REPRINTED FROM
FIRE TECHNOLOGY
Vol. 6 No. 2 MAY 1970

A Fire Simulation Facility for Materials Response Testing

B. BELASON, G. CASTLE, D. CROWLEY, and
L. D'AVANZO
Avco Systems Division

The people who did much of the test work in the search for a suitable heat shield material for the Apollo spacecraft have turned their attention toward fire protection through materials. The authors are part of a thermodynamics laboratory team that is studying the thermal behavior of newly developed materials.

IN RECENT years, there has been a strong trend to engineer materials for specific applications — especially in the field of plastics and composites. An excellent example is the development of ablative re-entry vehicle heat shield materials. An important factor in this development was the construction and use of test facilities in which materials could be screened and materials thermal response models generated. Characteristically, such facilities were well calibrated, were reproducible, provided good simulation of the real environment, permitted observation of the specimen during test, and were relatively inexpensive to operate — especially in terms of the test specimen itself.

FACILITY CHARACTERISTICS

At Avco, attention is now being turned to designing materials for fire protection. For this purpose, it was decided that a test facility that would permit evaluation of the one-dimensional response of a material in a real fire environment was necessary. Specifically, the facility would have the following characteristics:

- Inexpensive test specimen — preferably a flat slab about 5 in. square and up to 2 in. thick. (The 5-in. by 5-in. surface is the heated surface);
- Inexpensive test operation;
- Real fire environment — the correct thermodynamic parameters of the fire should be simulated;

NOTE: At the time of this writing, there was a patent pending on the Fire Simulation Facility discussed in this paper.

- Well calibrated — good engineering measurements of heat fluxes, temperatures, pressures, material response, and other data;
- Reproducible environment;
- Visual observation of specimen during test; and
- Continuous operation.

Table 1 summarizes briefly a survey made of the types of fire testing facilities existing today. These facilities were built for purposes usually other than materials response evaluation, and serve those purpose quite well. Tests that produce large fires undoubtedly yield the correct fire environment; but the expense, transients, problems with specimen response geometry,* and reproducibility preclude their value for materials testing. Other facilities, which provide smaller more controllable environments, lack correct fire simulation or are not flexible enough in specimen design or display to do the job. Thus, for the purpose of materials response testing, no existing facility had all the characteristics desired; therefore, it was decided to build an appropriate facility.

THERMODYNAMIC PARAMETERS OF FIRE ENVIRONMENT

A literature survey was conducted to determine the character of fires, their important parameters, and their relative intensities. Figure 1 summarizes the results. Basically, a fully developed fire is a high-temperature chemically reacting turbulent gas. The length and intensity of the fire depends primarily on heat available, fuel supply, and oxygen supply. The

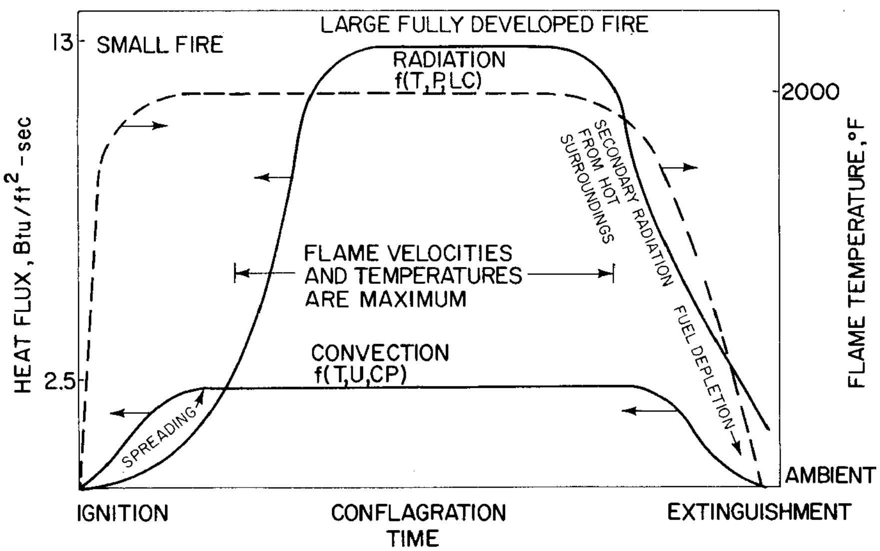

Figure 1. Fire environment thermal model.

