THE UNIVERSITY OF MICHIGAN

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EFFECTS OF RADIATION AT IGNITION POINT OF CONSTANT-VOLUME COMBUSTION

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ABSTRACT

The presence of 1.6 curies of alpha activity at the spark gap of a constant-volume spherical "bomb" has no significant effect on the ignition delay, rate of pressure rise, or lean-mixture ignition limits of propane-air mixtures, within the range of the tests performed.

However, the presence of radiation does cause a large scale change in the voltage requirement of the ignition system. If the spark gap is greater than the "quench" value for a given set of conditions, the effect of radiation can be to decrease the ignition voltage requirement from 30 to 50%. In general, a reduction in minimum ignition voltage requirement by use of radiation can be obtained only by increasing the spark gap considerably above that required for normal ignition.

Investigation of spark energy considerations indicates that the total energy is primarily a function of spark voltage rather than gap setting regardless of the presence of radiation, and that the energy requirement for ignition is therefore considerably less with radiation present at the spark gap.

ACKNOWLEDGEMENTS

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I. INTRODUCTION

A. Combustion Processes

Combustion can be defined as the rapid, high temperature self-sustaining oxidation of a fuel.

So-called "explosive combustion" occurs in homogeneous mixtures of fuel and air with a flame front progressing rapidly through the mixture. This type of flame may be classified as either (1) constant-pressure, in which the fuel-air mixture is not restrained from expanding as combustion takes place, or (2) constant-volume, in which combustion takes place in a restricted volume and consequent high pressures are produced.

Another type of combustion, referred to as "detonation", is characterized by a greatly increased reaction rate accompanied by a very high velocity shock wave, and a much higher rate of pressure rise than encountered in "normal" combustion.

The constant-volume combustion process is of widespread interest due to its application in reciprocating internal-combustion engines, where a compressed fuel-air mixture is ignited by a spark and subsequent combustion occurs before any appreciable piston movement takes place, thereby achieving high cylinder pressures for production of mechanical work by expansion of the combustion products.

B. Initiation of Combustion

In order to establish a self-propagating reaction in a combustible mixture either the entire mixture must be brought up to an ignition temperature, or a local high temperature source must be introduced.

Considerable experimental work has been done to establish the "ignition temperature" of various fuel-air mixtures by such means as introducing combustible mixtures into containers of known temperature, compressing mixtures adiabatically until ignition occurs, and inserting heated metal strips into mixtures of fuel and air.

In the latter work it was found that much higher temperatures were required to obtain ignition with very thin metal strips than with larger strips or rods. The lowest ignition temperatures were obtained when the entire vessel surrounding the gas was heated. The general trend is well established that the smaller the heat source, the higher must be the temperature of the source to initiate a combustion reaction.[1]

From a practical standpoint the most convenient means of igniting homogeneous fuel-air mixtures appears to be by means of an electric spark across electrodes within the mixture. As a spark represents a very small ignition source, rather high voltages (in the kilovolt range) are required to provide the requisite high temperature.

Depending on initial pressure, temperature, and mixture conditions, it is sometimes found that a minimum spark gap distance occurs below which the spark energy requirement for ignition increases greatly.[2] This effect has been attributed to a "quenching" effect due to the proximity of the electrodes to the area in which a combustion "kernel" is being started; that is, the physical heat transfer from the mixture to the electrodes is so great as to prevent flame propagation.

C. Ignition Delay

In a fuel-air mixture at an initial temperature below the "ignition temperature" there will always be a finite time interval between the occurence of the ignition spark and the start of rapid combustion. This time interval, known as ignition "delay", is apparently required for a sufficient flame propagating nucleus to be established to cause rapid burning of the remainder of the mixture.

Delay time of a given fuel can be decreased considerably by addition of small amounts of "active" chemicals such as aldehydes, which apparently promote the initial ignition reaction at a much greater rate.[3] However, for a given fuel, the length of ignition delay is primarily a function of the initial pressure, temperature, and mixture (fuel-air ratio) conditions, delay period decreasing with increasing temperature and/or pressure, and being a minimum at a fuel-air ratio slightly "richer" than stoichiometric.

D. "Lean" Mixture Ignition

A lean mixture is herein defined as a mixture of fuel with an excess of air above that required for stoichiometric burning.

From a combustion efficiency standpoint it is often desirable to burn a fuel with an excess of air over stoichiometric, as in this manner virtually all the fuel will be oxidized even though the mixture is not completely homogeneous at the start of the combustion process.

Combustion of lean mixtures is characterized by (1) slow flame speeds, (2) long delay periods, and (3) high ignition energy requirements.

Thus, although the so-called "limits of flammability" of paraffin fuels (determined by heating an entire volume until ignition occurs) are between 50 and 60% of the stoichoimetric fuel-air ratio,[4] it is generally very difficult to ignite by means of a spark mixture leaner than 80% of stoichiometric, when the mixture is initially at atmospheric temperature and pressure. This is due to the physically small nature of a spark acting as an ignition source, as described in Section B, above.

However, as the initial pressure and/or temperature of the mixture are increased, the "limits of flammability" can be more nearly reached.[5] The limiting factor in all cases appears to be the physical size of the spark that is available as an ignition source.

E. Purpose of Investigation

In considering the number of combustion characteristics which depend directly or indirectly upon the means of ignition, it was decided to investigate the effects of ionizing radiation located at the ignition point of a combustion device.

Effects of ionizing radiation on the combustion process considered are:

1) Possible decrease in ignition delay period, with possible resultant increase in flame speed.

2) Possible extension of lean mixture ignition limits.

3) Possible reduction in spark energy requirement for ignition.

II. METHOD OF CONDUCTING TESTS

A. Equipment (See Appendix for Detailed Schedule of Apparatus)

1. Constant-Volume "Bomb"

The containment vessel used for this investigation is a spherical pressure vessel, or "bomb", of 9-9/16-inch inside diameter and 1/2-inch wall thickness, formerly used by the National Bureau of Standards for determination of flame velocities under constant-volume combustion conditions.[6] An insert containing a glass window is available for visual or photographic observation of the spark or combustion process; however, a solid steel replacement ring was used during most of the test work. Figure 1 depicts the geometric layout of the "bomb" components.

The ignition source is provided by two electrodes located at 180°, with micrometer adjustment provided by setting of the spark gap. Two source holders located at either side of the spark gap are provided for mounting either the "dummy" or "hot" sources during the runs. Radius of the stainless steel electrode "points" is approximately 1/32 inch.

Heating "tapes" are wrapped around the outside of the "bomb" for temperature control. Initial temperatures of the mixtures are measured by means of an iron-constantan thermocouple and potentiometer arrangement.

2. Ignition Circuit

Ignition voltage is provided by a 130 to 1 transformer, the primary of which is energized by a capacitor (precharged to a known potential) to provide the ignition energy. See Figure 2a for circuit.

At the conclusion of the main series of tests, the ignition circuit was modified as indicated in Figure 2b, for determination of spark energy considerations under variable conditions.

3. Pressure Pick-up

The pressure-rise vs. time characteristics of the burning mixtures are determined by use of a strain gauge pressure pick-up connected directly to the "bomb" volume. The "output" of the strain-gauge element is fed to a bridge-amplifier, this output in turn being fed to a cathode-ray oscilloscope for visual observation. Permanent record of the oscilloscope trace is made by means of a "Polaroid" camera affixed directly to the fact of the scope screen.

A square-wave generator is provided for checking horizontal sweep speed calibration of the oscilloscope.

4. Mixture Storage

In order to assure uniform mixtures of fuel and air for each run, the gases are premixed at the start of the tests and stored in six five-cubic-foot storage tanks located in a small shed 50 feet from the building, and connected to the control board valving manifold by 1/4-inch copper tubing.

To monitor initial pressure conditions and provide for evacuation and filling of the "bomb" prior to each run a control board containing the necessary pressure measuring devices, valves, and manifolding is provided. Figure 3 depicts a schematic layout of the control board components.

Fuel used is "chemically pure" propane (C_3H_8) purchased from the Matheson Company, Joliet, Illinois. Air used is provided from 2,000 psi high-pressure cylinders, in order to have minimum moisture content.

B. Sources

Ionizing radiation at the spark gap is provided by two polonium-210 alpha-emitting sources. The sources were purchased from Mound Laboratories, Miamisburg, Ohio. In fabricating the sources, the polonium was first electrodeposited onto the face of a steel "blank". The active material was then covered with a .00027-inch thick stainless steel "window", and nickel electroplated around the edges of the window to secure a tight seal for containment. (See Figure 4.)

The sources were shipped from Mound Laboratories on February 24, 1956, and at that time had the following activities:

source	A-36	1.20 curies
source	A-37	1.06 curies .

The half life of polonium is 138 days; therefore, the approximate activities during the test period, some 70 days later, were .84 and .76 curies, respectively, for a total of 1.6 curies.

As polonium emits alpha particles of 5.3 Mev energy, and all energy is dissipated within a few centimeters of the source, the maximum ionizing power in the vicinity of the spark gap would be:

$$1.6 \text{ curies} \times 3.7 \times 10^{10} \frac{\text{disintegrations}}{\text{sec-curie}} \times 5.3 \frac{\text{Mev}}{\text{disintegration}}$$

$$\times 1.6 \times 10^{-10} \frac{\text{milliwatt-sec}}{\text{Mev}} = 50 \text{ milliwatts} .$$

With the stainless steel "window" in place, the measured maximum range of the alpha particles at atmospheric pressure is 1/2 inch. When in use in the "bomb" the sources are located at a distance of 1/8 inch from the spark gap.

C. Procedure

1. Pre-mixing of Gases

Mixtures of propane-air ratios of 1.17, 1.0, 0.85, and 0.80, 0.70, and 0.60 of stoichiometric fuel-air ratio (one part fuel to 23.8 parts air on a volume basis) were made according to the following procedure:

(a) All tanks evacuated to less than 1,000 microns.

(b) Propane introduced to give tank absolute pressures of 8.65, 7.40, 6.27, 5.90, 5.20, and 4.46 in. Hg, as read on a mercury manometer.

(c) Tanks filled to 89.4 psia, or 75 psig, as determined by a "dead-weight" tester.

2. Initial Conditions

Ignition of all mixtures was attempted under the following conditions:

(a) "Cold" runs (using "dummy" sources):

Initial pressures of 20, 40, and 60 in. Hg abs.

Initial temperatures of 100 and 300°F at each pressure level.

(b) "Hot" runs (using polonium sources):

Same conditions as cold runs.

At 0.70 fuel-air ratio some initial temperatures between 100° and 300°F were employed in an attempt to establish closer ignition "limits".

Before each filling of the "bomb" it was evacuated to approximately 1,000 microns absolute pressure, as read on a Stoke's "McLeod" gauge. Under all conditions where ignition was possible, at least three pressure-time records were made, to obtain reasonable statistical accuracy.

After each set of runs under a given initial pressure and temperature conditions, a photographed calibration of oscilloscope vertical deflection vs. "bomb" pressure (as monitored by a "dead-weight" tester) was made for reference when analyzing the combustion pressure-rise trace photographs.

The initial pressures used were determined during preliminary tests by the following factors: Ignition of even stoichiometric mixtures could not be obtained at 100°F and pressures below 20 in. Hg absolute; and, the range of the alpha particles was so short at pressures of 80 in. Hg absolute that practically no effect on the ignition voltage requirement could be noticed (a minimum source-to-spark gap distance of 1/8 inch was necessary due to arc-over considerations).

The maximum allowable temperature is limited by the melting point of polonium (approximately 320°F).

