THE UNIVERSITY OF MICHIGAN

INDUSTRY PROGRAM OF THE COLLEGE OF ENGINEERING

RATE OF PROPAGATION OF PROPANE-AIR FLAMES IRRADIATED WITH A 10,000-CURIE GOLD SOURCE

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The gold was transported to and from the reactor by personnel of the Selfridge Air Force Base.

ABSTRACT

Bunsen flames of premixed propane and air were irradiated with an irradiated gold source having an initial strength of about 10,000 curies. Both the flame zone and the propane-air mixture were exposed to the radiation. The rate of propagation of the flame was increased up to 50 percent by the radiation. The flame speed fell off rapidly to the normal value as the source decayed below 10,000 curies. The effect of radiation appeared to be about the same over a range of propane to air mass ratios from 0.055 to 0.080 and a range of pressures from 4 to 10 in. Hg abs. The effect is attributed to beta radiation since the estimated number of ion pairs produced by beta radiation exceeds the number produced by gamma radiation.

INTRODUCTION

Previous irradiations of flames with relatively weak gold and palladium sources indicated a slight increase in combustion efficiency[3] and no effect upon flame speed.[6,7] The objective of this investigation was to study the effect of more intense radiation.

The source of radiation was approximately 30 grams of irradiated gold wire. The strength of the source decayed from an initial value of about 10,000 curies to a negligible level during the experimental program. The flame zone and the fuel-air mixture were both irradiated strongly.

The experimental equipment was designed to measure both the emission spectra of flat flames and the rate of propagation of bunsen flames from mixtures of propane and air over a range of low pressures. This paper reports the observed effect of irradiation upon flame speed. Data on spectral emission obtained with the same source will be reported separately.

EXPERIMENTAL EQUIPMENT

The equipment used in the flame speed studies consisted of a premixed propane-air supply and metering system, a burner, a vacuum tank and an exhaust system, shielding, and a source of radiation. The essential parts of the equipment are shown in Figure 1.

The burner and source assembly are shown in Figure 2. The burner head was a converging nozzle with a 100-mesh copper screen stretched across the 1-inch ID opening. With this screen a flat flame, as well as a bunsen flame, could be established at pressures below one-half an atmosphere, permitting emission data as well as velocity data to be obtained with the same burner. As indicated in Figure 2, the source was contained in a tapered hollow cylinder covered at the top and bottom with a 100-mesh copper screen. Cooling water was circulated through an annular space in the top of the burner tube. A thermocouple was placed in the screen to measure the preflame temperature but it was destroyed during initial flame adjustments. Five mixtures of air and propane vapor were prepared and stored in cylinders. The propane was 99.5 percent pure. The rate of flow to the burner was regulated with a hand-operated needle valve and was measured with a rotameter.

The burner assembly was located inside a tank 2-1/2 feet in diameter and 9 feet high. The exhaust gas passed from the tank through a filter to remove possible radioactive particles and then through a rotary vacuum pump, using water as a working fluid, to the atmosphere. The pressure in the tank was controlled by bleeding air into the pump. The tank also contained a spark plug mounted on a swinging arm for ignition.

SHIELDING

Considerable shielding was necessary to protect personnel from gamma radiation during the installation of the gold source and during the experimental work. A hemi-cylindrical ring of lead 7 inches thick, weighing 2500 pounds, shielded one side of the burner as indicated in Figure 1. About 500 pounds of additional lead sheet were installed at strategic positions at the beginning of the experimental work. Portland cement was found to be the cheapest bagged material on a mass basis, and four hundred fifty 100-pound bags were stacked around the perimeter of the tank.

During installation of the source and burner head, the vacuum tank was filled with water. The water provided transparent shielding and permitted direct observations and manipulations from the top of the tank.

SOURCE SELECTION AND PREPARATION

Gold was selected as a source material for beta radiation because the average half life of about 3 days allowed twenty-four hours of experimental work to be completed with only a 20 percent decrease in activity. The gamma radiation which is emitted from both Au-198 and Au-199 is, of course, somewhat disadvantageous because of shielding and of the difficulty in sorting out the individual effects of beta and gamma radiation. The disintegration schemes of Au-198 and Au-199 are shown in Figure 3.[8]

The source was prepared from 99.95 percent gold wire, 0.005 inch in diameter. The wire was wound helically on a 1/16-inch rod into coils approximately 12 inches long. The coils were then coiled into two loose balls of 15 grams each. Each ball was placed in an aluminum cylinder and irradiated for about 4-1/2 days in a high-flux section of the Materials Testing Reactor.*

After irradiation, the gold wire was transferred from the aluminum cylinders to the basket shown in Figure 2. The basket was then placed in a lead container and flown to the laboratory. The basket was removed from the lead container and installed in the burner under water.

The entire transfer operation and experiment were carefully monitored. As a result of considerable rehearsal, all of the transfer operations were carried out with dispatch and with an exposure of less than 100 milliroentgens for any individual. A maximum exposure of 300 milliroentgens per week for personnel was maintained during the experimental work.

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* Phillips Petroleum Company, Idaho Falls, Idaho.

SOURCE ACTIVITY

Theoretically, 25,000 curies could be obtained from 30 grams of gold irradiated in a high-flux region of the Materials Testing Reactor.[4] The gold wire was irradiated somewhat less than planned and on the basis of neutron flux calculations the activity of the gold on removal from the pile was reported by W. B. Lewis[5] to be 15,270 curies as shown in the top line of Table I.

Experimental measurements of the radiation from the gold source were made through water in the tank during installation. These data were compared with data taken under similar conditions with a known Co-60 source. The activity of the gold computed from these measurements agreed within 20 percent with the above values.

TABLE I. STRENGTH OF SOURCE

	Curies		
Condition	Au-198	Au-199	Total
Removal from Pile	9,600	5,670	15,270
Experiment No. 1	6,380	4,000	10,380
Experiment No. 2	5,100	3,320	8,420
Experiment No. 3	0	0	0

After completion of the combustion experiments the gold was removed from the burner and the gamma spectrum was measured. The ratio of Au-198 to Au-199 determined from the gamma spectrum and extrapolated back to removal from the reactor was also in agreement with the values estimated by Lewis. Accordingly, the strength of the source at the time of the various experiments was computed from these values and the half lives of 2.69

days for Au-198 and 3.15 days for Au-199. The computed strength of the source during the three experimental conditions is given in Table I.

The rate of production of ion pairs in the gas phase in various regions would appear to be the most significant phenomenon resulting from the gold source. The disintegration scheme shown in Figure 3 was used to compute the number of ion pairs produced per second per cubic centimeter per curie within the cylinder containing the source and in the region of the flame. Suitable corrections were made for scattering and absorption by the gold wire, cylinder wall, and the retaining screens. The results for gas at atmospheric pressure are summarized in Table II. Since the production of ion pairs is proportional to pressure, the production at other pressures can be estimated readily from Table II.

