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ARC DRIVER OPERATION FOR EITHER EFFICIENT ENERGY TRANSFER OR HIGH–CURRENT GENERATION

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ABSTRACT FOR STAR

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An investigation is made to establish predictable electric arcs along triggered paths for research purposes, the intended application being the heating of the driver gas of a 1 MJ electrically driven shock tube. Trigger conductors consisting of wires, open tubes, and tubes pressurized with different gases were investigated either on the axis of the arc chamber or spiraled along the chamber walls. Design criteria are presented for successful arc initiation with reproducible voltage-current characteristics. Results are compared with other facilities and several application areas are discussed.

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ABSTRACT

The electric-arc, heated-helium driver is shown to be a versatile research device which can be adapted to a variety of experiments by changing the form of the trigger conductor which initiates the arc discharge. Experimental studies of the electrical behavior of the driver system for the trigger conductor positioned either on the axis or spiraled along the inner surface of the chamber walls are reported and discussed. The conductors consisted of solid wires, open tubes, and tubes pressurized with different gases. For zeta-pinch plasma experiments, a straight gas-filled conductor (hydrogen or deuterium) and a low arc-chamber pressure result in a fast-pulsed discharge in which large magnetic fields are generated by the intense current flows. For strong shock-wave generation, a spiraled conductor and a high chamber pressure substantially improve performance for shock-tube application and offer operational simplicity. Shock mach numbers as high as 46 have been achieved. The parameter, volts/cm, based on preset conditions, is found to correlate the electrical discharge characteristics from different arc-driver facilities over a large range of energy ratings and chamber sizes. In particular, it establishes the minimum voltage requirement for a given triggered arc path.

INTRODUCTION

In an electric-arc driver, helium (or other gas) under several atmospheres of pressure is heated at constant volume by an arc discharge between electrodes located at each end of a cylindrical arc chamber. The chamber walls are electrically insulated and, generally, a large capacitor bank is connected directly across the electrodes. A triggering mechanism which provides a conducting path between the electrodes is required to initiate the arc discharge. Historically, a fine wire has been used. At the proper time, the wire is vaporized (exploding-wire technique) and its path is transformed into the conducting medium for the resulting arc strike. Since the inception of arc-driven shock tubes, some ten years ago, virtually all drivers have used a trigger wire located generally along the axis of the chamber. Operating experience has shown that the shock-driving ability of the arc driver (with a straight trigger wire) was significantly below the predicted values, particularly at the energy density levels of current interest.

A recent trigger innovation,[1] that of spiraling the trigger wire along the inner surface of the chamber, offered significant improvement in driver performance. In particular, the efficiency of the transfer of energy from the capacitor bank to the driver gas was increased substantially and higher incident shock speeds were generated. Analysis of the arc current waveforms initiated by the straight and spiraled trigger arrangements indicated a systematic behavior in the arc process. Large peak currents were drawn by initiating the arc with a straight wire, whereas, with a coiled trigger wire the peak values were reduced. In this regard, the arc acted as a conductor whose resistance increased directly with its triggered length. Another apparent correlation was in the duration of the dwell or dark-pause period between the exploded wire and the start of the arc current flow. A qualitative interpretation of the dwell period had been made[2] based on the experimental data using only straight trigger wire results. While the dwell process cannot yet quantitatively be accounted for, it is generally agreed that the dwell phase (i.e., pre-breakdown growth) is ultimately related to the gasdynamic expansion of the cylindrical shock wave arising from the wire explosion.

A similar process occurs if a small tube (hypodermic type) is substituted for the wire.[3] A tube has the advantage that it can be evacuated or pressurized. Thus, any gas can be sealed within the trigger tube. If installed with the ends open, the gas is the same as that in the arc chamber. The utilization of a tube conductor in lieu of a wire was equally effective in initiating a satisfactory arc discharge. Further, a tube trigger increased the versatility of operation of the arc driver.

A series of experiments were made to explore the operation of straight and spiraled trigger arrangements in the same driver chamber under similar initial conditions. Both wires and tubes were used as trigger conductors, with the tubes open, evacuated or gas-filled. Results are presented that demonstrate the broad range of arc discharge characteristics available simply by the selection of a particular trigger arrangement. Trigger operation is discussed and parameters necessary for predictable and reproducable current-voltage values are indicated. In particular, the field intensity (V/cm) of conductor length is shown to have a minimum value for arc initiation. The experimental data for the dwell period of the arc discharge are compared with the results from several other facilities and the agreement is shown to be satisfactory. Driver arrangement for either high-current or strong shock generation is discussed.

ARC-DRIVER SYSTEM

At the Ames Research Center, an electric-arc driver system[4] is used to power either of two parallel facilities. One is a shock tunnel with a 10-cm diam by 12-m length driven tube, and the second is a 60-cm diam low-density shock tube having a length of 21 m. The energy for the driver is supplied by a 1250 μF capacitor storage system, rated at 1 megajoule when charged to 40 kV. The driver arc-chamber is 10-cm in diam and its length (electrode spacing) can be adjusted to 76, 137, or 290 cm. The chamber surface is electrically insulated by a fiberglass liner (6.3-mm wall thickness) whose inner surface is coated with a 1-mm layer of RTV silicon rubber. Trigger conductors (wires or tubes) were positioned either "straight" along the chamber axis, or "spiraled" along the inner surface of the liner as illustrated in Fig. 1. All conductors were attached to the electrode terminal at the downstream or ground end of the driver chamber. At the upstream or breech end, the conductor does not connect directly with the high-voltage electrode. This electrode is hollow and a pull rod is located within the breech. The conductor is attached to a non-conducting thread which passes through the electrode and is fastened to the rod. The space (occupied by the thread) acts as a switch to prevent the capacitor bank from discharging, since the bank is connected directly across the driver electrodes.

After the appropriate initial conditions have been set and the bank charged to its preset voltage, an air cylinder draws the rod with string and wire attached toward the high-voltage electrode. As the gap is reduced, the insulation (gas) breaks down and a pulse of electrical energy vaporizes the conductor in a short period of time (1 μsec or less). The subsequent arc discharge heats the helium driver gas and raises the pressure to a maximum of 1100-atm with the 76-cm driver. The high pressure gas bursts an X-scribed stainless steel diaphragm located just downstream of the ground electrode and a shock wave is propagated into the shock tube. The arc discharge process is completed before the diaphragm starts to open. The current and voltage waveforms during the arc-strike period are recorded routinely for each test in either facility together with measurements of the shock arrival at several stations along the driven tube.

Other trigger conductor arrangements that were tried included a thin nickel film, electro-deposited on the RTV surface, and multiple wires mounted concentric with the chamber axis. Film and multiple wire arrangements are not recommended, since their performance was inferior to that of straight or spiraled conductors.

