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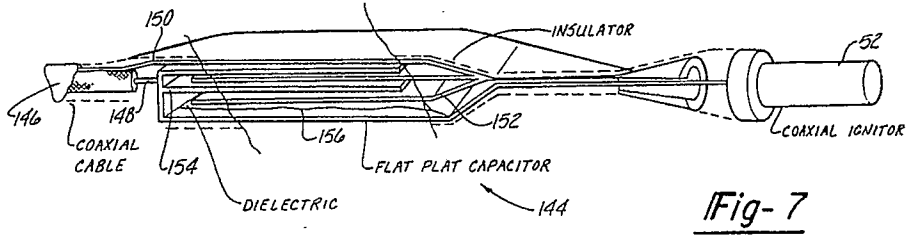
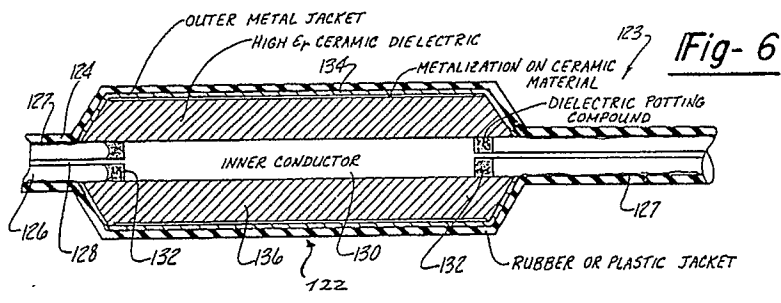
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Pulse forming device for internal combustion engines.

A pulse forming device for the generation of alternating current pulses which are to be supplied to a gap of an ignitor in an internal combustion engine, comprising an electrical circuit including a capacitor (158) for storing a quantity of electrical energy, and a pair of electrical conductors (160, 164) for electrically connecting said capacitor (158) with said ignitor. The capacitor (122, 158, 144) is inserted and/or distributed along at least a portion of an electrical distribution cable (123, 146, 180).



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PULSE FORMING DEVICE FOR INTERNAL COMBUSTION ENGINES

This invention relates to an apparatus for initiating combustion of fuel-air mixtures in an internal combustion engine, comprising an electrical circuit including a capacitor for storing a quantity of electrical energy, a discharge device having a pair of spaced electrodes, forming a gap across which an electrical discharge channel of alternating electrical current may be established for initiating said combustion using
5 electrical energy stored in said capacitor, and means for electrically connecting said capacitor with said discharge device, for forming the discharge channel.

An apparatus of this kind is known from US-A-4,333,125. Furthermore, it is referred to Combustion and Flame 27, published 1976, R. Knystautas and J.H. Lee, On the Effective Energy for Direct Initiation of Gaseous Detonations, pages 221-228. The known apparatus includes a capacitive portion for storing a large
10 quantity of electrical energy therein derived from a power supply, and an electrode portion integral with the capacitive portion which comprises a pair of concentric, rod shaped electrodes for producing a high energy, umbrella shaped plasma discharge, using the inverse pinch technique. Due to the close proximity between the capacitive and electrode portions of the initiating device, rapid energy transfer from the former to the latter creates high magnetic pressures which transform the discharge into a high energy plasma jet which is
15 delivered well into the combustion area.

According to this principle, despite the fact that the ignition can be enhanced, the power coupling efficiency from a relatively high impedance ignition source circuit to the very low impedance of an established discharge channel is quite low, resulting in a greater fraction of the available energy being lost through power dissipation in circuit resistance other than the discharge channel itself. Somewhat greater
20 power dissipation in the discharge channel can be achieved by increasing the magnitude of current flow. However, for a given discharge duration, this may be accomplished only at the expense of greater energy input requirements and severe electrode wear.

Accordingly, it is the problem to be solved by this invention to create a pulse forming device for initiating combustion of fuel-air mixtures, which generates a very rapid intense high power electric
25 breakdown.

The invention solves this problem by an apparatus having the features of the main claim. Further developments of this apparatus are described in the subclaims.

According to the present invention, a system for initiating the combustion of fuel employs a hard-discharge-ignition (HDI) process which is generated by a very rapid, intense, high-power electrical
30 breakdown which we shall refer to as a "hard" spark discharge. HDI initiation of combustion employs highly effective energy coupling mechanisms which reach high levels of intensity. The term "hard-discharge" as used herein refers to the regime of operation in which the discharge circuit inductance and resistance are sufficiently low that the rate of current flow and rate of energy deposition in the discharge channel during the breakdown phase are largely governed by the resistance of the spark channel itself.

This extreme regime of operation is characterized by highly efficient coupling (80-95%) of the initially stored electrical circuit energy, during approximately the first half-period of the discharge current cycle, into the various transient processes associated with gaseous discharge formation and expansion. As a result, hard-discharge operation delivers most of the available pulse energy within the breakdown phase of the discharge (usually within the first few tens of nanoseconds of the discharge), thereby achieving maximum
40 power coupling from the driving circuit to the rapidly dropping effective load impedance of the discharge channel. Using typical discharge circuit energy levels of between 0.05 to 2 joules, and with rates of rise of breakdown current flow on the order of 10^{10} to 10^{12} amperes per second, the resulting power deposition can approach an order of 10's of megawatts within the time span of a few 10's of nanoseconds. Discharges of this type give rise to intense light emission and strong hydrodynamic blast wave effects in addition to the
45 usual high-temperature thermal plasma volume formation. As used herein light is a general term which includes ultraviolet and infrared as well as the visible spectrum of electromagnetic radiation.

The "vacuum" or "hard" ultraviolet portion of the photon flux (with wave lengths equal to or less than 2000 angstroms) and the hydrodynamic blast wave are, in fact, major energy redistribution and transfer mechanisms which play a primary role in the initial expansion of the breakdown channel. Qualitatively, HDI
50 generates a hard-spark-discharge that gives rise to a rapidly expanding plasma channel in which the generation of a strong, hydrodynamic blast wave is coupled with an intense burst of high-ultraviolet-content light. The shockfront of the blast wave is initially driven, and hence followed by, a high density shell or "piston" of hot plasma which forms the leading ionization front of the expanding discharge channel. At some point during the discharge, usually near the crest of the peak discharge current flow when the plasma channel expansion slows significantly, the shockfront detaches from the driving plasma piston and moves

on out at supersonic speed into the surrounding gas.

Energy transferred to the combustible mixture by means of shock-induced excitation and radiation absorption causes mixture sensitization, formation of reaction-promoting species, regions of increased temperature and pressure, pre-flame reactions, and micro turbulence. This is further complemented by the subsequent expanding, high temperature plasma volume with its thermal gradient and high-energy ionic species content. This combined, high intensity presence of these multiple energy transfer processes may give rise to synergistic phenomena such as SWACER (shock-wave-amplification-by-coherent-energy-release), which is believed to be an important mechanism in the transition of deflagration (burn) combustion to supersonic detonation combustion. Under the relatively high pressure (5 to 12 atmospheres), high temperature (500 to 800 °K) initial conditions existing in an engine combustion chamber during the latter stages of the compression stroke, this ensemble of HDI energy coupling mechanisms gives rise to a rapid overall combustion event which may consist of a combination of high-velocity turbulent deflagration and supersonic detonation combustion processes. The HDI process is very robust in nature and is capable of extending stable engine operation to ultra-lean fuel mixtures.

Additionally, the greatly enhanced speed of the overall combustion event significantly reduces the amount of ignition timing advance necessary for MBT (maximum brake torque) operation with a given fuel-air mixture. Depending upon the mixture ratio, engine conditions, and HDI energy and power level, the need for timing advance may be entirely eliminated. Consequently, highly efficient engine operation is provided with significantly reduced ignition timing advance.

In the drawings, which form an integral part of the specification and are to be read in conjunction therewith, and in which like reference numerals are employed to designate identical components in the various views:

FIGURE 1 is a schematic diagram of an equivalent electrical circuit for generating a hard discharge ignition in accordance with the present invention;

FIGURES 2A and 2B are a series of graphs respectively displaying the electrical characteristics of spark discharge operation in a marginally hard discharge regime and a much harder discharge regime;

FIGURE 3 is a combined broad block diagram and diagrammatic view of the combustion initiation system employing hard discharge which forms the preferred embodiment of the invention;

FIGURE 4A is a fragmentary, cross-sectional view of a firing tip geometry which forms a portion of a hard discharge system of the present invention;

FIGURE 4B is an end view of the firing tip shown in FIGURE 4A;

FIGURES 4C-J are views similar to FIGURE 4A but depicting alternate forms of geometry for the firing tip;

FIGURE 5 is a longitudinal sectional view of an ignitor unit employing an integral discrete, lumped capacitance, pulse forming network;

FIGURE 6 is a longitudinal sectional view of a distribution cable employing another form of the pulse forming network having lumped capacitance;

FIGURE 7 is a perspective view, parts being broken away in section, of still another distribution cable having a pulse forming network employing lumped capacitance;

FIGURES 8A and 8B are longitudinal, sectional views of portions of distribution cables employing a pulse forming network having distributed capacitance;

FIGURE 9 is a cross-sectional view of a termination connector for use with the distribution cable shown in FIGURE 8;

FIGURE 10 is a view showing the primary power source and charging network;

FIGURE 11 is a schematic diagram of an inductively coupled dc charging circuit;

FIGURE 12 is a combined block and detailed schematic diagram of the combustion initiation system of the present invention employing a mechanical distributor;

FIGURE 13 is a combined block and detailed schematic diagram of an alternate form of the combustion initiation system using demand-charging;

Overview and Characterization of HDI

The rate of admission of energy into the breakdown channel in a spark gap must be maximized in order to achieve high power coupling efficiency and to maximize the intensity of the energy transfer mechanisms which are important in accordance with the present invention for ignition applications. This may be accomplished by using a very low inductance, low impedance, capacitive-discharge driving circuit represented by the simplified equivalent model shown in FIGURE 1. As used in this description, the term "driving

circuit" refers to all of the high voltage discharge circuit components, connecting conductors, and structures other than the breakdown gap and gaseous discharge path itself. Capacitor C represents the total effective discharge circuit capacitance, inductor L_o represents the total effective driving circuit inductance, and resistance R_o represents the total effective driving circuit resistance. The reactive term component of the characteristic impedance of the driving circuit is expressed as:

$$Z = \sqrt{L_o/C}$$

C may be a discrete, lumped-element capacitor connected to the spark gap by means of a low inductance lead configuration, or it can be a distributed capacitance in the form of a very low-impedance, low-inductance waveguide structure which acts as a distributed pulse-forming-network (PFN). With operating voltages typically in the range of 20 to 40 kv, the magnitude of the capacitor C will fall within the range of approximately 100 picofarads to about 5 nanofarads. L_o includes the inductance of all connecting conductors and the inductance associated with the discrete or distributed capacitive unit and must generally be on the order of a few hundred nanohenries or less. R_o includes the resistance of the circuit conductors as well as the effective resistive loss associated with dielectric losses in the capacitive element. In practice, R_o should be no more than a few ohms, and preferably should be minimized to the sub-ohm level. In general, this approach toward ignition system operation contrasts with the prior art approach which lays heavy emphasis upon higher impedance, higher inductance, lower capacitance driving circuitry and considerably longer discharge duration at lower intensities.

The equivalent lumped circuit model components for the spark gap are indicated by dashed lines in FIGURE 1. C_g is the capacitance of the gap prior to breakdown and is typically on the order of 10 picofarads (10pf). C_g is important for storing the charge needed during the very early stages of the breakdown channel formation, but the magnitude of C_g is small compared to C and can be neglected once the early breakdown channel has been established. Closing of switch S_b represents the onset of the breakdown event in which an ionized current flow path is formed between the spark gap electrodes.

