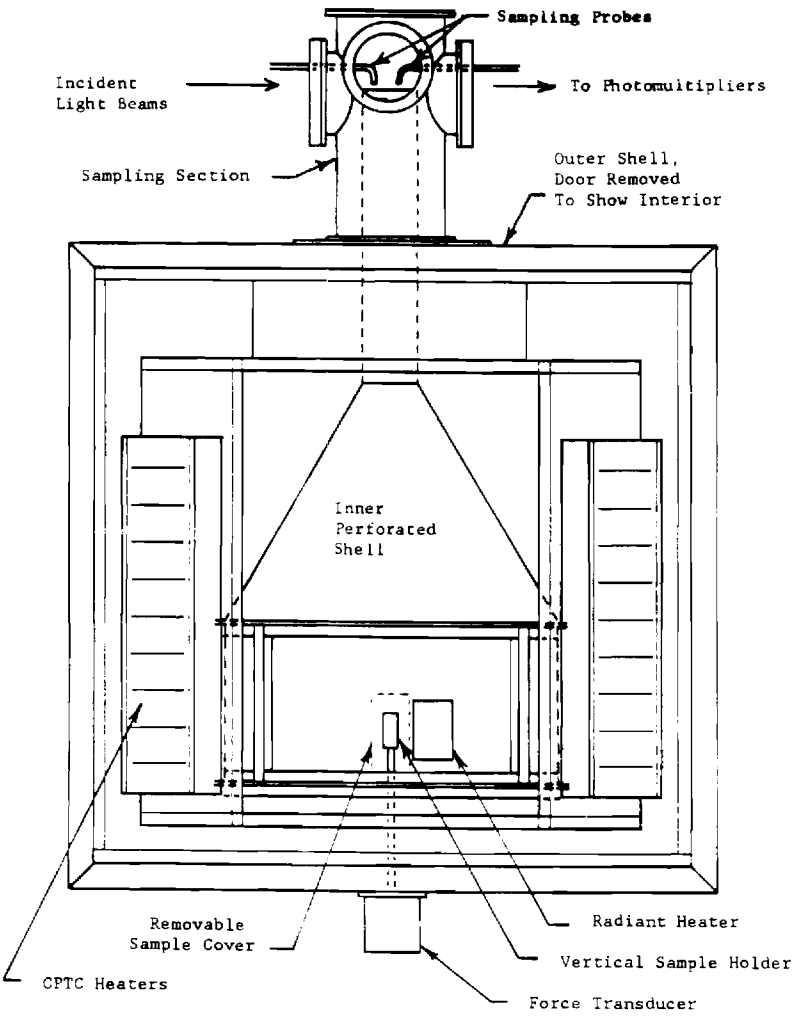
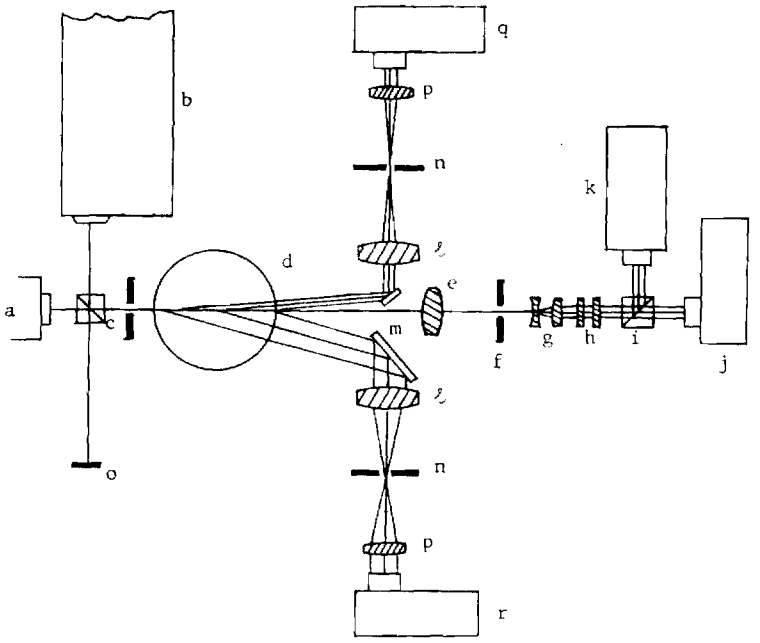


Figure 2. Combustion Products Test Chamber.



a. Helium-Neon Laser
b. Argon -Ion Laser
c. Beam Combining Cube
d. 4" Diameter Stack from CPTC
e. Objective Lens
f. Pinhole Aperture
g. Beam Expander
h. Neutral Density Filters
i. Beam Splitter Cube
j. Transmitted Blue Light Detector
k. Transmitted Red Light Detector
l. Objective Lenses
m. Mirrors
n. Pinhole Apertures
o. Light Stop
p. Collimating Lenses
q. 5^{o} - Scattering Detector
r. 15^{o} - Scattering Detector

Figure 3. In-Situ Optical Measurements.

been described in detail by Zinn et al. The ratios of the scattered light intensities at 5^{o} and at 15^{o} are calculated and used to determine a volume-surface mean diameter D_{32} (Powell et al, 1976) which can be thought of as an effective optical diameter for the particles. At the near forward scattering angles of 5 and 15^{o}, the ratio of the scattered light at the two angles is not highly sensitive to variations in particle refractive indices or shape. The measurement of this ratio is applicable for the calculation of D_{32} in the range of 0.15 to 2.0 microns.

The aerosol sampling system drew a small volume of air from the exhaust line. This air was used to provide sample air to an optical particle counter (PMS LAS-X), a cascade impactor (Anderson 1-CFM), a single stage filter, and the ASAM instrument. The PMS optical particle counter and the two aerosol collection devices were provided with undiluted air. The ASAM air was diluted so that the instrument signal would be within its range of validity. Consequently, the ASAM extinction and scattering measurements must be normalized to the in-situ measurements.

The data system for the CPTC was modified for this program to provide for computer controlled data acquisition using a PC compatible system. The voltage outputs from the optical detectors (two attenuation and two scattering), the detector voltage setting, and the force transducer are converted to digital readings with a Metrabyte data acquisition board for PC compatible computers. The computer acquires data at a rate of 5 samples per second for each of the six data channels. This high speed data is then processed to produce 5 second averages for each channel. These 5 second averages are then used to calculate attenuation values, relative scattering values, and sample weight values as a function of time during the burn. The nephelometer and ASAM instrument data were acquired by the individual instruments rather than by the CPTC data acquisition system.