3. Ignition of Mixtures

Before starting the actual combustion runs, and with the glass window still in place in the "bomb", a series of runs was made to determine primary circuit minimum voltage requirement to break down the air gap as a function of spark gap, pressure, and presence of radiation. (See Figure 8).

Having this data, the minimum voltage that can be relied upon for producing a spark under any given set of gap-pressure-source conditions is known for reference during the actual combustion runs.

When actually igniting the various fuel-air mixtures, the procedure is as follows:

(a) At a given gap setting the primary voltage is set at the minimum value determined by the calibration runs. A series of five sparks is then produced.

(b) If ignition does not occur, the primary voltage is then increased in 20 to 40 volt steps until either ignition occurs or the maximum output of the primary circuit is attained.

(c) If no ignition is possible in (b), the gap setting is then increased and steps (a) and (b) repeated. This procedure is continued until a point is reached where gap and voltage requirements agree with the minimum values as determined by Figure 10.

(d) If ignition occurs immediately in (a), the gap setting is then reduced, with the voltage being reduced correspondingly in accordance with the calibration data (see Figure 10), until the point is reached where considerably higher than minimum voltage for a given gap setting is required.

At the conclusion of the main series of tests the ignition circuit, altered as indicated in Figure 2b, was connected to the oscilloscope and voltage and current vs. time records of the secondary circuit were made under variable gap and radiation conditions for determination of spark energy considerations.

III. RESULTS

A. Rate of Pressure Rise and Delay Period

Comparative results showing delay and pressure-rise conditions with and without the presence of ionizing radiation at the spark gap are given in Figures 5 through 7. In all cases the results under radiation conditions are indicated by dashed lines.

B. Ignition Voltage Requirement and Ignition Limits

Minimum voltage requirement for break-down of air gap under different conditions is given in Figure 8.

Figure 9 summarizes minimum voltage requirements as determined by the procedure outlined in Section II-C-3, above.

The detailed voltage-versus-gap and relative ignition limit data for all fuel-air ratio, pressure, and temperature conditions are given in Figures 10 through 14. In all cases, the "horizontal" (positive slope) curves represent the "spark limit" conditions, the values being taken directly from Figure 8. The "vertical" (negative slope) curves represent the "ignition limit" conditions, as determined by experiment. The intersection of the two curves represents both the minimum ignition voltage condition and the start of the "quench" range (i.e., spark gaps to the left of the intersect point are in the "quench" region).

Ignition of fuel-air mixture 0.6 of stoichiometric was impossible under any of the test conditions employed.

C. Spark Energies

Secondary voltage and current characteristics vs. time are depicted in Figures 15 and 16.

Spark energy (area under V x I curve) as a function of spark gap, primary voltage, and presence of radiation is also shown in Figures 15 and 16.

IV. DISCUSSION

A. Rate of Pressure Rise and Delay Period

Reference to Figures 5 through 7 indicates no discernable trend in either rate of pressure rise or delay period caused by the presence of ionizing radiation at the ignition point of the mixture.

At very lean fuel-air ratios the delay periods are so long, and the rates of pressure rise so slow, that statistical variations make interpretation difficult; even so, it is clear that no major changes are produced by the presence of radiation.

At fuel-air ratios near stoichiometric the slight variances observed are of the same magnitude as the experimental error of the equipment used, and are not considered significant.

The following expected general trends are clearly evident (regardless of the presence of radiation):

(1) Delay period increases with leaner mixtures, being a minimum at a fuel-air ratio slightly richer than stoichiometric.

(2) Delay period increases with decreasing initial temperatures and pressures, with temperature being the more important variable.

(3) Maximum pressures increase with increasing fuel-air ratio, increasing pressure, and decreasing temperature, due to the greater mass of fuel present when going in these directions.

Data obtained under any given set of conditions was very consistent and reproducability good. This is believed attributable to the method of premixing and storing the fuel-air mixtures prior to the start of the runs.

B. Ignition Voltage Requirement and Ignition Limits

1. Break-down of Air Gap

It is of interest to note in Figure 8 that the voltage requirement for break-down of an air gap is reduced almost half by the presence of ionizing radiation, at lower pressures. At pressures of 60 in. Hg absolute and above, the effect is less noticeable, due probably to the limited range of these particular sources in the denser air.

It was also observed that is is possible to jump gap distances of well over two times as great before break-down occurs at other points in the system, when ionizing radiation is present.

In obtaining the curves of Figure 8, it should be mentioned that there was considerable statistical variation in the primary voltage requirement to jump a given gap when radiation was not present, the spread from an occasional spark occuring to consistent sparking being in the order of 10 volts (primary). Values reported are minimum for consistent sparking. With radiation present at the spark gap there was practically no spread in voltage requirement from "no spark" to consistent sparking.

The minimum voltage values determined in air (Figure 8) held very closely when fuel-air mixtures were present inside the "bomb" at an initial temperature of 100°F. This is to be expected, as the fraction of fuel by volume in the mixtures ranged only from 3 to 5%.

At initial mixture temperatures of 300°F minimum primary voltage requirements ran 10 to 20 volts below those given in Figure 10.

2. Ignition of Fuel-Air Mixtures

Reference to Figure 9, summarizing minimum ignition voltage requirements with and without the presence of radiation, indicates that although only half the voltage is required to break down the gap, only a one-third reduction in voltage requirement for ignition can be realized.

This condition is due to an increase in effective "quench" distance of the electrode gap when radiation is present, as will be noted in reference to Figures 10 through 14. In order to realize minimum voltage requirement when radiation is present at the spark gap, the electrode gap distance must be increased in the order of 20 to 40% above that required for minimum ignition voltage without the sources present.

Of course, at any fixed gap setting greater than the "quench" distance for a particular set of conditions with radiation present, the general considerations of Figure 8 will again apply; that is, ignition voltage requirements will be the same as the "break-down" voltage requirements.

Reasons for the increase in effective "quench" distance when ionizing radiation is present at the spark gap are covered in Section IV-C.

3. Ignition Limits

Reference to the ignition requirements for the "leaner" fuel-air ratios (Figures 12, 13, and 14) indicates that the factor tending to establish the ignition "limit" in these cases is the physical length of spark it is possible to produce with a given ignition system.

Thus, in Figure 12, for initial conditions of 20 in. Hg and 100°F, ignition without the presence of radiation is only possible at the very maximum spark gap (.120 in.) that can be obtained without break-down occuring at other points in the system. However, with radiation present, a spark gap of over .200 in. can be obtained if necessary, although only .160 in. is required for minimum voltage ignition.

In Figure 13, at initial conditions of 20 in. Hg and 100°F it is impossible to ignite the mixture whether the source is present or not, indicating that the effect of radiation on ignition limits is not a large-scale effect. At initial conditions of 40 in. Hg and 100°F it is noted that ignition was at least greatly facilitated by the presence of radiation.

In Figure 14, at an initial pressure of 40 in. Hg the temperature was increased until ignition was just marginally possible without the sources present. The addition of the sources then allowed ignition with a 50% decrease in voltage requirement. Much the same procedure was followed at an initial pressure of 60 in. Hg, with the temperature being increased until ignition was just possible with the sources present. In this case, when the sources were removed ignition was impossible, due to break-down at points in the ignition system other than the spark gap.

Thus, it appears that radiation would be of benefit in extending ignition limits in cases where design factors limit maximum voltages and/or insulator distances for a given ignition system.

The requirement that spark gap be increased to obtain minimum ignition voltage when radiation is present has apparently not been recognized in some previous studies, which have reported a definite decrease in ignition limits with radiation present at the spark gap.

C. Spark Energy Considerations

1. Energy Requirement at Spark Gap Less that "Quench" Distance

Figure 15 gives voltage, current and power characteristics of the ignition spark at two ignition conditions, without radiation.

Reference to Figure 11 indicates that at an initial pressure of 40 in. Hg minimum ignition voltage is obtained at 120 volts and .040 in. spark gap. If the gap is reduced into the "quench" range, increased voltage is required for ignition, increasing to approximately 250 volts at a spark gap of .025 in.

Comparison of the spark characteristics in Figure 15 indicates that although the "break-down" voltage requirement is higher at the larger gap the total spark energy input is less than a third, due to the lower initial primary voltage.

It is not thought that this gross difference in energy requirement can be adequately accounted for on the basis of heat transfer to the electrodes as described by the "quench" theory.

Even assuming a rather high air-to-metal heat transfer coefficient of 10 Btu/ft^2-^{o}F-hr at a temperature difference of 5,000^{o}F, the calculated energy dissipation to an area of 1/8 square inch during a 50 microsecond period due to heat transfer is less than one milliwatt-second.

It would appear likely that the process of ignition is more adequately explained by basing the ignition energy criteria upon the events taking place during the first ten microseconds of the ignition process, rather than upon the total energy input to the spark.

As the spark power reaches levels of 5 to 10 kilowatts at the instant of gap "break-down", as compared to .5 to 2 kilowatts during later periods, it would appear that maximum spark temperature would be reached at maximum power, and ignition therefore would either occur at the instant following gap "break-down" or not at all.

In obtaining the current vs. time curves it was impossible to discern an accurate trace of the current "spike" immediately during spark gap "break-down", due to the limited sensitivity of the type of oscilloscope screen used. The results given are, therefore, approximate. However, if a constant resistance of the gas in the vicinity of the gap is assured, the current during the break-down period can be considered proportional to the voltage, and the power to vary as the square of the voltage.

Thus considered, the concept of "quench" distance becomes no more than a condition wherein a minimum gap is reached at which break-down voltage is so low that the requisite power input (and therefore temperature) cannot be achieved by any means other than gross increases of primary voltages. At high voltages (within the "quench" region) the high-power period immediately following the initial "spike" is apparently sufficiently long to be able to initiate combustion, even though the temperature is considerably lower.

2. Energy Considerations under Radiation Conditions

(a) Gap and Voltage Constant

Reference to the dotted curves in Figure 15 indicates that the effect of radiation at the spark gap is to change the characteristics of the spark only during the "break-down" period, as the curves after a period of 10 microseconds are identical with those obtained without radiation present.

As ignition is not possible under the gap and voltage conditions of Figure 15 with radiation present, this would indicate further that the initial power pulse is of primary importance in initiating combustion, as power areas under both the radiation and non-radiation conditions indicate the same total energy input in each case.

(b) Gap and Voltage Variable

Figure 16 indicates spark characteristics when the gap setting is increased to its optimum setting under radiation conditions.

It is noted that under optimum gap conditions the presence of ionizing radiation acts to decrease both the power requirement of the initial "pulse" and also the total energy of the spark.

From this it can only be deduced that the effect of radiation under optimum conditions is other than a thermal or energy input consideration, probably having to do more with the chemical processes involved in instigating the initial chain reaction of the combustion process. In this regard, the increased length of the spark available under radiation conditions would undoubtedly be favorable to initiating the ignition process in spite of the lower spark energy input.

That the ignition energy input due to radiation is negligible is evident when it is considered that total radiation energy during a 50-microsecond period is in the order of .002 milliwatt-seconds, whereas spark energy is in the order of 10 milliwatt-seconds, a difference in magnitude of 5000.

V. CONCLUSIONS

A. The presence of 1.6 curies of ionizing radiation at the ignition point of a combustion reaction has no effect on the delay time or rate of pressure rise of the process.

B. The presence of radiation may have a very slight effect tending to increase the ignition limit of lean fuel-air mixtures, providing optimum spark gap is used.

C. At spark gaps near the "quence" value for a given set of conditions without radiation, the addition of radiation will make ignition impossible.