TABLE II. ION PAIRS PRODUCED BY GOLD SOURCE IN GAS AT ATMOSPHERIC PRESSURE

	Ion pairs/(cc)(sec)(curie of Au-198 or Au-199)		
	Beta Production	Gamma Production	Total Production
		In Flame Front	
From Au-198	5.38×10^9	2.07×10^9	7.45×10^9
From Au-199	8.00×10^4	1.03×10^9	1.03×10^9
		In Cylinder Containing Source	
From Au-198	2.42×10^{13}	3.16×10^9	2.42×10^{13}
From Au-199	2.68×10^{12}	1.68×10^9	2.68×10^{12}

FLAME-SPEED EXPERIMENTS

Satisfactory bunsen flames were established at four different rates of flow between blowoff and flashback at each of several pressures and propane-air ratios by manipulating the vacuum system. The experiment was repeated on succeeding days at lower intensities of radiation as the source decayed.

The velocity of propagation was determined from photographs of the flame. A 4 x 6 inch film holder was placed in a film-holder frame. No shutter was used. The room was darkened and the mask was removed from the film holder and quickly replaced. With Contact Process Ortho* film, this procedure yielded a satisfactory image. A typical photograph is shown in Figure 4.

When the rate of flow was reduced at a given pressure, propane-air ratio, and intensity of irradiation, the area of the flame front decreased but the flame speed remained relatively constant. The flame speed would be independent of the rate of flow if a heat sink (burner head) were not located near the flame. Although the variation in flow rate was in every case greater than 2 to 1, no trend was apparent with flow rate and the flame speeds obtained at the four rates of flow were averaged. Only the averages were considered in the correlations.

The circumferential areas of the flame surfaces were determined from enlargements of the negatives, and the flame speeds were computed from the relations,

$$v_f = Q/A_f \qquad (1)$$

and

$$A_f = 2\pi \int_0^L R \, dL \qquad (2)$$

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* Eastman Kodak Company, Rochester, New York.

where

v_f = flame speed (rate of propagation of flame normal to flame front), ft/sec

Q = volumetric rate of flow of propane-air mixture through burner head, cu ft/sec

A_f = surface area of flame, sq ft

R = radius of element of flame surface, ft

L = distance along perimeter of major vertical cross section of flame, ft

Equation 1 assumes that the density of the material leaving the burner head is equal to the density of the material entering the flame front, which is the usual assumption made in computing flame speeds by the area method. In calculating this density, the stream was assumed to be at room temperature.

Data for no radiation were obtained after the source was removed from the burner and replaced with an identical container and an equal volume of copper wire.

RESULTS AND DISCUSSION

The average flame speeds computed from the photographs at four different ratios of flow are plotted versus the propane-air ratio for different pressures with source strength as a parameter in Figures 5a, b, c, and d. Although the effect of propane-air ratio upon the flame speed is not clearly defined by the data, this effect is well known and was not considered worthy of additional attention in this experiment. Curves were roughed through the raw data and the maxima of these curves are plotted versus source strength with pressure as a parameter in Figure 6 and versus pressure with source strength as a parameter in Figure 7.

The experimental data in Figure 5 and the cross-plotted data in Figures 6 and 7 demonstrate a significant increase in flame speed due to irradiation. The flame speed at a source strength of 10,380 curies was about 50 percent greater than the flame speed of unirradiated flames.

The effect of radiation was relatively the same at all pressures. The slight decrease in flame speed with decreasing pressure below a certain pressure (6 in. Hg abs in this experiment) was previously shown by Cullen[1,2] to be due to the action of the burner head as a heat sink.

The negligible effect of radiation on flame speed reported by Morrison, Cullen, and Weir was based on experiments performed with a 6.6 curie source[6] and again with a 36 curie source.[7] Figure 6 confirms this earlier work by indicating that a source considerably stronger than 36 curies is necessary to produce a significant increase in flame speed.

The increase in flame speed probably should be attributed to the energy imparted to the reacting molecules by beta particles since Table II indicates that the number of ion pairs produced by gamma radiation is small in comparison to the number produced by beta radiation.

The propane-air stream was heated somewhat due to direct absorption of beta and gamma radiation and due to self-absorption by the gold and subsequent conduction to the stream. At the lowest flow rates and under adiabatic conditions the stream could be heated as much as several hundred degrees. However, under the experimental conditions most of this thermal energy was transferred from the propane-air stream and gold to the wall of the burner and hence to the cooling water and surroundings. As a result of failure of the thermocouple in the burner screen, the temperature of the propane-air stream was unknown and was assumed to be at room temperature. A higher temperature at this point would lead to two somewhat compensating errors. First, the reported flame speeds would all be increased by the ratio of the actual temperature to the assumed temperature in absolute units. Second, the increase in flame speed attributed to ionization would in part be due to purely thermal effects. Cullen[2] found that an increase in temperature from 70°F to 120°F resulted in an increase of 20 percent in the rate of propagation of propane-air flames at one atmosphere.

CONCLUSIONS

The velocity of propagation of low-pressure bunsen flames from premixed propane and air can be increased as much as 50 percent by irradiation with a 10,000-curie gold source. Essentially the same increase is obtained over a considerable range of propane-air ratios and pressures. The effect of radiation falls off rapidly with the strength of the source. Since the number of ion pairs produced by beta radiation exceeds the number produced by gamma radiation, the increase in flame speed is attributed to beta radiation.

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2. Cullen, R. E., "The Effect of Pressure on the Propagation Rate of Bunsen Flames in Propane-Air and Ethylene-Air Mixtures," U.S.A.F Contract No. W33-038-ac-21100, December, 1950.

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4. Lewis, W. B., Nucleonics, 12, 30 (1954).

5. Lewis, W. B., Private Communication.

6. Morrison, R. B., Cullen, R. E., and Weir, A., Jr., "Utilization of Gross Fission Products; Performance of Combustion Engines under the Influence of Radiation - Jet Engines," A.E.C. Contract No. AT(11-1)162, Progress Report No. 2, January 31, 1952.

7. Morrison, R. B., Cullen, R. E., and Weir, A., Jr., "Utilization of Gross Fission Products; Performance of Combustion Engines under the Influence of Radiation - Jet Engines," A.E.C. Contract No. AT(11-1)162, Progress Report No. 3, June 30, 1952.

8. Supplement No. 3 to NBS Circular 499, "Nuclear Data," Department of Commerce, National Bureau of Standards, Washington, D. C., June, 1952.