Similar experimental procedures were followed for each of the burns. A given mass of fuel was placed in the sample tray and the sample was covered. The radiant heaters were turned on and allowed to equilibrate to the final radiance. Airflow into the chamber was adjusted to the desired flow, and the sample was then uncovered. There was, in general, a period of smoldering combustion followed by flaming combustion.

The in-situ optical data, ASAM data, and force transducer data were recorded continuously. Optical

particle counter data were recorded on a one minute average basis. Several filter samples were collected during each combustion test. One sample was collected during any smoldering and one or more samples during the flaming phase. The filter sampling arrangement was set up so that no sample was lost during filter changes. The cascade impactor was used to collect one sample only during each fire; in general, the cascade impactor sampling was started at the beginning of the flaming phase of the fire and ended at the conclusion of the fire.

The airflow through the chamber could be varied between approximately 2 and 20 cfm. The measurements were generally at 10 and 20 cfm. Variation in atmospheric composition was obtained by ventilating the chamber with a mixture of nitrogen and compressed air. Various mixtures were used; air/N_2 ratios are shown in the individual data sheets. The measurements used two values of radiant flux, a low value of 5.0 w/cm^2 and a high value of 8.0 w/cm^2. a small pilot propane flame was used to initiate the flaming phase of the combustion.

In the analysis of the data from each test fire, the <u>in-situ</u> optical data is averaged to provide integrated data that corresponds to filter sample time intervals. The fuel weight loss for the time period is calculated from the force transducer data. The mass emission factor is calculated using the filter mass data, the fuel mass loss data and the relative air flow for the filter sample and the CPTC. Where possible, emission factors were calculated for the different phases of the test burn. The attenuation coefficient was calculated from the average transmission for the blue and the red light and the path length through the smoke. The specific attenuation B_e was then calculated for both the blue and the red beams by dividing the average attenuation by the average mass concentration. In addition, the fuel specific attenuation coefficient was then calculated by multiplication of B_e values by the mass emission factors. The ratio of blue to red attenuation was calculated from the two attenuation measurements. Detailed size distributions were measured, as well as the D_{32} parameter which is an optically effective mean size.

SECTION 5

MEASUREMENT RESULTS

Results of measurements for the plastic fuels, rubber, wood, and hydrocarbon fuels are given in the following sections. The results are presented in Tables 2 through 9. In these Tables we list the data by sample or fuel type; for the individual samples the mass of fuel consumed is given. Emission factors (EF), B_e and B_e' for 488 nm blue and 633 nm red wavelengths, attenuation ratios of blue to red extinction, and ω_o are also given. Fire conditions list the chamber air flow in cfm and the radiant heating in Watts per cm^2.

PLASTIC FUEL RESULTS

PMMA

PMMA data are shown in Table 2. A total of nine test burns of PMMA were analyzed in detail, three with a complete data set and six with a partial data set, in which only the fuel specific attenuation coefficients (B' values) were measured. The range of fire conditions is also shown in Table 2; air flow was either 10 or 20 cfm and the radiant intensity onto the fuel was either 5 W/cm^2 or 8 W/cm^2. In all cases, including those in which the ventilation was with a mixture of air and nitrogen, the fires consisted almost entirely of flaming combustion. Very little fuel consumption or smoke emissions occurred in the smoldering phase; and smoldering aerosol emissions were not sufficient for accurate measurements.

The data appeared consistent for this material. The average emission factor for the PMMA was 0.015 g/g. Average fuel specific attenuation, B_e, values were 0.153 for the 488 nm blue light and 0.12 for the 633 nm red light with an attenuation ratio of 1.28 and an α value of 0.95. B_e values showed more variation, averages calculated for the PMMA data were 10.2 for the blue and 8.0 for the red. ω_o values were in the range of 0.18 to 0.23. In general, most of the values were between .21 and 0.23. We estimate that a value of 0.22 is the most probable value for ω_o, with a resulting B_a value of 6.2 in the red. Although not shown individually in the table for the different runs, the average D_{32} value for the PMMA was 1.3 microns.

Little variation in the emission properties was observed for the variation in fire conditions.

Table 2. PMMA Summary.

SAMPLE	FUEL BURNED [g]	EF [g/g]	BLUE Be [m^2/g]	BLUE Be' [m^2/g]	RED Be [m^2/g]	RED Be' [m^2/g]	ATTN RATIO	ω_o (RED)	SCATTERING RATIO	COMBUSTION CONDITIONS (AIRFLOW-HEATING)
PMMA-1	24.5	.015			10.1	.15				9.6 l/s(AIR)-5W/cm^2
PMMA-2 TOTAL	21.9	.018	8.1	.14	6.2	.11	1.31	.23	2.45	4.8 l/s(AIR)-8W/cm^2
PMMA-3 TOTAL	22.4	.018	6.9	.12	5.5	.10	1.25	.22	1.42	4.8 l/s(60%A/40%N)-8W/cm^2
PMMA-4 TOTAL	19.4	.008	14.0	.12	9.8	.08	1.43	.18-.21	1.20	4.8 l/s(60%A/40%N)-5W/cm^2
PMMA-5 TOTAL	20.9			.15		.12	1.20			4.8 l/s(AIR)-8W/cm^2
PMMA-6	20.6			.16		.11	1.37			4.8 l/s(AIR)-8W/cm^2
PMMA-7 TOTAL	20.3			.21		.15	1.36			9.6 l/sCFM(AIR)-8W/cm^2
PMMA-8 TOTAL	18.7			.16		.13	1.30			
PMMA-9 TOTAL	18.8			.16		.13	1.24			

Polycarbonate

Polycarbonate data is shown in Table 3. For the polycarbonate, unlike the PMMA, the combustion included a significant smoldering component. In addition, there were some differences in the results for the air and for the air/nitrogen mixture combustion.

Considering flaming combustion only, the air-only measurements resulted in emission factors of approximately 0.1, B_e values of 11 in the blue and 9 in the red, B_e' values of 1.1 in the blue and 0.95 in the red, and ω_o values of 0.3. Those air-nitrogen mixture measurements resulted in emission factors of 0.07, B_e values of 8 to 9 in the blue and 6 to 7 in the red, B_e' values of approximately 0.6 in the blue and 0.5 in the red, and ω_o values of 0.4 and higher. The high ω_o values are of particular interest because they indicate that B_a values for these cases would be only of the order of 4 to 5 m^2/g. Optically effective diameters were approximately 1.0 micron.

Smoldering combustion measurements resulted in lower B_e values and ω_o values of approximately 0.9.

The effects of variation of fire parameters discussed above may be summarized as follows: The changes in radiance had little effect; as the percent oxygen in the air decreased ω_o increases, the emission factors decrease and B_e' decreases.