TRIGGER CONDUCTOR OPERATION

For conventional shock tube usage, the arc drivers operate with gas load pressures in the chamber from several to about 40 atm of helium. In this range, the possibility of a spontaneous discharge is eliminated, since such a process would require electrical field intensities of the order of several hundred kV/cm. Present day facilities are operating at maximum field strengths of about 500 V/cm. Hence the necessity for a device to start the arc process. The way an exploding conductor leads to an arc discharge is still a subject of some controversy, but it is generally agreed that the conducting path between the electrodes has to reach a characteristic low pressure, of the order of one thousandth of the initial chamber pressure.[2, 5]

The general description of what happens in the wire-to-arc process is as follows. At the instant of closure of the circuit, a current pulse flows in the conductor causing it to explode and change from its metallic state to a non-conducting column of hot gases and aerosols at high pressure. The abrupt decrease in the electrical conductivity stops the capacitor discharge with no distinguishable change in the bank voltage, since less than 1% of the bank energy is dissipated in this step. As a result of the local increase in pressure, the expanding gaseous column from the lightning like explosion produces a cylindrical shock wave in the surrounding driver gas. With a tube conductor, it seems likely that an implosion and an explosion occur simultaneously. In either case, a gasdynamic expansion follows the compression wave, and the pressure and density decrease in a core region of central symmetry. When the gas pressure decreases to a critical (Paschen) value,[6] avalanche breakdown occurs, large currents are generated, and the energy on the capacitor bank is discharged. The time required for the central core region to reach the necessary low pressure for arc strike is generally designated as the dwell or dark-pause period. If the critical value of pressure is not reached, the arc will not occur and the capacitor bank will remain in a charged condition. In essence, the exploding conductor serves as a "pumping" mechanism which provides a low-density region conducive to voltage breakdown. Further support of this concept is provided by the results of present tests using tube conductors. By evacuating the tube, the dwell period was reduced relative to the open tube case. If the tube was pressurized well above the arc-chamber load pressure, the period was doubled or tripled.

Experiments [2,4] conducted with a wide variety of conductor materials have shown that, although all could be exploded within the arc chamber, only a particular class of metals would culminate in an arc discharge. Materials with a high-boiling point and high heat of vaporization (W, Nb, Cr, Ni, Fe, Ti) were all successful in drawing an arc in helium; their use as trigger conductors was recommended for arc driver operation. Tungsten, titanium, and 304 stainless steel conductors were used extensively in initiating arc discharges in various gases and gas mixtures including helium, argon, nitrogen, hydrogen, deuterium and He/Ar, He/D_2 mixtures. Altering the size of the conductor such that its mass varied from about 1 to 10% of that of the mass of the gas in the chamber did not significantly change the discharge characteristics; nor was the resistance of the solid conductor pertinent to the wire/arc process. Conductors with a high ($\sim 10^3 \Omega$) or a low ($\sim 1/2 \Omega$) resistance generated similar discharges. Wires less than 0.1 mm in diam were brittle and difficult to handle. Wires of 0.13 mm diam and larger were easily installed.

ELECTRICAL PERFORMANCE

Typical electrical performance for various straight and spiraled arrangments of the trigger conductor is shown in Fig. 2 for the same preset driver conditions of gas loading and bank voltage. The voltage and current waveforms of the arc discharges initiated by straight conductors, both wires and open tubes, exhibited generally similar results, see Figs. 2(a) and 2(b). The waveforms are characterized by short dwell periods and high peaks currents. The distinguishing traits for a spiraled conductor, compared to a straight conductor, are a longer dwell period and a smaller peak current Fig. 2(c). The duration of the discharge also is increased. Although the preset voltages across the electrodes in the arc chamber were equal, the ratio of preset voltage to the conductor length (i.e., field intensity) was always less for a spiraled installation. Increasing the field intensity decreases the dwell period as noted by comparison of Figs. 2(c) and 2(d). It will suffice here to note that with the same spiraled installation, the dwell periods for both wire and open tubes were found to be essentially equal.

The behavior of the gas-filled tubes shows some similarities to the open tubes, with some significant differences. Pressurizing a straight tube with a light molecular weight gas increased sizably the peak current value. Oddly enough, with a spiraled tube (open or gas filled), the current waveform was flattened or chopped, yielding a lower peak value compared to a wire (Figs. 2(c) and 2(d)). The physical explanation for this flattening is not readily apparent. While it was noted on all discharge records of spiraled tubes, the level and duration of the flattened region varied somewhat. It is not believed to be associated with an arc-over between adjacent coils. Whatever the explanation, the spiraled tube initiated discharge resulted in an easier electrical duty cycle, with less wear (e.g., erosion) on the liner surfaces.

The differences in the electrical characteristics between straight or spiraled trigger conductors did not appear to be affected by the arc-chamber pressure; however, in both cases the magnitude of the current peak was significantly decreased by increasing the initial load pressure. Also, the voltage reversal or overshoot decreased while the dwell period increased. These effects are shown by comparing the waveforms in Fig. 3 for a 7-coil spiraled wire arrangement initiating a 1MJ discharge. Overshoot, as indicated by the negative peak of the voltage record in Fig. 3(a), is generally detrimental to the life expectancy of the capacitor bank and should be avoided. The increase in the dwell time from the exploded wire (beginning of traces) to the start of the main discharge of energy from the capacitor bank indicates a slower pumping speed (slower cylindrical shock wave) as would be expected for a constant energy input driving a denser gas. The peak currents obtained with all the various trigger conductors decreased with increasing chamber load pressure as shown in Fig. 4. Although not apparent from the figure, circuit damping improved with the arc-chamber pressure. In fact, a spiraled conductor with a high chamber pressure exhibited the most favorable operation (low current, well overdamped). Waveform records illustrate intrinsic changes in the conductivity of the arc during the discharge period. Overall circuit performance is reflected by the voltage-current relationship, as shown in Fig. 5 for the 76-cm driver with two trigger arrangements. When the bank charge or preset was from 40 kV to about 21 kV with a straight wire trigger, all of the stored electrical energy was discharged in the arc chamber. In this range, the arc resistance as calculated on the basis of the average slope of the preset voltage curve was about 0.04 ohm/meter of arc length. At lower bank voltages, an appreciable portion of the stored energy remained on the bank after a discharge. Eventually, a minimum voltage (< 8 kV) was reached below which an arc would not occur.

For a spiraled trigger wire, the minimum bank voltage for an arc strike was higher (~26 kV) as typified by the 7-coil arrangement presented in Fig. 5. At higher voltages, the circuit performance was similar to that for a straight conductor. It was found that for the respective minimum bank voltages, the field intensities (based on total conductor length) were about equal. Test results indicated also that too long a conductor length would not induce an arc discharge. For example, the results given in Table I, for a preset voltage of 28 kV (Fig. 5), indicate the changes in current characteristics associated with conductor length.

Table I. 28 kV, 490 kJ helium discharge

Trigger Conductor		V/cm	I-Characteristics	
Type	Length, cm		Dwell, μsec	I_p, kA
Straight	76	368	33	473
4-coil	182	154	270	261
7-coil	244	115	430	184
9-coil	301	93	No arc	

Although the available bank energy was 490 kJ, the arc did not strike with the 9-coil conductor length. With an 8-coil assembly, the arc discharge was sporadic. These results indicate that for arc initiation in the driver chamber environment, the proper potential rather than energy was critical to the formation of the arc discharge.

DISCHARGE THRESHOLD

It has been noted previously,[1] that the minimum voltage required to draw an arc increased with the chamber length; however, the corresponding values of the field intensities were essentially the same. It was established by the results of the present study that a clearly defined correspondence existed between the gas pressure in the arc chamber and the initial field intensity necessary to induce an arc discharge along the path of the exploded conductor. Fig. 6 presents the discharge threshold based on a summary of various driver and trigger conductor arrangements. The open symbols represent successful discharges that lie close to the threshold; other data (not shown) extend to the upper limit of the test conditions at about 500 V/cm. The breakdown field intensity is of the order of 100 V/cm and increases slightly with increasing pressure. The discharge threshold is a useful design parameter which establishes the minimum (bank) voltage necessary across the driver electrodes.