The detailed mechanisms involved in this process depend upon the conditions of the gas in the gap and the manner in which the voltage is applied. For purposes of this disclosure, it may be assumed that the establishment of current flow across the gap may be represented by the closing of the switch S_b . C_g is then effectively shunted by the time-varying channel inductance $L_g(t)$ and resistance $R_g(t)$. The circuit operation begins after capacitor C is charged to an initial voltage V_o which is of sufficient magnitude to initiate the breakdown process at the discharge gap. The charging circuit (not shown in FIGURE 1) is assumed to be sufficiently isolated from this discharge circuit to have negligible influence on its operation. At the time of initial breakdown ($t=0$), a conductive channel in the gap is formed (i.e., switch S_b closes) and current $i(t)$ begins to flow in the discharge circuit. In fact, the initially formed breakdown channel in a spark discharge can have appreciable current flow associated with it at the instant that the gap is bridged ($t=0$). Neglecting the time-varying character of L_g and R_g , or assuming they are negligibly small compared to L_o or R_o , the discharge current may be approximately described by the formula

$$I(t) = \frac{V_o}{L\omega} e^{-\alpha t} \sin \omega t, \quad (1)$$

where $\alpha = \frac{R}{2L}$, $\omega^2 = \frac{1}{LC} - \alpha^2$,

$R = R_o + R_g$,

and $L = L_o + L_g$.

Taking the derivative of equation (1) provides

$$\frac{dI}{dt} = \frac{V_o}{L\omega} e^{-\alpha t} \cos(\omega t + \zeta), \quad (2)$$

where $\zeta = \tan^{-1}(\frac{\alpha}{\omega})$. (3)

From this it follows that the maximum rate of rise of discharge current flow is at $t=0$ and is given by

$$\left. \frac{dI}{dt} \right|_{\max} = \frac{V_o}{L}, \quad (4)$$

where L is some constant total effective discharge circuit inductance and V_0 is the initial charge voltage. Equation (4) above, with L taken to be approximately L_0 , often forms the initial condition for solutions of spark discharge current flow and is typically taken to be the value of steepest current rise during discharge operation. However, the condition given by equation (4) is an upper limit approximation which will be
 5 approached to the extent dictated by the "hardness" or "softness" of the actual discharge.

The "hardness" parameters of an actual discharge may be characterized as follow:

$$10 \quad \phi = \frac{\left. \frac{di}{dt} \right|_{\max}}{V_0/L} \leq 1, \quad (5)$$

$$15 \quad \psi = \frac{1}{\phi} = \frac{V_0/L}{\left. \frac{di}{dt} \right|_{\max}} \geq 1, \quad (6)$$

where V_0/L is the upper limit condition of equation (4), and $\left. \frac{di}{dt} \right|_{\max}$ is the actual maximum rate of rise of
 25 current flow attained in a real discharge circuit. Thus, where phi and psi are nearly equal to unity the discharge is "soft" whereas hard discharge operation in accordance with the present invention is achieved when phi is less than one and psi is greater than one. The "harder" the discharge the greater phi and psi depart from unity.

Closer examination of the time-dependent equation which describes the behavior of the circuit shown in
 30 FIGURE 1 provides a better understanding of hard-discharging phenomena and the significance of the conditions given in equations (5) and (6). The voltage equation for FIGURE 1, upon closure of switch S_b at time = 0, takes the form

$$35 \quad V_0 - \frac{1}{C} \int_0^t i(\tau) d\tau - L \frac{di}{dt} - \frac{i}{2} \frac{dL}{dt} - Ri = 0, \quad (7)$$

where $L(t) = L_0 + L_g(t)$,
 40 and $R(t) = R_0 + R_g(t)$.

Considering very early times only, and neglecting all but the dominant terms in equation (7) at early time gives the first order approximation

$$L \frac{di}{dt} + Ri = V_0. \quad (8)$$

The commonly used conditions of equation (4), which characterizes soft-discharge operation, is seen from
 45 equation (8) to arise when the resistive voltage drop in the discharge circuit is negligibly small relative to the inductive voltage drop. However, in a gaseous discharge circuit employing a very low inductance (L_0), low resistance (R_0) driving circuit, the magnitude of early-time current flow cannot be neglected. The resulting resistive voltage drop, which is predominately due to the initially high but rapidly falling active resistance of the early-time breakdown channel, can be a major factor that can actually dominate over the
 50 inductive voltage term. From equation (8) it follows that

$$55 \quad \phi \approx \text{maximum} \left\{ 1 - \frac{R(t)i(t)}{V_0} \right\}, \quad (9)$$

which demonstrates that hard-discharging operation occurs when the drive circuit inductance and resistance

are so low that the rate of rise of current flow is largely governed by the resistance of the discharge channel itself. Using a truncated power series in time (t) as an approximation for i(t) at early time, it can be shown that

$$\phi \sim \frac{L/l_g}{\frac{t_m^2}{4Cl_g} + \frac{2R_m t_m}{3l_g} + L/l_g - 1} \quad (10)$$

where t_m is the time at which the rate of rise of current flow is maximum (nanoseconds)
 R_m is the discharge channel resistance at time t_m (ohms),
 C is capacitance (nanofarads),
 L is inductance (nanohenries), and
 l_g is gap length (centimeters).

From experimental observations in the literature the following approximation can be obtained for channel formation time:

$$t_m = \frac{425 P^{1/2}}{Z_o^{1/3} E_o^{1.1}}$$

where t_m is in nanoseconds,
 Z_o is drive circuit impedance in ohms,
 E_o is breakdown field in kv/cm, and
 P is ambient gap pressure in atmosphere.

For ignition applications of HDI, maximum performance is obtained with operation in the region of ϕ approximately equal to or less than 0.5, and ψ equal to or greater than 2, which follows directly from the high power dissipation achieved by delivering 80% or more of the available energy within the breakdown phase during the first discharge current lobe. Using voltages from 20 kV to 40 kV, and discharge circuit capacitance of 100 picofarads to several nanofarads, hard discharge operation requires values of L/l_g on the order of a few hundred nanohenries of discharge circuit inductance (L) per centimeter of discharge gap length (l_g), or less. Operation in the region of ϕ approximately equal to or less than 0.5 typically requires L/l_g approximately equal to or less than 80 nanohenries per centimeter, depending on the value of capacitance C and the effective working gap breakdown electric field E_o .

As a practical matter, reducing the overall circuit inductance to values of L/l_g below approximately 10 nH/cm is quite difficult in high voltage discharge circuits where certain minimum physical spacing is required for electrical insulation. In fact, the breakdown channel itself typically has self-inductance on the order of 10nH/cm. In cases where insufficient hardness has been achieved despite the minimization of L/l_g to practical limits, the major alternative for increasing hardness are to decrease the capacitance C and/or to effectively increase E_o by overvoltageing the discharge gap. Investigations with hard (ϕ equal to or less than 0.3) open air discharges have shown that for values of C less than or approximately equal to 3 nanofarads, an increase in energy caused by increasing the working voltage V_o and gap length l_g yields a shorter discharge current duration and a longer duration of light output with light output in very hard discharges (ϕ equal to or less than 0.2) continuing well beyond the cessation of current flow (afterglow). If constant energy W_o is maintained by reducing C while increasing V_o and l_g , the total discharge duration is again reduced. Hence, for sufficiently small capacitance C (approximately equal to or less than 3 nanofarads) increased discharge power output is obtained by increasing the working voltage V_o and the gap length l_g . Experimentation has shown that optimum discharge conditions in terms of the rate of energy release and light output intensity, occur when most of the available energy is liberated before the time t_{cr} when the resistance of the spark channel drops below the critical value, given by

$$R_g (t = t_{cr}) = R_{cr} = 2\sqrt{\frac{L_o}{C}} = 2 Z_o \quad (13)$$

Under these conditions, the discharge current flow is highly aperiodic in character with a total duration approximately equal to the first half-period pulse width.

The criteria for obtaining optimum aperiodic discharge in which most of the available energy is deposited within a time frame less than t_{cr} are given by the equations:

$$\sqrt{Cl_g} \leq \frac{t_{cr}}{j\pi\sqrt{\frac{L_0}{l_g} + \hat{L}}} \quad (14)$$

$$\sqrt{\frac{W_0}{l_g}} \leq \frac{E_0 t_{cr}}{j\pi\sqrt{2\left(\frac{L_0}{l_g} + \hat{L}\right)}} \quad (15)$$

where \hat{L} is the inductance per unit Length of the discharge channel itself, and j is the broadening factor.

E_0 increases with pressure according to the paschen curve for a given gap configuration and is also dependent on the rate at which voltage is applied to the gap. Similarly, the critical time t_{cr} for a particular gap configuration in air depends on pressure, breakdown field (E_0), and the effective impedance Z_0 of the circuit driving the discharge gap. Experimental results with very hard, linear gap, open air discharges under low overvoltage conditions for which $E_0 \sim 25\text{kV/cm}$, $t_{cr} \sim 20\text{ nsec}$, and $j \sim 2.2$ have shown that under such conditions the optimum criteria for achieving effectively critically damped aperiodic discharge are approximately

$$Cl_g \lesssim (Cl_g)_{\max} \approx 840 \text{ [pf.cm]} \quad (16)$$

$$\frac{W_0}{l_g} \lesssim \left(\frac{W_0}{l_g}\right)_{\max} \approx 260 \text{ [mJ/cm]} \quad (17)$$

With differing gap geometry under higher pressure conditions with hydrocarbon fuel present in the air mixture, such as experienced in an engine combustion chamber, the values given by equations 16 and 17 may change to an extent that cannot be readily predicted without consideration of the parameters unique to the gap configuration rate of voltage application, and chamber environment.

The rate of rise of the voltage applied to the gap can affect the dynamics of the breakdown process. With sufficiently rapid voltage application, a given gap can be "overvolted" and the resulting effective breakdown field E_0 can be significantly higher than the field attained under slower voltage rise conditions. However, for a given gap configuration operated in a specific ambient environment with known discharge circuit parameters at a fixed rate of voltage rise, optimum criteria as given by equations (14)-(17) exists for obtaining totally aperiodic, hard discharge operation. When Cl_g is then greater than $(Cl_g)_{\max}$ or W_0/l_g is greater than $(W_0/l_g)_{\max}$ the discharge becomes oscillatory and its overall duration increases. For small values of L/l_g , the overall discharge duration will remain relatively brief, even though oscillatory. Open air experiments have shown that for situations where hard discharge operation is nearing optimum, but is still in the oscillatory regime, the duration of the light flash changes relatively little for $30 \eta\text{H/cm} \leq L/l_g \leq 10 \eta\text{H/cm}$. (18)

Although the specific hard discharge criteria and conditions for optimum discharge performance will vary depending upon the particular circuit parameters and operating conditions, the estimates given hereinabove for open air experimental investigations give a reasonable order of magnitude approximation that can be considered generally characteristic of hard discharge operation.

The discharge channel, as referred to in this disclosure, is the transition region wherein the electrical

energy is released within the combustible air-fuel mixture. The various coupling mechanisms transfer energy to the fuel charge for initiation of the chemical reaction. The description of the processes involved in the initiation may be grouped into three main areas: channel formation, channel expansion, and combustion initiation.