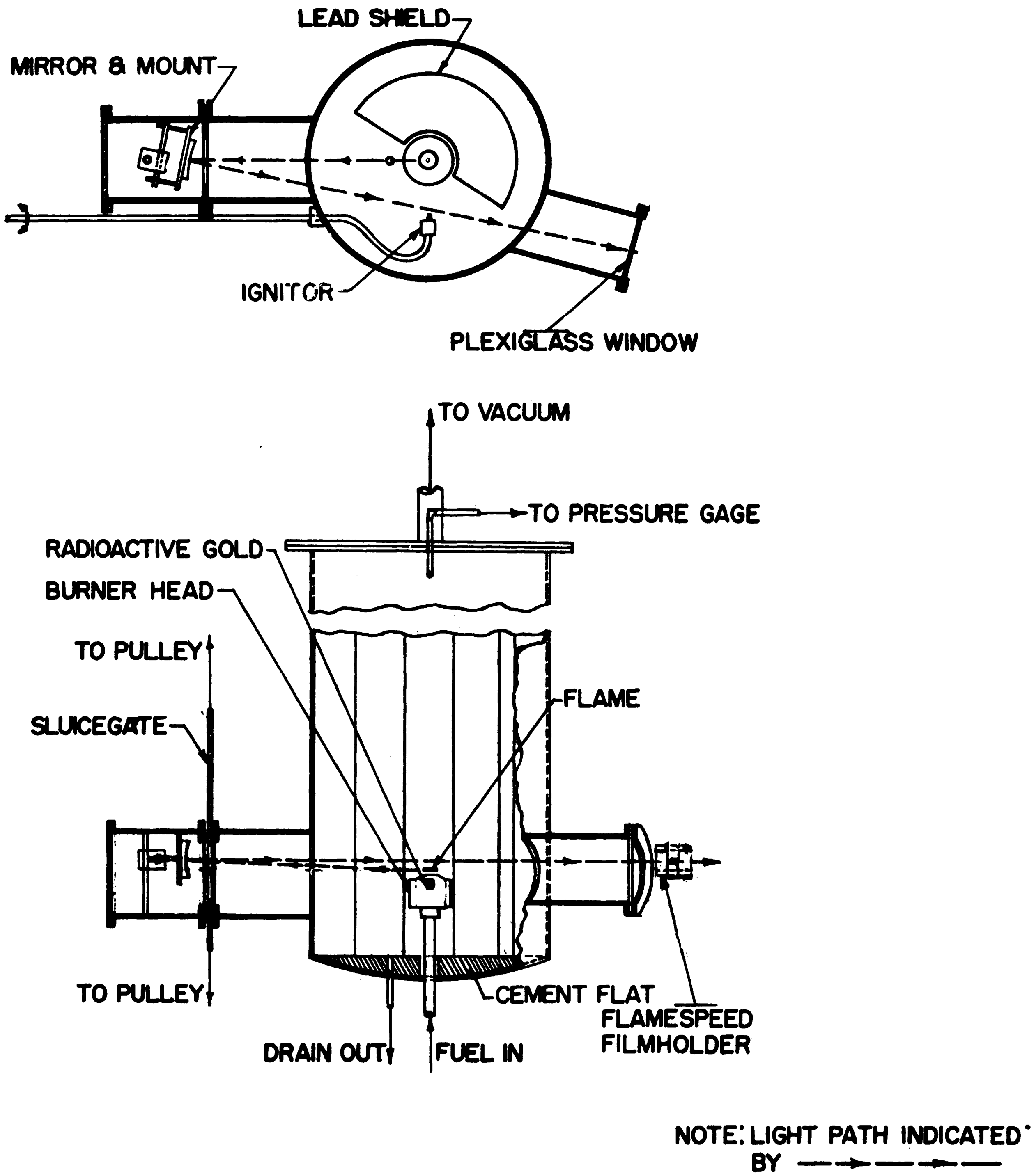
LEAD SHIELD
MIRROR & MOUNT
IGNITOR
PLEXIGLASS WINDOW
TO VACUUM
TO PRESSURE GAGE
RADIOACTIVE GOLD
BURNER HEAD
TO PULLEY
SLUICEGATE
FLAME
TO PULLEY
CEMENT FLAT
FLAMESPEED FILMHOLDER
DRAIN OUT
FUEL IN
NOTE: LIGHT PATH INDICATED BY ——►——►——

Figure 1

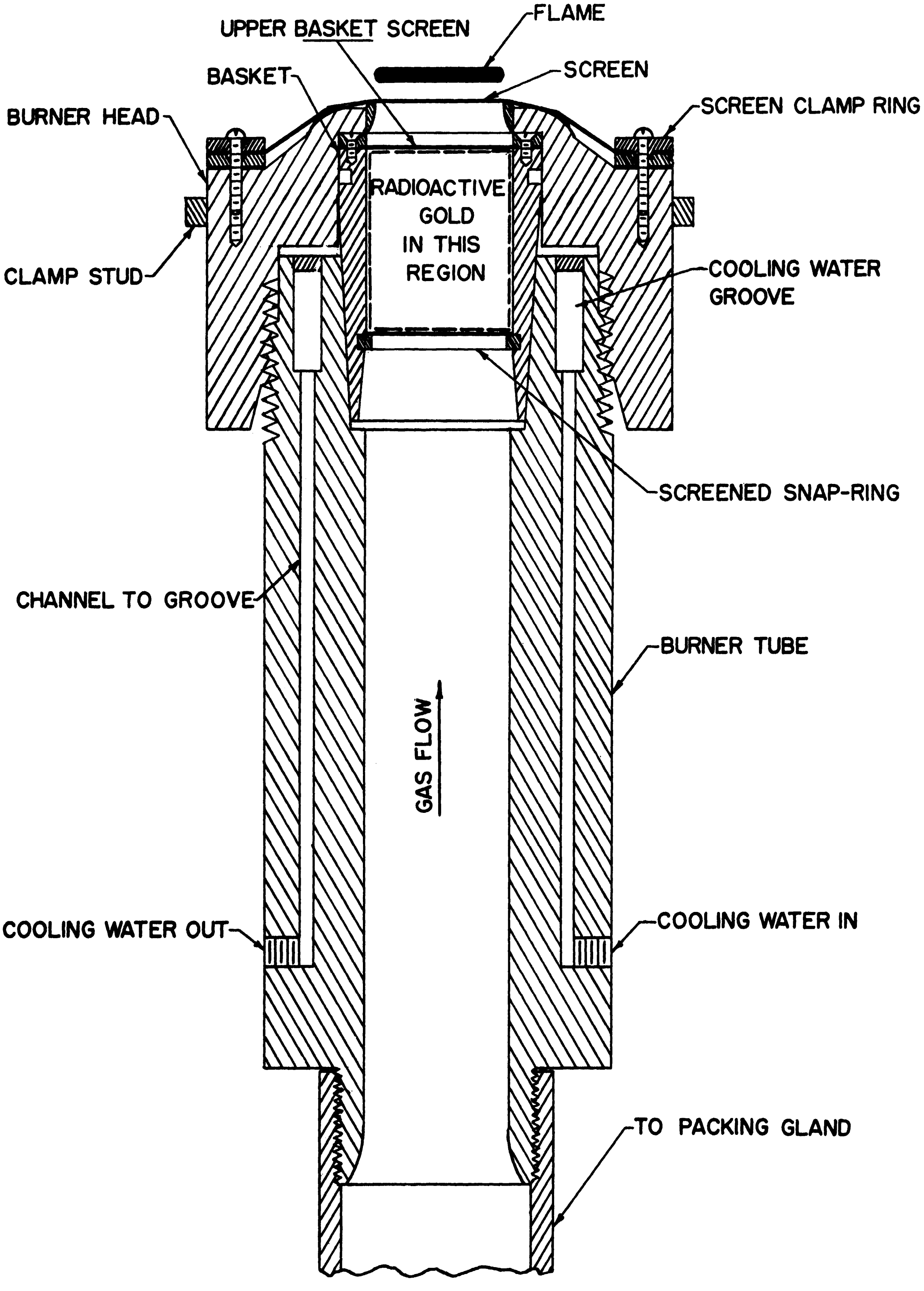
FLAME
UPPER BASKET SCREEN
BASKET
SCREEN
BURNER HEAD
SCREEN CLAMP RING
RADIOACTIVE GOLD IN THIS REGION
CLAMP STUD
COOLING WATER GROOVE
SCREENED SNAP-RING
CHANNEL TO GROOVE
BURNER TUBE
GAS FLOW
COOLING WATER OUT
COOLING WATER IN
TO PACKING GLAND