D. If optimum spark gap is employed, ignition voltage and energy requirement can be reduced 30 to 50% by the presence of radiation at the ignition point.

VI. SUGGESTIONS FOR FUTURE WORK

A. Spark Energy

As it appears that the controlling factor in the ignition process is the initial power "pulse" immediately following break-down of the spark gap, it would be desirable to investigate this portion of the spark period in more detail, under both "normal" and radiation conditions.

The equipment as now set up would be basically satisfactory for this work, the main change required being an oscilloscope having a screen sufficiently sensitive to allow recording of voltage and current characteristics at a sweep speed of 1 cm/microsecond.

B. Increased Source Strength

In view of the significant reduction in ignition energy requirement made possible by the presence of 1.6 curies of ionizing radiation, it would be of interest to employ increased source strengths to determine the general trend of minimum ignition voltage requirement vs. degree of ionization of the spark gap.

Also, means should be devised to allow full ionizing effect at the spark gap at higher pressure levels, in order to allow testing under conditions more nearly approaching compression conditions in power producing machinery.

This line of investigation could be followed using the existing test equipment.

C. Irradiation of Entire "Bomb" Volume

In order to evaluate the effects of radiation during the entire combustion process it would be possible to construct a lighter weight pressure vessel (to minimize shielding effects) and place it in the vicinity of a gamma-emitting source, such as cobalt-60, for evaluation of the effects of radiation. By operating at low initial pressures with a "non-detonating" type of fuel (propane or similar), reasonable safety of operation could be assured in the vicinity of a strong gamma source within a suitable "cave" area.

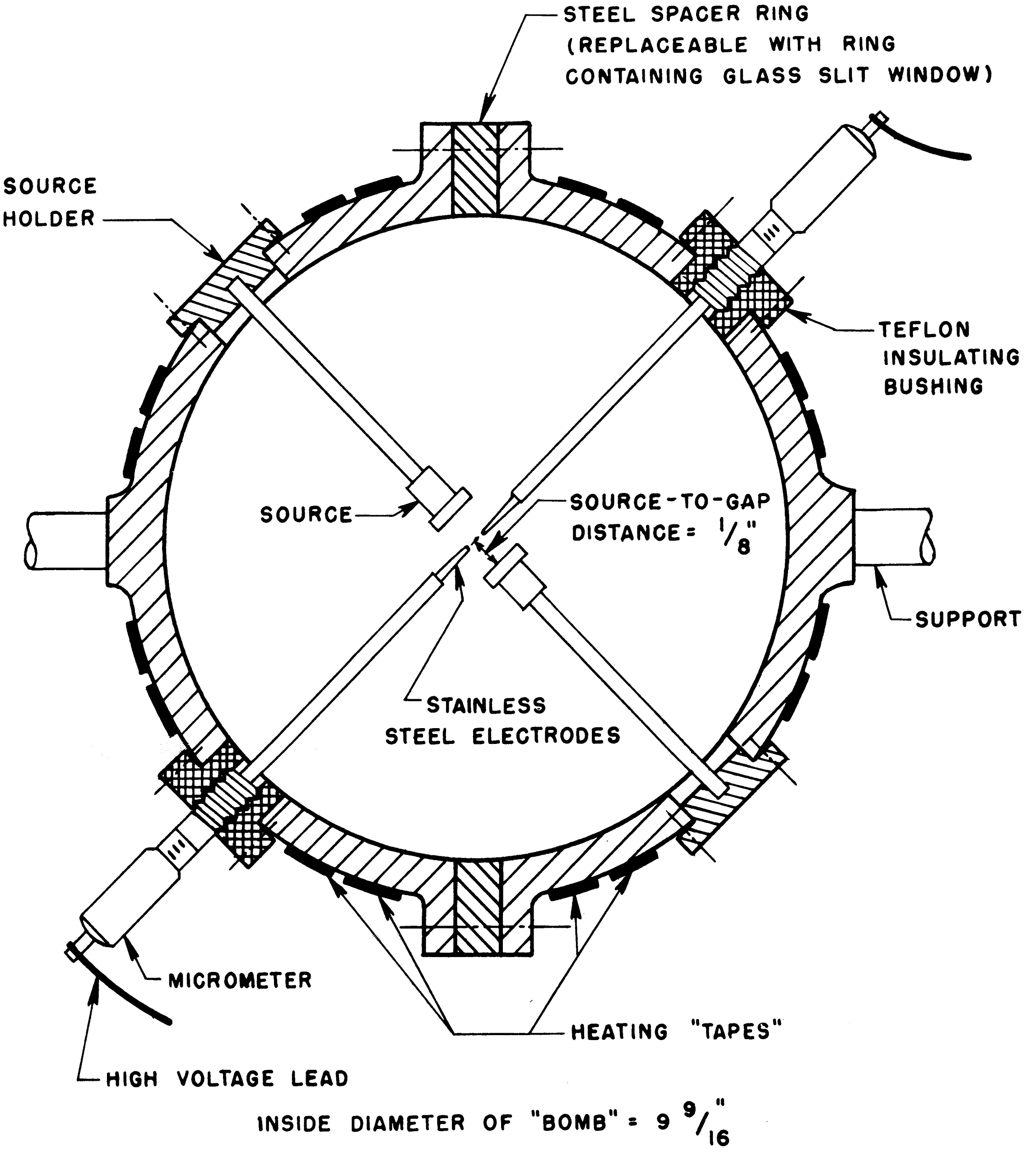


FIG. 1 — CONSTRUCTION OF CONSTANT-VOLUME "BOMB"