5 The breakdown of a spark gap occurs when the voltage applied across the electrodes reaches a minimum level such that the electric field strength in the gap exceeds the minimum threshold necessary to generate and accelerate charge carriers at a rate which precipitates the multiplicative growth of the process. Application of voltage above this minimum threshold "overvolts" the gap and causes breakdown. Upon
10 establishment of the minimum breakdown field, the inception of the breakdown process requires the elapse of a brief but non-zero amount of time. The time delay from minimum breakdown voltage application until the beginning of the voltage collapse that accompanies breakdown formation is normally termed the "time-to-breakdown". The processes which initiate breakdown are governed by statistical laws, multiplicative growth rates, and transit times which depend on gap length and field strength. For this reason, time-to-breakdown is a variable quantity which is responsible for "jitter" in spark gap firing. "Statistical delay time"
15 is a useful number which is the mean of the distribution of times-to-breakdown for a given gap situation. Statistical delay times can range from tens of nanoseconds to hundreds of microseconds depending on gap geometry, gap length, gas atmosphere, pressure, level of initial charge carrier density, and rate of voltage application. If voltage is applied rapidly enough, the peak voltage attained during the delay period prior to the onset of breakdown may reach well beyond the minimum breakdown voltage threshold. This high
20 overvoltage condition increases the electric field strength which in turn can influence the dynamics of the breakdown process. As used in this disclosure, "overvolting" of a gap will generally refer to the application of significantly higher (perhaps 20%) voltage than the minimum breakdown threshold, and implies a relatively rapid rate of voltage application.

Regardless of the exact mechanisms involved, at some point in time a column or "channel" of heated,
25 ionized plasma forms a complete path between the electrodes. This newly formed ionized channel is typically approximately 0.05 mm to 0.1mm in visible diameter and has associated with it an initial non-zero current flow which can approach several hundred to several thousand amperes in magnitude. For temperatures below about 12,000 °K, the conductivity of a gas is highly dependent upon temperature. Thus, the hotter regions of the initial ionized column present the easiest path for subsequent current flow.
30 The increasing current flow through the hotter regions of the still relatively resistive plasma channel cause rapid joule heating which results in increased plasma temperatures that in turn increase the plasma conductivity. This positive-feedback process rapidly leads to the production of very high internal pressure within the channel which brings about the initially explosive process of channel expansion and eventually leads to a decrease in the effective resistance and inductance of the discharge path.

35 For the specific case of a breakdown channel in air with early current flow $I(t)$ proportional to time, the radius of the channel may be expressed approximately from Braginskii's theory as:

$$40 \quad a(t) \approx .93 \frac{I(t)^{1/3} t^{1/2}}{\rho^{1/6}} + a_0 \quad (19)$$

where

- a is the channel radius in millimeters (mm) at time t,
- 45 I is channel current flow in kiloamperes,
- t is in microseconds,
- ρ is the density of air in units of g/cm³, and
- a_0 is some initial non-zero channel radius in mm at the instant of channel formation at $t=0$.

Taking the time derivative of equation (19) yields:

$$50 \quad v(t) = \dot{a}(t) = \frac{.31 t^{1/2}}{\rho^{1/6} I(t)^{2/3}} \left[\dot{I}(t) + \frac{3}{2} \frac{I(t)}{t} \right]. \quad (20)$$

55 From equation (20) is it apparent that the radial velocity of expansion of the channel is a function of both the current magnitude and the rate of rise of current. The rate of channel expansion may be maximized in

accordance with the teachings of the present invention by very low inductance, high speed, high current, high power deposition hard-discharge operation.

Channel expansion rates on the order of tens of kilometers per second have been observed in rapid, high current, hard spark discharges. At these rates of channel expansion, a significant shockwave is generated. The maximum shock energy generated under these conditions is given approximately by:

$$W_s \approx 6.8 \times 10^{-4} \frac{V^{4/3}}{Z^{3/4}} (d) \left(\frac{1}{CR}\right)^{2/3}, \quad (21)$$

where W_s = the overall cylindrical shockwave energy content in joules,

V = Effective Breakdown Voltage (volts)

Z = Discharge Circuit Impedance, $(L/C)^{1/2}$ (ohms)

d = Arc Gap Length exposed to the fuel (meters)

CR = Ratio of initial pressure to ambient pressure (compression ratio)

Similarly, the maximum velocity of the shockwave is given approximately by

$$V_s \approx 3.11 \times 10^{-2} \left[\frac{V}{l_g^{2/3} Z_0^{1/6}} \right] \left[\left(\frac{1}{CR}\right)^{5/12} \right], \quad (22)$$

where V_s is the shock velocity in meters per second, and where l_g is the total effective breakdown gap length in meters.

As previously discussed, the effective breakdown voltage is a variable parameter governed by electrode geometry, ambient pressure, rate of rise of applied voltage, and discharge gap length.

Numerous energy transport phenomena emanate from the arc channel, and these phenomena collectively form an ensemble capable of establishing, within the chemically reactive fuel mixture, an outwardly increasing gradient in the effective reaction induction time. Such gradient (reaction time increasing with radial distance from the discharge) is capable of giving rise to the synergistic SWACER mechanism of reaction energy release. HDI, according to the present invention, may be further capable of establishing a stimulated-SWACER type of synergism which shall term SWASER. The SWASER (shock-wave-amplification-by-stimulated-energy-release) mechanism combines physical and chemical energy transport phenomena in a synergistic manner to not only provide the conditions for, but also then stimulate, the coherent energy release from an induction-time gradient, thereby affording substantially increased energy coupling efficiency to the mixture and promoting rapid combustion phenomena. Such an HDI-generated synergistic energy release mechanism would be capable of producing a supersonic detonation shockwave by virtue of an induction time gradient-induced positive-feedback mechanism in which chemical reaction energy is released in phase with the passing, developing wave.

HDI operation not only establishes strong gradients in the chemically reactive mixture, but also provides additional means of stimulating those gradients into the initiation of a rapid combustion process. Specifically, various gradients established through energy transfer by radiation absorption in the layers of gas immediately outside of the expanding discharge channel are soon subjected to the strong shockfront of the blast wave created during the explosive phase of the blast wave created during the explosive phase of channel expansion. This is followed sometime later by the arrival of the hot plasma kernel and its associated thermal gradient and high-energy ionic species content.

Investigation of ignition by radiation, or "photolysis", has shown that radiation absorption can lead to a reduction in the effective induction time in a chemically reactive mixture. Hence, the presence of intense radiation may yield a decrease in the effective Auto-Ignition limit, thereby reducing the necessary shock strength required for the establishment and propagation of a steady-state supersonic detonation reaction flow. "Hard discharge" according to the present invention optimizes these effects. In addition, by proper orientation of the discharge geometry, additional physical enhancement may be achieved in radial shock velocities.

We have found that the HDI method has a high energy transfer efficiency during the very early times of discharge channel formation and expansion. If the total system is tailored such that most of the available electrical energy is dissipated in this breakdown phase of the discharge, then peak power coupling will result. Because a major portion of the total energy is distributed in the plasma channel and the adjacent

gases in a relatively brief time frame, (on the order of tens of nanoseconds) less energy in the form of heat is retained at the electrodes. Thus, a major factor in electrode wear is reduced. Some electrode wear caused by rupture phenomena will occur, however, the severe melting erosion found in relatively long duration, high energy arc discharge operations is greatly reduced.

5 As previously mentioned, using a higher operating voltage V_0 maximizes hard discharge performance by maximizing the gap length (l_g) and for given individual inductance (L), minimizing the ratio L/l_g . Operating with higher voltage is also preferred for reducing electrode wear. It is well known in the art that electrode erosion is generally proportional to the amount of pulse energy supplied to the electrodes, the amount of charge transferred decreases with increasing voltage. Furthermore, the enhancement to the hard
10 discharge process which is achieved through higher voltage operation can lead to a reduction in the amount of pulse energy required to produce a desired level of performance for ignition applications. This in turn leads to a reduction in the total charge transfer per pulses, thereby providing an additional potential decrease in electrode wear.

Once the reaction has begun, according to the present invention, a major portion of the fuel charge will
15 be rapidly consumed through the initiation of a combustion event consisting of a combination of rapid turbulent deflagration and/or supersonic detonation processes. The result is an effective combustion reaction velocity which is greater than normal burn velocities. Additionally, the transport phenomena of conventional burn reactions are primarily thermal gradient-driven molecular kinetics, whereas the HDI energy transport mechanisms also include intense radiation and high speed shockwave pressure discontinuities which provide the elements necessary for SWACER and SWASER type synergy. Accordingly, the
20 HDI method of the present invention provides highly probable and robust ignition, extends the lean ignition and combustion limits beyond the capabilities of conventional thermal ignition systems, and promotes higher Otto-cycle engine efficiency by initiating a more rapid overall combustion event.

The description thus far has been limited to the closely-coupled, low inductance, capacitive-discharge
25 circuit for producing HDI operation. In order to achieve HDI operation with the closely-coupled, low inductance, capacitive-discharge circuit, it is necessary to pulse-charge the discharge circuit to a sufficiently high voltage to cause breakdown of the ignitor tip gap. The description will now turn to the details of a typical pulse generation and distribution system for pulse-charging the discharge circuit.

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Operating System

Reference is now made to FIGURE 3 which depicts the broad functional components or sub-systems of the pulse generation and distribution circuit of the present invention. A source of 12 volt dc, such as a
35 conventional automobile battery 50 provides dc power to a primary power conditioning unit 40. Power conditioning unit 40 consists of an essentially free-running, resonant, multi-vibrating 12 volt to between 200 and 6,000 volt regulated supply. 200 to 6,000 volts dc is supplied by the power conditioning unit 40 to a charging network 42 which includes a later discussed flywheel capacitor which stores enough energy to supply a plurality of high voltage pulses. A high voltage pulse generator 44 produces high voltage pulses
40 using the charge supplied by charging network 42 and delivers these high voltage pulses to a pulse distributing and peaking circuit 46. The charging network 42, pulse generator 44 and pulse generation and peaking circuit 46 are controlled by a timing and control circuit 48 which receives a train of timing signals from an appropriate source, such as a magnetic sensing coil or breaker points 56 which sense the rotation of some portion of the engine, such as the crankshaft or camshaft 54.

45 High voltage pulses are delivered to a pulse forming network (PFN) which is closely coupled with a later discussed ignitor unit 52. Ignitor unit 52 includes a discharge tip communicating with a charge of reactive fuel mixture 72 within a closed combustion chamber 68 having a piston 70 connected with the crankshaft 54. The ignitor unit 52 in combination with the PFN 50 produces the previously discussed hard spark discharge 58 within the combustion chamber 68. The hard spark discharge 58 comprises an ignition kernel
50 from which there radiates a supersonic blast wave front 66 followed by a high temperature, high density plasma shell or "piston" 60. The region 62 from the piston 60 and extending beyond the blast wave front 66 consists of a steep gradient in temperature, density, and pressure. Hard ultraviolet radiation 64 also radiates from the discharge 58, and cooperates with the blast wave shock front 66 and plasma piston 60 to initiate combustion of the reactive mixture 72 in a very rapid manner according to the synergistic SWASER
55 phenomena.

A conventional capacitive discharge or induction system can be employed to pulse charge the PFN 50 and ignitor unit 52, such conventional systems are limited in the amount of capacitive loading which can be achieved while maintaining a relatively high output voltage. Such systems are typically limited to secondary

circuit capacitance of about 100 pf or less with output voltages in the range of 20 to 30 kV. Consequently, these systems are capable of delivering maximum pulse energies of approximately 50 mJ or less to the PFN 50 and ignitor unit 52; these energy levels offer some degree of enhanced ignition performance, however we have found that in order to achieve significantly enhanced combustion with relatively high efficiency, it is necessary to deposit energy in the reactive mixture 72 amounting to several hundred mJ/cm discharge gap length. Experiments have demonstrated that combustion enhancement increases significantly as the deposited energy increases from about 60 mJ per pulse to several Joules per pulse. In general, the range of combustion enhancement will depend upon the operating characteristics of the engine and the discharge power level.