PVC

The PVC data was collected in two series, one, Series A, in which the measurements were made prior to the completion of the aerosol scattering and attenuation instrument and the other, Series B, in which the measurements included the ASAM data. The Series A runs data were not separated by combustion phase; series B data, which was separated by fire phase is the only data set considered here. This data is shown in Tables 4 (Series A data) and 5 (Series B data).

The PVC also burned with an appreciable smoldering component which was characterized by low B_e values and high ω_o values, indicating essentially no absorption. For the flaming phases of the fires, there were some apparent differences between the runs in which there was air only and those in which there was a mixture of air and nitrogen for a reduced oxygen atmosphere. For the normal air-only runs, the B_e values were 10.4 for the blue and 8.8 for the red and the B_e' values were 1.8 for the blue and 1.5 for the red. ω_o values were 0.42.

Table 3. Polycarbonate Summary.

SAMPLE	FUEL BURNED [g]	EF [g/g]	BLUE Be [m^2/g]	BLUE Be' [m^2/g]	RED Be [m^2/g]	RED Be' [m^2/g]	ATTN RATIO	ω_o (RED)	SCATTERING RATIO	COMBUSTION CONDITIONS (AIRFLOW-HEATING)
PC-1										9.6 1/s(AIR)-5W/cm^2
A	.2	.32	2.38	.76	3.6	1.13	.67	.88	2.63	SMOLDERING
B	13.5	.104	10.74	1.12	9.0	.94	1.19	.29	2.78	FLAMING
TOTAL	13.7	.107	10.38	1.11	8.8	.94	1.19		2.76	
PC-2										9.6 1/s(AIR)-8W/cm^2
A	.1	.35	1.88	1.64	1.4	.56	1.18	.70	1.57	SMOLDERING
B	13.9	.102	11.23	1.15	7.4	.95	1.21	.30	2.72	FLAMING
TOTAL	14.0	.104	10.95	1.14	9.1	.95	1.20		2.67	
PC-3										4.8 1/s(60%A/40%N)-8W/cm^2
A	.2	.13	6.40	.82	5.8	.75	1.10	.91	1.35	SMOLDERING
B	11.9	.079	9.01	.71	7.4	.58	1.22	.48	1.89	FLAMING
TOTAL	12.1	.079	8.94	.71	7.3	.58	1.22		1.82	
PC-4										9.6 1/s(60%A/40%N)-8W/cm^2
A	3.4	.057	5.5	.32	5.0	.28	1.11	.90	1.76	SMOLDERING
B	8.9	.056	8.8	.49	6.6	.37	1.33	.41	1.39	FLAMING
TOTAL	12.3	.056	7.9	.44	6.2	.35	1.28		1.59	

Table 4. PVC Summary Series A.

SAMPLE	FUEL BURNED [g]	EF [g/g]	BLUE Be [m^2/g]	BLUE Be'	RED Be [m^2/g]	RED Be'	ATTN RATIO	ω_o (RED)	SCATTERING RATIO	COMBUSTION CONDITIONS (AIRFLOW-HEATING)
PVC-A1										
TOTAL	5.2	.094	11.1	1.04	9.4	.89	1.174			10/5W/cm^2 FLAMING
PVC-A2										
TOTAL	9.1			.87		.74	1.18			20/5W/cm^2 MIX FLAMING AND SMOLDERING
PVC-A3										20/5W/cm^2
TOTAL	7.7	.057	4.5	.25	4.5	.25				SMOLDERING ONLY
PVC-A4										SMOLDERING ONLY
TOTAL	22.7	.038	6.2	.46	6.2	.46	1.0		.30	20(10A/10N)8W/cm^2
PVC-A5										
TOTAL	9.3	0.75	7.0	.53	7.0	.53	1.0			15(5A/10N)8W/cm^2
PVC-A6										15(5A/10N)8W/cm^2
TOTAL	9.8	0.62	-	-	6.1	.38				SMOLDERING
PVC-A7										
TOTAL	17.8					.43				
PVC-A8										
TOTAL	8.9	.018(Cl)				.49				
PVC-A9										
TOTAL	17.9	.034								
PVC-A10										10(8A/2N)8W/cm^2
A	5.4									SMOLDERING
B	13.7	.084	-	-	8.3	.70				FLAMING
TOTAL										

Table 5. PVC Summary Series B.

SAMPLE	FUEL BURNED [g]	EF [g/g]	BLUE Be [m^2/g]	BLUE Be' [m^2/g]	RED Be [m^2/g]	RED Be' [m^2/g]	ATTN RATIO	ω_o (RED)	SCATTERING RATIO	COMBUSTION CONDITIONS (AIRFLOW-HEATING)
PVC-B1										9.6 l/s(AIR)-5W/cm^2
A	10.6	.037	3.2	.12	2.8	.10	1.15	.98	1.6	SMOLDERING
B	5.7	.185	11.3	2.09	9.6	1.8	1.18	.44	2.1	FLAMING
TOTAL	16.3	.087	9.1	.79	7.7	.67	1.17		1.9	
PVC-B2										4.8 l/s(AIR)-5W/cm^2
A	10.5	.017	5.8	.10	3.9	.07	1.48	1.0	1.5	SMOLDERING
B	6.0	.144	9.4	1.4	8.0	1.15	1.18	.40	2.3	FLAMING
TOTAL	16.5	.063	8.8	.56	7.3	.48	1.20		1.9	
PVC-B3										9.6 l/s(60%A/40%N)-8W/cm^2
A	6.0	.028	4.5	.13	3.6	.10	1.25	.98	1.8	
B	8.8	.148	5.0	.74	4.3	.63	1.17	.50	1.6	
TOTAL	14.8	.099	4.9	.49	4.2	.41	1.18		1.6	
PVC-B4										4.8 l/s(80%A/20%N)-8W/cm^2
A	10.2	.082	3.7	.30	3.4	.28	1.07	1.00	1.4	SMOLDERING
B	5.1	.105	10.2	1.1	8.6	.90	1.19	.45	2.0	
TOTAL	15.3	.084	6.2	.52	5.4	.46	1.15		1.7	
PVC-B5										4.8 l/s(80%A/20%N)
A	2.8	.036	3.7	.13	3.2	.12	1.14	1.00	1.6	SMOLDERING
B	13.8	.065	11.0	.72	9.6	.62	1.15	.45	1.8	FLAMING & SMOLDERING
TOTAL	16.6	.060	10.3	.62	8.9	.54	1.15		1.8	

Measurements with 80% air and 20% Nitrogen showed little difference in optical properties, with ω_o values slightly higher. A run with 60% air and 40% Nitrogen showed higher ω_o values of 0.50 with B_e values that are comparable to those in smoldering combustion.