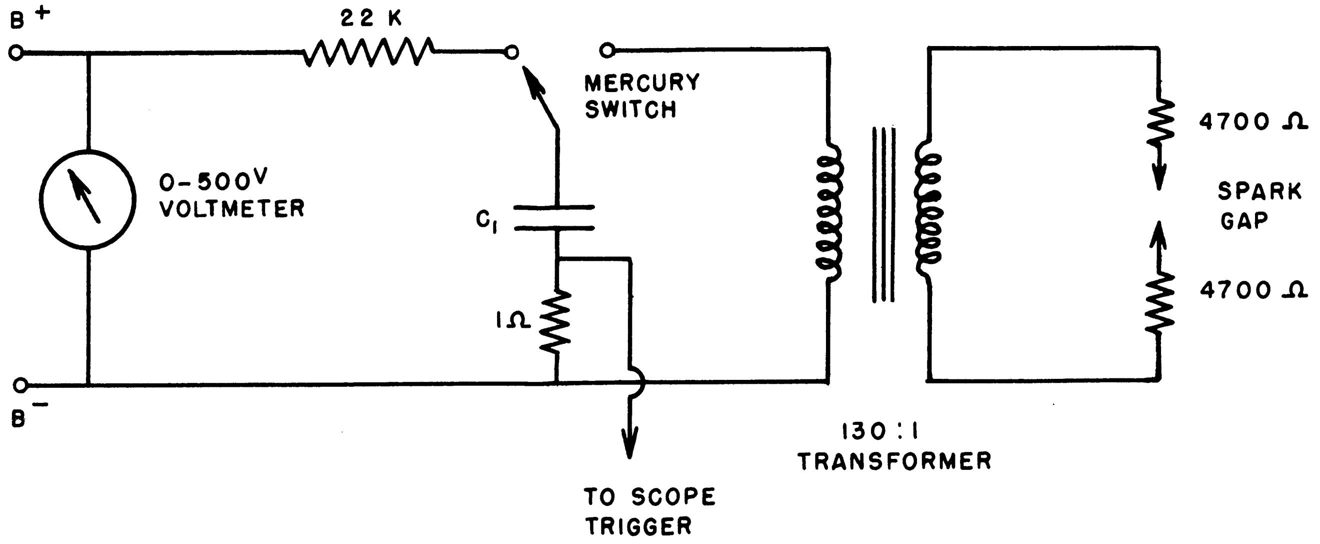


FIG.2A – IGNITION CIRCUIT USED DURING COMBUSTION RUNS

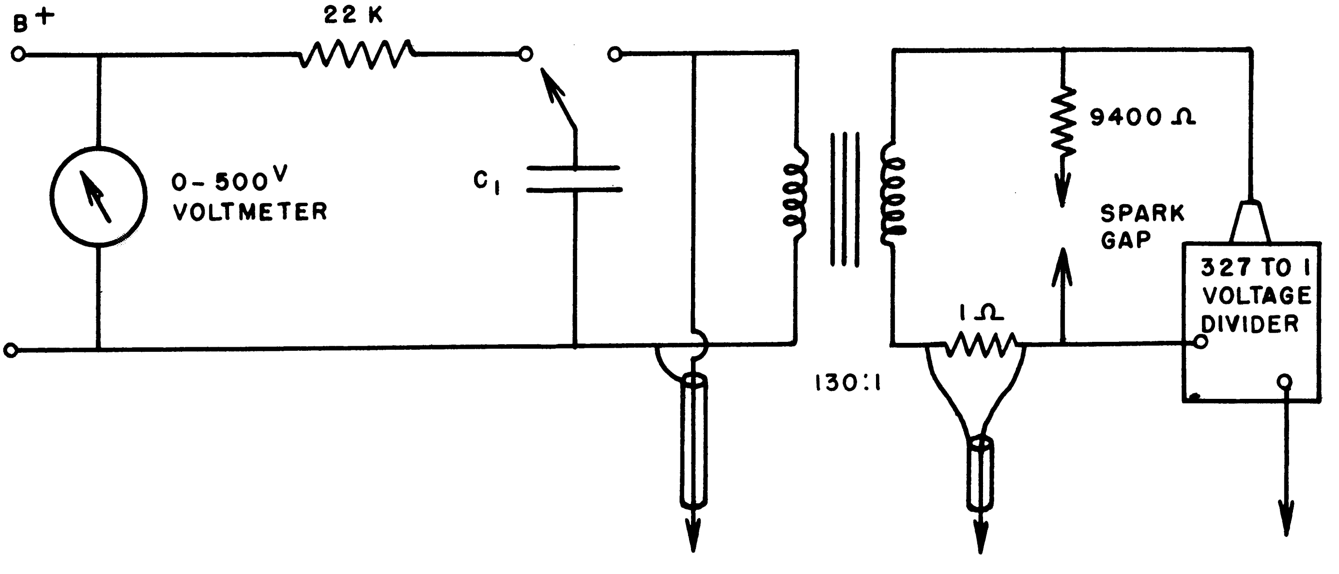


FIG. 2B – IGNITION CIRCUIT USED FOR SPARK ENERGY RUNS

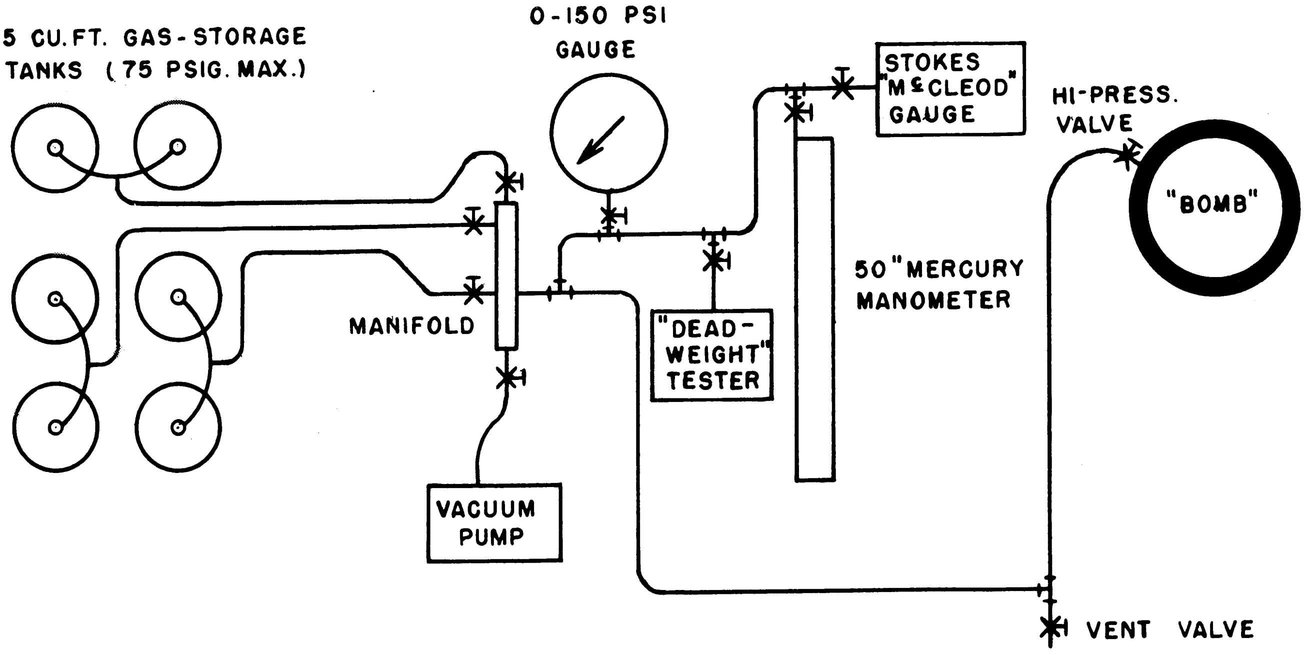


FIG. 3 - CONTROL PANEL AND MANIFOLDING ARRANGEMENT

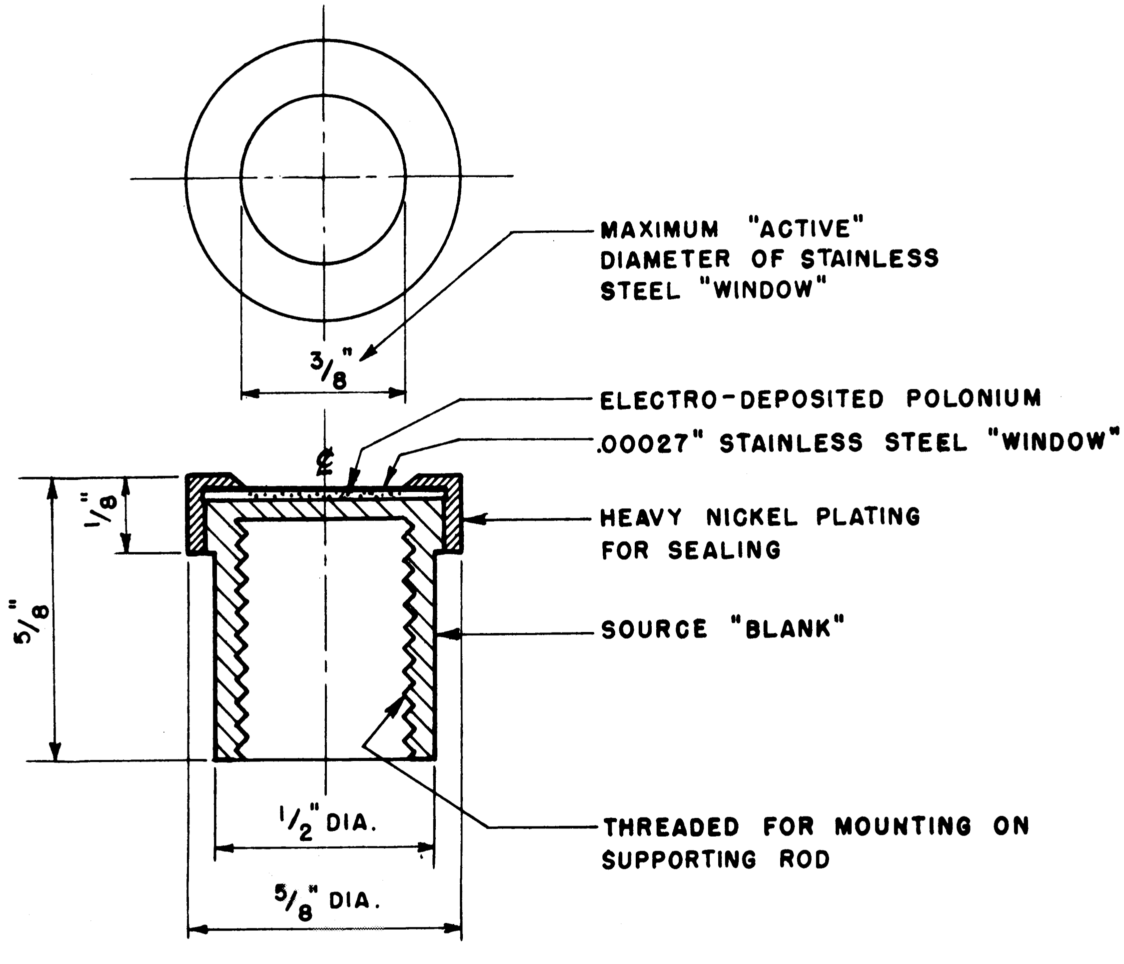
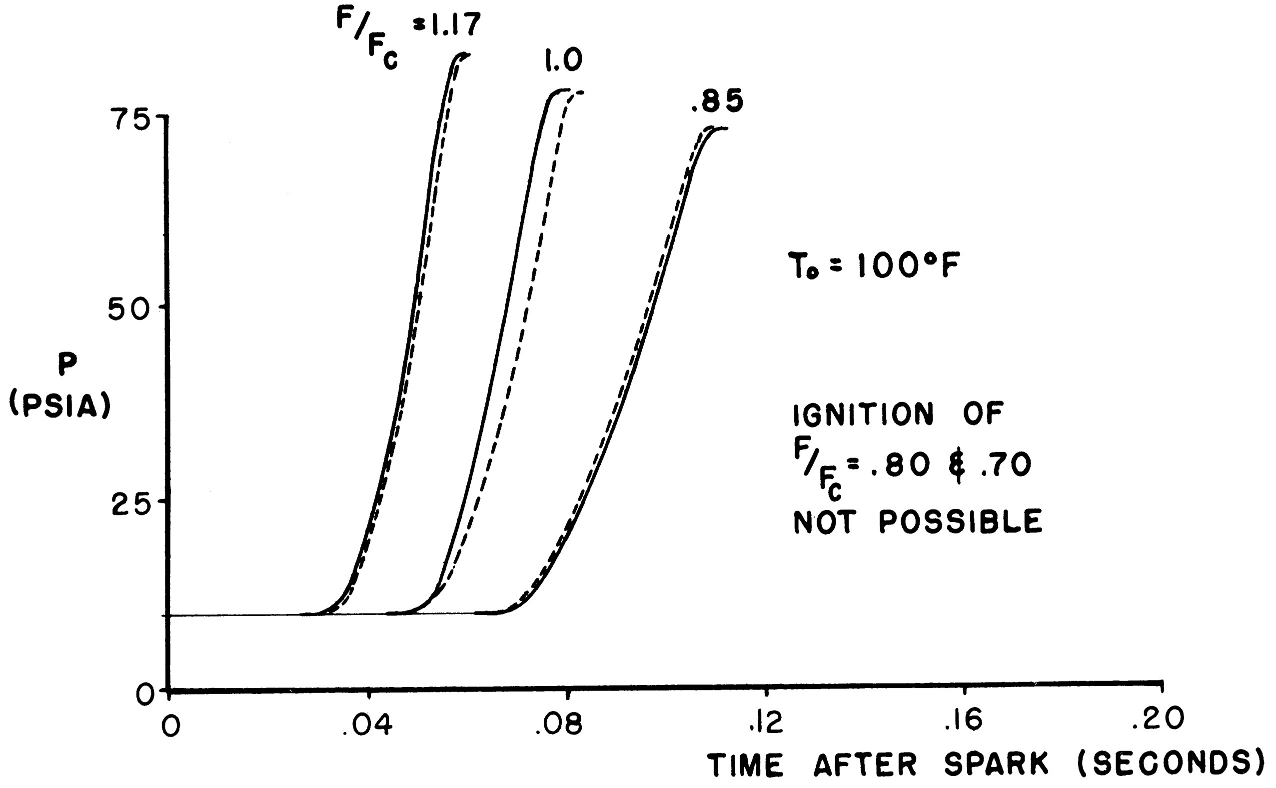


FIG. 4 — CONSTRUCTION OF POLONIUM SOURCES



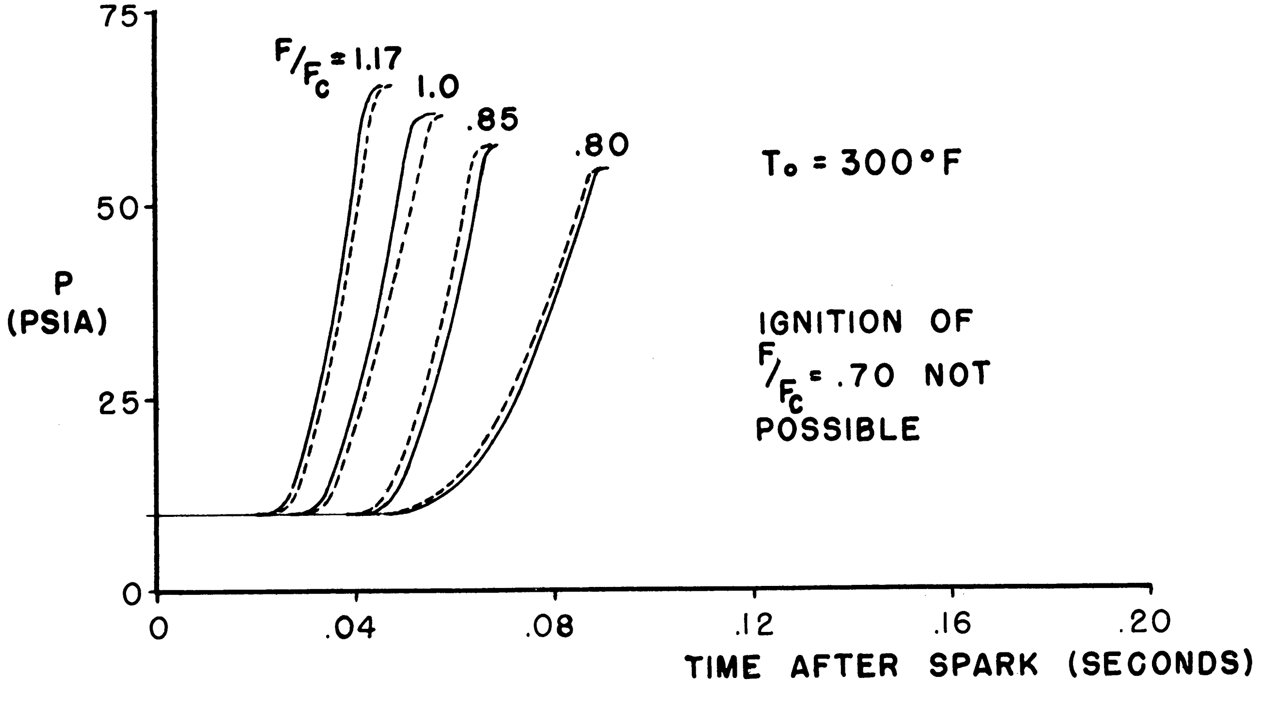


FIG. 5 – PRESSURE-RISE VS. TIME FOR PROPANE-AIR COMBUSTION
INITIAL PRESSURE = 20 IN.HG.ABS.

