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Subject: Semiannual Status Report No. 7 (Letter)
Project No. A-635-002
"Heat Transfer to a Gas Containing a Cloud of Particles,"
Research Grant NsG-273-62

Gentlemen:

From the initiation of this research the primary effort has been directed toward evaluating analytically and confirming experimentally the radiant heat transfer to particle clouds within a heated, cylindrical enclosure. A comprehensive treatment of developments to that time was reported in a Special Report, June 1965 and in Semiannual Report No. 6. During the subject reporting period, most emphasis has been given to (1) the construction of a new experimental system intended to test more severely the reported analytical results and (2) the measurement of the attenuation characteristics of carbon black particles suspended in a gas. This report summarizes these new developments.

Previous experimental work was not accomplished in an apparatus conforming as well as it might have to the accompanying theoretical analysis. The basic experimental chamber was a long (length-to-diameter ratio of 25) tube of small diameter (0.512 in.). This classified the experimental system as an infinitely long enclosure which meant that only part of the theoretical results were applicable. Also, convective heat transfer was large compared with radiation. These convective effects were reduced by surrounding the inner chamber with quartz but this also diminished the radiant heat flux penetrating the system. A new system is therefore being constructed which will eliminate many of these

adverse factors and permit heat transfer to be studied in systems having small length-to-diameter ratios. Such systems are of particular interest because nulcear rockets may ultimately have chambers of unity length-to-diameter ratio.

The new heat transfer apparatus incorporates an electrically heated, cylindrical enclosure formed from thin (5 mil) tungsten sheet. The heated enclosure, yet to be constructed, is to be made as large as possible. A diameter of between one and two inches is sought, the final size being fixed by the temperature that can be achieved with a 125 kilovolt-ampere power source. A temperature of at least 5000°F is hoped to be achieved. The radiant heat transfer to an enclosed carbon-black particle cloud at this temperature will be a much more significant part of the total heat transfer.

The heating element is to be surrounded by tungsten shields to control radiation heat losses, and the entire furnace assembly is to be enclosed in an inert nitrogen atmosphere to avoid oxidation of the tungsten components. The enclosure includes on one side a boron nitride strip to provide insulation between the power connections. Entrance and exhaust extensions are to be attached also with boron nitride connectors at the ends of the heated section. The unit is to be supported with its longitudinal axis vertical. Boron nitride will thus serve both as a refractory and as an electrical insulator.

The utility of the design is yet to be demonstrated. If limitations occur, they are most likely to result either from the failure of the boron nitride components in contact with the high temperature heating element or from thermal stresses in the heating element itself. It is thought that the assembly can, at the worst, be made to withstand operations of short durations and that damaged components can be replaced between experiments.

The power supply for the furnace can deliver a single-phase current of up to 1200 amperes at 480 volts. The input to the furnace is controlled by a General Electric saturable-core reactor. The capacity of this unit is 125 kilovolt-amperes. Control for the saturable-core reactor is being achieved with a solid-state circuit which at full power delivers up to 6 amperes and 75 volts of saturating direct current. The power level (alternating current) is proportional to the saturating direct current. Power consumption is monitored by voltage and current measurements. Current transformers, having a primary-to-secondary ratio of 600 to 1, give a proportional current that can be monitored by standard meters. The voltage is indicated directly.

The experiments to be performed with the new equipment will evaluate the heat transfer to a particle cloud within the heated length of the enclosure. Supplementary experiments are to be made of the heat transfer to the cloud while it is in adjacent, unheated regions. These data are needed to test theoretical derivations for heat transfer in extended sections. It is also anticipated that the furnace will be employed to study the disappearance of particles due to evaporation and sublimation. The wall temperature in these experiments will be determined by the flow conditions of the aerosol and by the nature of the particle material.

Concurrent with the development of these new heat-transfer capabilities, transmissivity measurements of carbon particle clouds have been in progress. The fundamental elements of this apparatus were described in Semiannual Report No. 6. The most significant change made in it has been the enlargement of the surge chamber to smooth pulsations in powder discharges from the particle feeder. The particles, on the average remain in the chamber 10 to 20 seconds after ejection from the feeder nozzle. Another change is the removal of air jets

for cleaning the windows in the aerosol conduit; it has been found that reliable data can be obtained without them before significant clouding occurs.

The surge chamber also aides in measuring the aerosol concentration. Once reliable transmissivity measurements have been obtained, particle feeding is discontinued and the contents of the chamber are filtered through an extraction filter. The powder collected is weighed and the result is divided by the chamber volume (246 liters) to give the weight-to-volume concentration. The results, except for very dense concentrations, have been reproducible within $\pm$ 10 per cent.

As previously reported, the transmissivity measurements are made with a Beckman, Model B, spectrophotometer (Beckman Instruments, South Pasadena, California). The results are given in attached figures. The first shows that the attentuation very closely follows Beer's Law, that is, that $I_s = I_o e^{-ks}$, where I_o is the radiation intensity at the cloud extremity and I_s is the intensity after passing through a cloud of thickness s. The second plot shows the independence of attenuation within the wave length range 0.4 to 0.65 micron. These results are consistent with those of Lanzo and Ragsdale (NASA TN D-1405, 1962) who made similar determinations for particles suspended in water.