The variation in our PVC data may be summarized as follows: PVC shows more sample to sample variation than some other plastics; with reduced air there is more smoldering, but in the flaming phase there is little variation in ω_o and B_e. Overall, ω_o will be higher, B_e somewhat lower, B_a significantly lower, and emission factors significantly higher. Higher radiant heating flux reduces smoldering--this can be important under reduced oxygen conditions.

HDPE

A high density polyethylene (HDPE) was used as the fuel for the polyethylene burns. This HDPE data is shown in Table 6 for Series A and B as in the PVC case. The data in Series A were more variable; the Series B data were, in general, more consistent with a greater contribution from flaming. Of particular interest are the ω_o data for Series B, which show quite consistent values of 0.26. Average B_e values (from Series B) were 0.19 for the blue and 0.14 for the red. The D_{32} diameters for the HDPE were approximately 1.2 microns. The HDPE showed no systematic variation with either heating or ventilation variation

Summary of Plastic Fuel Results

The plastic fuel data discussed above, with additional data from polystyrene and polypropylene, are shown in Table 7. There is a wide range of values of emission factors, with a much narrower range of values for B_e values. Because of the different emission factors, B_e' values also show a large variation. Attenuation ratio values are approximately 1.2 indicating consistancy in particle size; ω_o values range from 0.22 for the PMMA to 0.45 for the PVC.

WOOD EMISSIONS STUDY

As part of the study of the urban fuel mix we wanted to investigate the effect of wood materials in combination with plastic and alone. Consequently, several burns were made to investigated the optical properties of the smoke emissions from a wood fuel (red oak). The data for these burns are shown in Tables 8 and 9.

Table 6. HDPE Summary
Series A.

SAMPLE	FUEL [g]	EF [g/g]	BLUE Be [m^2/g]	BLUE Be'	RED Be [m^2/g]	RED Be'	ATTN RATIO	ω_o (RED)	SCATTERING RATIO	COMBUSTION CONDITIONS (AIRFLOW-HEATING)
HDPE-A1	10.3	.029	9.21	.26	7.2	.21	1.28		7.57	4.8 1/s-8W/cm^2
HDPE-A2 TOT FL	10.0	.021	11.6	.24	9.4	.19	1.23	.075*		4.8 1/s-8W/cm^2
HDPE-A3	10.1	.028	15.9	.41	12.5	.35	1.28	.25*	.27	9.6 1/s-5W/cm^2 FLAMING
HDPE-A4	10.1	.028	-	-	-	-	-			4.8 1/s-5W/cm^2 SMOLDERING & FLAMING
HDPE-A5	9.9	.021	14.4	.30	11.9	.25	1.21	.32*		4.8 1/s-44 FLAMING
HDPE-A6	2.6	.047	10.6	.50	8.3	.39	1.28	.11*	.24	9.6 1/s-8W/cm^2 SMOLDERING
HDPE-A7	10.2			.51		.49				MIX SMOLDERING & FLAMING
					Series B					
HDPE-B1		.020	10.3	.21	7.6	.15	1.36	.26	2.32	4.8 1/s-5W/cm^2
HDPE-B2		.018	8.4	.15	6.7	.12	1.25	.26	1.79	4.8 1/s-8W/cm^2 (<2% MASS NOT INCLUDED)
HDPE-B3		.023	8.2	.19	6.5	.15	1.26	.25	2.65	4.8 1/s-8W/cm^2
HDPE-B4		.020	9.3	.19	6.6	.13	1.41	.26	1.79	4.8 1/s(60%A/40%N)-8W/cm^2

*Data based on filter absorption measurements

Table 7. Plastics Summary.
(Flaming Combustion Only)

MATERIAL	EF	BLUE		RED		ATTN	ω_o
		Be	Be'	Be	Be'	RATIO	(RED)
	[g]	[m^2/g]		[m^2/g]			
PMMA	.015	10.3	.15	7.9	.12	1.30	.22
HDPE	.023	10.9	.25	8.5	.20	1.28	.26
PVC	.129	9.4	1.21	8.0	1.03	1.17	.45
POLYCARBONATE	.085	9.9	.84	8.0	.68	1.24	.29
POLYSTYRENE	.041			9.6	.39		
POLYPROPYLENE	.042			7.4	.31		

Table 8. Oak Summary Series A.

SAMPLE	FUEL BURNED	EF	BLUE Be	BLUE Be'	RED Be	RED Be'	ATTN RATIO	ω_o (RED)	SCATTERING RATIO	CONDITION
OAK-A1 TOTAL	21.5	.0036	-	-	11.9	.043	-	-	-	20(AIR)8W/cm^2
OAK-A2 TOTAL	22.8	.057	-	-	6.81	.376	-	-	-	10(3A/7N)8W/cm^2 Smoldering
OAK-A3	16.2	.0033			7.07	.023				10(5/5)8W/cm^2

Table 9. Oak Summary Series B.

SAMPLE	FUEL BURNED [g]	EF [g/g]	BLUE Be [m^2/g]	BLUE Be' [m^2/g]	RED Be [m^2/g]	RED Be' [m^2/g]	ATTN RATIO	ω_o (RED)	SCATTERING RATIO	COMBUSTION CONDITIONS (AIRFLOW-HEATING)
OAK-B1										9.6 1/s(AIR)-8W/cm^2
A	0.6	.053	4.8	.26	2.5	.13	1.75	.8	4.1	
B	26.2	.0026	14.6	.038	11.6	.030	1.27	.15	2.8	
TOTAL	26.8	.0038	11.4	.043	8.5	.032	1.33		3.3	
OAK-B2										4.8 1/s(50%/50%)-8W/cm^2 SMOLDERING
TOTAL	24.5	.183	3.9	.71	3.8	.69	1.03	.9	1.8	
OAK-B3										4.8 1/s(60%A/40%N)-8W/cm^2
A	12.5	.113	3.0	.34	2.8	.32	1.08	.86	3.7	SMOLDERING
B	12.6	.017	7.1	.12	6.0	.10	1.18	.2-.3	1.9	FLAMING
TOTAL	25.1	.065	3.3	.22	3.0	.20	1.10		3.5	
OAK-B4										4.8 1/s(60%A/49%N)
A	2.2	.12	1.5	.17	1.5	.18	.98	.85	3.8	SMOLDERING
B	24.1	.009	7.6	.068	5.8	.053	1.32	.17	1.8	FLAMING
TOTAL	26.3	.033	2.8	.095	2.4	.080	1.17		3.6	
OAK-B5										4.8 1/s(AIR)-8W/cm^2
A	.5	.029	-					.87		
B	24.7	.0041	10.1	.041	7.5	.031	1.35	.14-.16		
TOTAL	25.2	.0046	8.9	.041	6.6	.031	1.34			
OAK-B6										4.8 1/s(AIR)-8W/cm^2
TOTAL	26.3	.0046	7.6	.035	14.8	.026	1.36	.16-.17		

The data indicate the B_e and ω_o values for the flaming combustion of this dried wood fuel material are close to the values measured for the plastic materials, unlike the earlier measurements of Patterson and McMahon (1980) on natural vegetative fuels. Emission factors for the flaming combustion are much lower than for the plastic materials. D_{32} values for the flaming combustion are approximately 1.4 microns.