PRESENCE OF RADIATION INDICATED BY DASHED LINES
F/F_c = FRACTION OF STOICHIOMETRIC FUEL-AIR RATIO

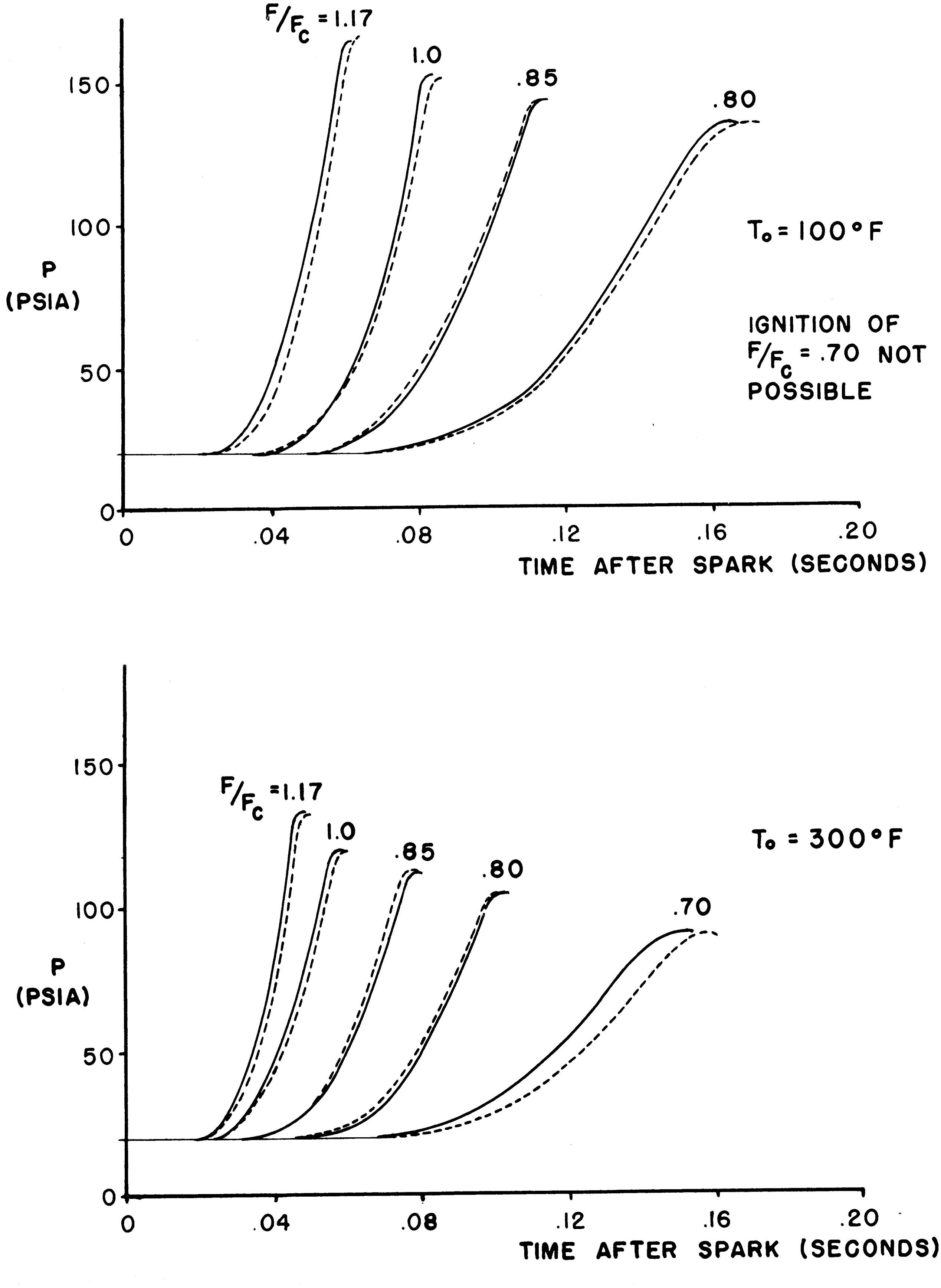


FIG. 6 - PRESSURE-RISE VS. TIME FOR PROPANE-AIR COMBUSTION
INITIAL PRESSURE = 40 IN. HG. ABS.

PRESENCE OF RADIATION INDICATED BY DASHED LINES
F/F_C = FRACTION OF STOICHIOMETRIC FUEL-AIR RATIO

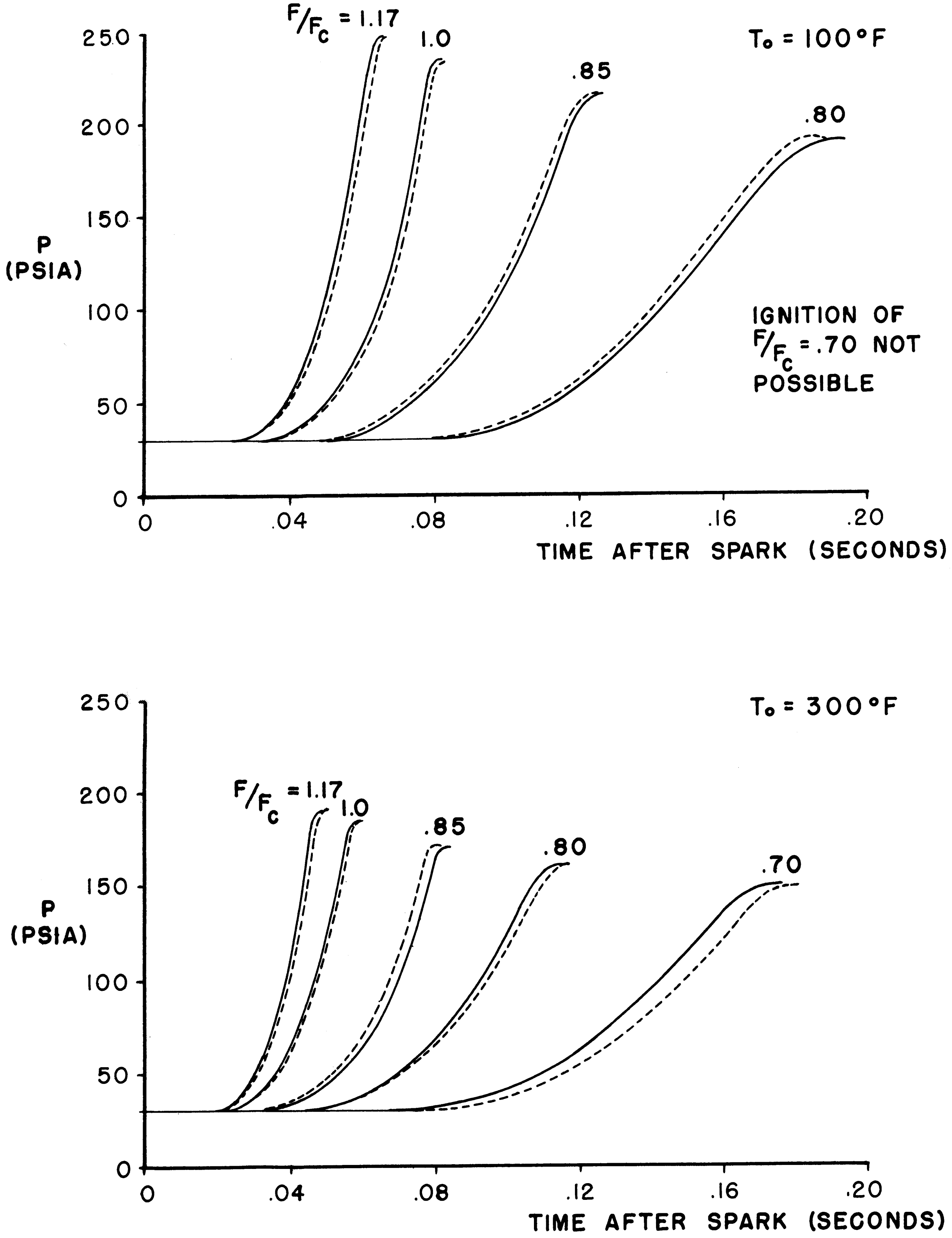


FIG. 7 - PRESSURE-RISE VS. TIME FOR PROPANE-AIR COMBUSTION INITIAL PRESSURE = 60 IN.HG.ABS.