*i.e. the requirement for either a non-slab specimen or a complicated specimen holder in order to obtain one-dimensional response of the material being evaluated.

majority of unplanned hydrocarbon fires are high in soot concentration and reach temperatures of 1600° F to 2000° F in the flame zone. The environment produced is primarily radiative in nature with intensity levels of up to 10 or 15 Btu/ft²-sec. The character of the radiation is essentially that of a grey gas with effective emittance of 0.8 to 1.0. It is the soot concentration that gives the gas its high effective emissivity. Convection plays a secondary but important role in large fires. Calculations of turbulent flow heat transfer indicate that cold wall convective heating levels can reach 3 to 5 Btu/ft²-sec in some situations.

Figure 2 presents a schematic description of radiation interchange between a solid and an idealized gas, and the following equation provides a means of calculating the net radiant energy interchange between the two bodies.

$$q_{net\ 1\text{-}2} = F_{2\text{-}1}\epsilon_1\sigma_1 T_1^4(1 - F_{2\text{-}1}\rho_2\epsilon_1) - \epsilon_2\sigma T_2^4 \qquad (1)$$

In Figure 2 and Equation 1, the radiating body of gas has been assumed to have a geometric boundary line — a simplification vs. calculating absorption and re-emission, etc., of the various constituents within the body of gas. Equation 1 shows that, in order to properly simulate $q_{net\ 1\text{-}2}$, the fire simulation facility must exactly reproduce T_1 and ϵ_1 — the temperature and effective emission properties of the gas. In Equation 1, T_2 is a dependent variable that is a function of the composition of Material No. 2, its surface properties, and the fire environment. The geometric view factor, $F_{2\text{-}1}$, also must be known. Summarizing . . . a fire simulation facility must be capable of meeting the following requirements.

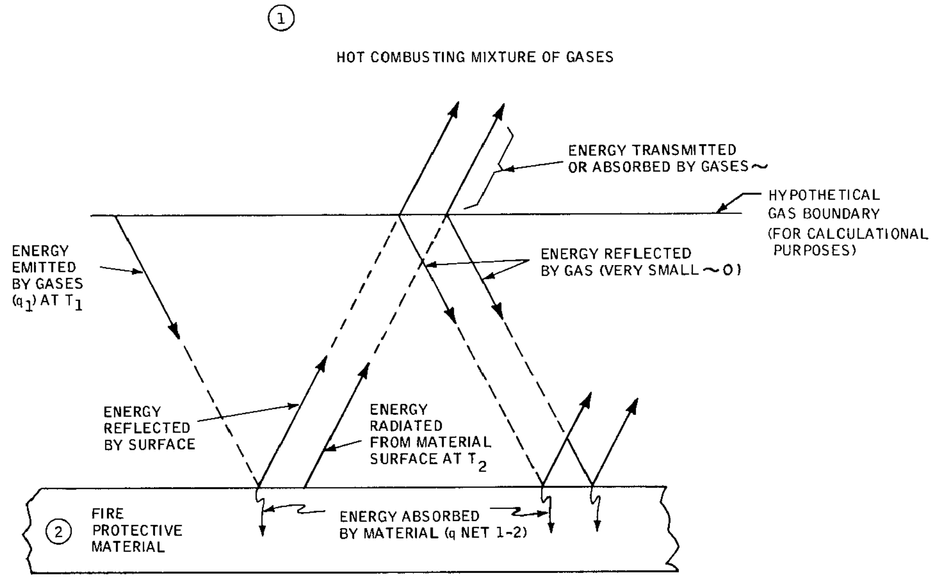

Figure 2. Schematic of radiant energy transfer between a solid and a body of gas.