The attenuation constant k (slope in Figure 1) for the carbon particle clouds is -3.7×10^5. If it is assumed that all the attenuation is due to absorption, the constant obtained in this work represents an average particle diameter of about 0.30 micron. Electron micrographs confirm that the apparent diameter of the particles and particle agglomerates is of this order of magnitude. These conditions imply that a measurement of particle size may be employed to evaluate the absorption of carbon-black particle clouds, and that the assumption of essentially total absorption is essentially correct for carbon black

particles. The assumption, it appears, is supported by the fact that agglomerates have highly irregular boundaries and sizable void spaces; both of which are conditions leading to improved absorption and lessened scattering. This result would not be calculated from the Mie theory if perfectly spherical, uniform particles were assumed. The independence of attenuation and wave length as found experimentally would also not be verified by idealized calculations.

The transmissive characteristics of carbon black clouds are very insensitive to the pressures (500 to 1000 psig) used to generate them. While further research is being conducted, it is believed that the generation of smaller-particle clouds (really clouds with fewer agglomerates) than already obtained is not likely to improve conditions significantly. It appears that carbon black clouds reagglomerate very rapidly.

Experiments for the immediate future will continue to emphasize deagglomeration and transmissivity measurements. It is expected, however, that efforts will gradually be shifted to (1) the collection of heat transfer data with the new furnace and (2) an analysis of particle disappearance due to evaporation and sublimation, a study recently authorized under the contract.

Respectfully submitted,

Clyde Orr, Jr.