In the case of a conventional eight-cylinder internal combustion engine, approximately 400 ignition pulses per second must be generated at 6,000 rpm. At this speed, the time interval between pulses would be approximately 2.5 ms. Assuming an overall ignition system operating efficiency of 50% and an available discharge pulse energy of 1 Joule, approximately 800 watts of power are required from the engine's electrical system to achieve energy deposition of 1 Joule per pulse. Normally, the maximum allowable power drain on a typical 12 volt dc automobile system is approximately 600 watts. Thus, it may be seen that for existing automobile electrical system, an upper practical limit for the deposited ignition system pulse energy is dictated by the overall ignition system efficiency and the expected maximum pulse repetition rate. A practical upper limit for typical existing automotive systems is probably somewhat less than 1 joule per pulse of delivered discharge energy. However, it has been found that the improvement in engine power for a given level of fuel consumption can be increased to a point which justifies the use of a higher capacity primary electrical system capable of supporting the higher power drain of the ignition system at deposition energies of 1 Joule or more.

Ignitor Tip Geometry

Attention is now directed to FIGURE 4 wherein various forms of a discharge tip for use with the ignitor 52 are depicted. Certain constraints must be placed on the gap between the electrodes at the discharge in order to achieve HDI operation. The predominant factor affecting HDI operation are the value of the inductance of the overall ignitor unit and a gap length sufficient to hold off the voltage level applied to the electrodes. These criteria may be satisfied by numerous discharge tip and gap geometries, providing that inductance and impedance are maintained below a prescribed value. However, it is desirable to provide a geometry and configuration which maximizes the efficiency with which the available circuit energy is coupled into the discharge, and from the discharge to the combustible mixture via light, heat, shock and ion production. Discharge tip geometry also affects longevity of the ignitor in terms of insulator and conductor wear due to the presence of extremely hot plasma and strong shockwave production.

Discussed hereinbelow are two preferred forms of discharge tip designs which are highly suitable for achieving HDI operation. One of the tip designs is depicted in FIGURES 4A and 4B and consists of inner and outer coaxial electrodes 80, 76 which are electrically insulated from each other by a cylindrically shaped insulator 82. The outer cylindrical wall of the outer electrode 76 is provided with a thread form 78 which is adapted to be matingly received in an engine block or the like in order to mount the ignitor so that a discharge tip communicates with the combustion chamber. The outer ends of electrodes 76 and 80, as well as the insulator 82, extend along a common plane or flat surface 84. The discharge gap formed by ignitor tip 74 is radial and extends circumferentially around the entire surface 84. Consequently, the electrical field indicated at 85 commences at the outer end of electrode 80 and possesses a radially outward trajectory to all points on the outer electrode 76 along its upper surface 84.

The ignitor tip 74 possesses minimum inductance and impedance because of the coaxial geometry of electrodes 76, 80 and the radial nature of the gap. The physical gap length of ignitor tip 74 is given by the difference in conductor radii $b-a$ shown in FIGURE 4B. The gap length will be selected in accordance with the voltage pressure conditions of the particular application and anticipated operating conditions. The wall thickness and nature of the insulator 82 must be selected so as to assure that breakdown between the electrodes 76, 80 does not occur along their lengths. It should be noted that for a coaxial geometry both the inductance and impedance are determined in large part by the natural logarithm of the ratio of conductor radii b/a and that the inductance and impedance may be minimized provided the difference in conductor radii, b/a equals the required thickness of the insulator 82 for internal voltage hold-off.

The electric field created by the voltage applied to electrode 76, 80 is shown at 85, with arrows indicating the direction that a positive test charge would move in the field (from positive to negative polarity). The field 85 is non-uniform, moving outwardly away from the surfaces 84, and it is believed that

this non-uniformity in addition to the curvature of the lines of the field enhance the resulting discharge. The sharply curving nature of the field 85 changes the characteristic breakdown potential of the gap, accelerates charges moving in the field and tends to push the arc channel outwardly away from the tip due to magnetic forces, particularly where large current densities exist in the discharge. Moreover, the linear flow of current through the central or inner conductor 80 produces a magnetic field which interacts with the fields produced by the discharge to further enhance the discharge.

The flat, radial design of ignitor tip 74 tends to produce a discharge which a spatial symmetry and uniformity which maximizes the volume of fuel mixture which is contacted by the discharge. The smooth, unobstructed surface 84 precludes any detrimental effects due to flow conditions within the combustion chamber and exposes larger electrode surface for participation in the discharge, which has a tendency to prolong the life of the electrode.

The ignitor tip 74 may be modified in various ways to further enhance its operation. For example, as shown in FIGURE 14C, either or both of the outer ends of the electrodes 76, 80 might be pointed, as at 86, 88 in order to further "peak" the field 85. In other words, the field would tend to emanate from the peaks of the pointed tips 86, 88.

In order to avoid possible trenching of the insulator 82 at the surface 84, the outer edge of the insulator 82 may be slightly recessed at 90 as shown in FIGURE 4D.

As shown in FIGURE 4E, the discharge gap could be lengthened without increasing wall thickness by extending the insulator 82 outwardly beyond the outer surfaces of electrodes 76, 80; this design would be particularly effective in low pressure combustion environments or where higher breakdown voltage is required.

Conversely, as shown in FIGURE 4F, the outer ground electrode 76 might be offset at 96 without comprising the internal hold-off voltage in those cases where lower voltage or higher compression operation is desired.

An alternative approach for lengthening the discharge gap consists of recessing the center electrode 80 from the end of the insulator 82 and outer electrode 76, as shown in FIGURE 4G. A pronounced "jet" action due to the resultant cavity above the center electrode 80 has been noted with ignitors of this type. This jet is not likely due to an expulsion of plasma from the cavity, but rather is caused by reflected shockwaves initially trapped during the channel expansion and/or possibly a stream of heavy ion species originally moving along electric field lines but at a later time following trajectories dictated by their inertia once the field has diminished.

To avoid excessive wear on the insulator 82, such insulator could be contoured at 83 as shown in FIGURE 4H to present a tapered surface extending from the end of center electrode 80 radially outward to the outer electrode 76. The geometry shown in FIGURE 4H provides the advantage of a recessed design which reduces insulator wear, but retains the jet or cannon line discharge effect.

Extension of the center electrode 80 beyond the end of the outer electrode 76 as shown in Figure 4I also provides a means of increasing the discharge gap length. The tapered outer surface 85 of the insulator 82 again reduces wear on the insulator. Such an extension of the center electrode 80 into the combustion chamber assists in coupling and transferring the discharge energy to a fuel charge and is relatively unconfined.

As previously mentioned hereinabove, various ignitor tip and discharge gap configurations may be successfully employed to achieve HDI operation and in some cases it may be desirable to employ a linear or longitudinally extending tip gap. One suitable tip design employing a linear gap is shown in FIGURE 4J. The ignitor shown in FIGURE 14J is broadly similar to conventional spark plug designs, with the outer electrode 76 having an L shaped extension 76a which provides an electrode surface axially aligned with the center electrode 80. Although the configuration shown in Figure 14J may be employed with beneficial results in connection with the present invention, it is not the preferred form of ignitor geometry and in any event, it is necessary to minimize inductance and impedance in those components of the ignitor which are directly adjacent to the discharge gap while at the same time allowing sufficient gap length for breakdown at peak voltages.

In connection with the linear gap geometry, discharge occurs with virtually no wear upon the insulation due to arc while a desirable cylindrical shockwave is produced which is impeded only in the direction of the extended ground electrode. This exposure of the entire breakdown path lends itself to strong coupling and efficient energy exchange. Multiprong designs can be used in order to increase ignitor life inasmuch as there are additional surface areas between which a discharge can occur. It is important to orient these extra electrodes such that the discharge is not impeded in its growth nor shielded from the fuel charge thus prohibiting or quenching combustion promoting reactions.

Pulse Forming Network

As previously discussed with respect to FIGURE 3, the pulse forming network 50 and ignitor unit 52 must be closely coupled. This close coupling results in a current flow discharge which is largely governed
5 by the impedance of the discharge channel itself.

The preferred PFN is shown in FIGURE 5 which discloses a coaxially configured ignitor 98. The integral PFN-ignitor 98 achieves the lowest possible inductance and therefore provides maximum coupling to the discharge channel. Additionally, a later discussed capacitive portion of the ignitor 98 need not be assigned to have an extended service life since it is removed and replaced periodically when the ignitor tip becomes
10 worn and requires replacement.

The ignitor 98 includes a cylindrical outer electrode 10 formed of metal or the like and includes a reduced diameter portion 104 at one end thereof which is connected to the larger diameter portion by a radially extending shoulder 105. The smaller diameter portion 104 is threaded at 104 so as to be threadably received within an engine block or the like. The outer end of the larger diameter portion of the electrode
15 100 is threaded at 102 so as to threadably connected with a power supply distribution cable.

A central, metal electrode 108 is cylindrical in shape and is disposed coaxially within the outer electrode 100. One end of the central electrode 108 includes a reduced diameter extension 120 which is received within a passageway 118 and an insulating sleeve 114 which is secured within the reduced diameter portion 104 of the outer electrode 100. One end of the central electrode 108 is beveled around its
20 entire circumference 109 and a suitable dielectric potting compound 116 is interposed between the end of the insulator 114 and the beveled surface 109 of the central conductor 108.

The outer end of the central electrode 108 is defined by a reduced diameter portion or tip 111 which terminates at its outer end in a hemispherical surface 112. The base of the central electrode 108 surrounding the tip 111 is defined by a ring-shaped, radially extending shoulder 110. The outer end of the
25 electrode 100 extends longitudinally approximately the same length as the tip 111 of the central electrode 108.

A ring-shaped body 113 formed of a ceramic capacitor compound is disposed between the outer electrode 100 and central electrode 108. Body 113 extends the full length of the outer electrode 100 from the base or shoulder 105. The outer end 106 of body 113 extends beyond the outer longitudinal extremities
30 of tip 111 or electrode 100. The central electrode 108, outer electrode 100 and capacitor compound 113 form the capacitive portion of the PFN.

Reference is now made to FIGURE 6 wherein another form of a discrete capacitance PFN is disclosed. The PFN, generally indicated at 122 is formed in a coaxial cable 123 which connects a power supply (not shown) with a connector (not shown) which is adapted to be the cable 123 with an ignitor 52.
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The PFN 122 comprises an inner conductor 130 surrounded by a sleeve 136 of high dielectric material, such as ceramic. A layer 134 of metalization on the outer surface of the dielectric sleeve 136 is connected with the outer conductor 127 and thus forms a continuous path for the flow of current through the cable 123. The inner conductor 130 is of substantially larger diameter than the central conductor 128 of the cable 123 and is connected at its ends to the central conductor 128 as by welding or the like. A layer of dielectric
40 potting compound 132 surrounds the connection between the central conductor 128 and inner conductor 130. Inner connector 130 in combination with the dielectric sleeve 136 and metalization 134 forms a capacitor which is in close proximity to the ignitor 52.

Although the PFN 122 provides a discharge circuit which is somewhat higher in impedance and inductance than that depicted in FIGURE 5, it possesses the advantage of providing an ignitor which is relatively small and eliminates the problem of deleterious effects on the capacitor by additional heat to which
45 it is subjected if positioned contiguous to the combustion chamber.

Still another form of discrete capacitance PFN is depicted in Figure 7. The PFN 144 is connected in series with the coaxial power supply cable 146 which connects the power supply (not shown) with the coaxial ignitor 52. The PFN 144 comprises first and second sets of flat plate capacitors 152, 154 which are interleaved and spaced apart using a dielectric material 156 to form a series of capacitor plates. Plates 12
50 are connected with the outer conductor of cable 146 while capacitor plates 154 are connected with the central conductor 148.