TABLE 1. *Summary of Typical*

Type of facility	*Location (representative)*	*Intended use of facility*	*Environment produced*
Furnace	Ijmuiden, Holland	Flame research related to furnace design and fuels	Radiation from hot surfaces and flames
Wood crib	U.S. Forest Fire Laboratory, Riverside, Ca.	Ignition studies, flame patterns, flame spread, and mass fire studies	Actual fire, but transient
Large pool fires	Naval Weapons Laboratory, Dahlgren, Va.	Determine effects of fire on full-scale hardware assemblies	Actual fire, but transient
Large structure fires	Factory Mutual Research Corp. Rhode Island	Study flame spread in buildings, extinguishment	Actual fire, but transient
Radiant panel tests (quartz lamps)	Boeing Co., Seattle, Wa.	Materials evaluation, ignition	High source temperature radiation, no convection
NASA fire simulation	NASA, Ames, Ca.	Materials evaluation	Radiant and convective sources fairly well simulated for an average fire
Room fires	Underwriters' Laboratories, Northbrook, Il.	Fire tests of structural assemblies	Actual fire

• A radiant heat flux of 0–15 Btu/ft^2-sec must be produced with a source emissivity of 0.8–1.0. Hence the source temperature should be able to vary from 1000° F to 2000° F to simulate the most common fires. The view factor should be known and, if possible, be close to unity.

• Simultaneously, a convective heat flux of 0–5 Btu/ft^2-sec must be produced by a gas at the same temperature as the radiation source and of the correct chemical composition, i.e. hot air plus combustion products.

• The radiant and convective heat fluxes must be independently controllable, known, reproducible, and uniform on the specimen, and should be capable of being programed.

CONSTRUCTION AND CALIBRATION OF FACILITY

Figure 3 presents an exploded schematic of the Fire Simulation Facility designed to meet the criteria defined earlier, and Figure 4 is a photograph of the facility in operation. The design is composed of four basic components.

Available Fire Testing Techniques

Operation time	*Instrumentation*	*Estimated relative cost*	*Applicability for materials response testing*
Continuous	Thermometry Calorimetry Radiometry Pyrometry	Moderate to expensive	No provisions for material testing
Limited by fuel supply	Calorimetry Thermometry	Inexpensive to very expensive	Not practical — reproducibility problems, transient effects, and size of crib needed for proper radiation simulation; specimen complex to get one-dimensional response and not viewable.
Limited by fuel supply	Thermometry	Expensive	Not practical — reproducibility problems, transients, and complications of obtaining one-dimensional specimen response. Specimens cannot be observed.
Limited by fuel supply	Thermometry	Expensive	Not practical — reproducibility problems, transients, and lack of setup to obtain one-dimensional specimen response. Specimens cannot be observed.
Continuous	Thermometry Calorimetry Radiometry	Inexpensive	Does not thermodynamically simulate a hydrocarbon fire because radiant source temperature is too high and no convection is present.
Continuous	Calorimetry	Inexpensive	Can be used for material evaluations. Limitations are radiant and convective heat flux cannot be independently varied, and the test specimen cannot be observed.
Continuous	Thermometry	Expensive	Specimen cannot be observed. Some fluctuation in environment with respect to materials response studies. Complex specimen setup to ensure one-dimensional response.

Test Chamber

The crux of the design is the radiant energy source. Radiant flux is supplied by the inner surface of a ceramic hood, not by a large volume of burning gases. The outer surface of the hood is wrapped with a metal element that is electrically resistance-heated. Steady state hood temperatures from room temperature to 2300° F are readily achieved. The hood is 7.2 in. wide at the base and 21.6 in. long. The ceramic hood material selected has an emissivity of about 0.9 at 1800° F. Insulation is mounted on the outer side of the heater elements. A thermocouple, mounted in the hood, is incorporated in a servo-mechanism circuit with the electrical power supply to permit programing of the hood temperature.

An oil burner is used to generate the hot gases for convective flux. In general, the gas temperature is adjusted to equal the hood temperature, and gases are channeled through the radiant hood. An alternative source of convective flux is the burning of methane in a multi-pored tube mounted at the inlet of the hood in lieu of the oil burner. In both cases, the approximate correct chemical composition of hydrocarbon fire gases is achieved.