Figure 2

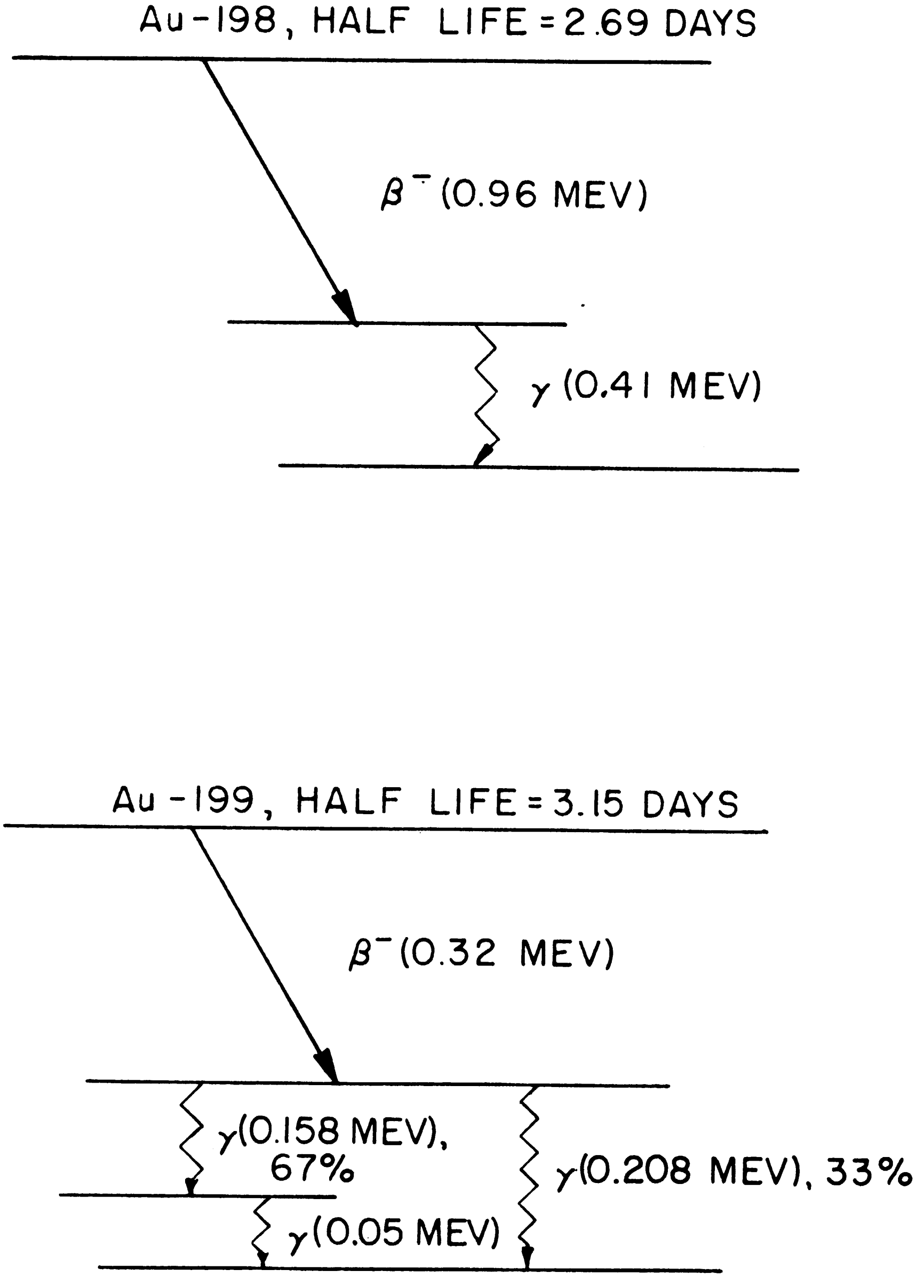
Au-198, HALF LIFE = 2.69 DAYS
β^- (0.96 MEV)
γ (0.41 MEV)
Au-199, HALF LIFE = 3.15 DAYS
β^- (0.32 MEV)
γ(0.158 MEV), 67%
γ(0.208 MEV), 33%
γ(0.05 MEV)