A distributed capacitance PFN 158 is depicted in FIGURE 8A, which is formed integral with the distribution cable connecting the ignitor with the high voltage power supply. The cable including the PFN
55 158 is substantially flexible but yet does not possess a diameter too large to be used in existing automobile engines. The PFN 158 comprises a stripline geometry in which a plurality of flexible, outer foil conductors 160 are interleaved with a plurality of inner foil conductors 164 and are separated therefrom by a plurality of layers of dielectric material such as a polyamide film. The foil conductors 162, 164 may extend a

substantial portion of the length of the entire cable and the sandwiched construction is enclosed by an outer rubber or plastic jacket 166. As shown in FIGURE 9, the stripline configuration may be terminated in a connector 168 which is adapted to releasably connect the cable with an ignitor. The inner foil conductors 164 are terminated in a single connection which is secured to the center conductor 172 which in turn is connected with a metal contact 174 disposed within a cap 176 which fits over the electrical leads of the ignitor. The foil conductors 160 are terminated in a connection with lead lines 170 within the cap 176. Contacts 174 and lead lines 170 respectively interconnect with the electrodes of the ignitor.

Another form of distributed capacitance PFN is depicted in FIGURE 8B. The PFN comprises the coaxial cable 123 which is connected to an ignitor (not shown) by a connector 138. The connector 138 includes an outer threaded coupling 142 which is threadably received by a portion of the ignitor, and an inner electrical connecting portion 140 which electrically connects the electrodes of the ignitor with the central conductor 128 and outer conductor 127 of the cable 123. The inner and outer conductors 127 and 128 from the distributed capacitance.

High Voltage Pulse Generator

The high voltage pulse generator 44 depicted in FIGURE 3 will now be discussed in more detail, and in this regard reference is first made to FIGURE 10.

Generation of the high voltage pulses for delivery to the ignitor unit 52 can be accomplished using inductive-coil techniques or capacitive-discharge techniques. The inductive-coil approach is well known in the art, is quite simple and requires relatively few components. However, because of the inherently slow rise times of the output voltage and the severe demands placed on the current-interrupt switch at higher energy levels, the preferred form of pulse generator employs transformed capacitor discharge.

FIGURE 10 depicts a simple step-up transformer circuit in which energy originally stored in a primary capacitor C_1 at voltage V_1 is transferred through a step-up transformer T_1 to a capacitor C_2 at a higher voltage V_2 . This method of high voltage pulse generation is particularly well adapted for use in the HDI system of the present invention because output load of the pulse generator is formed basically of the capacitance of the high voltage circuit of the pulse forming network 50 (FIGURE 3). L_{11} and L_{22} are the self-inductances of the primary and secondary windings respectively of transformer T_1 . Inductor L_{12} is the mutual inductance between the primary and secondary windings. Thus, the circuit shown in FIGURE 10 comprises two inductively coupled resonant circuits, each of which has a fundamental resonant frequency governed by the inductance and capacitances of each circuit. The general solution of these two coupled circuits consists of primary and secondary current flow, $i_1(t)$ and $i_2(t)$, each being defined by two superimposed sinusoidal functions of different frequency. The overall operation of this current consists of the cyclical transfer of energy from the primary to the secondary circuit and then back to the primary circuit. In general, an increase in coupling between the primary and secondary circuits increases the rate of energy transfer and decreases the overall period of energy cycling between the circuits.

When the primary and secondary circuits of FIGURE 10 have the same fundamental resonant frequency and the coupling coefficient (k) is exactly equal to 0.6, the overall circuit operates in a dual-resonance transformation mode and is characterized by total energy transfer from the primary circuit to the secondary circuit during the duration required for two half cycles of current flow in both the primary and secondary circuits.

Because of its potentially high energy transfer efficiency and its high power capacity, the present invention employs a high voltage pulse design based on the use of an air-core, spiral strip dual resonance transformer. The air-core design eliminates loss and breakdown problems associated with magnetic core materials and allows for low loss, high efficiency operation at relatively high energy levels. Spiral strip construction allows for relatively easy transformer design and assembly, and is less susceptible to transient voltage breakdown problems.

In order to successfully employ dual resonance transformation, which requires current and voltage reversal in both the primary and secondary circuits, it is necessary to employ a switch S_p which allows current flow in both directions. The extraction of energy from the secondary circuit must be timed to occur near the attainment of peak output voltage at the crest of the second half-cycle of voltage on capacitor C_2 . In the absence of a hold-off device such as a saturable inductor diode or a gas breakdown switch designed to turn on at the desired output voltage, this requires that the ignitor spark gap be preferably sized to breakdown within a specified voltage range for given conditions of temperature and pressure. Premature breakdown due to loss of compression or a significant advance in engine timing would reduce the available energy stored in the hard discharge circuit at the moment of breakdown and would lead to additional

electrode wear due to continued delivery of current during the later arc phase of the discharge.

As will be discussed in more detail later, this problem can be substantially reduced or eliminated by employing a pulse compressing hold-off device such as a saturable inductor or gas switch, between the output capacitor C_2 and the discharge pulse forming network. This approach also provides the advantage of a faster rising output voltage pulse which can be potentially "overvolt" the ignitor gap. Alternatively, the pulse generator can be designed to operate in an off resonance mode (i.e., as a common pulse transformer) in order to deliver a fast rising output pulse which reaches maximum voltage on the first half cycle. This latter mentioned mode of operation has a lower theoretical energy transformation efficiency but is nevertheless capable of transferring a reasonable fraction of the available energy in a relatively short time frame without the need for reversal of voltage and current. This approach would also eliminate the need for a bidirectional primary switch and reduces the dielectric stress on capacitors C_1 and C_2 caused by the voltage reversal.

Prior to generating a high voltage pulse by closing switch S_p in the circuit shown in FIGURE 10 the primary capacitor C_1 is charged to a prescribed voltage by the previously discussed primary power source 40 via the charging network 42 shown in FIGURE 10. The primary power source of voltage V_o and impedance Z_s charges a relatively large storage capacitor C_s . Capacitor C_s is sufficiently large to store the equivalent of a plurality of pulses, thereby acting as a system buffer or "flywheel" which smooths out the energy demands on the previously discussed power supply. Although the primary power supply might consist simply of 12 volt dc battery/alternator/regulator system of a conventional automobile electrical system, it is desirable and considerably more efficient to employ a power conditioning stage which converts the 12 volt dc power supply to a higher voltage, typically on the order of several hundred to several thousand volts as previously discussed. In this manner, considerably less voltage step-up is required in the pulse generator, lower magnitudes of current are required to transfer a given quantity of energy, and the given quantity of energy can be stored in less physical volume due to the higher energy densities possible at higher voltages.

The inductive charging network 42 shown in FIGURE 10 comprises a diode D_c connected in series with an inductor L_c and provides a low-loss transfer of energy from capacitor C_s to capacitor C_1 and can also yield a voltage gain by nearly a factor of 2.

The operation of dc inductive charging is best understood by reference to FIGURE 11 which depicts an idealized case with no resistive losses. As is apparent from FIGURE 11, the use of the blocking diode D_c prevents the energy in capacitor C_1 from ringing back into the capacitor C_s , thereby holding the charge voltage on C_1 .

The charging network 42 also provides electrical isolation of the primary circuit of the pulse generation circuit from the electrical power source 40 and energy storage capacitor C_s ; this is achieved by choosing a value for inductor L_c sufficiently large to make the charging circuit time constant T_c much larger than the discharge constant of the pulse generation circuit. In practice, T_c will typically be on the order of several hundreds of microseconds to a few milliseconds, while the discharge time constant of the pulse generator will usually be no more than a few tens of microseconds.

In order to achieve reliable operation and isolation, it is important that the pulse not be initiated by closing the switch S_p (FIGURE 10) prior to the completion of the charging of capacitor C_1 . For this reason, the minimum time interval between impulses should always be longer than the time required for the charging network current flow to terminate. It is apparent that this minimum time interval is $T_c/2$.

Reference is now made to FIGURE 12 which depicts the details of one embodiment of the present invention wherein the inductively charged high voltage pulse generator is employed in combination with a conventional mechanical distributor 182 of an automobile ignition system. The 12 volt dc power supply 50 and dc to dc convertor 40 charges the flywheel storage capacitor C_s , and pulses of energy are drawn from the flywheel capacitor C_s through the previously discussed charging network 42 to a storage capacitor C_1 . High voltage pulses generated by the pulse generator 44 are delivered through the coupling transformer T_1 to the pulse distribution and peaking circuit 46 in accordance with the opening and closing of primary switch S_p .

The secondary coil L_{22} of the transformer T_1 is connected to the rotatable contact of distributor 182 through a later discussed optional pulse hold-off and unit denoted by P. Alternatively, the optional distribution line between the distribution system and the discharge PFN unit. The high voltage pulses are delivered from the distributor 182 via a coaxial distribution line or cable 188 to the closely coupled pulse forming network 50 and ignitor unit 52. Timing signals are generated by the distributor 182 by means of a magnetic pickup 56 which produces a train of timing pulses that are squared up and amplified by a timing pulse conditioner 48a and are delivered to a trigger pulse generator 48b. The trigger generator 48b uses the timing signals to control the operation of the primary switch S_p through firing pulses delivered through line

186. Lines 184 provide the necessary power to the primary switch trigger generator 486.

FIGURE 13 depicts another alternate form of a circuit for the present invention which is generally similar to that depicted in FIGURE 12 but further provides for demand charge of the pulse generator 44 by means of an SCR in the charging network 42, in lieu of the diode D_c in the circuit of FIGURE 12. Timing pulses output from the timing pulse conditioner 48a are delivered to a time delay circuit 48d and a demand charge trigger generator 48c. The time delay circuit 48d is conventional in design and functions to delay the delivery of the timing pulse from the coil 56 to the trigger pulse generator 48b for a prescribed interval. The undelayed timing pulses delivered to the demand charge trigger generator 48c are employed to control triggering of the SCR in the charging network 42. The use of a time delayed trigger pulse from pulse generator 48b assures that capacitor C_1 has been fully charged following switching of the SCR, and the charging SCR has turned off, before switch S_p is closed.

High Voltage Pulse Distribution and Compression

The energy transferred from the secondary L_{22} of the pulse transformer T_1 (FIGURES 10, 12, 13) can be distributed to the ignitor units 52 either mechanically or electronically by means of a modified conventional distributor or by later discussed saturable inductor devices. In either case, a desirable compression of the electrical pulse may result as discussed previously.

As previously discussed with respect to FIGURE 12, mechanical distribution of the pulse may be achieved by connecting an electrical conductor 194 between the output of the pulse generator 44 and the input terminal of the distributor 182. The distributor 182 functions as a mechanical switch for transferring the incoming pulse to a mechanical rotor 196. The rotor 196 is caused to rotate by the engine at a speed commensurate with the engine and includes a conductor which rotates past connector terminals 198 to which each of the cables 188 is connected. A rapidly rising voltage pulse appears on the input cable 194 which ionizes a small gap between the rotor 196 conductor and the terminals 198, thus closing a circuit so that current from the pulse flows to the corresponding PFN 50 and ignitor unit 52.

Claims

1. A pulse forming device for the generation of alternating current pulses which are to be supplied to a gap of an ignitor in an internal combustion engine, comprising an electrical circuit including a capacitor (158) for storing a quantity of electrical energy, and a pair of electrical conductors (160,164) for electrically connecting said capacitor (158) with said ignitor, **characterized** in that said capacitor (122,158,144) is inserted and/or distributed along at least a portion of an electrical distribution cable (123,146,180).
2. The pulse forming device of claim 1, **characterized** in that said distribution cable is a coaxial cable (123) the inner conductor (130) of which has an increased diameter on a certain length and is surrounded by a sleeve (136) of high dielectric material having an outer metalization layer (134) which is connected with the outer conductor (127) of said coaxial cable (123).
3. The pulse forming device of claim 2, **characterized** in that the portion (130) of increased diameter is connected at its ends with the inner conductor (128) of small diameter, the connection being surrounded by a layer (132) of dielectric potting compound.
4. The pulse forming device of claim 1, **characterized** in that the distribution cable is connected in series with first and second sets of flat plate capacitors (152,154) which are interleaved and spaced apart.
5. The pulse forming device of claim 1, **characterized** by a stripline geometry in which a plurality of outer foil conductors (160) are interleaved with a plurality of inner foil conductors (164) and are separated therefrom by a plurality of layers of dielectric material.
6. The pulse forming device of claim 5, **characterized** in that the stripline configuration terminates in a connector (168) for the connection with an ignitor.
7. The pulse forming device of claim 1, **characterized** by a connector (138) configuration in which an inner and an outer conductor (127,128) of said distribution cable (123) form a distributed capacitance.
8. The pulse forming device of any one of the foregoing claims, **characterized** in that its components like inductance, capacitance and resistance are dimensioned in such a manner with respect to the inductance, the capacitance and the resistance inherent to said ignitor gap prior to breakdown that the circuit inductance is so low that at least 50% of said stored quantity of electrical energy is transferred to said gap within the first one-half cycle of said alternating current.