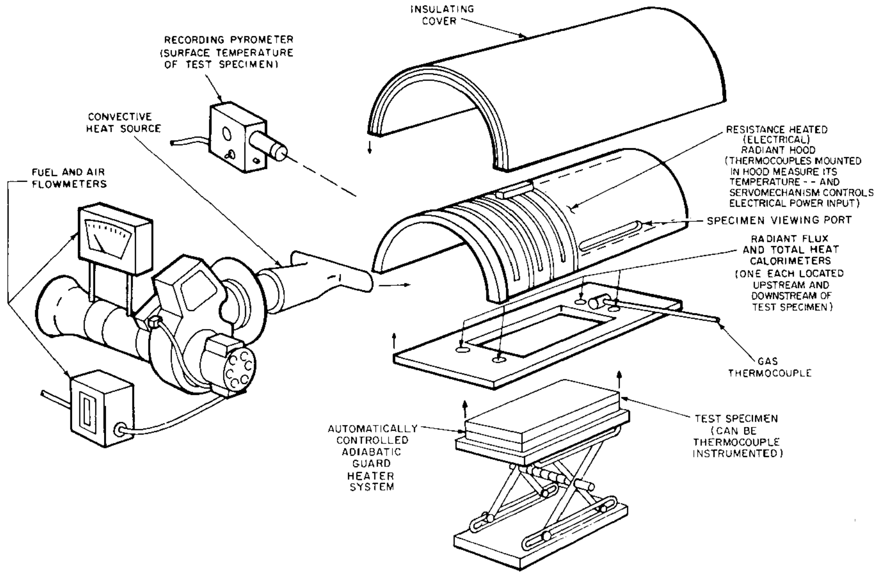

Figure 3. Exploded view of Avco fire simulation facility.

Specimen Holder

The 5-in. by 5-in. specimen is mounted in the center of the floor of the radiant hood, so that the flow direction of the convective gases is parallel to the specimen's surface. The specimen's surface is maintained flush with the bottom of the hood. The specimen has a minimum view factor of 0.96 to the hood, and can be readily seen from outside the hood. A water-cooled shield is maintained over the specimen until the desired thermodynamic conditions of the hood are achieved. The shield, not shown in Figure 3, is placed over the specimen through the viewing port; the test commences when the shield is removed.

An automatic guard heater is used at the rear of the specimen to assure a known rear face boundary condition during test. The guard heater is constructed of a thin foil, resistance network mounted on a 0.25-in. thick Fiberfrax board. The 0.25-in. thick piece of Fiberfrax is placed between the rear face of the specimen and the heater. Thermocouples monitor the temperature at the interface of the rear surface of the specimen and the Fiberfrax spacer, and at the interface of the heater surface and the spacer. When a difference of 1° F is sensed between the two interfaces, the heater is automatically turned on until the error is corrected. In this fashion, the flow of heat through the rear face of the specimen is restricted to a negligible level, and a nearly adiabatic boundary condition exists at the rear of the sample.

Safety — Exhaust Gases

The hot convective gases are exhausted through a commercially available system, which meets safety requirements.

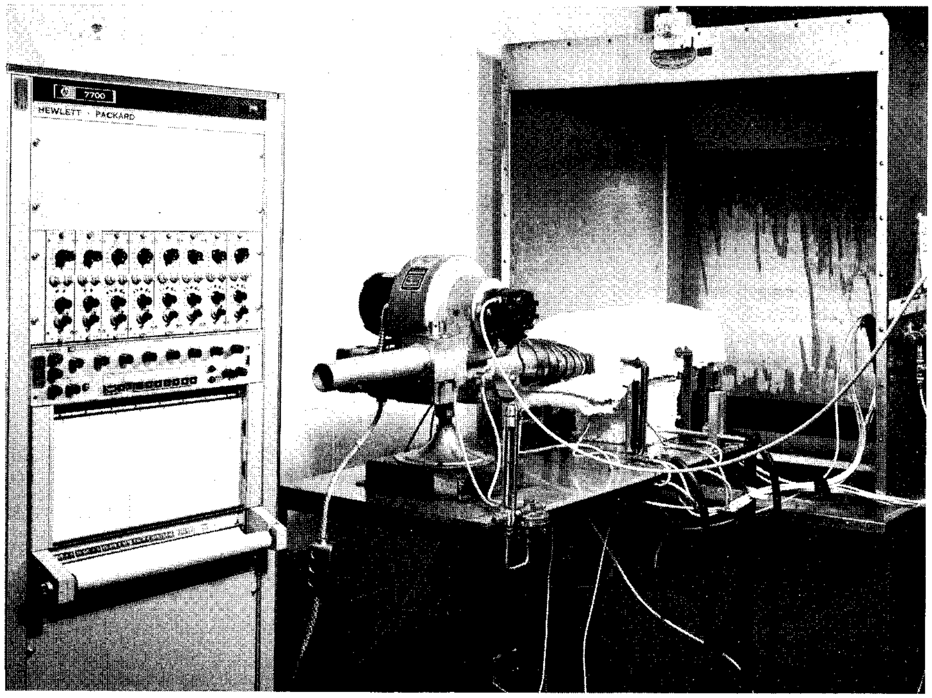

Figure 4. Avco fire simulation facility.