Figure 3

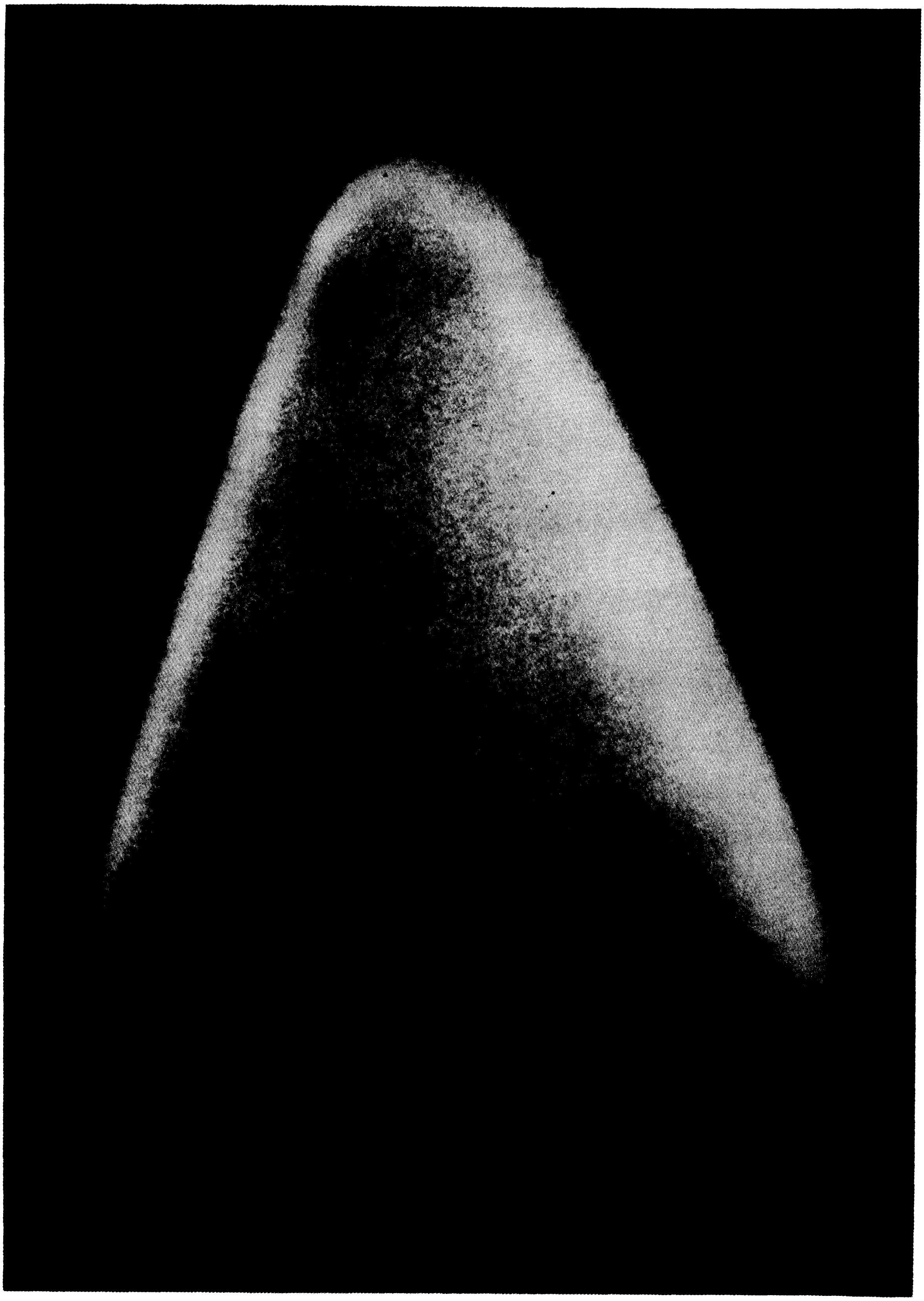

Figure 4

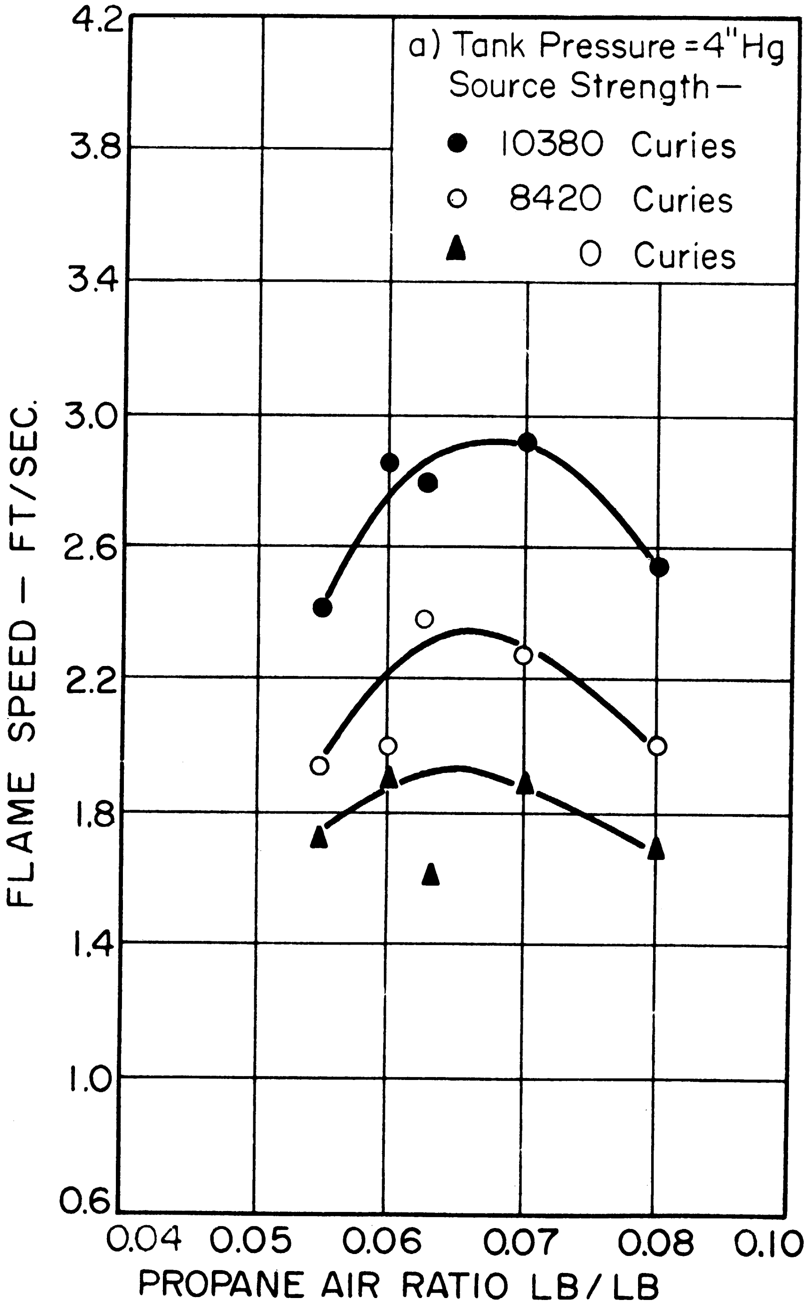
a) Tank Pressure = 4" Hg
Source Strength —
● 10380 Curies
○ 8420 Curies
▲ 0 Curies
FLAME SPEED — FT/SEC.
4.2
3.8
3.4
3.0
2.6
2.2
1.8
1.4
1.0
0.6
0.04
0.05
0.06
0.07
0.08
0.10
PROPANE AIR RATIO LB/LB

