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(54) **Titre : ALLUMAGE PAR MICRO-ONDES DE PROPULSEURS ELECTRIQUES**
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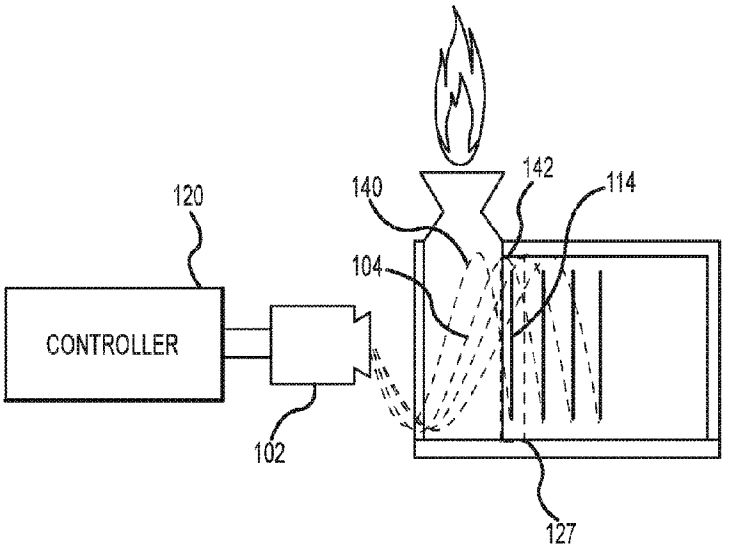

(57) **Abrégé/Abstract:**
Microwave energy is used to ignite and control the ignition of electrically operated propellant to produce high-pressure gas. The propellant includes conductive particles that act as a free source of electrons. Incoming microwave energy accumulates electric charge in an attenuation zone, which is discharged in the form of dielectric breakdowns to create local randomly oriented currents. The propellant also includes polar molecules. The polar molecules in the attenuation zone absorb microwave energy causing the molecules to rapidly vibrate thereby increasing the temperature of the propellant. The increase in temperature and the local current densities together establish an ignition condition to ignite and sustain ignition of an ignition surface of the attenuation zone as the zone regresses without igniting the remaining bulk of the propellant.

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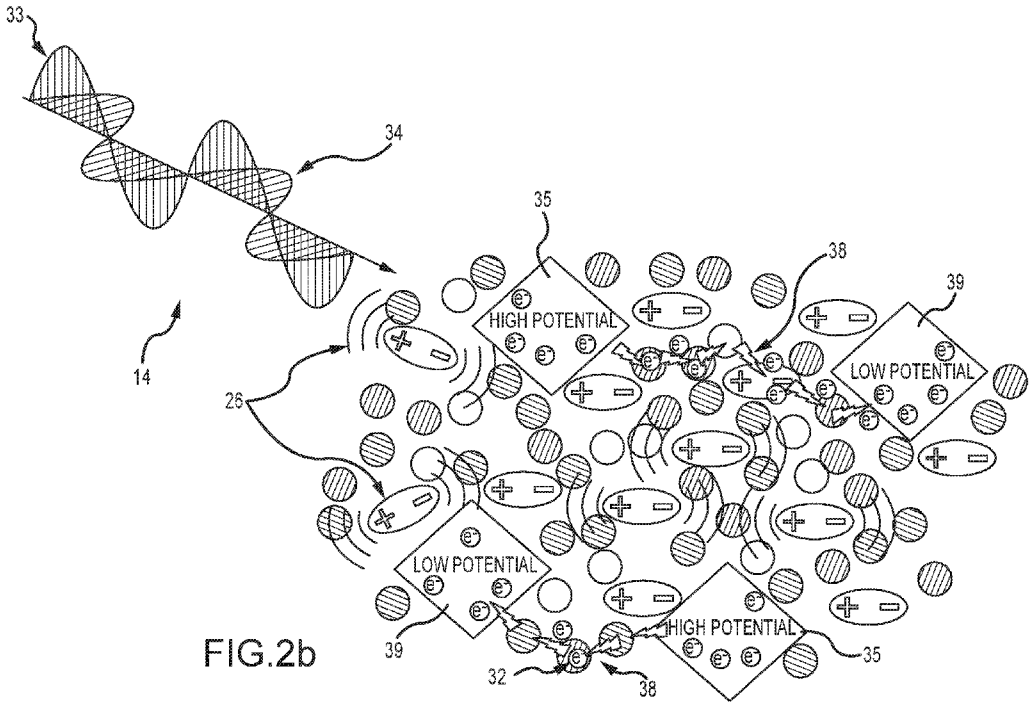