DWELL PERIOD

The dwell period of the discharge cycle is one parameter that operating experience has shown to be remarkably repeatable and systematic. It decreases with increasing preset voltage and increases with increasing chamber pressure (Fig. 3). It has been shown recently [2] that for a given driver pressure and a straight trigger wire, the dwell period is a function of only the initial field intensity. If the field intensities of the spiraled wire arrangements are based on the total length of the conductor coiled between the electrodes, their dwell periods agree well with the straight wire results (open symbols in Fig. 7). This suggests then that the arc follows the original path of the spiraled conductor and the results obtained to date substantiate this premise. For example, examination of hundreds of peak current measurements indicates that the resistance of the discharge per unit length of conductor (coiled or straight) is relatively constant. In essence, the arc acts as a conductor whose resistance increases directly with its length. Optical observations of straight-wire explosions in different gases at pressures up to 50 atm show that the discharge occurs "precisely in the axis of the vapor cylinder".[7] Calculations using cylindrical blast-wave solutions indicate that the shock wave emanating from the explosion decays within a distance of 10-to 20-times the initial diameter of the conductor.[8,9] Hence, if the size of the agitated region does not change much, the conducting column will retain the shape of the initial configuration, particularly in the high-pressure environment of the driver chamber. Further corroboration is based on the fact that the dwell periods measured in eight other arc-driver facilities (Table II) show a close agreement with those presented in Fig. 7. In all cases, the driver gas was helium (at various pressures) but the size and type of trigger wire material differed widely. For this comparison, the dwell periods measured at their respective pressures were corrected to 18.5 atm using Fig. 3 of Ref. 2.

Table II. Arc Driven Facilities noted in Fig. 7

Ref.	kJ	μF	kV	L_4, cm	D_4, cm
Trigger conductor: Straight wire					
10	2,500	34,000	12	61	15
11	1,000	5,000	20	30	15
12	750	960	40	76	6.4
13	304	380	40	76	7.6
14	120	610	20	66	3.7
15	25	264	13	27	3.3
16	6.6	58	15	15	1.9
Trigger conductor: spiraled wire					
17	500	625	40	76	10

The duplication of the dwell period (i.e., prebreakdown growth) between facilities of widely different energy ratings and chamber sizes provides strong evidence that the mechanism of the arc formation is similar in all cases. It would be desirable to be able to correlate or to predict the arc current associated with a dwell period (and chamber environment). Unfortunately, the measurement of large kiloampere arc currents is not a simple task and the diversity of measuring techniques introduce uncertainties in the absolute values. It should be noted, however, that for a given measurement circuitry, the measurements are reproducible and the relative values are undoubtedly good. Until accurate current data are available, the dwell measurement offers a useful parameter by which the electrical circuit performance of one arc chamber can be applied to another with a high degree of confidence.

Mention must also be made of a most spectacular example of a long-triggered electrical breakdown, i.e., triggered natural lightning discharges.[18] One investigation[19] employed a shipboard rocket to fire a fine wire to altitudes of a few hundred meters toward a cloud. This represents a wire length of over 100 times those used in the arc drivers. Pertinent to this paper is the fact that the wire deployed in a loose helical form and that the lightning followed the spiraled path back to the ship (Fig. 8). Also, the current waveform indicated that the discharge was well-overdamped as might be expected for such a long arc (high resistance). No determination of the dwell period was possible with the particular instrumentation platform. Hopefully, the pretriggered behavior of the circuit parameters in lightning discharges can be obtained in future studies.

All the evidence indicates that an arc driver facility is able to operate over a wide range of parameters. This broad range of performance is made possibly by the choice of the trigger conductor and its arrangement within the arc chamber. Two examples will be discussed.*

INCIDENT SHOCK GENERATION

The conversion of the electrical energy into gas flow energy becomes of prime concern in shock tube performance, particularly for the generation of high shock speeds. Many experiments have shown that if the energy density of the discharge is below about 100 J/cm^3, the driver performance (in terms of shock speed) is of sufficient quality with a straight conductor that a spiraled installation is not warranted. However, as the energy level is increased, driver performance falls off markedly and it is for the higher energy densities that spiraled conductors are advantageous. The shock generating capability of the 76-cm driver into 1 torr of dry air in the 10-cm diam driven tube is used to illustrate this point. A shock Mach number of 34 was obtained with a straight trigger wire. With a 7-coil spiraled trigger wire, the shock Mach number was increased to about 45. In both instances, the electrical discharges were 1MJ and the driver records are those shown in Figs. 2(a) and 2(c), respectively. A high initial load pressure in the arc chamber contributed significantly to the driver performance. Since arc heating is a constant volume process, the pressure rise of the driver gas is determined by the energy density (J/cm^3), whereas the temperature change is a function of the specific energy (kJ/g of He).

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*Contouring of the arc chamber has recently[26,27] been shown to offer an additional effective technique for improving driver performance, particularly for the production of higher shock speeds. The potentiality of chamber geometry together with trigger selection will, hopefully, further extend the capability of the arc-discharge driver for wider scientific usage.

As the initial chamber load pressure is decreased, the specific energy increases as noted in Fig. 4. Both the straight (wire) trigger tests [20] and the spiraled conductor tests showed a modest improvement in shock speed with increasing initial pressure, all other driver conditions being constant. This is in opposition to the trend predicted by ideal shock-tube theory. Chamber pressure presented no difficulities to the arc initiation up to about 35 atm of helium, above which the arc strike became sporadic. With the aforementioned 7-coil spiraled conductor, raising the initial chamber pressure from 14 to 34 atm increased M_s from about 43 to 46.

The substantial increase in shock speed obtained with a spiraled conductor is indicative of a more uniform heating of the gas within the arc chamber. In fact, the ratio of the effective specific energy in the test gas (based on M_s) to that actually discharged into the chamber approached unity. One contributing factor to this high-energy transfer is the relatively low gas temperature ($T_4 < 9,000°$ K) corresponding to the low specific energy. With increasing specific energy (temperature), the energy transfer decreases; at about 54 kJ/g (the operating condition of Ref. 1), the transfer ratio is reduced by more than 20%. In a recent review [20] of (straight trigger) drivers, it was shown that with higher values of specific energy, performance is degraded rapidly (in terms of shock velocity). Spiraled conductors appear to follow the same trend. The gas temperatures generated with energy inputs of at least 100 kJ/g or greater are sufficiently high that helium real-gas relations are needed. As ionization becomes important (say 10,000° K and above), calculations indicate little increase in the speed of sound in the driver gas with greater energy input. Thus, even if radiation effects are neglected, the ionization depression of sonic velocity may limit performance. From an engineering standpoint, there appears to be a practical upper bound for efficient shock-tube performance (i.e., >70%). On this basis, a reasonable criterion for arc driver usage is to keep specific energy below 60 kJ/g of helium.

The shock driving capability of electric-arc drivers is summarized in Fig. 9 for a constant-area shock tube with helium as the driver gas and air as the driven gas. The shaded region shown in the figure represents the demonstrated performance for cylindrical arc-heated drivers with straight wire triggered discharges. Included in this region are data compiled through 3 years of tests with the 76-, 137-, and 290-cm drivers. The increase in shock Mach number obtained by means of the spiraled triggered discharges is indicated by the cross-hatched area given in Fig. 9. The highest shock speeds achieved thus far, as represented by the solid heavy line in the figure, were obtained using the 76-cm driver. As a point of interest, the best performance to be expected on the basis of the aforementioned specific energy limitation is also indicated in Fig. 9 (dash line). The driver calculated to generate this projected shock tube performance (with the 1MJ energy storage system) would require a chamber length of 50 cm, a 5-coil spiraled trigger wire (V/cm of 217), and an initial load pressure of 30-atm helium.