We also attempted to simulate the effect of reduced ventilation on the combustion products by burning the wood in an oxygen poor environment. For oxygen concentrations of 50% or less the wood fuel would not sustain flaming combustion at chamber flows of 10 cfm. In other cases of air nitrogen mixtures, the relative contribution of the smoldering phase to the total fire emissions was increased relative to the air only cases. In all of the cases in which the emissions factors were significantly increased over the lowest purely flaming values, the single scattering albedo also showed an increase over the lowest values. This suggests that high emission factors under reduced oxygen fuel consumption are not accompanied by correspondingly low single scatter albedos or high absorption. This inference is corroborated by Fig. 4, which is a plot of the single scatter albedo vs. the emission factor for the oak data of Table 9, omitting those data for which there was low fuel consumption.

EMISSIONS FROM COMBINATIONS OF WOOD AND PLASTIC

As part of the study of the urban fuel mix we measured the emissions from a combination of the oak and plastic fuels. These data are shown in Table 10. There do not appear to be any major variations in the data from the data that would be expected from a linear combination of the two components.

RUBBER EMISSIONS STUDY

Data for several burns with rubber as a fuel are shown in Table 11. Two representative types of rubber were burned, a plain rubber and tire rubber. The tire rubber differs from the plain rubber because it contains a large amount of carbon black to improve its strength properties for tire applications. Although the ω_o values are about the same for the flaming combustion for both types of rubber, the emission factors are different (0.05 for the plain and 0.08 for the tire) as are the B_e values (11 m^2/g for the plain and 16 m^2/g for the tire). Resulting B_e' values are larger for the tire material than for the plain rubber.

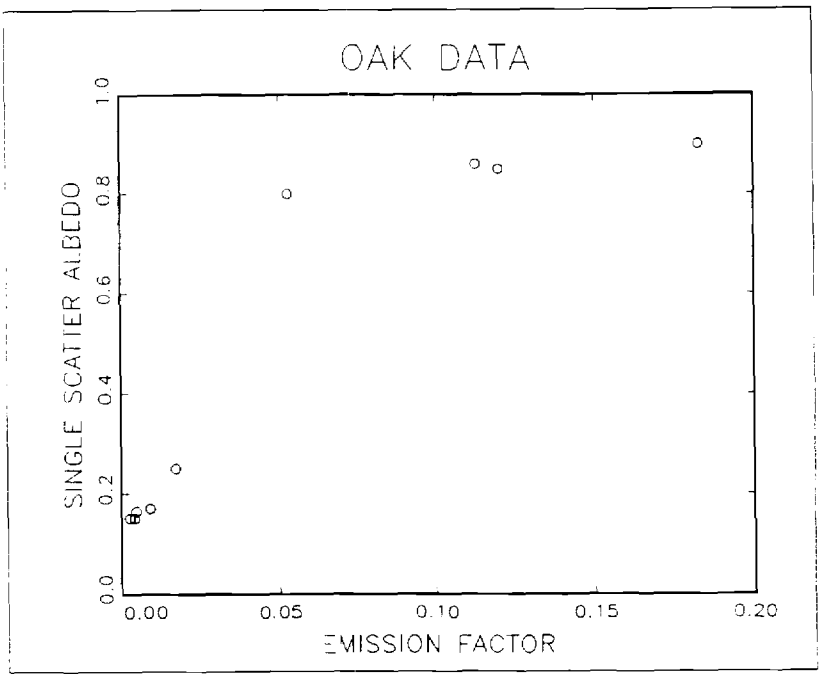


Figure 4. Single Scatter Albedo as Function of Emission Factor.

Table 10. Mixed Wood and Plastic.

SAMPLE	FUEL	EF	BLUE		RED		ATTN	ω_o	SCATTERING	CONDITION
			Be	Be'	Be	Be'	RATIO	(RED)	RATIO	
OAK & PMMA-1										10(AIR)8W/cm^2
A		.011	1.5	.016	1.3	.014	1.13	.85	3.6	
B		.008	14.4	.114	11.3	.090	1.27	.21	3.2	
TOTAL		.008	11.7	.100	9.5	.079	1.27		3.3	
OAK & PMMA-2										10(6A/4N)8W/cm^2
A		-	-					.86	2.2	
B		.005	8.0	.040	6.2	.031		.14	1.8	
TOTAL		.005	7.5	.038	5.8	.030			1.8	
OAK & HDPE-1		.018			10.7	.20				
OAK & PVC-1		.028								

Table 11. Rubber Summary.

SAMPLE	FUEL BURNED [g]	EF [g/g]	BLUE Be [m^2/g]	BLUE Be' [m^2/g]	RED Be [m^2/g]	RED Be' [m^2/g]	ATTN RATIO	ω_o (RED)	SCATTERING RATIO	COMBUSTION CONDITIONS (AIRFLOW-HEATING)
RUBB-1 (CLEAR)										4.8 1/s(AIR)-5W/cm^2
A	.2	.12	15.5	1.86	5.8	.69	2.6	.9	1.16	SMOLDERING
B	10.7	.045	11.9	.53	9.4	.42	1.27	.28	2.6	FLAMING
TOTAL	10.9	.047	12.0	.56	9.2	.43	1.31		2.54	
RUBB-2 (CLEAR)										9.6 1/s(AIR)-8W/cm^2
A	.1	-						.93		SMOLDERING
B	10.5	-						.29		FLAMING
TOTAL	10.6	.064	12.2	.78	9.7	.62	1.26		1.70	
RUBB-3 (CLEAR)										4.8 1/s(60%A/40%N)-8W/cm^2
A	0.1	-						.9		SMOLDERING
B	12.4	-						.29		FLAMING
TOTAL	12.5	.045	8.2	.37	6.6	.30	1.25		1.74	
RUBB-4 (TIRE)										9.6 1/s(AIR)-5W/cm^2
A	0.3	.107	-	.91	-	.93	.98	.80	2.43	SMOLDERING
B	10.9	.082	17.2	1.41	15.0	1.22	1.15	.30	1.99	FLAMING
TOTAL	11.2	.083	17.0	.83	14.8	1.22	1.15		2.01	
RUBB-5 (TIRE)										9.6 1/s(AIR)-8W/cm^2
A	.2	.136	-	3.7	-	2.8	1.32	-	2.12	SMOLDERING
B	13.7	.089	14.0	1.24	10.8	.96	1.29	.30	2.08	FLAMING
TOTAL	13.9	.090	15.0	1.35	11.7	1.05	1.29		2.08	

