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**FINAL REPORT OF PROJECT**  
**MULTIPLE IGNITION, COMBUSTION AND**  
**QUENCHING OF HYDROCARBON FUEL SPRAYS**

80-0203  
AFOSR GRANT #76-3052

by

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## ABSTRACT

Objectives: The objectives were to modify the experimental apparatus so that aromatic fuels such as toluene could be included in the program. It was also intended to continue the theoretical analysis of the ignition of gaseous mixtures and to begin the study of the heterogeneous mixture ignition.

In the experiments methane and propane-air ignition by burning aluminum particles were studied. In this period of research it was of interest to study the ignition limits of mixtures of air with the vapor of a volatile liquid fuel. This information expanded the data base relevant to ignition of liquid fuel sprays by burning metal particles. Theoretical work on the ignition of gaseous mixtures was completed during this period. Both computational and analytical studies were made. Since delivery of the gas mixtures and vapor mixtures to the combustion chamber were fundamentally different, several modifications to the existing apparatus were made to meet the new objectives of the program. It was of interest to be able to obtain a direct measurement of the temperature of the burning particle. Therefore, the possibility of outfitting the experimental apparatus with an optical pyrometer was examined.

## ACHIEVEMENTS

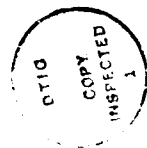
This section will summarize the firmly established results obtained thus far on this project and will, for clarity, present some data obtained during the previous study conducted at Princeton. The trends thus far observed with three vapor fuels, methane, propane and toluene, are interesting in that they suggest both some important parallels and some important distinctions between spark ignition and burning particle ignition.

To test the reproducibility of the general technique, one of the first tasks during the current contract period was verification at Carnegie-Mellon University of the methane data obtained at Princeton. In addition to settling this issue in a satisfactory way, these runs helped fill out the previously obtained data on ignition

of methane/air mixtures by burning aluminum particles. The results are shown in the top portion of Figure 1 as a plot of particle diameter versus atmospheric pressure fuel/air equivalence ratio. As has been past practice in presenting these data, the two curves are shown. The upper curve corresponds to the envelope of results recording cases in which the particle cannot burn in the gas without igniting it, while the lower curve corresponds to the largest particles which were observed to burn in, but not ignite, the mixture. Hence the two curves should bracket the true "critical particle size" necessary for ignition at a particular equivalence ratio. It can be seen that around stoichiometric, the technique has shown this value to be about 30  $\mu\text{m}$ , which corresponds to an energy of about 1.2 millijoules.

The bottom portion of Figure 1 shows the same sort of results for toluene. The curve clearly needs a few more points to be as well established as that for methane, but the trend with equivalence ratio is already quite obvious. It appears that a minimum is being approached at an equivalence ratio of 1.7. The reason that the curve is not continued to higher equivalence ratios is that under ordinary ambient temperature conditions, higher equivalence ratios will not be seen without the introduction of a second phase - liquid toluene droplets.

The fact that particle sizes are known, as is the heat of combustion of aluminum, means that the energies corresponding to combustion of these particles are easily calculable. This energy can be directly compared, as previously [1,2], to the spark ignition energies for these fuels. These comparisons are shown in Figure 1 for methane, propane and toluene, respectively. It is immediately apparent that the trend of minimum ignition energy versus fuel equivalence ratio is qualitatively the same for all these fuels; methane has a minimum just on the lean side of stoichiometric, while propane is definitely on the fuel-rich side and toluene even more so. It should be noted that the spark ignition curve shown for toluene is actually for n-heptane rather than toluene, but as Lewis and von Elbe have convincingly shown [3], the spark ignition energy versus equivalence ratio curves are practically coincident for all hydrocarbons having the same number of carbons (seven in this case).