PLASMA GENERATION

In plasma studies, high peak currents are of interest as they relate directly to the arc temperature and the magnetic field strength.[21] The arc driver utilizing a straight tube conductor, offers the unique feature of generating a plasma with properties that may be varied simply by the choice of different gases used within the trigger tube.[3] At high energy density levels, the arc discharge persists for about 100 μsec, generated large currents, and raises gas pressures to the order of 10^3 atm. The number density is of the order of 10^{18} particles/cm^3. The repeatability of the discharge characteristics implies a high degree of arc stability. This combination of high current, high pressure, relatively long time, and arc stability has not been achieved, apparently, in any existing linear-pinch plasma device.[22,23] It appears that the arc driver is a unique and exciting tool for the study of plasma physics in experiments directed toward controlled thermonuclear fusion, astrophysics, and space propulsion. In the present state of knowledge of high-pressure arcs, it is not possible to assess the arc temperature from the data. However, one observation can be made regarding its lower limit value from Spitzer's formula for the conductivity of a totally ionized gas in the absence of magnetic fields. Based on the reasonable estimate that the current at its peak value passes through a channel 1 mm in diam, the temperature of the arc is deduced to be in excess of 10^5 °K (for a 40 kV, 1 MJ discharge). Also, calculations indicate a corresponding magnetic field of the order of 10^5 gauss near the edge of the arc, which undoubtedly serves to confine the arc. It has been shown[24] that the occurrence of pinch is indicated by abrupt fluctuations in the discharge current, accompanied by large excursions in voltage. An indication of what is considered to be a linear pinch is noted in the discharge record shown in Fig. 10 by the multiple fluctuations in the current and voltage traces just after the start of the arc discharge cycle. The current rise rates in this region are quite large, $>10^9$ amp/sec. This phenomenon has been observed repeatedly on oscillogram records for straight conductors in the present facility, with different gases in the arc chamber. The gases tested were helium, hydrogen, deuterium, and mixtures of deuterium and helium. It is not known whether the flattened portions of the current records for spiraled conductors, Fig. 2(d), represent the same form of constriction.

It is interesting to speculate on a driver concept utilizing the release of fusion energy to heat the driver gas.[25] Calculations indicate that for a tube type of trigger conductor of 1-mm diam, pressurized to about 20 atm with deuterium gas, the energy release would be of the order of 3 MJ for a 76-cm-long chamber. It is assumed that the arc discharge through a D_2 core achieves the necessary ignition temperature and that 10% of the D_2 undergoes fusion. Such an arrangement could provide a heating technique for large volume, high-pressure and high-enthalpy drivers for use with large scale simulation facilities. An attractive point of this scheme is that the capacitor energy storage system need not be of the multi megajoule size. Operation would require only a few hundred kilojoule storage capacity, perferably at a high potential. One difficulty in achieving a fusion environment is the presence of impurities in the form of metallic vapor from the trigger conductor. This may be avoided, or at least reduced, by using gas-filled tube conductors.

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FIGURE CAPTIONS

Fig. 1. Spiraled arrangement of trigger conductor in the arc chamber.

Fig. 2. Discharge cycle characteristics of the 76-cm arc driver with different trigger conductors; preset 1 MJ at 40 kV, load pressure of 30-atm helium, energy density = 150 J/cm^3.

Fig. 3. Discharge cycle characteristics of the 76-cm arc driver for various load pressures; preset 1 MJ at 40 kV, spiraled (7-coil) tungsten trigger wire of 0.18 mm diameter.

Fig. 4. Peak arc current regimes as a function of pressure; 76-cm arc driver, preset 1 MJ at 40 kV.

Fig. 5. Performance of energy storage and 76-cm arc-driver system; $C = 1250\ \mu F$, tungsten trigger wire of 0.18-mm diameter, load pressure of 18.5-atm helium.

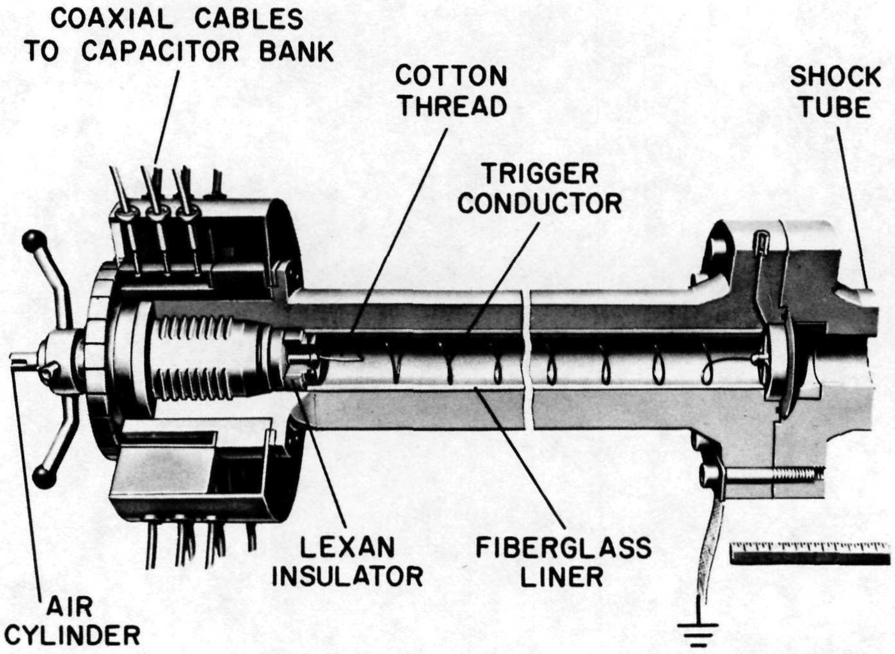
Fig. 6. Threshold of field intensity for an arc discharge along the core path of the exploded conductor.

Fig. 7. Dwell period variation with field intensity, chamber load pressure of 18.5-atm helium.

Fig. 8. Triggered natural lightning discharge (retouched). Photograph courtesy of Dr. J. D. Robb, Lightning and Transients Research Institute.

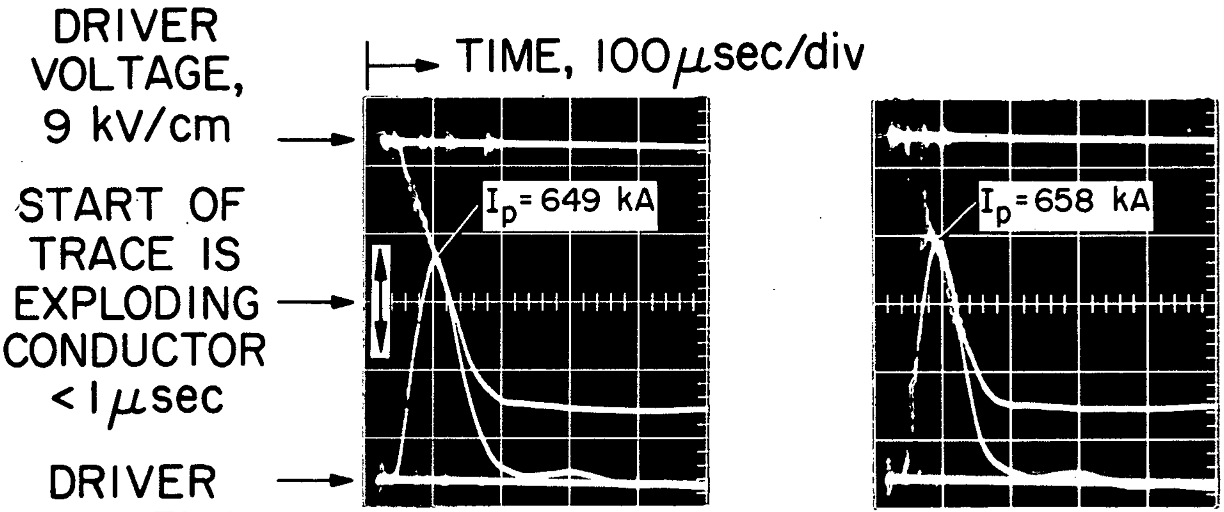
Fig. 9. Shock tube performance, arc-heated helium driver with dry air as the driven gas.