PETROLEUM PRODUCTS STUDY

A series of measurements were made on four petroleum products, kerosene, two diesel oil products, and asphalt. The kerosene was a K1 grade; the Diesel fuels were #2 and # 5 grades. The four fuel types spanned a range of viscosities, boiling points and molecular weights, with K1 the lightest and asphalt the heaviest. The purpose of the test series was to determine whether there were any consistent differences in the optical properties that are related to the differences in the physical properties of the fuels. The data for the individual products are shown in Tables 12 through 15; a summary of the results for the petroleum products emissions is shown in Table 16.

In general, each of the data sets used to generate Table 16 appears to be internally consistent, with no major differences in the different fire conditions. The summary data show some interesting trends. The emission factor data show an increase with the increasing molecular weight fractions from 0.029 g/g for the kerosene to 0.092 for the asphalt. The B_e values show little variation with the increasing weight fractions. The average is approximately 10.9 m^2/g for the blue and 8.8 for the red. with a ratio of 1.24 which corresponds to an α of 0.8. B_e values show an increase from 0.33 to .99 for the blue and from 0.25 to 0.82 for the red. ω_o values range for 0.24 for the kerosene to 0.31 for the asphalt. This is of particular interest because, in the absence of other data, this data can be used to scale the behavior of other hydrocarbon fuels.

ADDITIONAL STUDIES OF FIRE AND FUEL CONDITIONS

Three sets of additional studies of the effects of fire conditions on aerosol emissions were made. These included measurements of the effect of admixtures of sand with the plastic fuel, measurements of the effects of high concentrations of aerosols on the measured emissions, and measurements of the effects of variations in the amount of fuel.

Plastics in a Mixture with Sand

A series of burns were made in which the plastic fuel was mixed with sand. These were designed to simulate the effects of rubbleized fuel. The data from these mixed burns are shown in Table 17 and in summary form in Table 18; these data may be compared with the pure plastic data of Table 6. The most noticeable difference in the two tables is in the emission factor data. All of the plastic

Table 12. K1 Summary.

SAMPLE	EF	BLUE Be	BLUE Be'	RED Be	RED Be'	ATTN RATIO	ω_o (RED)	SCATTERING RATIO	CONDITION
K1-1	.031	10.9	.34	9.1	.25	1.20	.24	2.19	10/5W/cm^2
K1-2	-								
K1-3	.027	12.3	.33	9.2	.25	1.34	.24	2.01	10/5W/cm^2
K1-4			.12		.09	1.33	.30	1.35	10(4A/6N)8W/cm^2
K1-5			.09		.14	.64	.9	1.08	10(6N/4A)8W/cm^2 SMOL

Table 13. #2 Oil Summary.

SAMPLE	EF	BLUE		RED		ATTN	ω_o	SCATTERING	CONDITION
		Be	Be'	Be	Be'	RATIO	(RED)	RATIO	
20IL-1							.26		
20IL-2	0.35	11.0	.385	-	-	-	.26		10/5W/cm^2
20IL-3							.27		
20IL-4							.26		
20IL-5	.045	6.72	.303	5.29	.238	1.27	.25	1.88	10/5W/cm^2
20IL-6			.278		.280	.99	.75-.9	1.61	10(6N/4A)/65V SMOL
20IL-7	.028	9.9	.277	7.82	.219	1.27	.24	1.37	
20IL-8	.023	10.99	.241	8.38	.184	1.31	.25	1.84	10/5W/cm^2

Table 14. #5 Oil Summary.

SAMPLE	EF	BLUE		RED		ATTN RATIO	ω_o (RED)	SCATTERING RATIO	CONDITION
		Be	Be'	Be	Be'				
5OIL-1							.32		10/
5OIL-2	.045	12.3	.56	-	-		.29	1.573	10/5W/cm^2
5OIL-3	.041	12.2	.50	9.8	.40	1.25	.32	1.308	10(7A/3N)8W/cm^2
5OIL-4	.071	9.2	.64	8.7	.61	1.14	.29	3.07	20/5W/cm^2
5OIL-5	.053	11.5	.61	9.7	.51	1.19	.30	3.15	10/5W/cm^2

Table 15. Asphalt Summary.

SAMPLE		EF	BLUE Be	BLUE Be'	RED Be	RED Be'	ATTN RATIO	ω_o (RED)	SCATTERING RATIO	CONDITION
ASP-1		.061						.31		10/5W/cm^2 MAIN FLAMING
ASP-2		.207	5.13	1.06	4.38	.91	1.17	.95-SMOL .5-.7-MIX		10(5/5)8W/cm^2 SMOL+MIX
ASP-3	A	.288	3.5	.94	2.8	.75	1.26	.9		SMOLDERING
	B	.097	12.6	1.22	10.5	1.01	1.20	.31		FLAMING
	TOT	.117	9.9	1.15	8.2	.96	1.20	-		20/5W/cm^2
ASP-4	TOT	.119	9.0	1.07	7.4	.88	1.22	.31		20/8W/cm^2 FLAMING

Table 16. Petroleum Products Summary
(Flaming Combustion Only)

MATERIAL	EF	BLUE		RED		ATTN	ω_o
		Be	Be'	Be	Be'	RATIO	(RED)
	[g]	[m^2/g]		[m^2/g]			
K1	.029	11.6	.33	9.2	.25	1.27	.24
#2 OIL	.033	9.7	.32	7.5	.25	1.28	.26
#5 OIL	.053	11.3	.60	9.5	.50	1.19	.30
ASPHALT	.092	10.8	.99	8.9	.82	1.21	.31

Table 17. Plastics & Sand.