PRESENCE OF RADIATION INDICATED BY DASHED LINES
F/F_C = FRACTION OF STOICHIOMETRIC FUEL-AIR RATIO

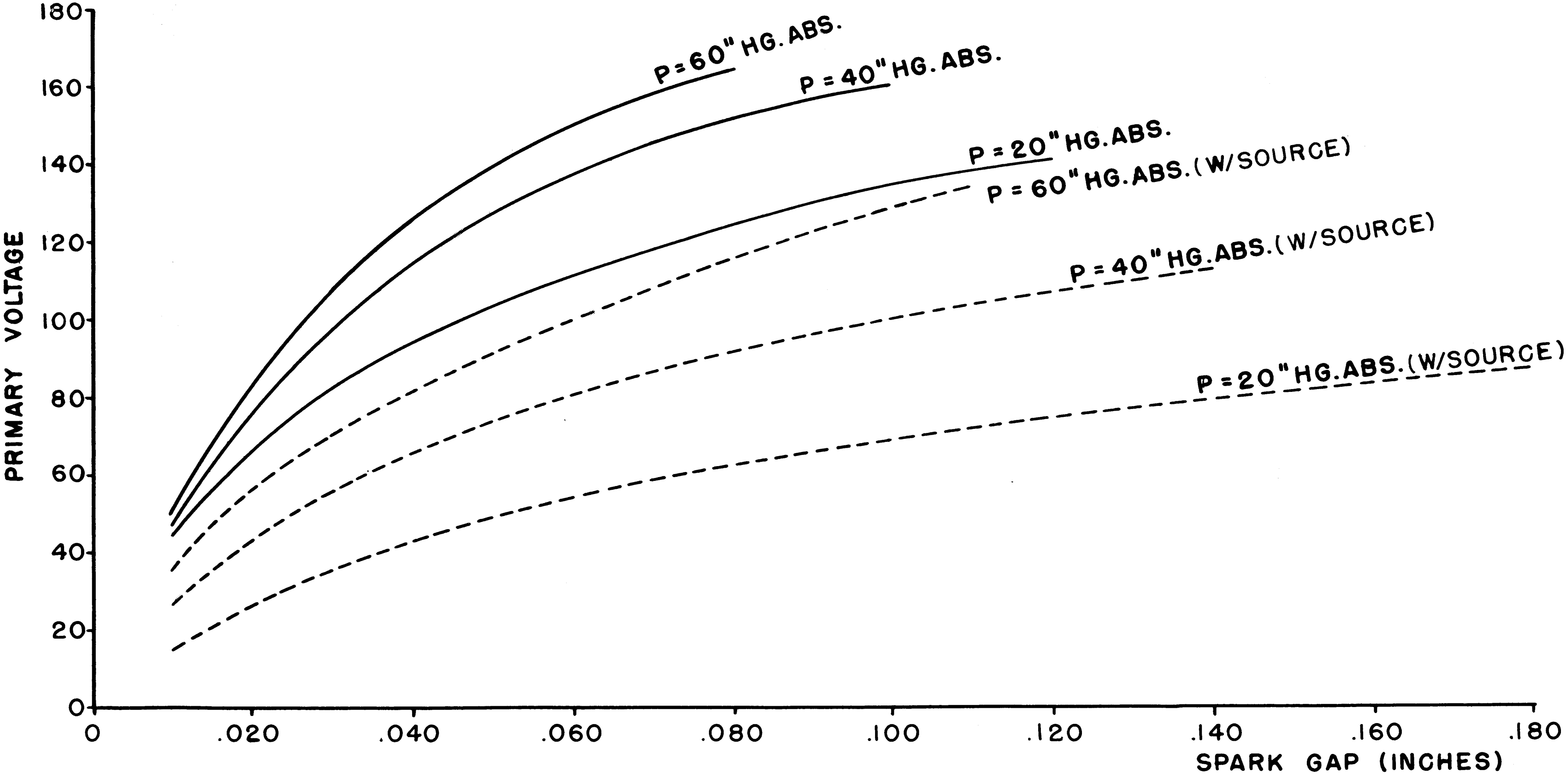


FIG. 8 – MINIMUM PRIMARY VOLTAGE REQUIREMENT VS. SPARK GAP (IN AIR), T=80°F

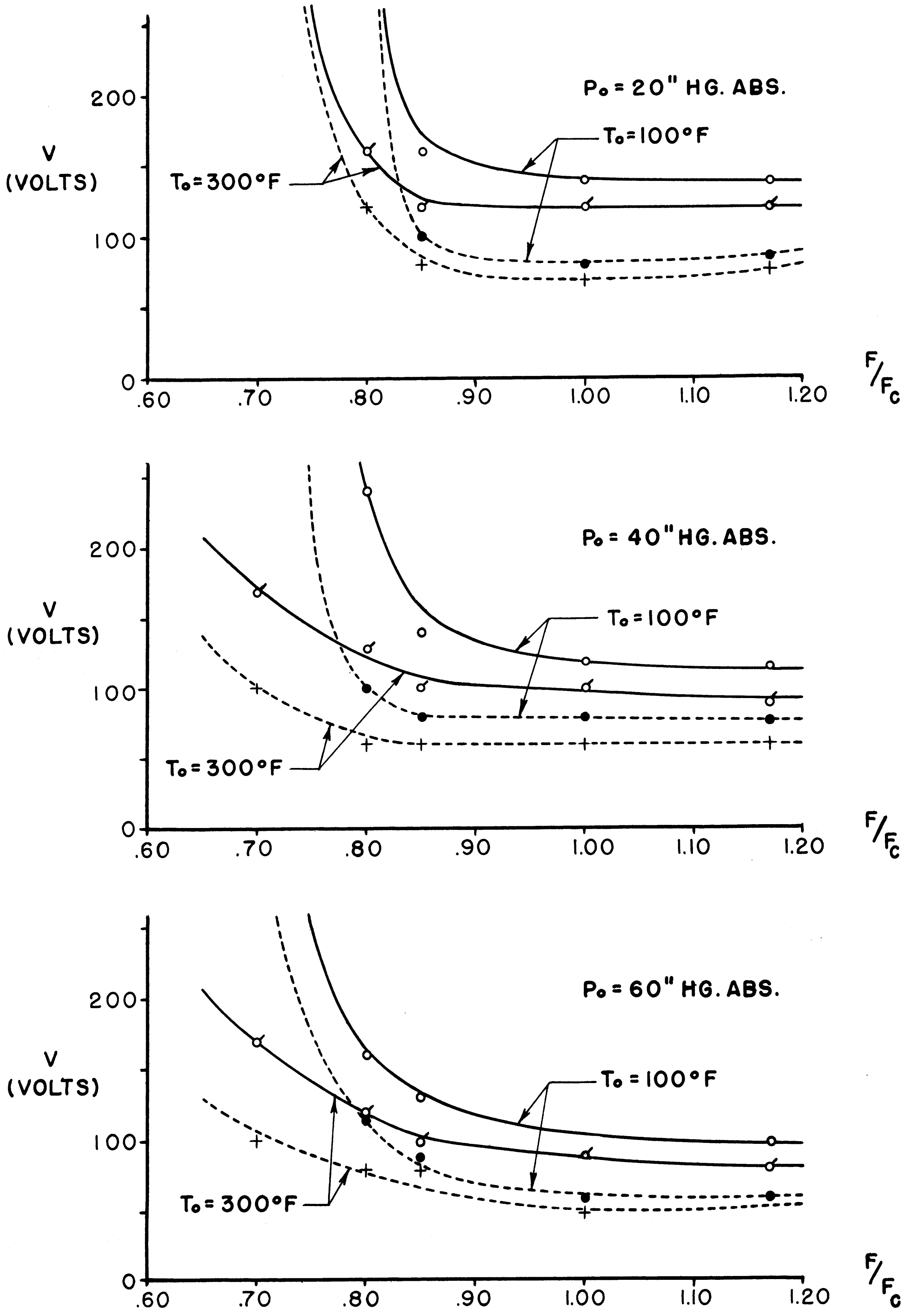


FIG. 9 - MINIMUM IGNITION VOLTAGE VS. FUEL-AIR RATIO
(DASHED LINE INDICATES PRESENCE OF RADIATION)

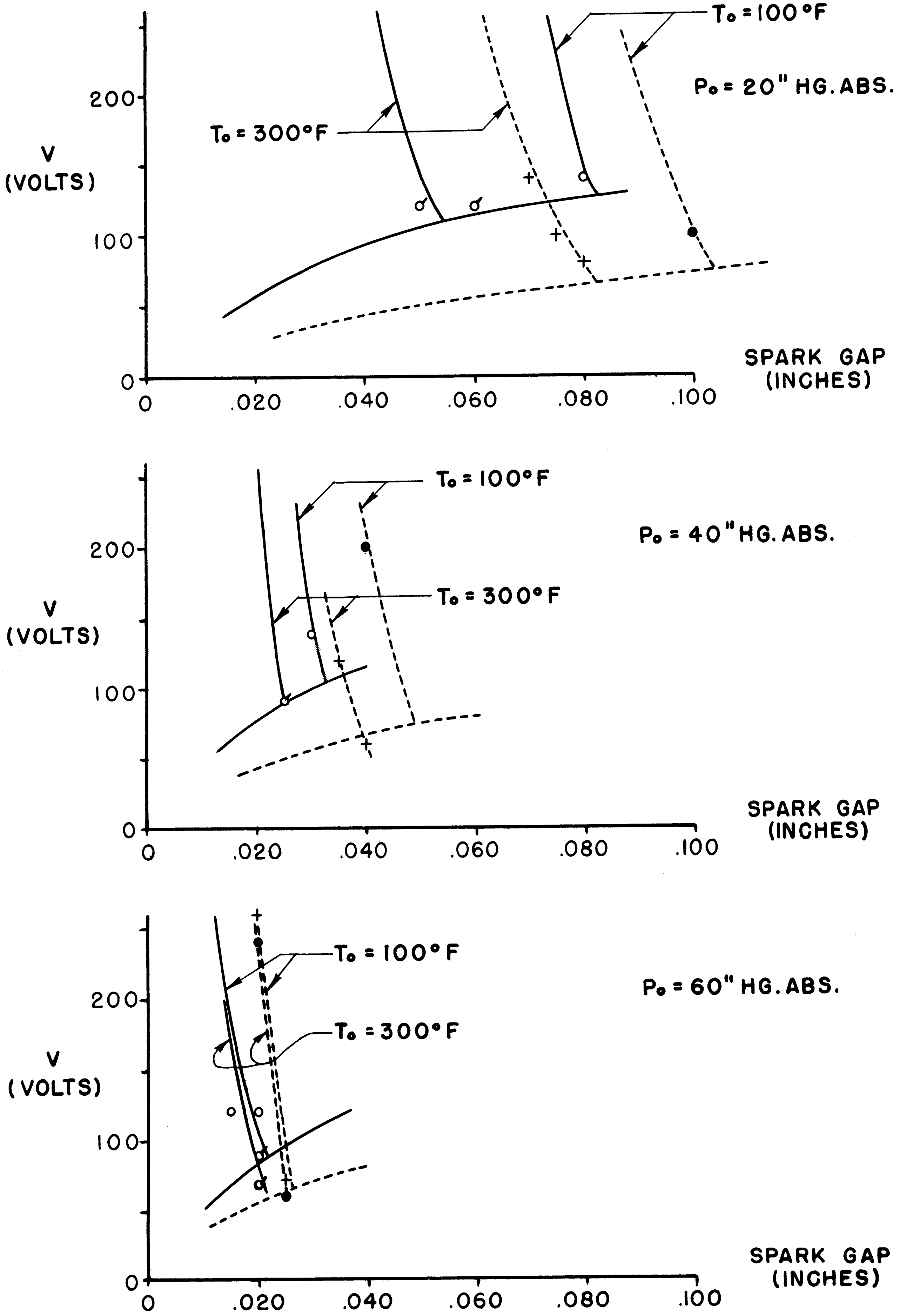


FIG. 10 – IGNITION VOLTAGE VS. SPARK GAP FOR MIXTURE $F/F_c = 1.17$

(DASHED LINE INDICATES PRESENCE OF RADIATION)

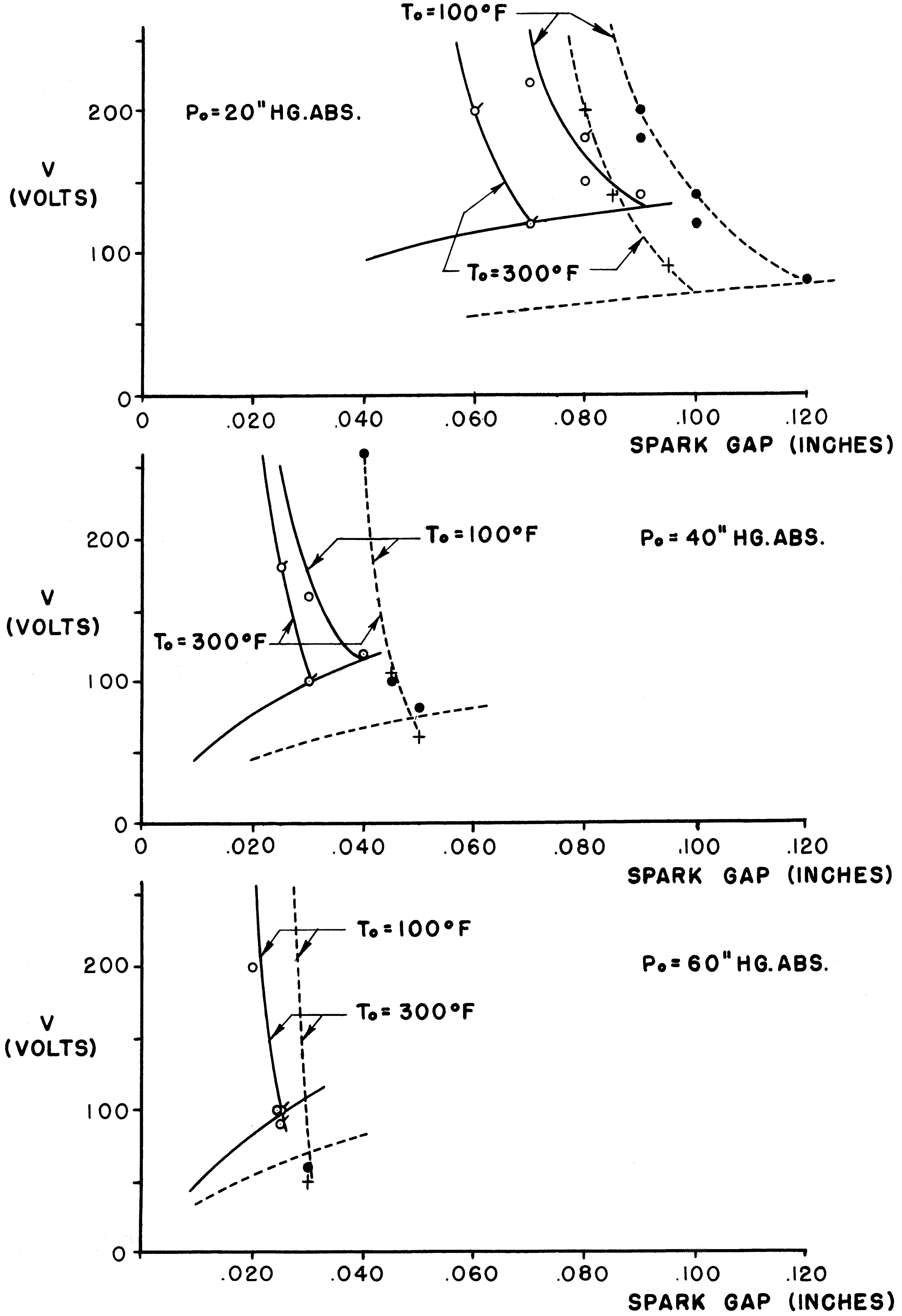


FIG. 11 – IGNITION VOLTAGE VS. SPARK GAP FOR MIXTURE $F/F_c = 1.0$

(DASHED LINE INDICATES PRESENCE OF RADIATION)