Fig. 10. Current and voltage fluctuations considered to be characteristic of pinch phenomena; 76-cm arc driver, straight titanium tube conductor (0.50 mm diam X 0.05 mm wall), preset voltage of 34.5 kV, load pressure of 6.8-atm deuterium.



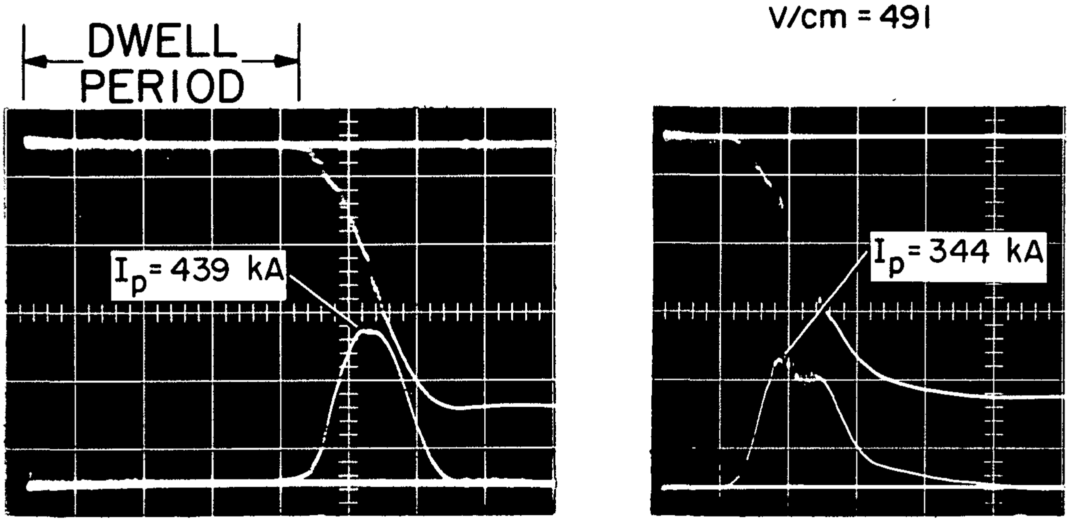
COAXIAL CABLES
TO CAPACITOR BANK
COTTON
THREAD
SHOCK
TUBE
TRIGGER
CONDUCTOR
LEXAN
INSULATOR
FIBERGLASS
LINER
AIR
CYLINDER

Figure 1.



(a) STRAIGHT TUNGSTEN WIRE,
0.13 mm dia
V/cm = 491

(b) STRAIGHT TITANIUM TUBE (OPEN),
0.65 mm dia
× 0.065 mm WALL
V/cm = 491



(c) SPIRALED TUNGSTEN WIRE,
0.18 mm dia
7 COILS × 274 cm LENGTH
V/cm = 141

(d) SPIRALED TITANIUM TUBE (OPEN),
4 COILS × 183 cm LENGTH
V/cm = 212

Figure 2.

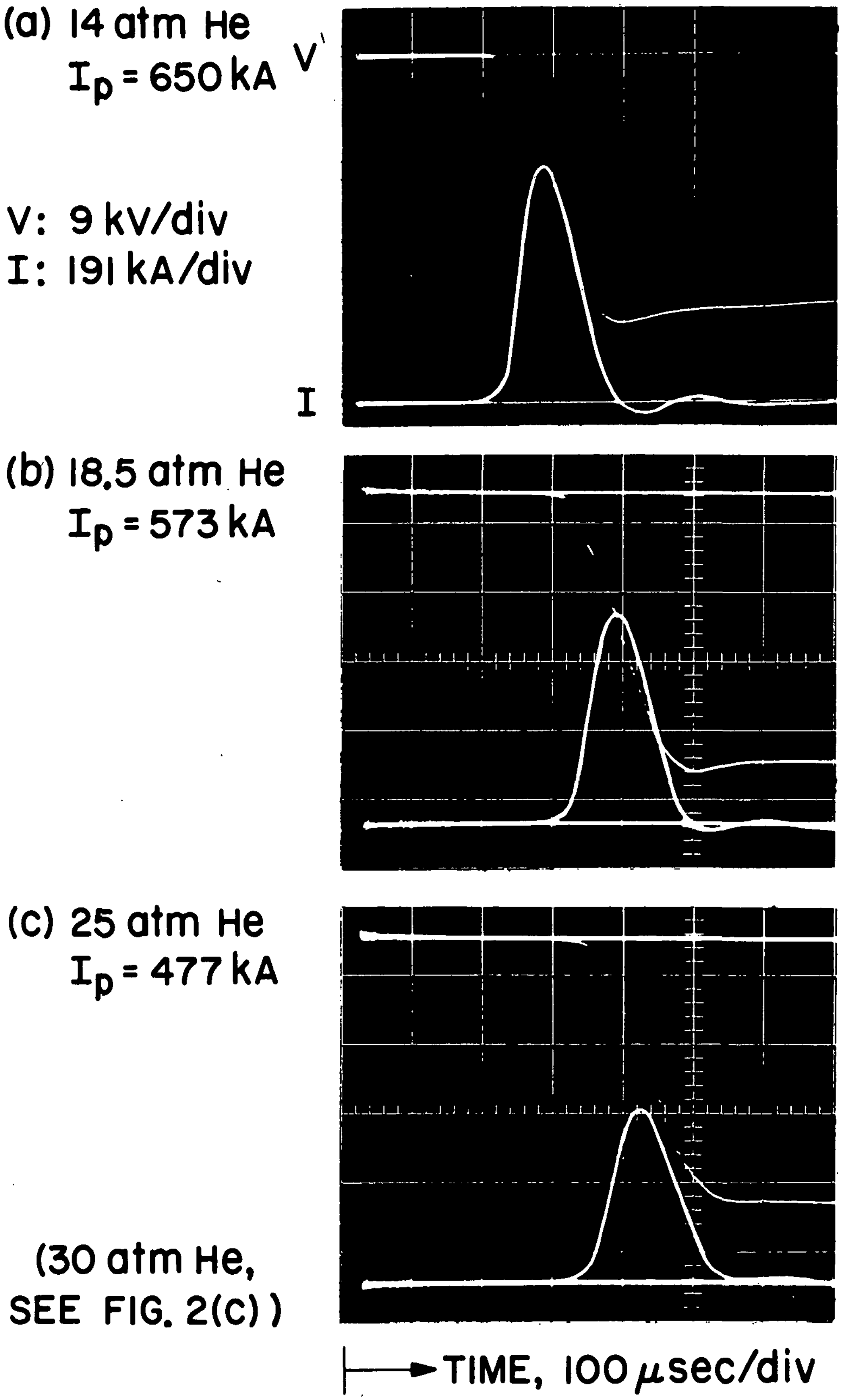

(a) 14 atm He
I_p = 650 kA
V: 9 kV/div
I: 191 kA/div
V
I
(b) 18.5 atm He
I_p = 573 kA
(c) 25 atm He
I_p = 477 kA
(30 atm He, SEE FIG. 2(C))
TIME, 100 μsec/div