INSTRUMENTATION

Both pyrometers and thermocouples are used to measure the surface temperature of the radiating hood. Two Hy-Cal asymptotic calorimeters can be mounted next to the test specimen to measure the radiative and total (radiative plus convective) heat fluxes. Appropriate instrumentation is used to measure the pressure and temperature of the convective gases. Meters measure the air and fuel flow rates. All of these readings, as well as data from thermocouples mounted in the test specimen, are recorded on a multichannel recorder.

Figure 5 provides a calibration plot for the radiative and convective fluxes incident upon the test specimen. Calibrations have been made for radiant fluxes from 2 to 12 Btu/ft^2-sec and for convective fluxes from 0 to 2.5 Btu/ft^2-sec. A radiant flux up to 20 Btu/ft^2-sec and a convective flux up to 10 Btu/ft^2-sec can be achieved with the existing equipment. The radiative and convective fluxes are independently controllable.

The Fire Simulation Facility also has the following features.

- It can be operated continuously for several hours.
- Operation is relatively inexpensive.
- The hood temperature is constant, controllable, and reproducible to $\pm 12°$ F (corresponding to a 2 per cent variation in radiant flux).
- Larger test specimens can be accommodated in larger hoods.

• The effective hood emissivity is almost 1.0. However, by selecting the proper ceramic hood material and eliminating the black body effects of an enclosure, a wide range of emissivities can be achieved.

SUMMARY AND APPLICATIONS

A facility has been designed and built to meet the desired specifications for materials response testing in a fire environment. The crux of the design is that (1) an electrically heated surface is used to generate the radiant heat flux instead of a large bonfire of hot gases, and (2) this electrically heated surface radiates at the correct temperature and emissivity.

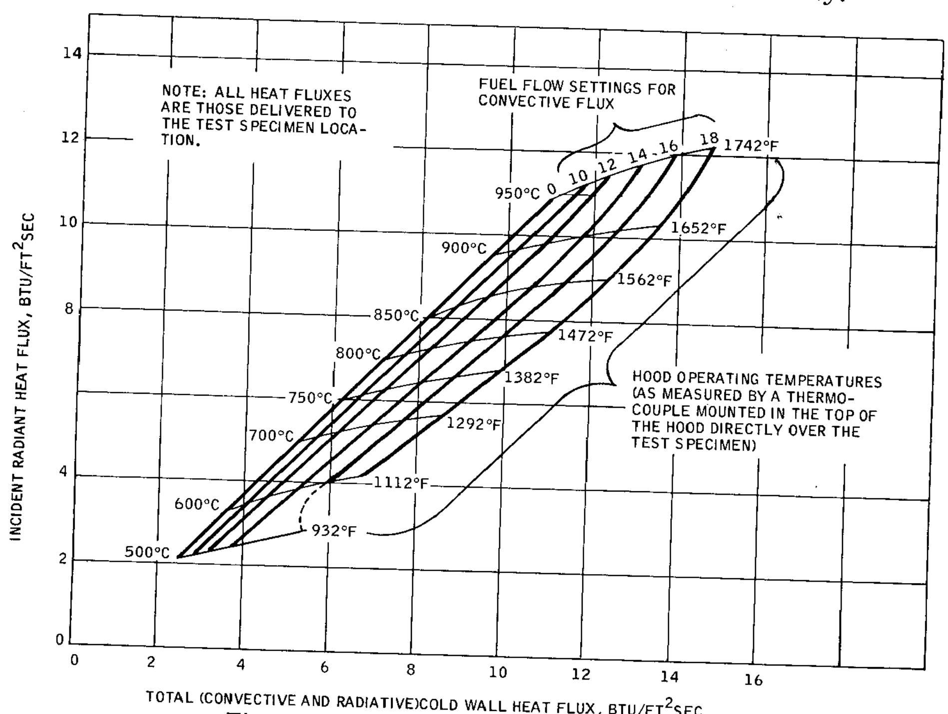

Figure 5. Fire simulation facility calibration.