Figure 5a

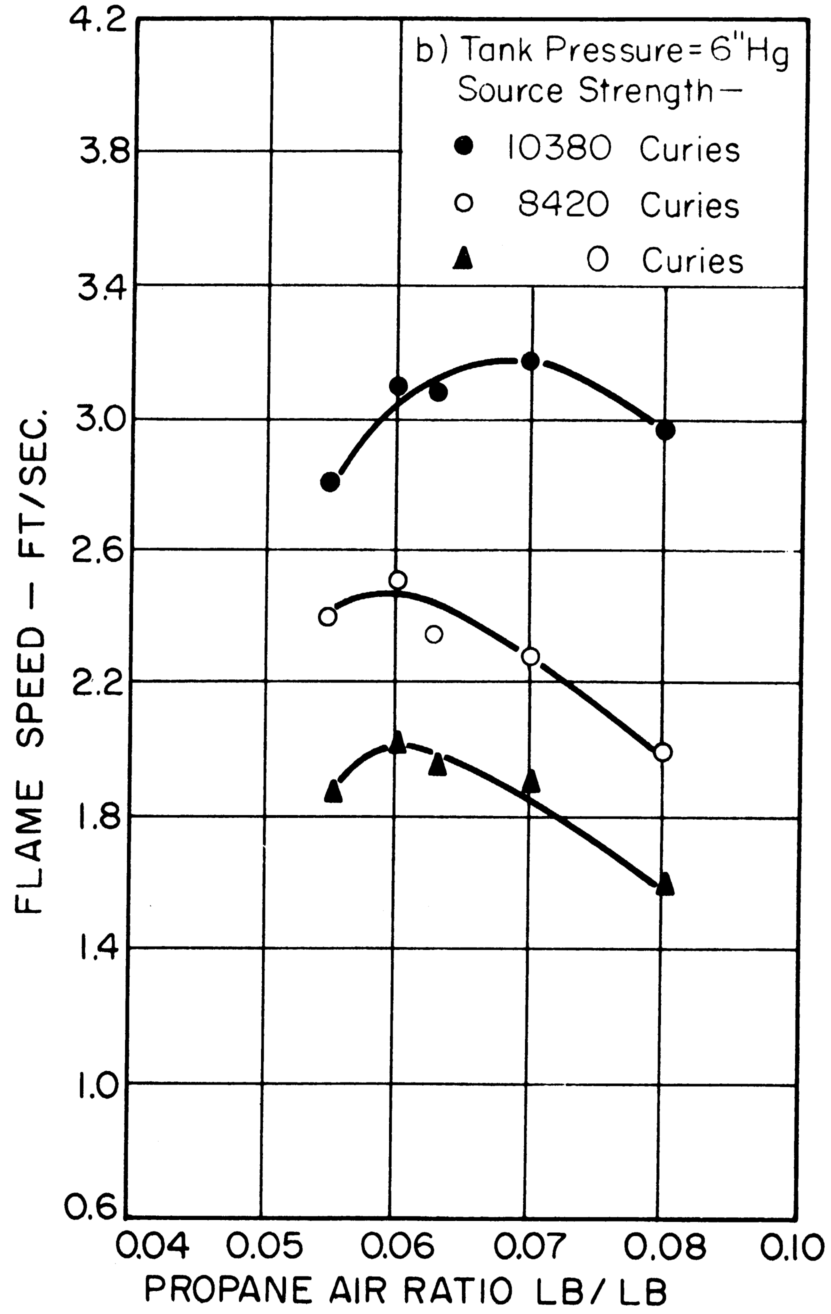
b) Tank Pressure = 6"Hg
Source Strength –
● 10380 Curies
○ 8420 Curies
▲ 0 Curies
FLAME SPEED – FT/SEC.
4.2
3.8
3.4
3.0
2.6
2.2
1.8
1.4
1.0
0.6
0.04
0.05
0.06
0.07
0.08
0.10
PROPANE AIR RATIO LB/LB

Figure 5b

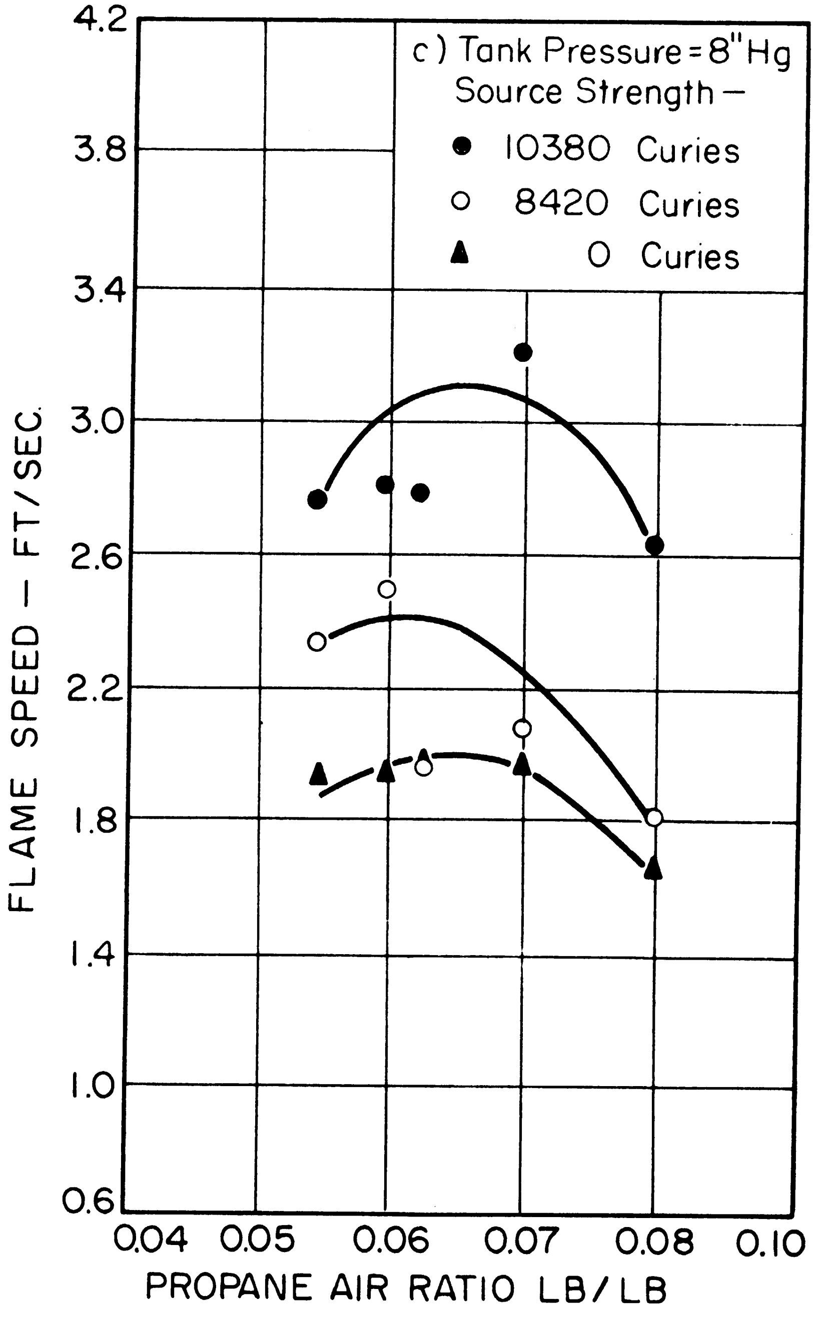
c) Tank Pressure = 8" Hg
Source Strength –
● 10380 Curies
○ 8420 Curies
▲ 0 Curies
FLAME SPEED — FT/SEC.
4.2
3.8
3.4
3.0
2.6
2.2
1.8
1.4
1.0
0.6
0.04
0.05
0.06
0.07
0.08
0.10
PROPANE AIR RATIO LB/LB