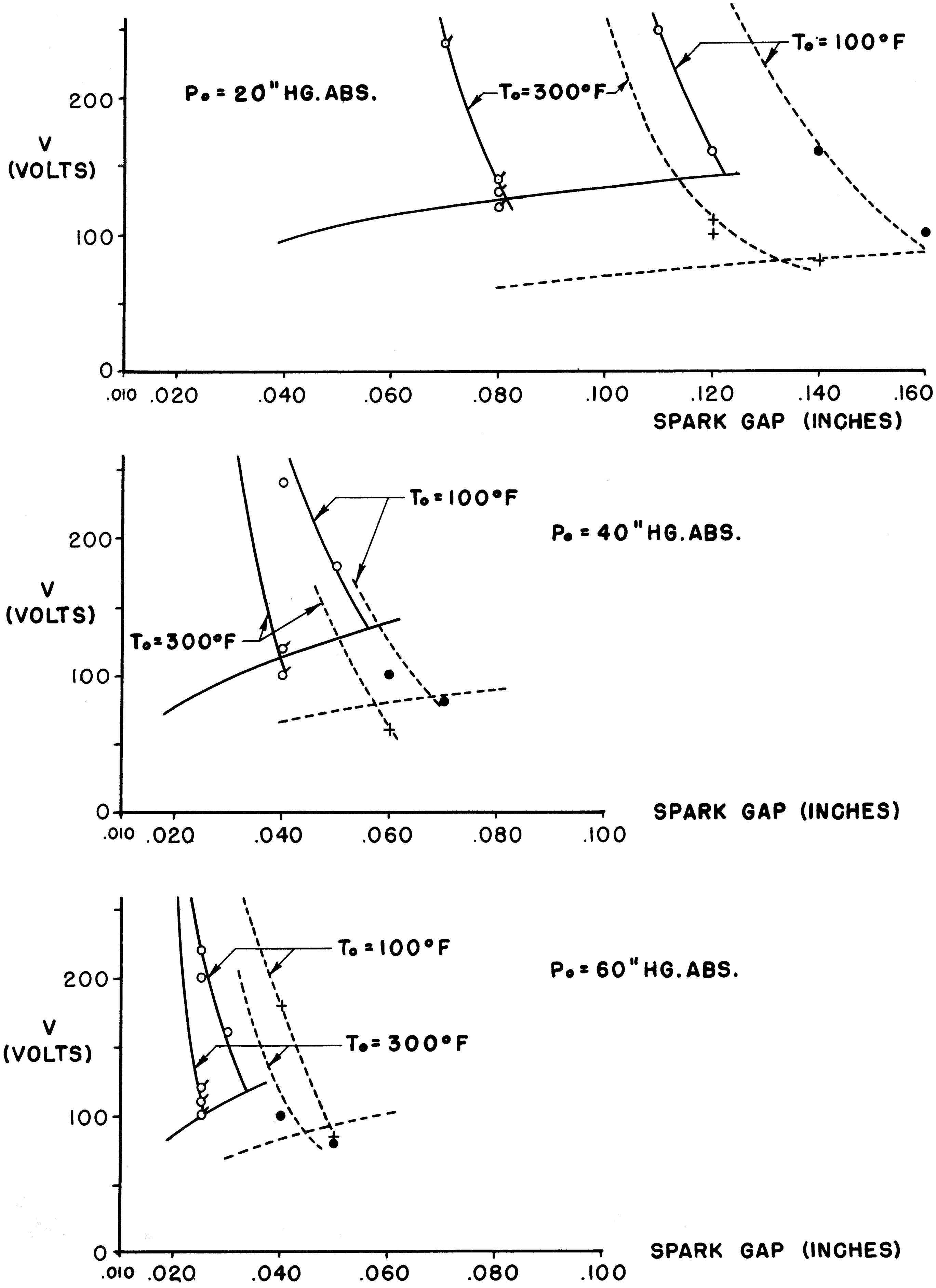


FIG. 12 - IGNITION VOLTAGE VS. SPARK GAP FOR MIXTURE $F/F_c = 0.85$
(DASHED LINE INDICATES PRESENCE OF RADIATION)

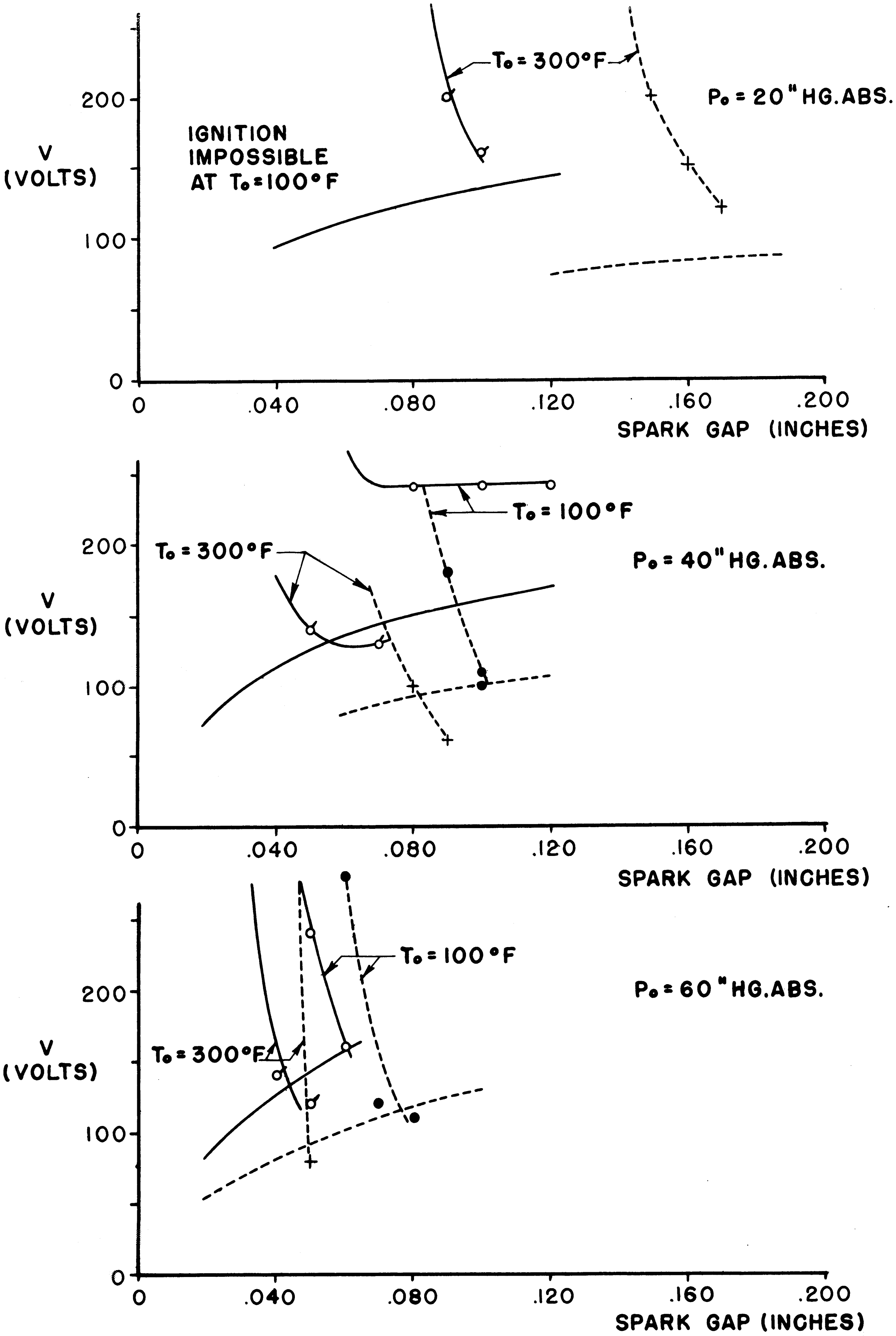


FIG. 13 – IGNITION VOLTAGE VS. SPARK GAP FOR MIXTURE $F/F_c = 0.80$
(DASHED LINE INDICATES PRESENCE OF RADIATION)