FIG.2b

(57) Abstract: Microwave energy is used to ignite and control the ignition of electrically operated propellant to produce high-pressure gas. The propellant includes conductive particles that act as a free source of electrons. Incoming microwave energy accumulates electric charge in an attenuation zone, which is discharged in the form of dielectric breakdowns to create local randomly oriented currents. The propellant also includes polar molecules. The polar molecules in the attenuation zone absorb microwave energy causing the molecules to rapidly vibrate thereby increasing the temperature of the propellant. The increase in temperature and the local current densities together establish an ignition condition to ignite and sustain ignition of an ignition surface of the attenuation zone as the zone regresses without igniting the remaining bulk of the propellant.

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MICROWAVE IGNITION OF ELECTRICALLY OPERATED PROPELLANTS

BACKGROUND OF THE INVENTION

Field of the Invention

This invention relates to electrically operated propellant and more particularly to techniques for ignition, control and extinguishment of electrically operated propellants.

Description of the Related Art

All solid propellants are a combination of oxidizer, fuel, binder and additives. The oxidizer provides oxygen required to burn the fuel. The binder provides a structural material to bind the fuel and oxidizer. The binder itself is a fuel. Additional fuel may or may not be required. Additives may be used for a variety of purposes including to assist mixing of the propellant, to control the burn rate, etc. For example, additives containing polar molecules such as H_20, glycerol, dimethul sulfoxide (DMSO), n-butanol, ethanolamine and 2-ethoxyethanol are used to mix the propellant. These polar molecules are substantially removed during the baking process leaving only a trace amount in the final propellant. Propellant may be used for gas generators, rocket motors, air bags and the like. It is desirable that substantially all of the propellant is or can be consumed.

Solid rocket motor (SRM) propellants are ignited thermally and burn vigorously to completion of the propellant. SRM propellants typically exhibit a designed burn rate and consume substantially all of the propellant. The burn rate may be controlled through complicated valve systems referred to as a "pintle". Furthermore, once ignited, SRM propellants cannot be "turned off" except by a violent and uncontrolled depressurization. The most common oxidizer for SRM propellants is a solid ammonium perchlorate (AP). The resulting SRM propellant ignites in response to heat but is electrically inert.

SRM propellants are typically initiated using a secondary pyrotechnic such as a 1.4 level explosive. This explosive is ignited via a bridgewire that heats up and transfers heat

energy to the energetic material. This very sensitive energetic material then ignites the primary SRM propellant. Another proposed approach is to use a laser to supply photon energy in the visible band from approximately 430-770 THz to directly heat the primary SRM propellant unit it reaches its ignition point.

Electrically operated propellants are ignited by application of heat and an electric input. In a simple configuration, a voltage is applied between parallel wires embedded in the propellant. This produces ohmic heating of the propellant that raises the temperature of the propellant to above a thermal ignition threshold. Application of the voltage across the propellant creates a current density (J) = current (I)/area (A) of the propellant. The current density J must exceed an electrical ignition threshold of the propellant to ignite and burn. To support electrical operation, the oxidizer is "ionic" in the sense of providing free-flowing ions necessary for electrical control. The burn rate of the propellant may be controlled via the electric input.

Certain formulations of the propellant, and more specifically the oxidizer, allow combustion to be extinguished by interruption of the electric input as long as the chamber pressure remains less than a self-sustaining threshold pressure. The propellant may be reignited by reapplication of the electric input. Sawka's hydroxyl-ammonium nitrate (HAN) based propellant (US 8,857,338) exhibits a threshold of about 150 psi. Villarreal's perchlorate-based propellant (US 8,950,329) can be configured to exhibit a threshold greater than 200, 500, 1.500 and 2,000 psi. These higher threshold pressures allow for more practical applications in which the combustion may be turned on and off at elevated chamber pressures. For these reasons, electrically operated propellants are an attractive option to more mature SRM propellants.

A challenge to achieve wide spread use is to provide an electrode configuration that provides for control of the ignition surface and burn rate and efficient consumption of substantially all of the propellant, and one that is scalable to combust greater propellant mass to support larger gas generation systems. In various configurations, the propellant will only ignite at or very close to one of the electrodes and burn down the electrode. "Burn Back" as this is referred is an uncontrolled and inefficient process to ignite and consume propellant.