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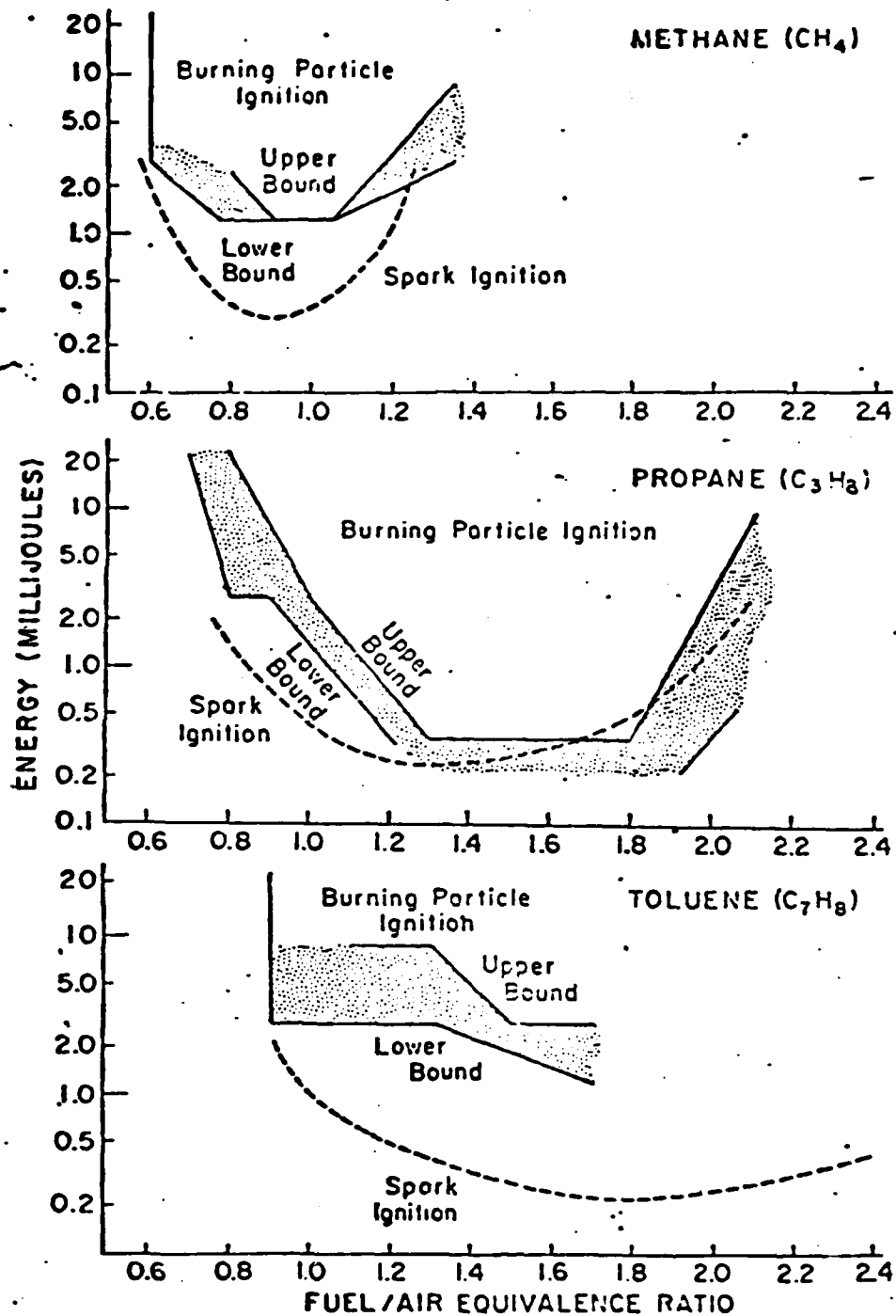


Figure 1: Comparison of Minimum Ignition Energies for Spark and Burning Aluminum Particle Ignition of Hydrocarbon Vapors

The fact that the results of particle combustion experiments follow the same trend as the spark data seems to suggest that the same diffusional stratification mechanism responsible for the trend in the spark data is also playing a role here.

The basic theory has developed from the fact that the position of the minimum relative to stoichiometric seems to depend upon the relative diffusivities of fuel and oxidant; the minimum is displaced towards an excess of the less mobile component [3].

The significance of the above finding, if it can be verified by further testing with other types of fuels, is that it allows one, on the basis of published spark data, to predict the position with respect to mixture strength of the minimum particle size needed for ignition. It is also unfortunately obvious that there is not necessarily a good correspondence between the actual energies required, however. The spark data are consistently lower, but not by a constant amount. The fact that they are lower is not surprising, since the spark is a much shorter and intense energy source than a combusting metal particle. In the latter case, there is ample opportunity for energy to be conducted and radiated away before a critical ignition kernel can develop, and hence it is expected that particle combustion is a relatively less "efficient" ignition mechanism.

The theory has been completed for the case of ignition of premixed combustible gases. Emphasis has been placed on hydrocarbon fuel-air mixtures, with careful consideration of both inert ignition sources and reacting (oxidizing) ignition sources. Spherical symmetry was assumed but unsteady behavior was taken into account. The 1981 report will provide more details about the results.

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## LIST OF PROFESSIONAL PERSONNEL

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## DEGREES RECEIVED

Y. P. Su, Ph.D. degree

T. J. Stanley, Master of Science degree

## PUBLICATIONS RESULTING FROM RESEARCH

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