Figure 5c

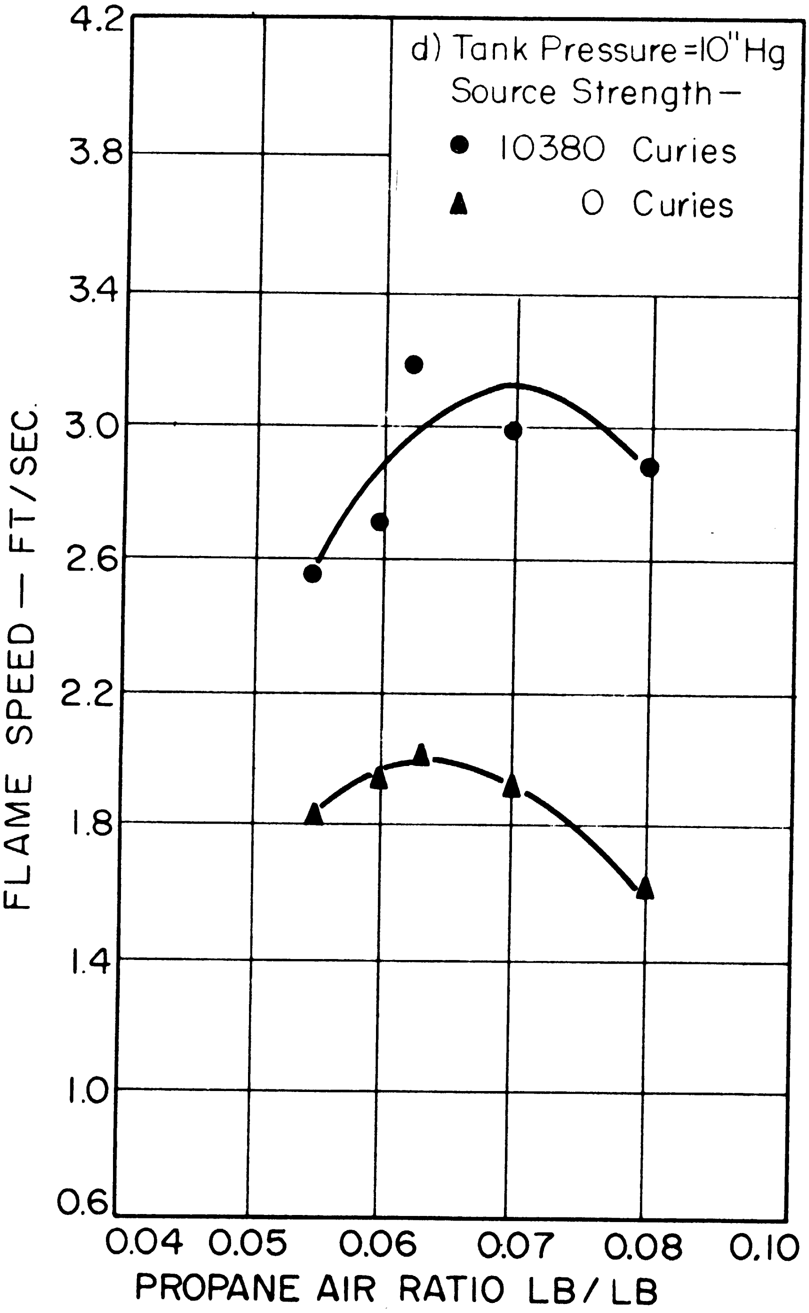
d) Tank Pressure=10"Hg
Source Strength–
● 10380 Curies
▲ 0 Curies
4.2
3.8
3.4
3.0
2.6
2.2
1.8
1.4
1.0
0.6
FLAME SPEED — FT/SEC.
0.04
0.05
0.06
0.07
0.08
0.10
PROPANE AIR RATIO LB/LB