9. The pulse forming device of claim 8, **characterized** in that the electrical circuit in which a discharge channel (58) is established satisfies the following equation:

$$0,5 \geq \frac{L/lg}{\frac{t_m^2}{4C \cdot lg} + \frac{2R_m t_m + L}{3 \cdot lg} - 1}$$

where t_m is the time in nanoseconds at which the rate of rise of current flow in the discharge circuit is substantially maximum,

R_m is the resistance in ohms of the discharge channel at t_m ,

C is the capacitance in nanofarads of the discharge circuit, preferably between 100 and 5000 picofarads,

L is the inductance in nanohenries of the discharge circuit, and

lg is the length in centimeters of the ignition gap, preferably between 0.01 and 1.0 centimeters, and the value L/lg being preferably less than 100 nanohenries per centimeter.

10. The pulse forming device of claim 8 or 9, **characterized** in that the ratio of the inductance of said capacitor (50) and said discharge device (52) to the length of said discharge channel (58) is less than approximately 100 nanohenries per centimeter.

11. The pulse forming device of claim 10, **characterized** in that the ratio of the inductance of the electrical discharge circuit which includes said capacitor (50), a connection between said capacitor (50) and said electrodes (104,120) and said ignition gap to the length of said discharge channel (58) is less than approximately 80 nanohenries per centimeter.

12. The pulse forming device of any one of claims 9 to 11, **characterized** in that said capacitor (50) is charged to a voltage of between approximately 20,000 and 40,000 volts.

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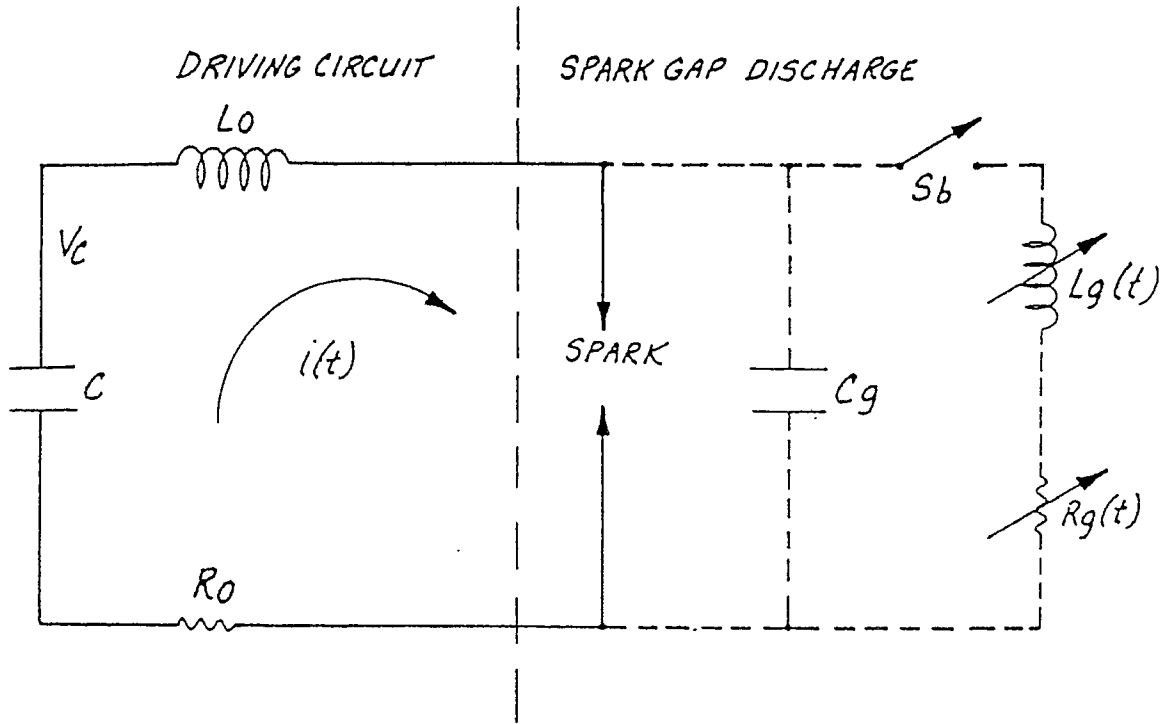


Fig-1

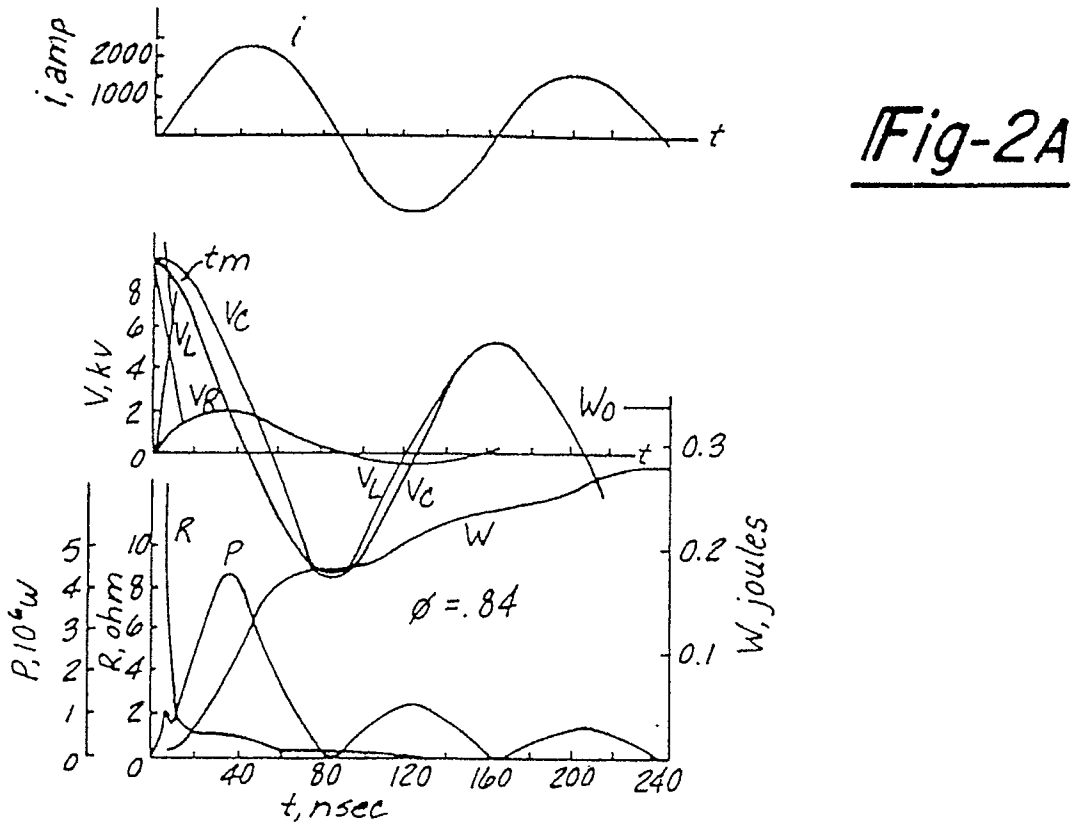
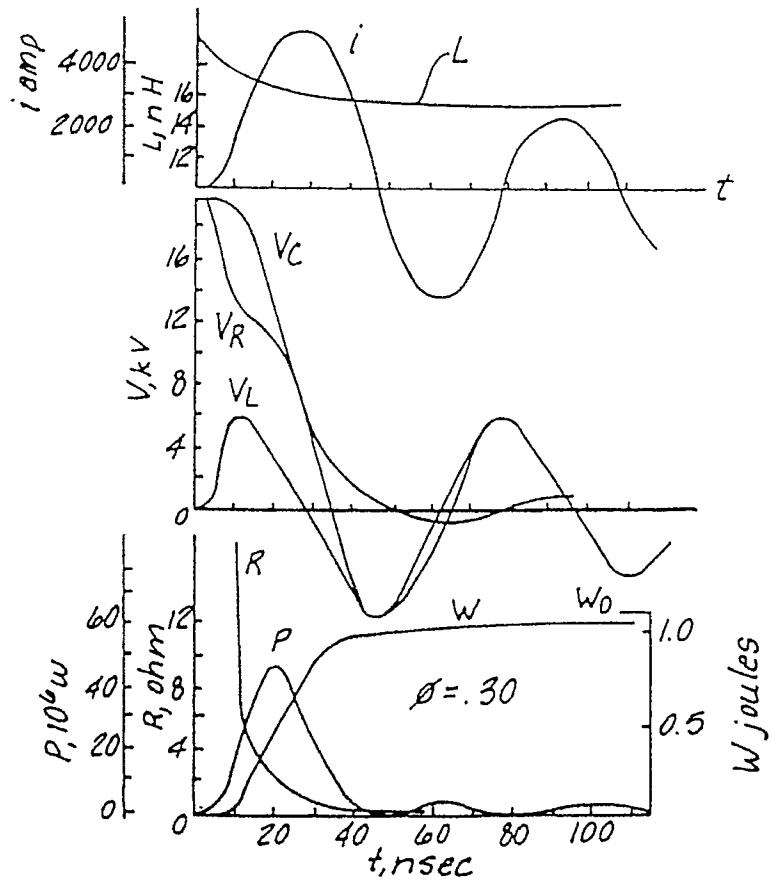