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Project Director

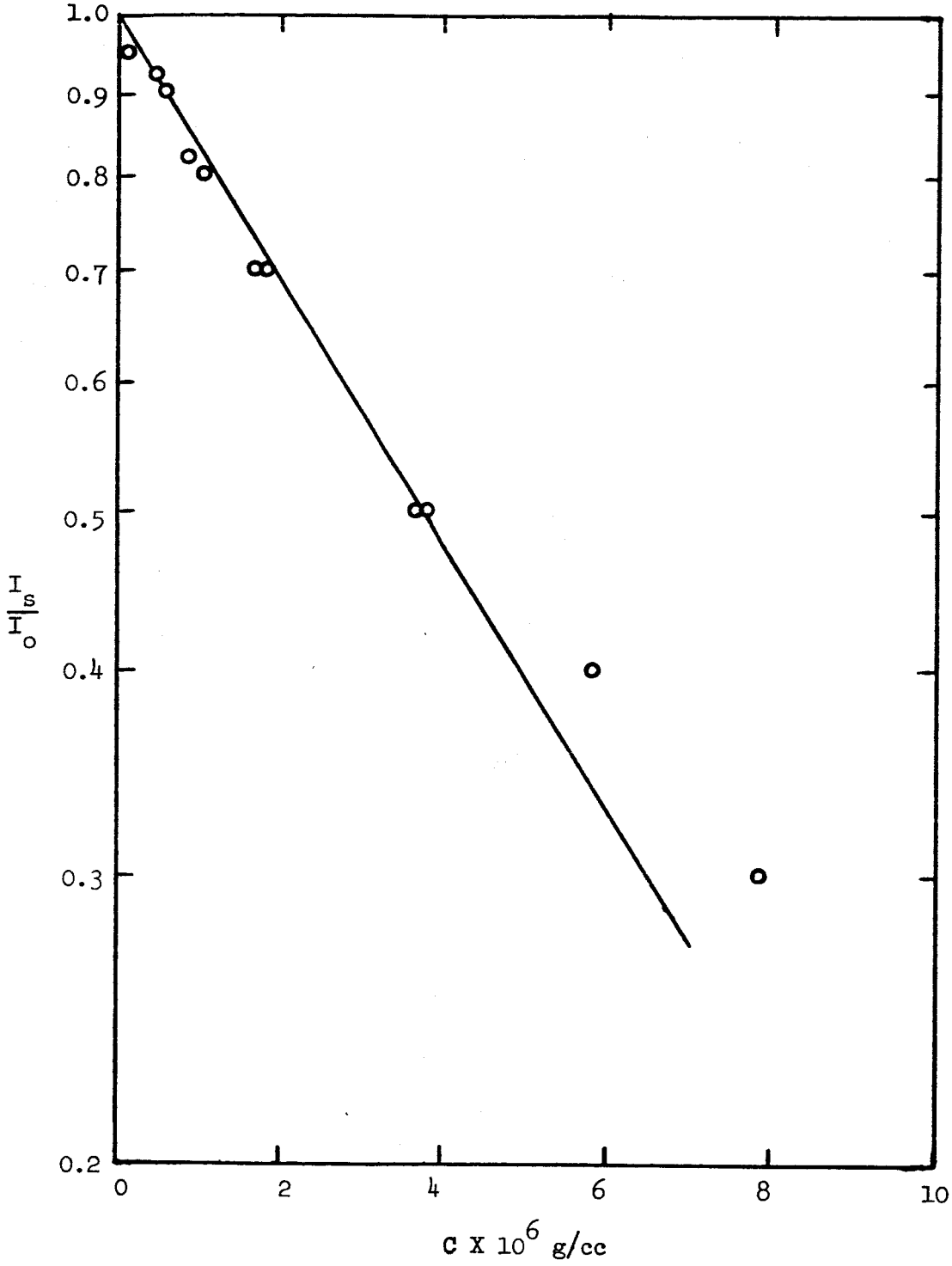

Figure 1. Transmissivity of Carbon Black Particles as a Function of Concentration for a Radiation Wavelength of 500 millimicrons.

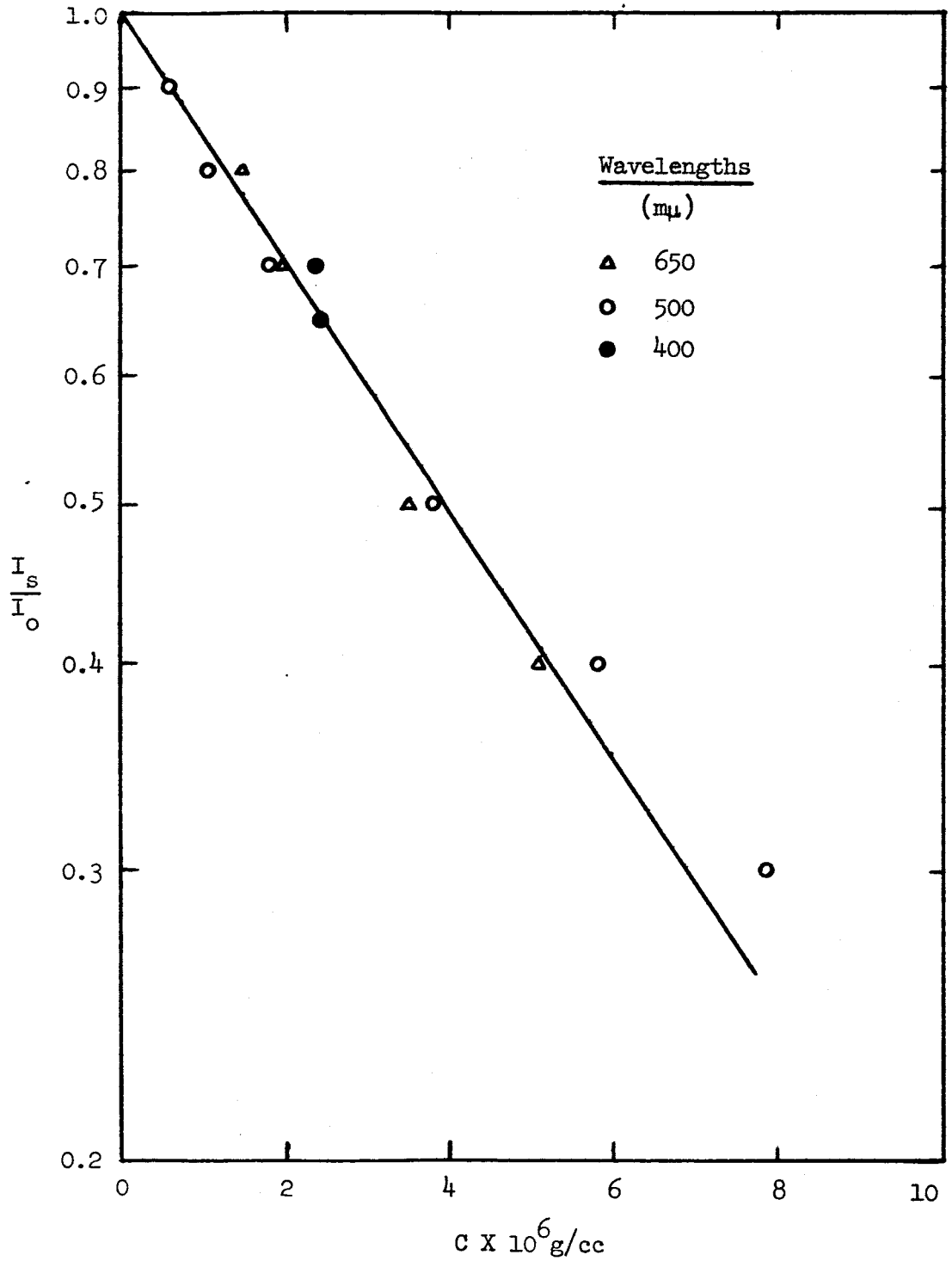

Figure 2. Transmissivity of Carbon Black Particles as a Function of Concentration for Radiation Wavelengths of 400, 500, and 650 millimicrons.