SAMPLE	FUEL	EF	BLUE Be	BLUE Be'	RED Be	RED Be'	ATTN RATIO	ω_o (RED)	SCATTERING RATIO	CONDITION
HDPE & SAND-1		.040	9.3	.37	8.1	.32	1.15	.22	4.0	20(AIR)8W/cm^2
HDPE & SAND-2										
A			4.5							
B			10.2		8.6		1.18	.23		20(AIR)8W/cm^2
TOTAL		.063	7.3	.54	7.9	.46	1.18			
HDPE & SAND-3		.073	5.7	.41	4.8	.35	1.18	.22		20(AIR)8W/cm^2
POLYCARB & SAND										
A								.85		
B			13.4		11.5			.28		
TOTAL		.106	12.9	1.37	11.1	1.18	1.17			
POLYSTYRENE & SAND		.124	10.4	1.29	9.3	1.16	1.11			
PVC & SAND-1	7.4	.063			9.9	.62				20(AIR)5W/cm^2
PVC & SAND-2										20(5A/5N)8W/cm^2
A	5.0	.058	2.4	.14	2.2	.13	1.07	.82		SMOLDERING
B	5.6	.118	9.8	1.16	8.3	.98	1.18	.34		FLAMING
TOTAL	10.6	.089	6.8	.61	5.8	.52	1.17			
PVC & SAND-3										20(AIR)8W/cm^2
A			5.8		4.7		1.23	.88		
B			10.7		9.6		1.11	.28		
TOTAL	11.5	.045	7.8	.35	6.7	.30	1.16			
PMMA & SAND-1		.021	8.3	.17	7.1	.21				20(AIR)8W/cm^2
PMMA & SAND-2		.020	10.1	.20	8.9	.18	1.14	.22		20(AIR)8W/cm^2

Table 18. Summary Plastics & Sand.

MATERIAL	EF	BLUE		RED		ATTN	ω_o
		Be	Be'	Be	Be'	RATIO	(RED)
PMMA & SAND	.021	9.2	.19	8.0	.17	1.16	.22
HDPE & SAND	.059	8.1	.44	6.9	.22	1.17	.22
POLYCARBONATE & SAND	.106	12.9	1.37	11.1	1.18	1.17	.28
PVC & SAND	.118	9.8	1.16	8.3	.98	1.18	.30
POLYSTYRENE & SAND	.124	10.4	1.29	9.3	1.16	1.11	

materials except for the PVC show an increase in emission factor when mixed with sand: PMMA from .015 to .021, HDPE from .023 to .059, polycarbonate from .085 to .106 and polystyrene from .041 to .124. The decrease for PVC is small, from 0.129 to 0.118. ω_o values seem slightly less in the mixed case, and the B_e' values are generally higher. In general it appears that our data indicate the the effects of burning the plastic material in the presence of a material such as sand will increase emissions and decrease single scatter albedo, enhancing the absorption effects.

Combustion of Plastic in the Presence of Ambient Aerosol

A series of burns were made to investigate possible effects of ambient non-combustible aerosols on the smoke emissions. These burns were made in the usual manner, except that an aerosol, either ammonium sulfate or titanium dioxide, was introduced into the CPTC in the ventilation air. The aerosol was introduced in a steady state condition so that the optical effects of the aerosol could be subtracted from the optical effects of the smoke. The subtraction was made, and the resulting data are shown in Table 19. No systematic changes in smoke properties are seen that could be attributed to the presence of the aerosol.

Measurements with Larger Fuel Volumes

A set of measurements of plastic fuel emissions were made with fuel weights approximately five times the usual values for the PMMA. HDPE, and PVC materials. These data are shown in Table 20. The only major change in the data from that in Table 6 is in the single scattering albedo data for the HDPE which is quite high for the larger fuel weight fire considered. The reasons for the different values are not known at this time; one future area of work should be measurements with fuel loadings in the range of a few kilograms to better explore the scaling questions.

MEASUREMENTS OF SIZE DISTRIBUTIONS

As discussed in the experimental procedures section, detailed size distribution measurements were made during the test burns. A summary of the cascade impactor data is shown in Table 21. The mass mean diameter is a measure of the central tendency of the data and the standard deviation is a measure of the breadth of the distribution. The large standard deviation indicate that these size distributions are, in general, very broad. Optical particle counter measurements were made, but not completely analyzed. They indicate smaller size distributions than measured by the cascade impactor.

Table 19. Plastic Fuel in Presence of Aerosol.

MATERIAL	EF	BLUE		RED		ATTN	ω_o
		Be	Be'	Be	Be'	RATIO	(RED)
PMMA & AMS04							
TOTAL	.023	8.2	.19	7.0	.16	1.17	.20
PVC & AMS04							
A	.044	1.7	.072	1.5	.067	1.08	.78
B	.093	10.3	.96	9.2	.86	1.12	.38
TOTAL	.078	8.7	.68	7.8	.61	1.12	
PMMA & T102							
TOTAL	.021	9.1	.19	7.9	.17	1/15	.22

* CORRECTED FOR EFFECTS OF INTRODUCED AEROSOLS

Table 20. Larger Burn Volumes.

MATERIAL	FUEL x NOM	EF	BLUE Be	BLUE Be'	RED Be	RED Be'	ATTN RATIO	ω_o (RED)
PVC	5X	.080	10.9	.87	7.4	.75	1.16	.40
PMMA	5X	.013	11.6	.15	10.3	.13	1.12	.20
HDPE	4X	.028	13.5	.38	12.3	.34	1.10	.40

Table 21. Summary of Cascade Impactor Data

Material	Mass Mean Diameter (microns)	Std. Dev.
HDPE	0.17 - 0.4	3 - 6
PVC	0.4 - 3	2.5 - 7
PP	0.6	11
PS	1.0	4
PMMA	1.1	9

These differences may be due to reduced inlet efficiency for the larger particles in the optical particle counter as well as to particle counter calibration effects.

SECTION 6

DISCUSSION

The plastic data show average B_e values near 10 m^2/g for the blue (488 nm) and 8 m^2 for the red (633 nm). This may be compared with earlier data of Seader and Ou (1977). The Seader and Ou data of particulate optical density are equivalent to our B_e data, except that the Seader and Ou definitions are in terms of logarithms to the base 10 rather than the base e. When converted to our B_e definition, the Seader and Ou data for flaming combustion of plastics are equivalent to a mean value of 7.6 m^2/g. are comparable to but slightly smaller than our measured values. A similar value of 10 m^2/g was measured by Roessler and Faxvog (1980) for acetylene smoke.

Values of B_e measured during smoldering combustion are significantly less than in flaming combustion and appear to be in the range of 3 to 5 m^2/g for these plastics; values which are also comparable to the earlier Seader and Ou data

B_e values for the rubber appear to be somewhat higher, particularly for the tire rubber; petroleum product fuel values are comparable to the plastic fuel values. Oak smoke emissions B_e values for flaming combustion range from 6 m^2/g to 12 m^2/g nm with an average value of approximately 7 m^2/g at 633 nm; these values are slightly lower than the plastic values.