The advantages of the Fire Simulation Facility are the following:

• Materials response tests can be conducted in a laboratory at a much reduced cost with good simulation of the fire environment.

• The fire environment can be closely controlled, reproduced, calibrated, and programed.

• The test specimen can be observed during test and quickly and easily introduced into, and removed from, the fire environment.

• Any type of fire (large, small, long, short) can be simulated with any kind of mix of radiative and convective heat inputs.

Some of the types of studies that can be conducted in the Fire Simulation Facility are assessment of the time temperature response of materials and the comparison of materials (see Figure 6); ignition response time of materials; and analysis of combustion products of materials by placing a water-cooled probe near the surface of a material to collect the gases generated.

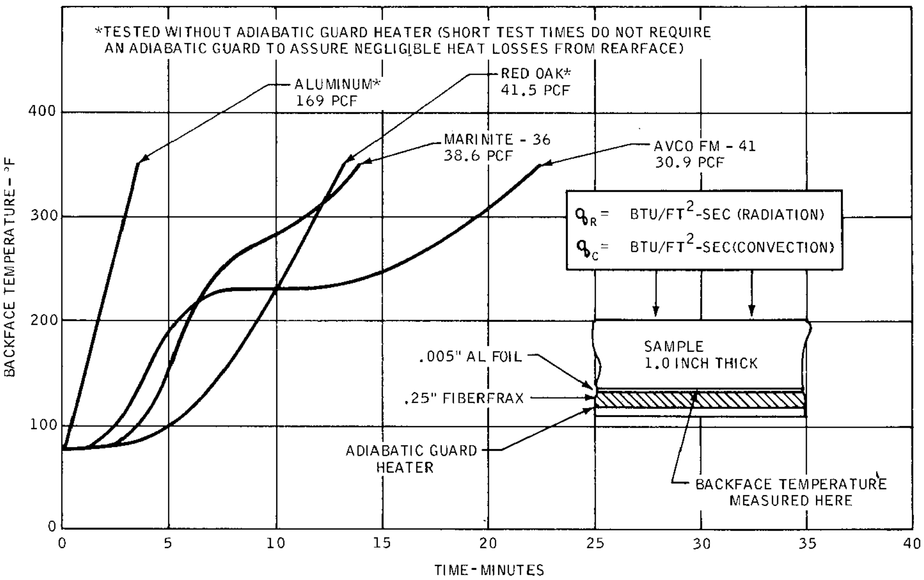

Figure 6. Typical materials response data obtained in Avco fire simulation facility.

NOMENCLATURE

$q_{net\ 1\text{-}2}$ = net radiant energy absorbed by Body 2 in the presence of radiation from Body 1, Btu/ft^2-sec
A_1 = area of Body 1, ft^2
A_2 = area of Body 2, ft^2
ϵ_1 = effective emittance of Body 1, thermodynamic equilibrium assumed
ϵ_2 = emittance of Body 2
σ = Stefan Boltzmann constant, 0.456×10^{-12} Btu/ft^2-sec °R^4
$F_{2\text{-}1}$ = mean geometric view factor between Body 2 and Body 1
T_1 = absolute temperature of Body 1, °R
T_2 = absolute temperature of Body 2, °R
ρ_2 = reflectivity of Body 2

BIBLIOGRAPHY

[1] Thring, M. W., Beer, J. M., and Foster, P. J., "The Radiative Properties of Luminous Flames," *Proceedings of the Third International Heat Transfer Conference*, Vol. 5, 1966.

[2] Howarth, C. R., Foster, P. J., Thring, M. W., "The Effect of Temperature on the Extinction of Radiation by Soot," *Proceedings of the Third International Heat Transfer Conference*, Vol. 5, 1966.

[3] Sherman, R. A., "Heat Transfer by Radiation from Flames," *Transactions of the ASME,* Nov. 1957.

[4] Kirt and Othemer, *Encyclopedia of Chemistry,* Vol. 15, 1954.

[5] Countryman, C. M., "Mass Fires and Fire Behavior," U.S. Forest Service Paper PSW-19, 1964.

[6] Canfield, J. A., and Russell, L. H., "Measurements of the Heat Flux Within a Luminous Aviation Fuel Flame," U.S. Naval Weapons Laboratory, Dahlgren, Va. Presented at the September 1969 meeting of the Eastern Section of the Combustion Institute.