Fig-2B



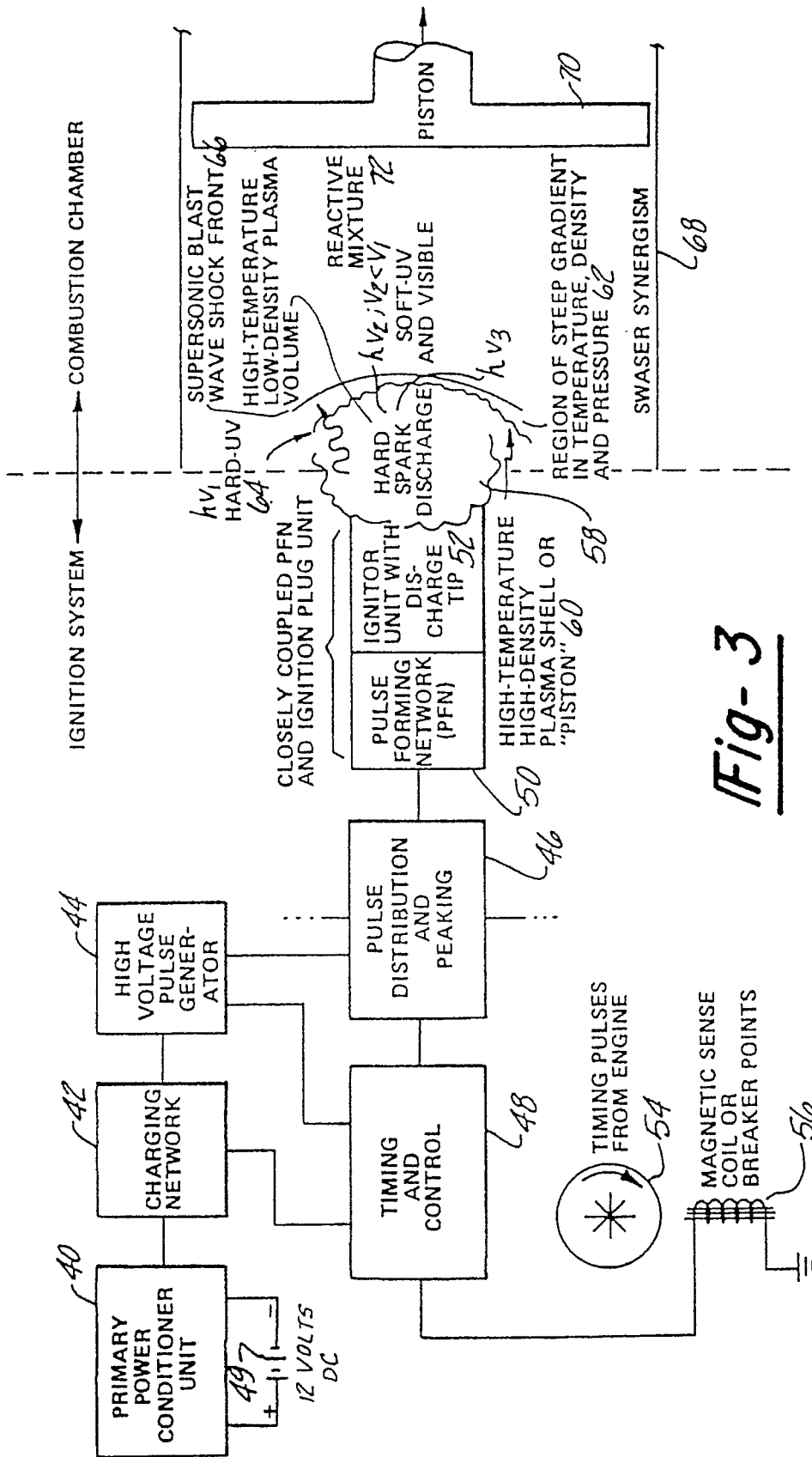


Fig- 3

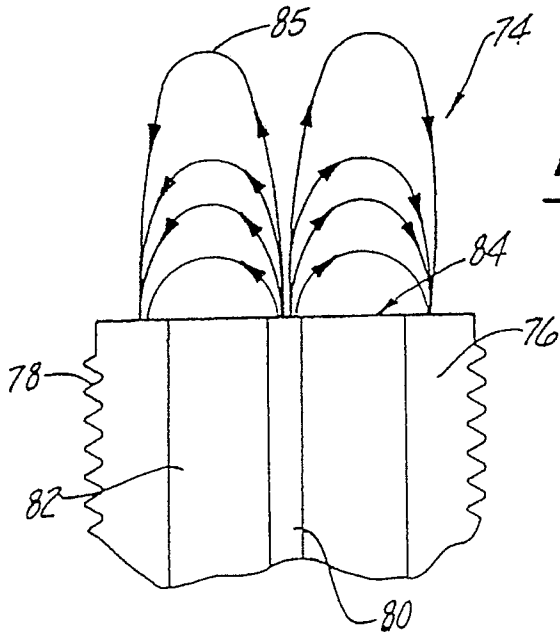


Fig- 4A

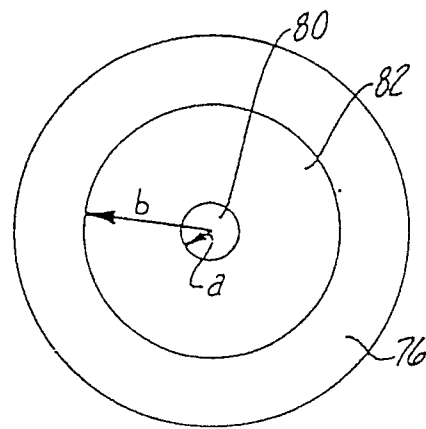


Fig- 4B

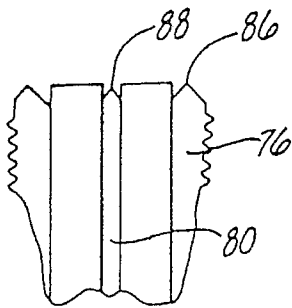


Fig- 4C

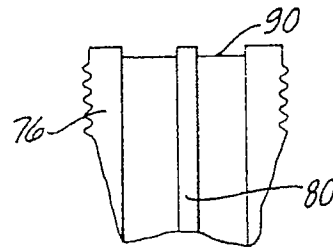


Fig- 4D

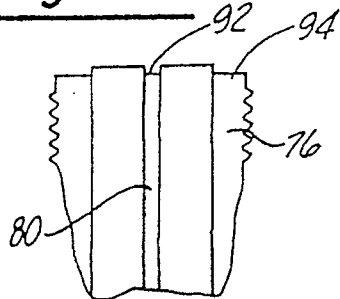


Fig- 4E

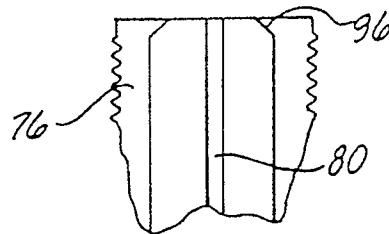


Fig- 4F

Fig- 4G

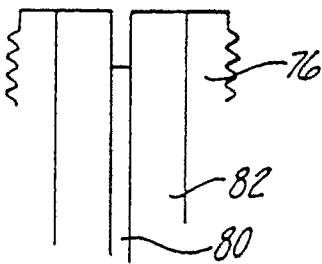


Fig- 4H

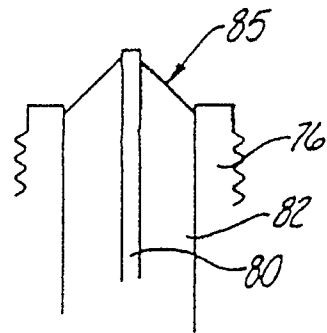
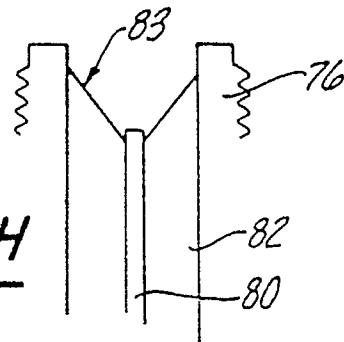
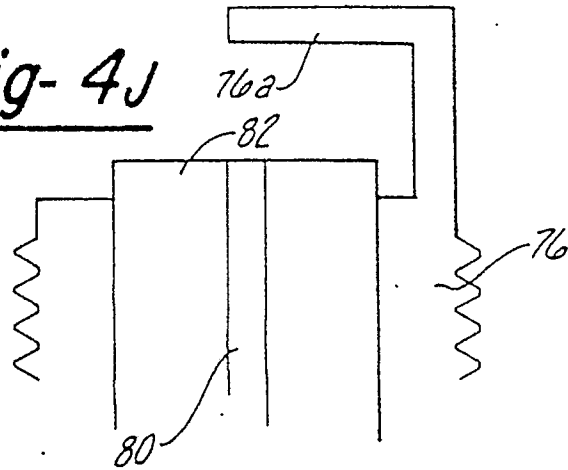