Figure 3

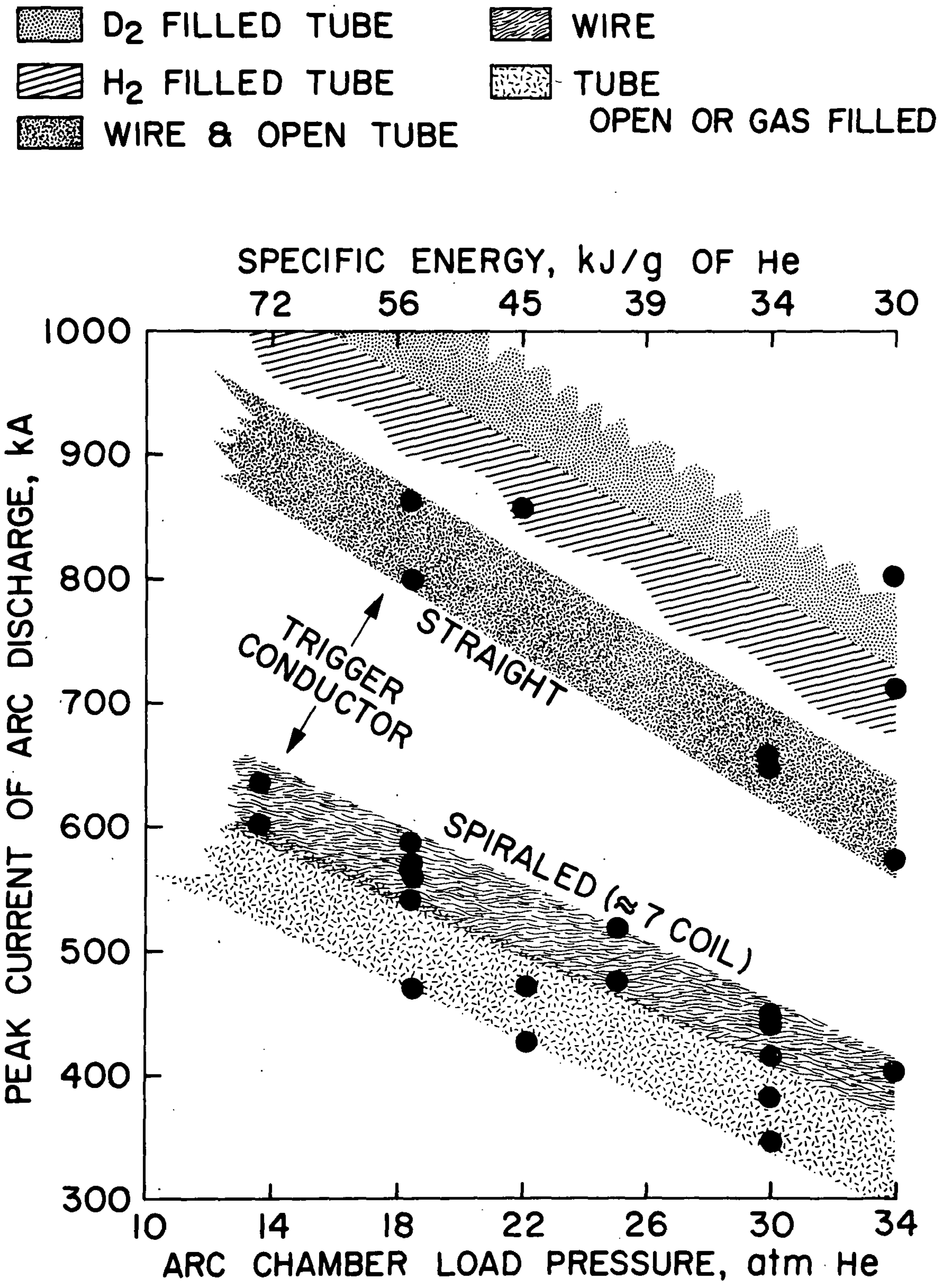

D2 FILLED TUBE
H2 FILLED TUBE
WIRE & OPEN TUBE
WIRE
TUBE
OPEN OR GAS FILLED
SPECIFIC ENERGY, kJ/g OF He
72
56
45
39
34
30
PEAK CURRENT OF ARC DISCHARGE, kA
1000
900
800
700
600
500
400
300
TRIGGER CONDUCTOR
STRAIGHT
SPIRALED (≈7 COIL)
10
14
18
22
26
30
34
ARC CHAMBER LOAD PRESSURE, atm He

Figure 4

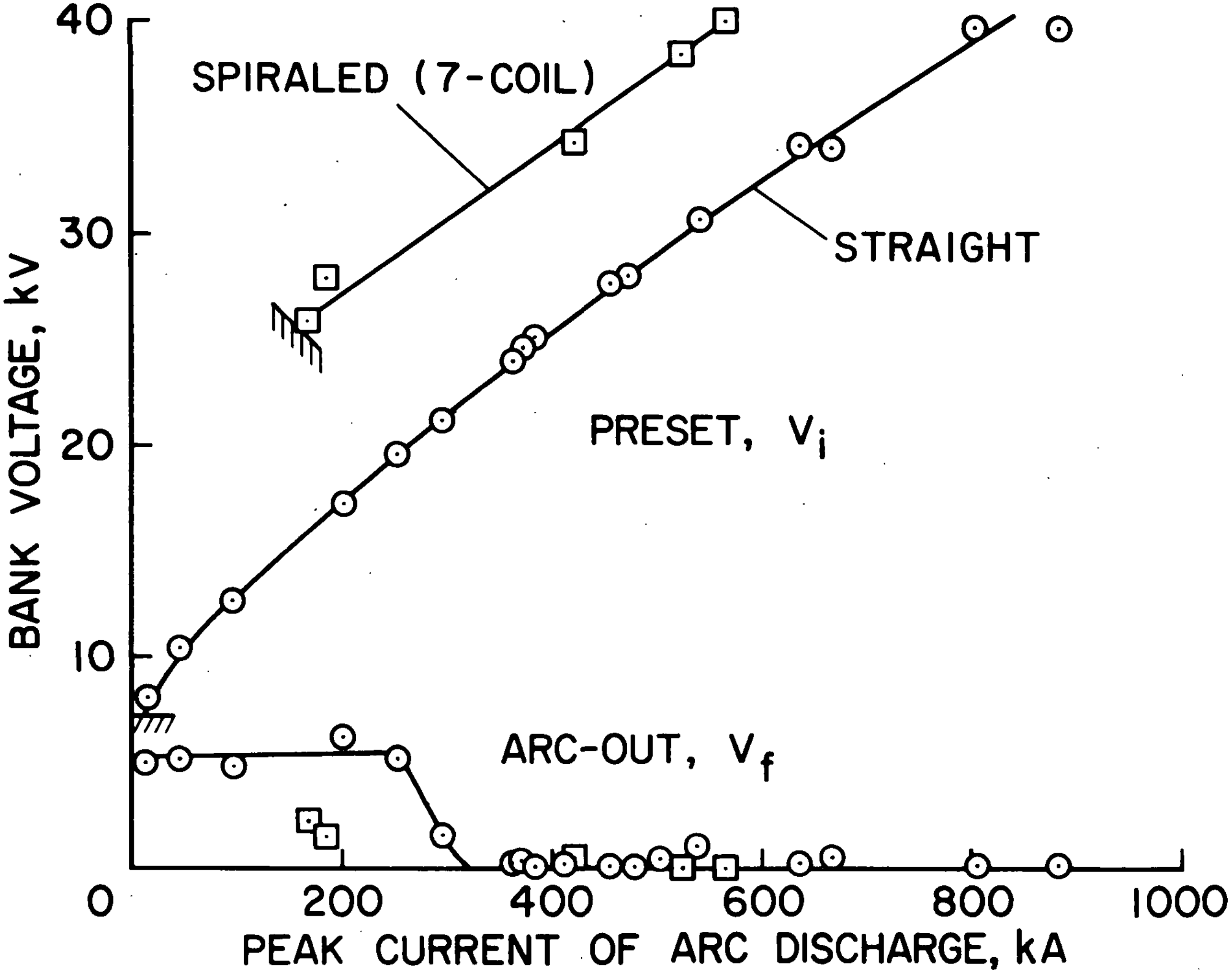

40
30
20
10
0
200
400
600
800
1000
BANK VOLTAGE, kV
PEAK CURRENT OF ARC DISCHARGE, kA
SPIRALED (7-COIL)
STRAIGHT
PRESET, V_i
ARC-OUT, V_f