Figure 5d

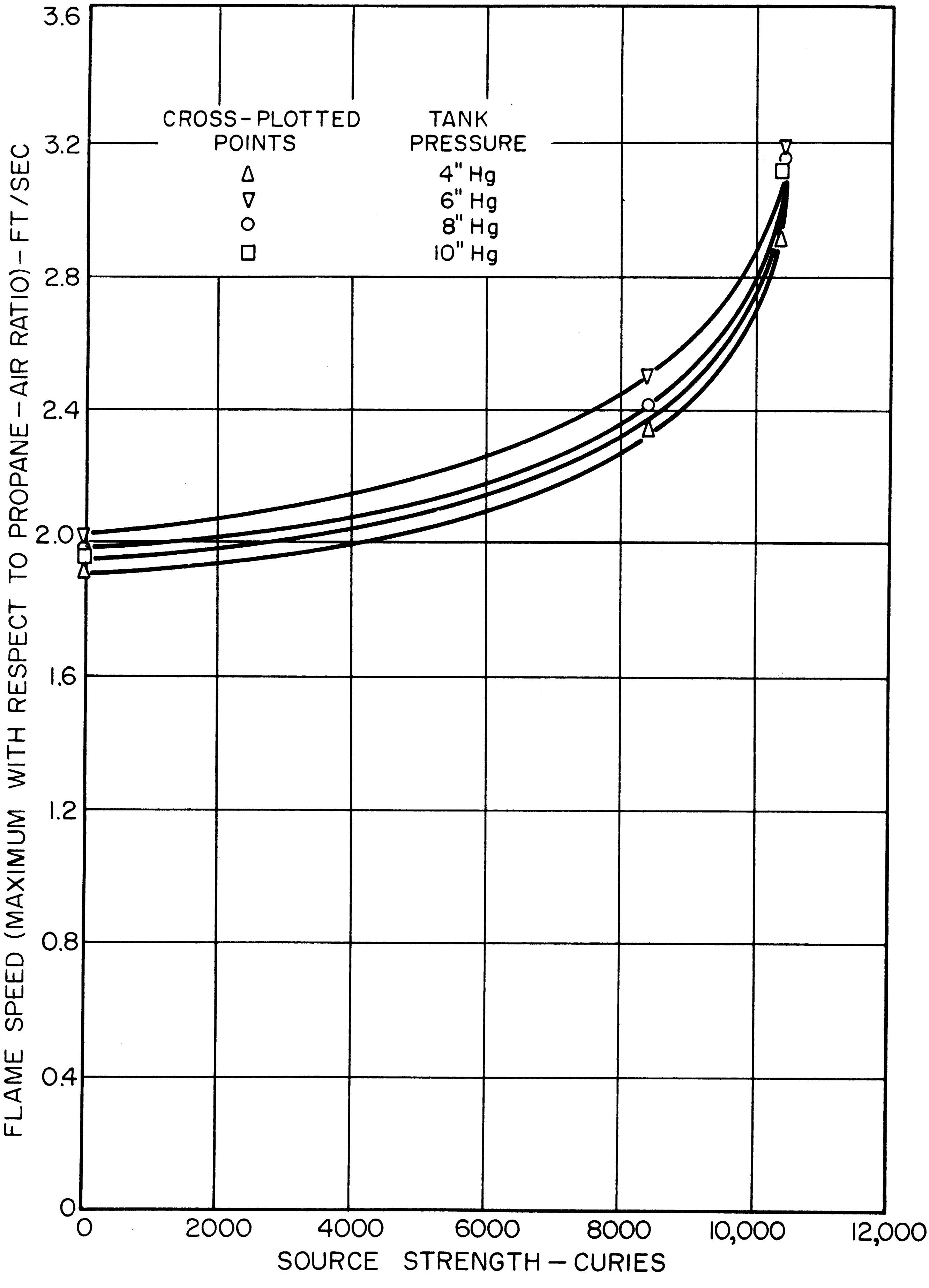
CROSS-PLOTTED POINTS
TANK PRESSURE
Δ 4" Hg
∇ 6" Hg
○ 8" Hg
□ 10" Hg
FLAME SPEED (MAXIMUM WITH RESPECT TO PROPANE - AIR RATIO) - FT/SEC
SOURCE STRENGTH - CURIES
0
0.4
0.8
1.2
1.6
2.0
2.4
2.8
3.2
3.6
0
2000
4000
6000
8000
10,000
12,000

Figure 6

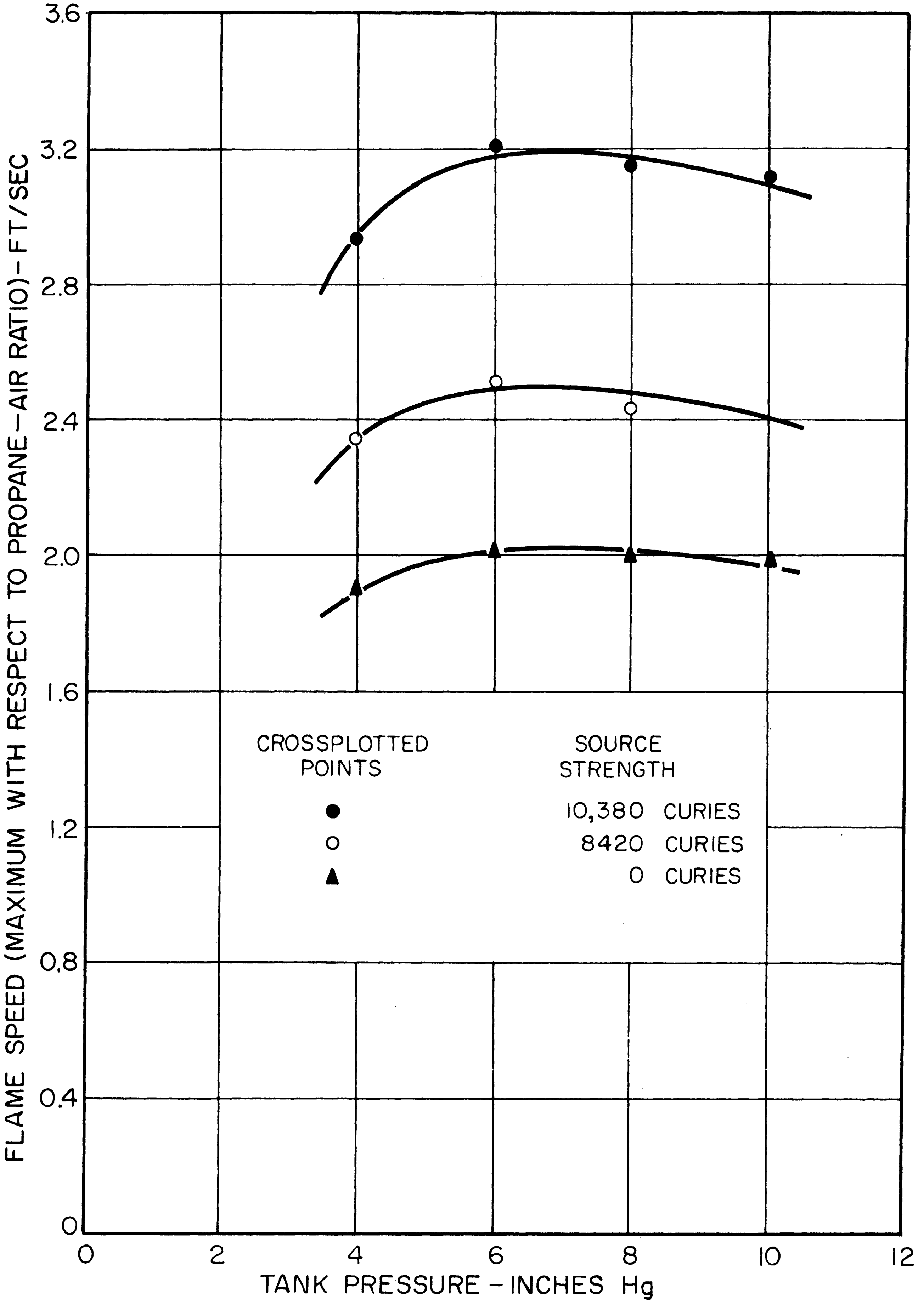
FLAME SPEED (MAXIMUM WITH RESPECT TO PROPANE-AIR RATIO) - FT/SEC
3.6
3.2
2.8
2.4
2.0
1.6
1.2
0.8
0.4
0
0
2
4
6
8
10
12
TANK PRESSURE - INCHES Hg
CROSSPLOTTED POINTS
SOURCE STRENGTH
● 10,380 CURIES
○ 8420 CURIES
▲ 0 CURIES

Figure 7