U.S. Patent No. 8,857,338 "Electrode Ignition and Control of Electrically Ignitable Materials" also discloses an apparatus for providing electrically initiated and/or controlled combustion of electrically ignitable propellants is provided. In one example, the apparatus includes a volume of electrically ignitable propellant (solid and/or liquid), which is capable of self-sustaining combustion, and two (or more) electrodes operable to ignite the propellant. The apparatus may further include a power supply and controller in electrical communication with the electrodes for supplying a potential across the electrodes to initiate combustion of the propellant and/or control the rate of combustion of the propellant. For instance, by increasing or decreasing the power and current supplied through the propellant the rate of combustion may be varied.

Various configurations and geometries of the propellant, electrodes, and apparatus are described. In one example, the electrodes are in electrical contact with the electrically ignitable propellant and are supplied a direct current, which may cause combustion of the electrically ignitable propellant at the contact location of the positive electrode with the electrically ignitable propellant. In another example, the electrodes are supplied an alternating current, which may initiate nearly simultaneously combustion of the electrically ignitable propellant at the contact locations of the electrodes with the electrically ignitable propellant. In some examples, one or more of the electrodes may include an insulator material insulating a portion of the electrode from the electrically ignitable propellant (which may burn away with combustion of the propellant).

In one configuration, a center insulated wire electrode is positioned along the axis of a cylindrical electrode in a coaxial configuration around the propellant (FIGs. 1a-1b). As combustion of the propellant is initiated, the insulation burns away and the propellant regresses along the axis. In another configuration, parallel plate electrodes are positioned to either side of the propellant (FIGs 3a-3b). In the FIG. 3a embodiment, one of the parallel plate electrodes is insulated to produce combustion of the propellant to spread across the gain-end to the outer cathode. The combustion of the propellant propagates to the left along the axis of the structure, in a generally uniform manner as illustrated. In contrast, in the FIG. 3b embodiment both of the plate electrodes are un-insulated. The propellant is broadly ignited along much of or the entire length of the positive electrode.

SUMMARY OF THE INVENTION

The following is a summary of the invention in order to provide a basic understanding of some aspects of the invention. This summary is not intended to identify key or critical elements of the invention or to delineate the scope of the invention. Its sole purpose is to present some concepts of the invention in a simplified form as a prelude to the more detailed description and the defining claims that are presented later.

The present invention provides for microwave ignition of electrically operated propellant.

In an embodiment, a gas generation system includes an electrically operated propellant and a source configured to generate microwave radiation in a defined microwave band between 0.3 GHz and 300 GHz e.g., 5 GHz +/- 5%. One or more additives include conductive particles (e.g., metals such as tungsten, magnesium, aluminum ... or non-metals such as graphene or carbon nanotubes) suspended within the propellant that increase the conductivity of the propellant by acting as a free source of electrons. These metal additives may be the same or different than metal additives that may constitute the fuel for the propellant. One or more additives include polar molecules (e.g., H_20, glycerol, dimethul sulfoxide (DMSO), n-butanol, ethanolamine or 2-ethoxyethanol) suspended within the propellant (which remain after baking).

In an ignition condition, incoming microwave energy creates an electric field **E** within an attenuation zone of the propellant that oscillates at the microwave frequency. The electric field **E** causes the free electrons to accumulate at conductive particles of high potential and be discharged in the form of dielectric breakdowns through the other constituents of the propellant to conductive particles of low potential. These discharges form randomly oriented local currents that exhibit local current densities J that exceed an electrical ignition threshold. The electric field **E** also causes the polar molecules to vibrate rapidly, which raises the temperature of the propellant above a thermal ignition threshold in the attenuation zone. In this ignition condition, an ignition surface of the attenuation zone ignites and burns as the zone regresses without igniting the remaining bulk of the

propellant to generate gaseous byproducts that pressurize a combustion chamber.

In an embodiment, the microwave energy coupled into the propellant is split between vibrating the polar molecules ("dielectric heating") and the dielectric breakdowns within the attenuation zone. At least 5% of the coupled microwave energy is directed to dielectric heating and at least 5% to dielectric breakdown. More typically, 70-90% of the coupled microwave energy is directed to dielectric heating and 10-30% to dielectric breakdown. The balance may be affected by the selection and relative concentrations of the conductive particles and polar molecules as well as the microwave frequency.

In an embodiment, to efficiently couple microwave energy to the attenuation zone, an anti-node (peak of the oscillating wave) of the microwave energy is positioned at the ignition surface. In one embodiment, the phase of the microwave energy is modulated such that the anti-node tracks the position of the ignition surface as the attenuation zone regresses. In another embodiment, an actuator displaces the propellant to hold the ignition surface in place at the fixed anti-node of the microwave energy.