Figure 5

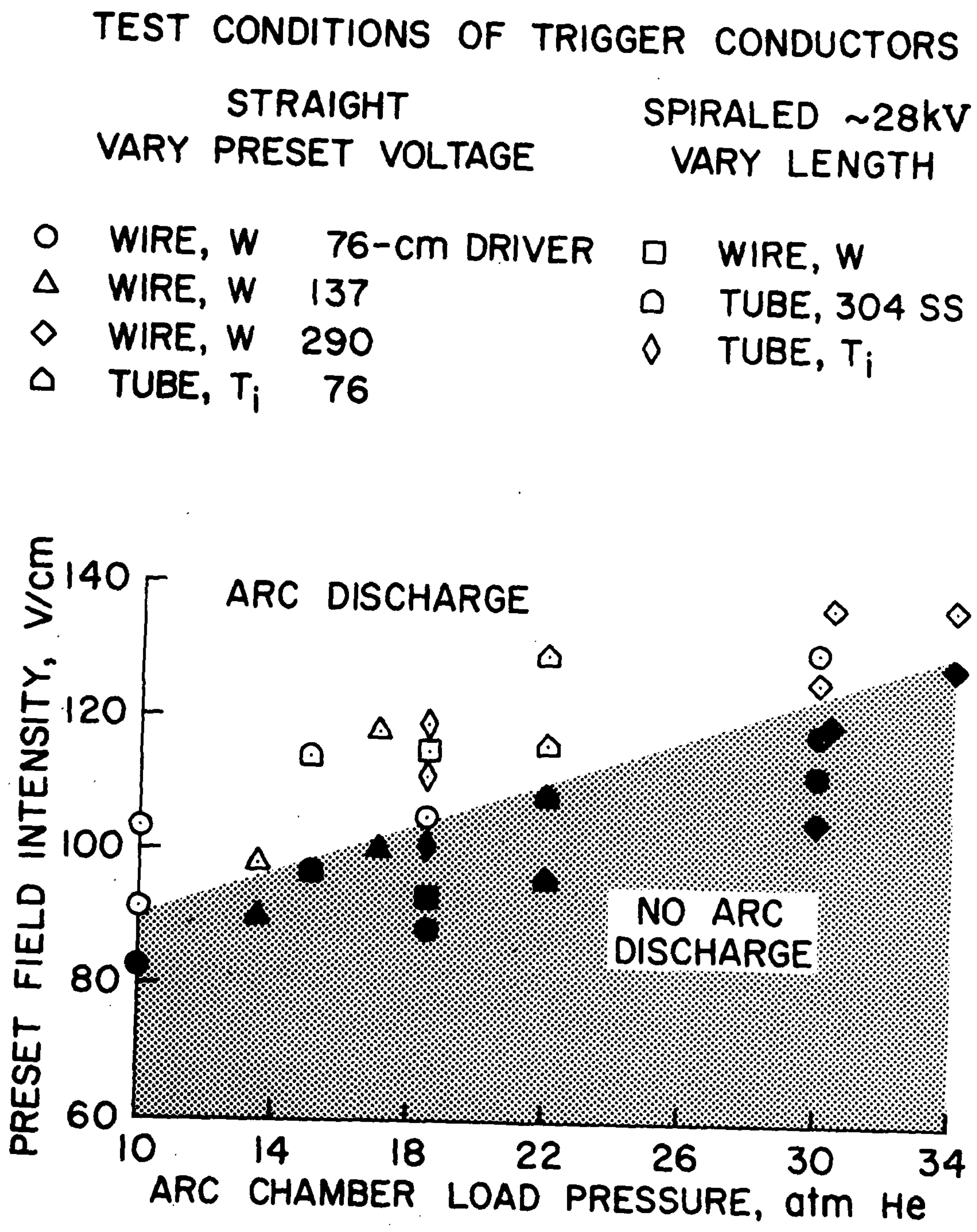

TEST CONDITIONS OF TRIGGER CONDUCTORS
STRAIGHT
VARY PRESET VOLTAGE
SPIRALED ~28kV
VARY LENGTH
○ WIRE, W 76-cm DRIVER
△ WIRE, W 137
◇ WIRE, W 290
⌂ TUBE, Ti 76
□ WIRE, W
⌂ TUBE, 304 SS
◇ TUBE, Ti
ARC DISCHARGE
NO ARC DISCHARGE
PRESET FIELD INTENSITY, V/cm
140
120
100
80
60
10
14
18
22
26
30
34
ARC CHAMBER LOAD PRESSURE, atm He