Fig- 4I

Fig- 4J



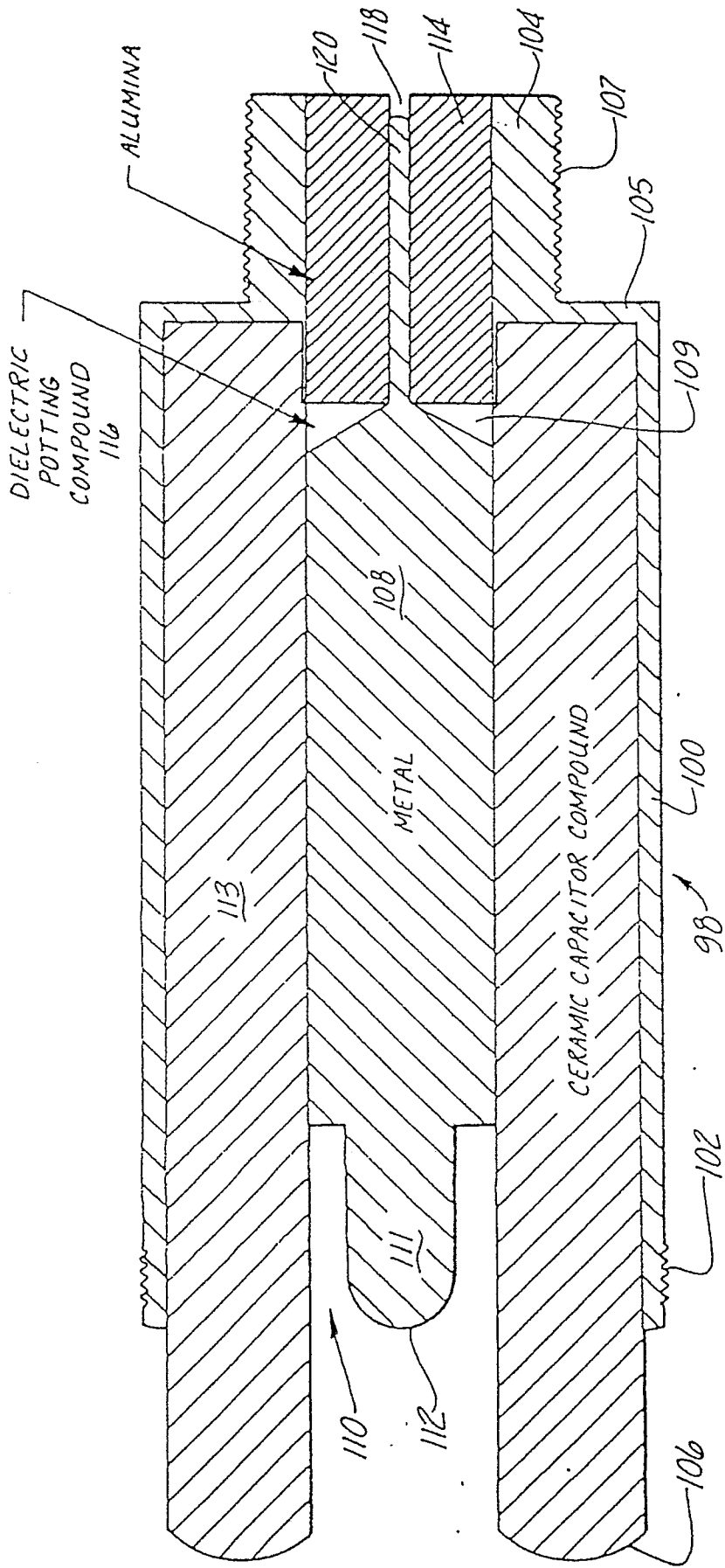
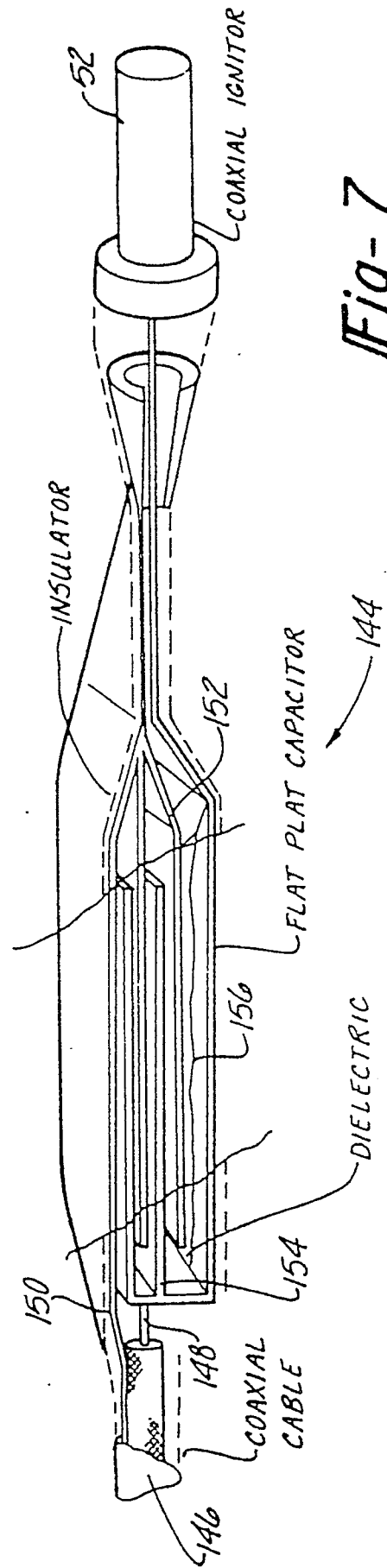
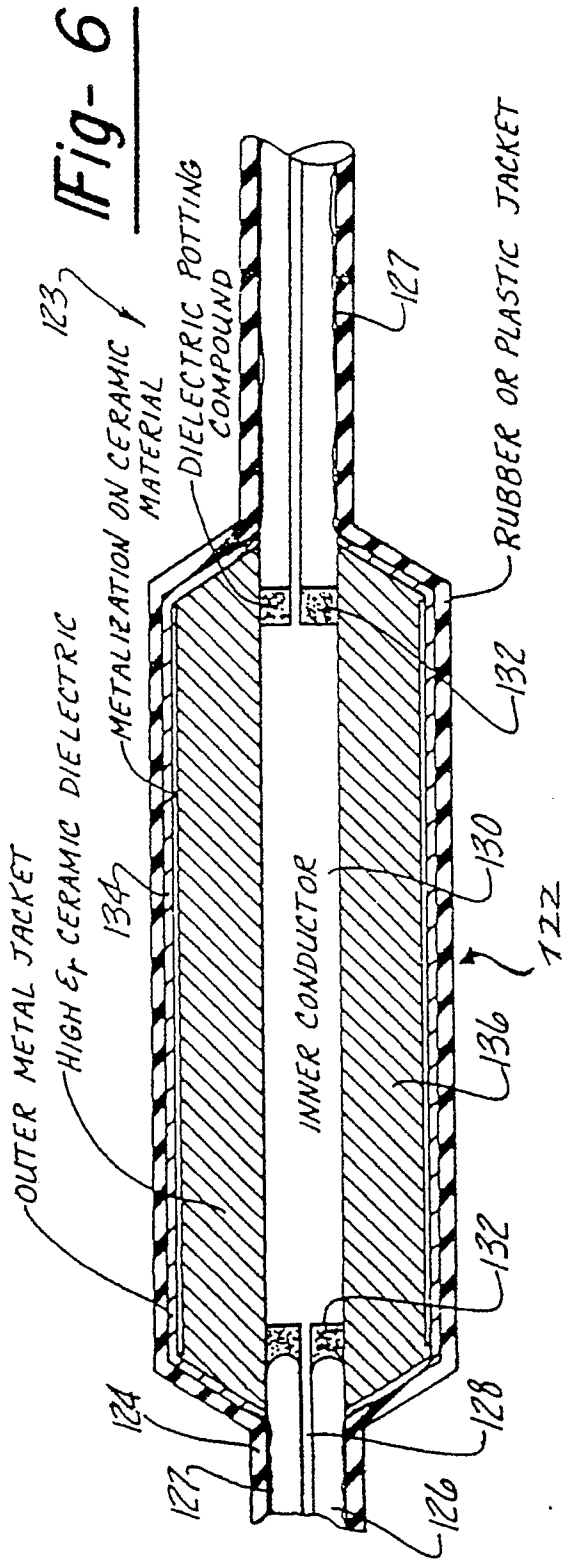
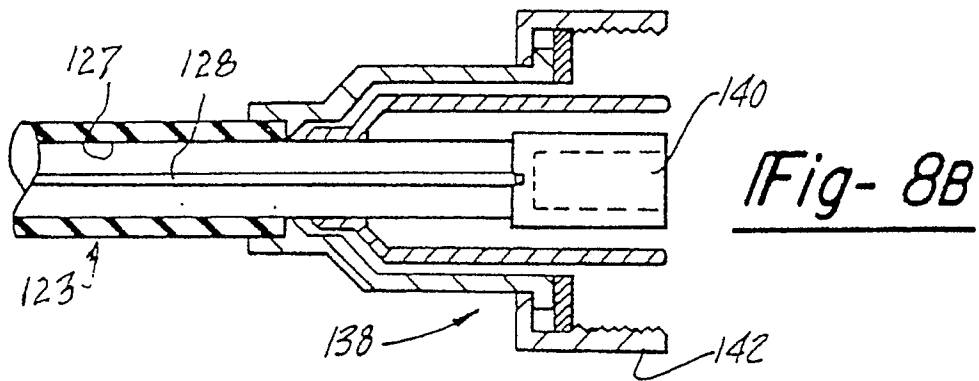
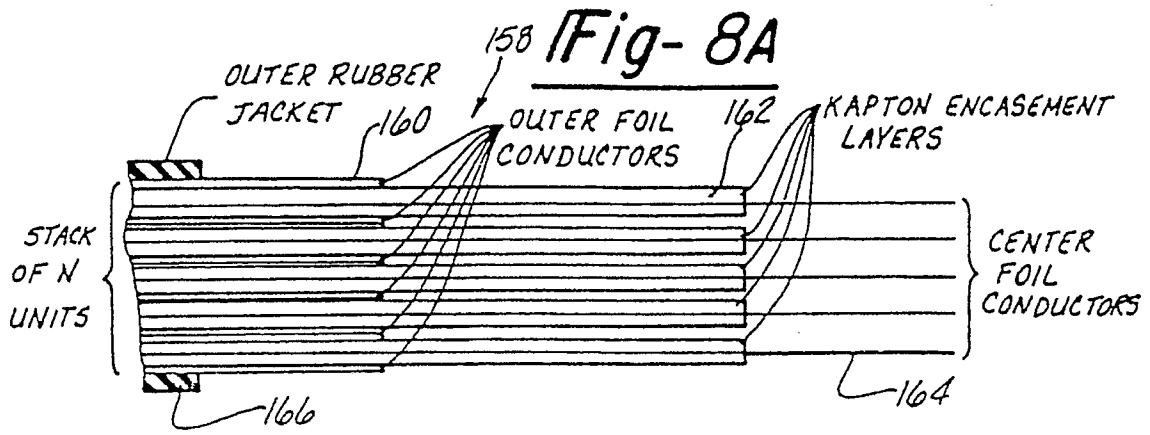
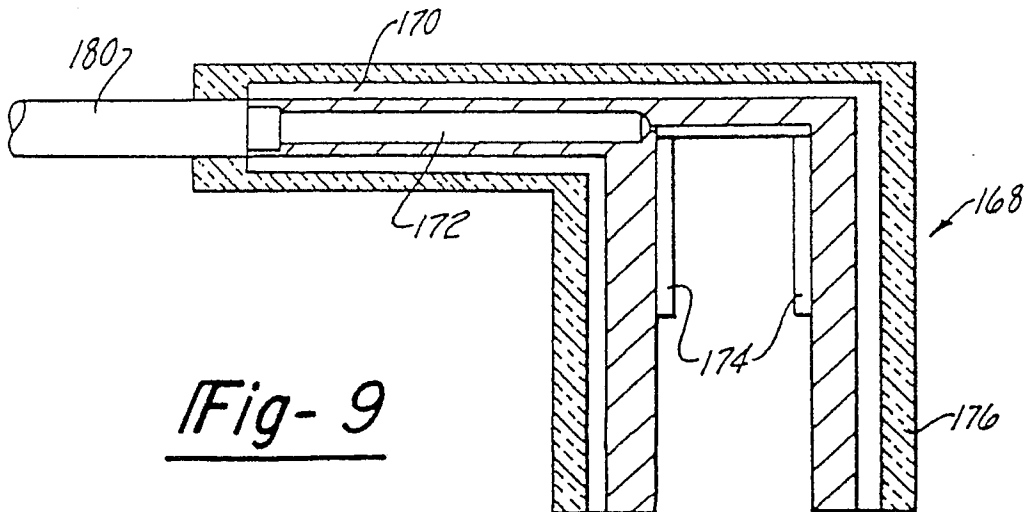


FIG - 5





POSSIBLE STRIPLINE TERMINATION-
CONNECTOR



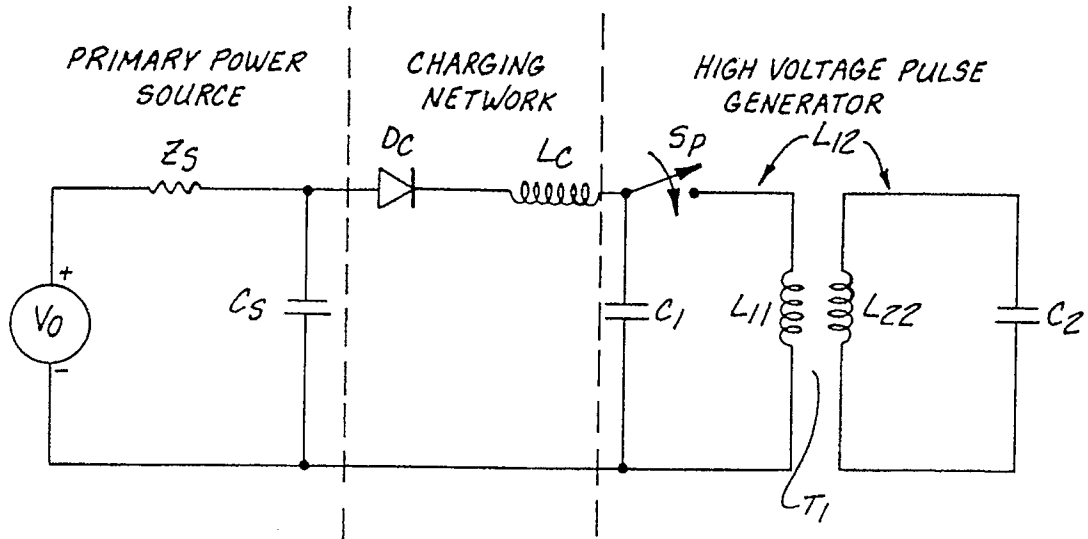


Fig- 10

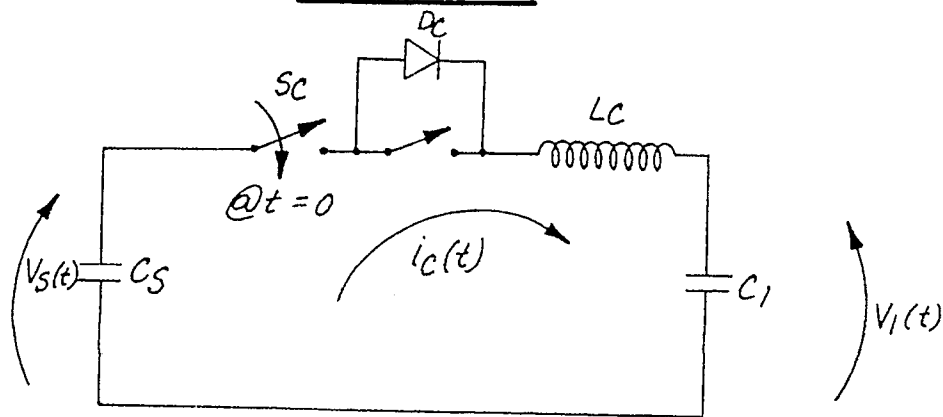


Fig- 11