Inferred B_a values at 633 nm for the plastic fuel emissions range from 4.4 for the PVC to 6.5 for the HDPE. If we assume a $1/\lambda$ dependence the comparable midvisible B_a values would range from 5.1 to 7.5. Similarly the B_a values range from 6 to 7m^2/g for the petroleum products, from 5 m^2/g to 11 m^2/g for the rubber, and from 6 m^2/g to 12 m^2/g for the oak at 633 nm. Conversion to average values at mid-visible wavelengths gives values of 7 m^2/g for the petroleum products, 8 m^2/g for the rubber and 11 for the wood. These numbers for B_a are in general less than assumed in the earlier models of climatic effects from urban fires, primarily due to the higher values of single scatter albedo that we measured relative to that assumed in the earlier models.

SECTION 7

SUMMARY AND CONCLUSIONS

We have measured the optical properties of the smoke emissions from the combustion of a series of plastics, wood, and petroleum products. The plastic data show average B_e values near 10 m^2/g for the blue and 8 m^2 for the red. Values of B_e measured during smoldering combustion are significantly less than in flaming combustion and appear to be in the range of 3 to 5 m^2/g for these plastics. B_e values for the rubber appear to be somewhat higher, particularly for the tire rubber; petroleum product fuel values are comparable to the plastic fuel values. Oak smoke emissions B_e values for flaming combustion range from 6 m^2/g to 12 m^2/g nm with an average value of approximately 7 m^2/g at 633 nm; these values are slightly lower than the plastic values.

Conversion of measured B_a values to average values at mid-visible wavelengths (550 nm) gives values of 7 m^2/g for the petroleum products, 8 m^2/g for the rubber and 11 m^2/g for the wood. These numbers for B_a are in general less than assumed in the earlier models of climatic effects from urban fires, primarily due to the higher values of single scatter albedo that we measured relative to that assumed in the earlier models.

Emission factors for the plastics show a wide range of values, from 0.015 for the PMMA to 0.13 for the PVC. Emission factors and overall absorption effects appear to be enhanced by burning in the presence of sand, which has been used as an analog for rubbleized fuel. Little effect was seen for combustion in the presence of aerosols or for the larger fuel amounts that we tested.

Wood emission factors were lower than for the plastics, and the highest absorption cases were those in which the emission factors were lowest. There does appear to be a relationship between single scatter albedo and emission factor.

SECTION 8

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GTRI

January 9, 1991

Mr. Wolford Swimmer, President
Cavert Wire Company, Inc.
P. O. Box 1167
Uniontown, PA 15401

Ref: Project A-8636, Proposal No. ME-ES-2762

Dear Mr. Swimmer:

A report has been submitted to you dated September 7, 1990. We have indicated that an alternative coating for galvanizing is feasible for bailing applications. We conducted extensive research to come up with a suitable technique/process to meet the following criteria for your application.

1) Pollution free
2) Cost comparable to galvanizing or less
3) Simple

There are two alternative processes that can be applied to your continuous wire drawing and annealing processes: dipping and electrodeposition.

The submitted report gives the details about both the processes. The design and manufacturing of the equipment were not part of the contractual agreement. However, we would provide you the necessary help in this matter and also conduct trials at your facilities. This would require additional funds. If agreed, the additional cost would be submitted to you.

Mr. Terry Rack and I agreed to coat approximately 250 lbs of wire by electrodeposition process and to try in a bailing equipment. The cost of coating the coil would be approximately $475.00. He was going to send me the coil but I have not heard from him yet.

Also I have provided him the additional information regarding the dipping process. You will find enclosed the details of the dipping process.

I would like to see a trial of 250 lbs. coil and will assist you further based on this test.

I look forward to working closely with you on this project.

Thanking you,
Sincerely,

Gautam Patel

cc: Bill Atcheson
David Benham
Lynn Boyd
Dr. Jan Gooch
Mildred Heyser

Georgia Institute of Technology is an equal education/employment opportunity institution of the University System of Georgia

Attachment

Dipping Process

Shell Chemical Company

1-800-832-3766 (Gary Hunter)

I. a. Epoxy resin $1.64/lb
Epon 828

Hardner "Y" $2.10/lb

Pot life (before it starts to jel) is between 8 to 12 hours, depending upon the ratio of resin/hardner.

b. Curing temperature
100 to 150°F/1 hour min.

II. a. Eponol (#53BH35) $1.67/lb
It is a premixed solution:
40% resin by wt. + 60% MEK by wt.

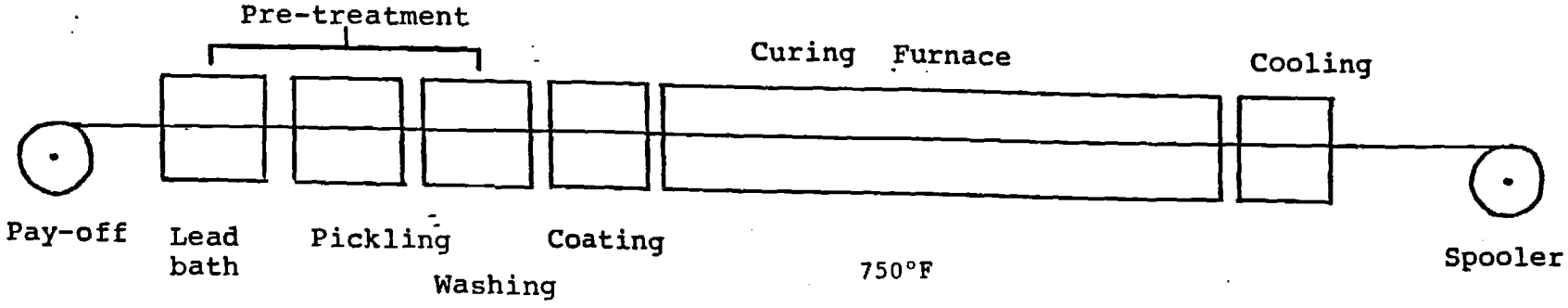
No curing agent or hardner is required. It can be diluted to give a desired coating thickness. The material is used in copper enamelling.

b. Curing temperature
350 to 400°F/3 to 4 minutes or less

NOTE - I suggest you try Eponel first, because Epon 828 cures very slow.

FLOW CHART

Dipping Process



Shell Chemical Co.

1-800-832-3766

1. Epoxy Resin
   Epon 828
2. Hardner "Y"

Pacific Anchor Chemical Co.

1-800-722-3769

Hardner supplier
(alternative to "Y")