Figure 6

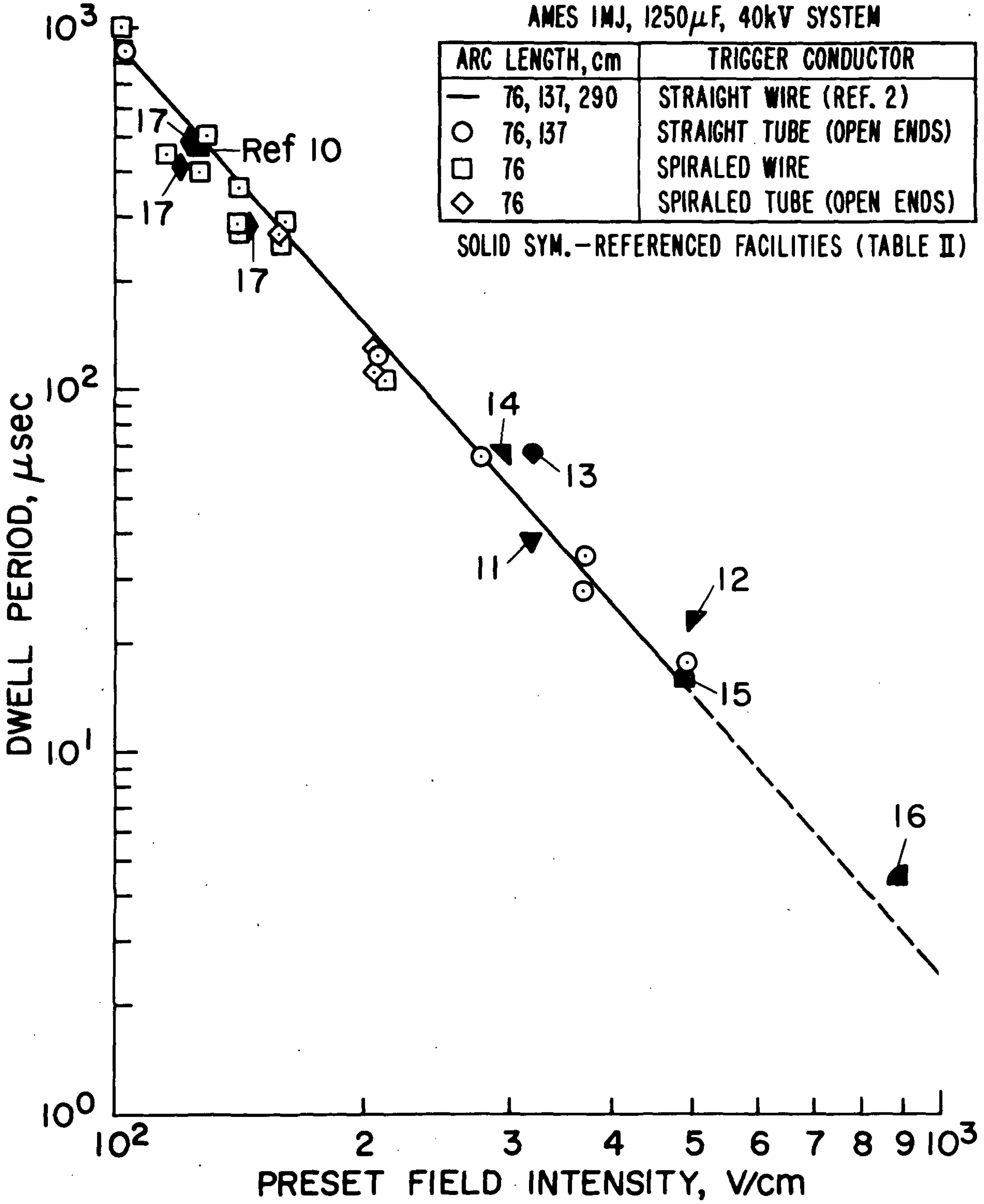

AMES 1MJ, 1250μF, 40kV SYSTEM
ARC LENGTH, cm | TRIGGER CONDUCTOR
— 76, 137, 290 | STRAIGHT WIRE (REF. 2)
○ 76, 137 | STRAIGHT TUBE (OPEN ENDS)
□ 76 | SPIRALED WIRE
◇ 76 | SPIRALED TUBE (OPEN ENDS)
SOLID SYM.-REFERENCED FACILITIES (TABLE II)
DWELL PERIOD, μsec
PRESET FIELD INTENSITY, V/cm
10^3
10^2
10^1
10^0
10^2
2
3
4
5
6
7
8
9
10^3
17
Ref 10
17
17
14
13
11
12
15
16

Figure 7

Figure 8

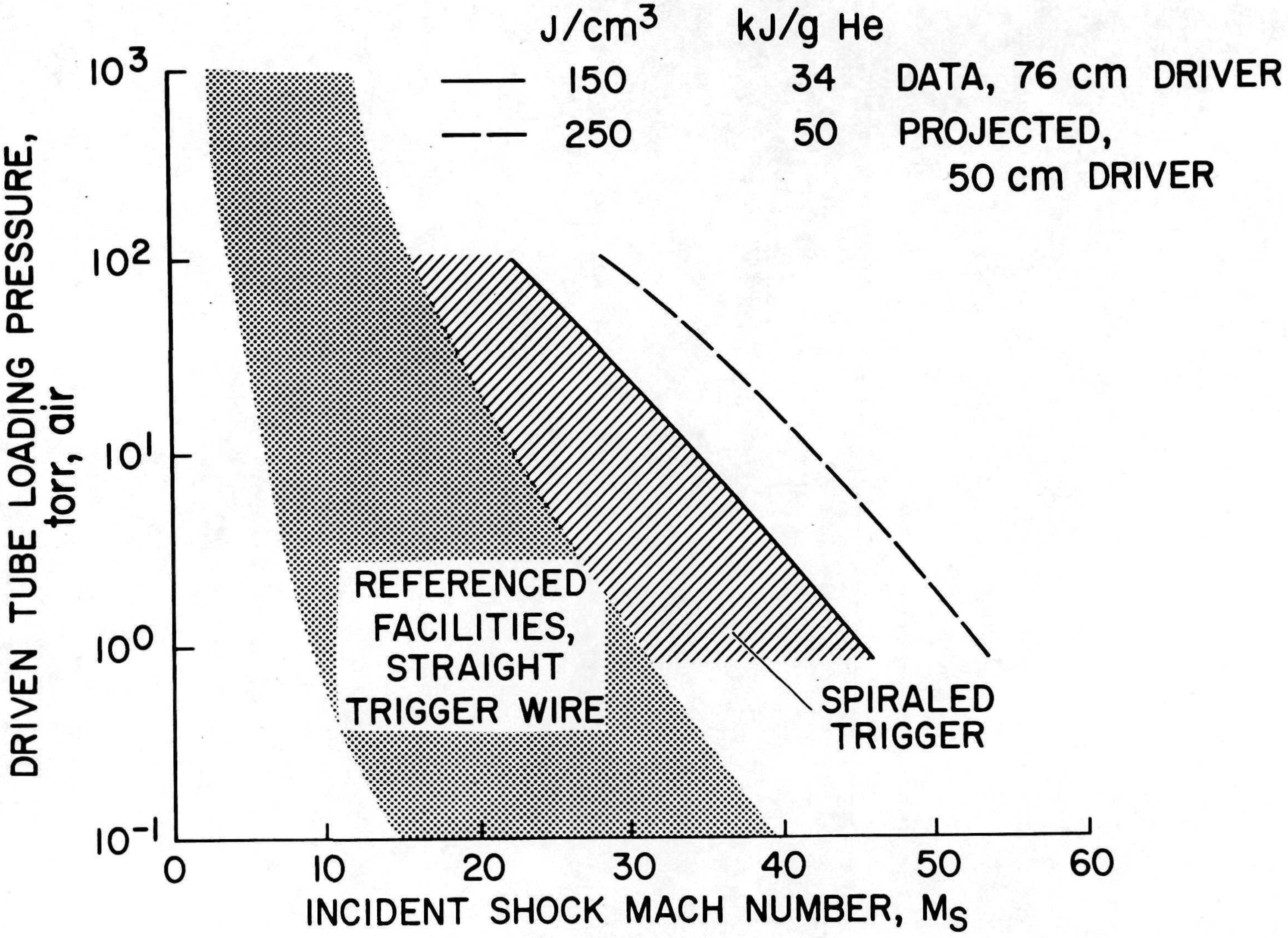

J/cm³
kJ/g He
150
34
DATA, 76 cm DRIVER
250
50
PROJECTED, 50 cm DRIVER
10³
10²
10¹
10⁰
10⁻¹
DRIVEN TUBE LOADING PRESSURE, torr, air
REFERENCED FACILITIES, STRAIGHT TRIGGER WIRE
SPIRALED TRIGGER
0
10
20
30
40
50
60
INCIDENT SHOCK MACH NUMBER, M_S

Figure 9

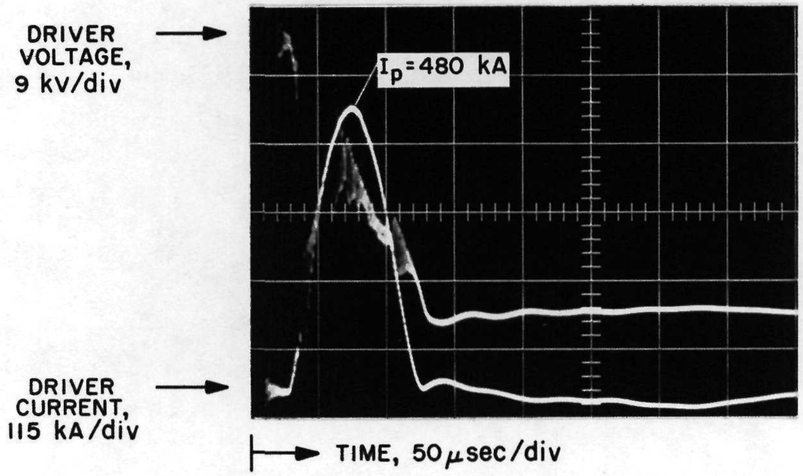

DRIVER VOLTAGE, 9 kV/div
I_p = 480 kA
DRIVER CURRENT, 115 kA/div
TIME, 50 μsec/div

Figure 10.