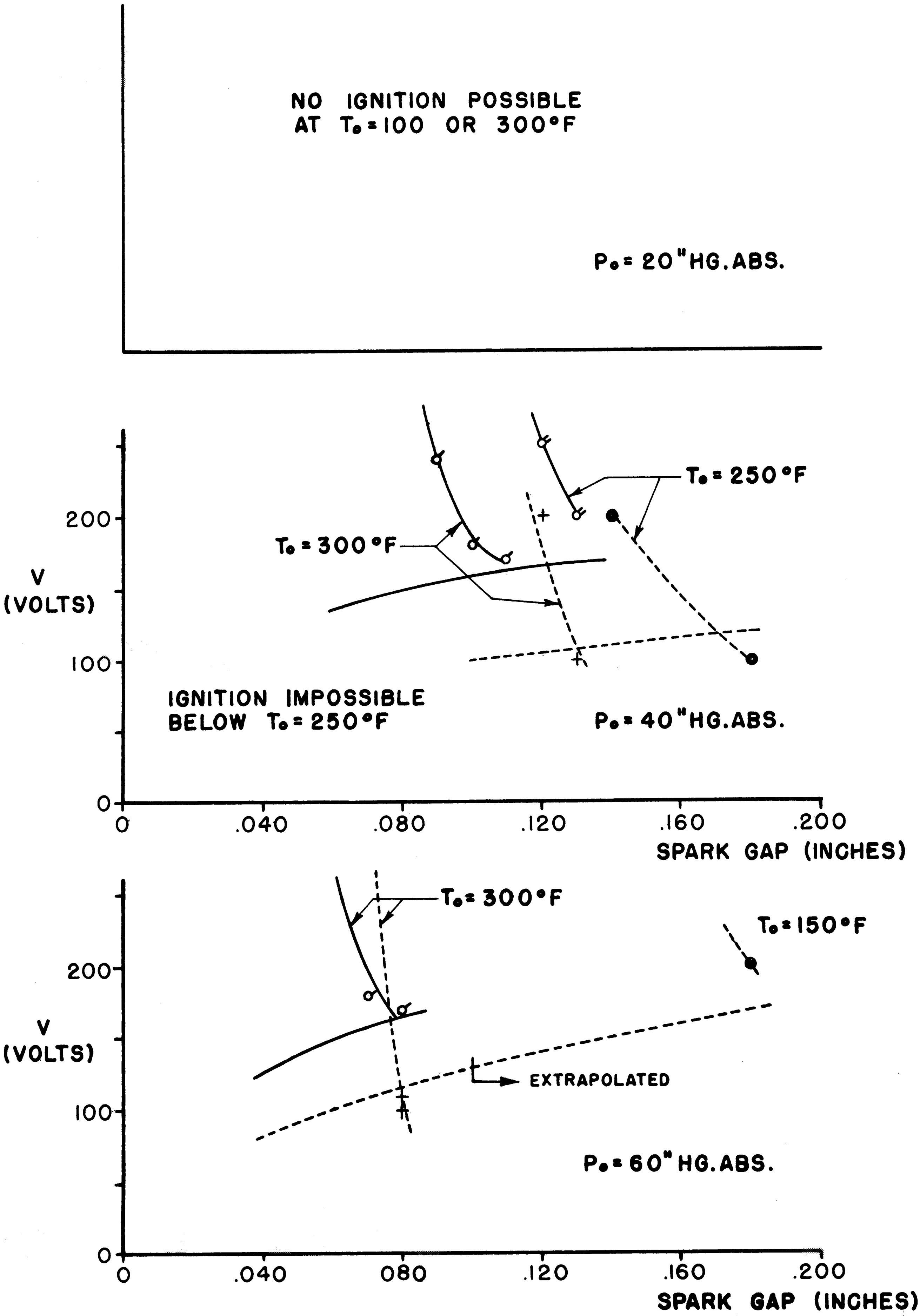


FIG. 14 – IGNITION VOLTAGE VS. SPARK GAP FOR MIXTURE $F/F_C = 0.70$
(DASHED LINE INDICATES PRESENCE OF RADIATION)

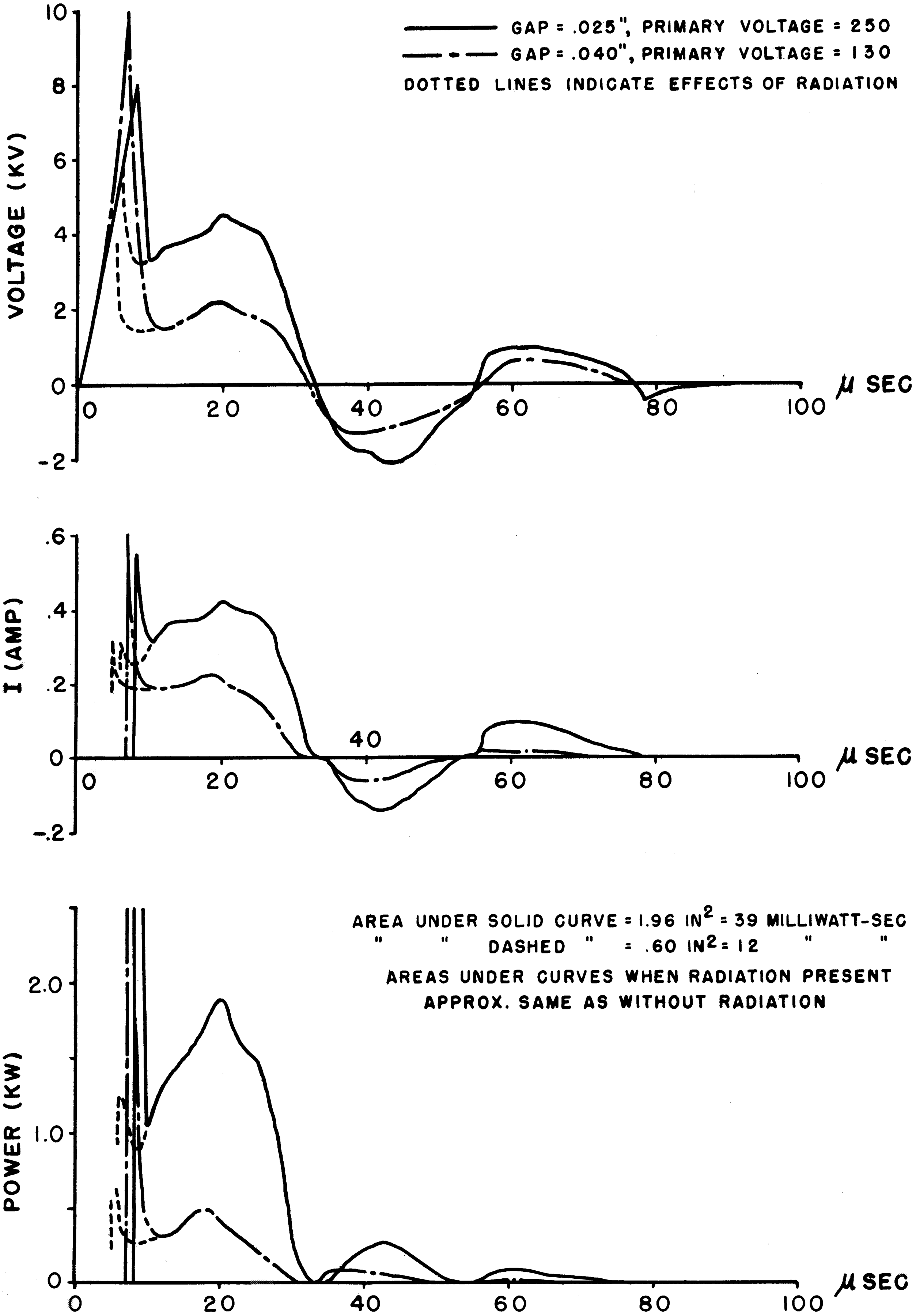


FIG. 15 – COMPARATIVE SPARK ENERGY DATA FOR IGNITION OF MIXTURE F = 1.0, P_0 = 40" HG., T_0 = 100°F

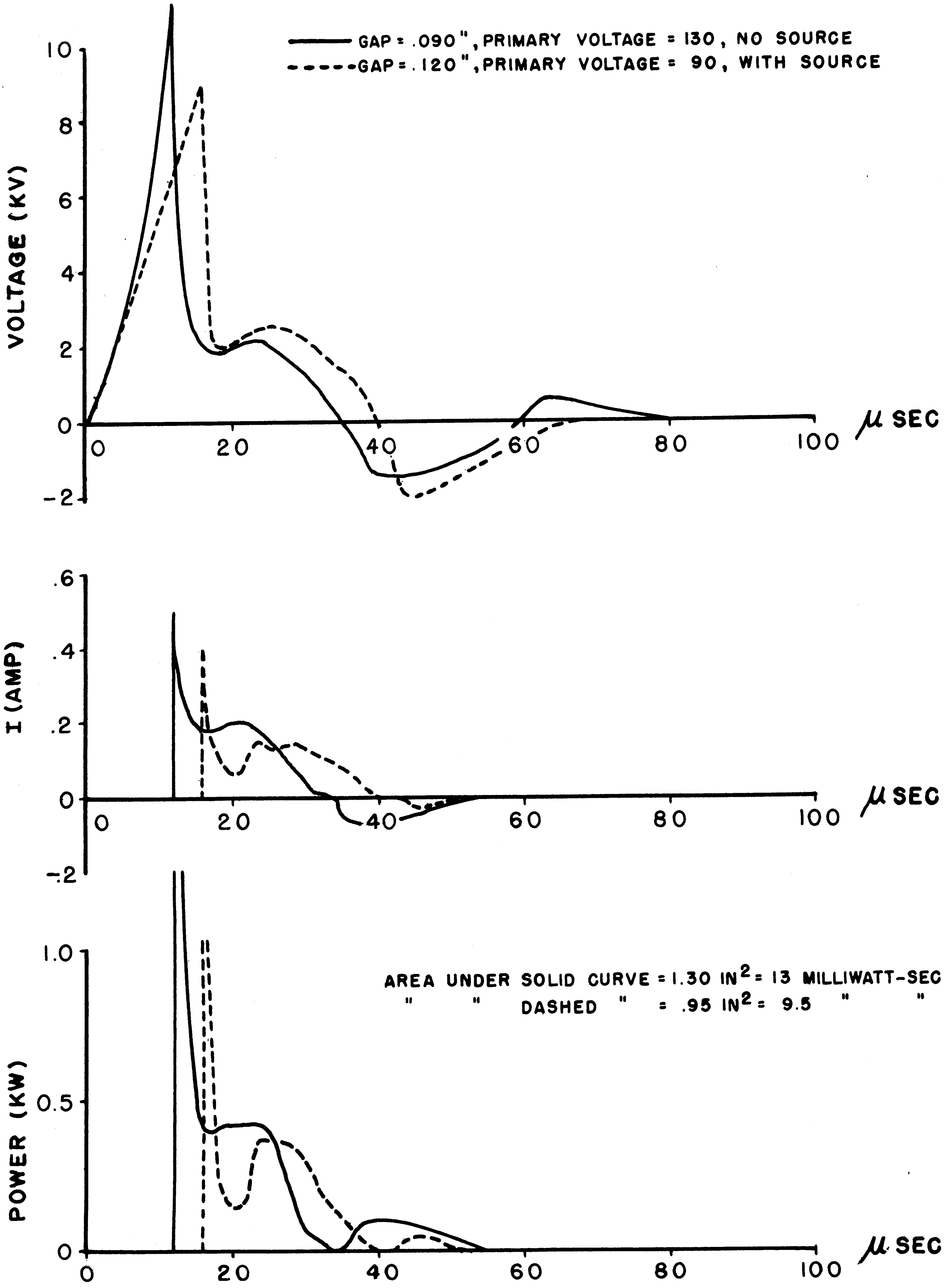


FIG. 16 – COMPARATIVE SPARK ENERGY DATA FOR MINIMUM VOLTAGE IGNITION OF MIXTURE F = 1.0, P_o = 20" HG., T_o = 100°F

EQUIPMENT SCHEDULE

1. National Bureau of Standards Spherical "Bomb"
2. Primary Voltage Supply; 0-500 volts DC
3. Transformer (Turn Ratio 120)
4. Tektronix Type 512 Cathode Ray Oscilloscope
5. Ellis Associates Model BA-2 Bridge and Amplifier
6. Control Engineering Company 0-500 psi Strain Gauge Pressure Pick-up No. 785
7. DuMont Type 297 Oscillograph-Record Camera
8. Hewlett-Packard Model 211A Square-Wave Generator
9. Leeds and Northrup Model 8662 Potentiometer
10. Cenco "Hypervac-4" Vacuum Pump
11. 2 Polonium-210 Sources (1 curie each)
12. 6 Gas Storage Tanks (5 cu ft each)
13. 0-150 psi Pressure Gauge
14. 50 in. Mercury Monometer
15. Stokes "McLeod" Vacuum Gauge
16. 0-500 psi Ashcroft Dead-Weight Tester
17. 1 Tank Propane (CP) Matheson Company
18. 2 Tanks Compressed Air (2,000 psi) Liquid Carbonic Company
19. Standard Electrical Products Company Variable Transformer (for heater control)
20. 4 Heating "Tapes" (10 watt)
21. "Celotex" box for Insulation of "Bomb" (during high temperature runs)

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