In an embodiment, the electrically operated propellant exhibits a self-sustaining threshold pressure at which the propellant once ignited cannot be extinguished and below which the propellant can be extinguished by interruption of an electrical input. This threshold may be as low as 150 psi and range up to 200, 500, 100, 1,500 and above 2,000 psi depending on the formulation of the propellant. In an extinguishment condition, combustion of the propellant is turned off by interrupting of the microwave energy as long as the chamber pressure has not exceeded this threshold.

In an embodiment, the electrically operated propellant includes an ionic oxidizer, a binder and a fuel plus the conductive additive and polar molecules. The ionic oxidizer, suitably a liquid when mixed, provides the free flowing ions necessary to achieve the elevated thresholds. For example, the oxidizer may be a liquid perchlorate based oxidizer. The propellants have demonstrated thresholds in excess of 2,000 psi. The fuel may comprise a metal fuel such as aluminum or magnesium selected for their IR emittance or heat absorbance properties. The metal additive may be for example gold or tungsten selected for their electrical properties to provide free electrons. A concentration of the polar molecules remains after the baking process.

In an embodiment, an electrically operated propellant for microwave ignition is formulated by adding polar molecules and conductive particles to a base composition of an oxidizer, fuel and binder, mixing the constituent elements and baking the propellant to leave some concentration of polar molecules in the cured electrically operated propellant. The concentration of polar molecules and conductive particles defining ignition mechanisms responsive to incoming microwave energy to generate both the dielectric heating and dielectric breakdowns to establish an ignition condition to ignite and sustain ignition of an ignition surface without igniting the remaining bulk of the propellant. The metal additive and polar molecule additive may each constitute between 5 and 40 percent of the mass of the propellant.

In an embodiment, a gas generation system comprises: a combustion chamber; a source configured to generate microwave energy in a defined microwave band between 0.3 GHz and 300 GHz and to provide said microwave energy as an electrical input; and an electrically operated propellant in which an ignition condition of the electrically operated propellant is defined by satisfying both a thermal ignition threshold and an electrical ignition threshold, wherein said electrically operated propellant has a self-sustaining threshold pressure at which the electrically operated propellant once ignited cannot be extinguished and below which the electrically operated propellant can be extinguished by interruption of the electrical input in an extinguishment condition, said electrically operated propellant further including: one or more conductive additives including conductive particles suspended within the electrically operated propellant that increase a conductivity of the electrically operated propellant; and one or more polar additives including polar molecules suspended within the electrically operated propellant, wherein the one or more conductive additives and the one or more polar additives reduce an amount of the microwave energy otherwise required to satisfy the ignition condition and to sustain combustion of the electrically operated propellant; and a controller configured to control the source such that in the ignition condition, the microwave energy accumulates electric charge in the electrically operated propellant in an attenuation zone, with said electric charge being discharged in the form of dielectric breakdowns between the conductive particles through the electrically operated propellant such that a local current density J

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surpasses the electrical ignition threshold, and wherein in the ignition condition, the microwave energy also rapidly vibrates the polar molecules to increase a temperature of the electrically operated propellant in the attenuation zone to surpass the thermal ignition threshold, whereby the controller controls the source such that the electrical ignition threshold and the thermal ignition threshold are met only at an ignition surface of the attenuation zone whereby only the ignition surface is ignited without igniting a remaining bulk of the electrically operated propellant, to thereby generate gaseous byproducts that pressurize the combustion chamber while maintaining a combustion chamber pressure of the combustion chamber at less than the self-sustaining threshold pressure, wherein the controller is further configured to control the source to vary a phase or frequency of the microwave energy such that an anti-node of the microwave energy tracks the ignition surface as the attenuation zone regresses, and wherein in the extinguishment condition the source interrupts generation of the microwave energy to interrupt the electrical input and extinguish the electrically operated propellant.

In an embodiment, a method of generating gaseous byproduct to pressurize a combustion chamber comprises: providing an electrically operated propellant in which an ignition condition of the electrically operated propellant is defined by satisfying both a thermal ignition threshold and an electrical ignition threshold, said electrically operated propellant having a self-sustaining threshold pressure of at least 200 psi at which the electrically operated propellant once ignited cannot be extinguished and below which the electrically operated propellant can be extinguished by interruption of an electrical input, said electrically operated propellant including metal particles and polar molecules suspended within the electrically operated propellant to reduce an amount of energy supplied by the electrical input required to satisfy the ignition condition; supplying microwave energy as the electrical input to the electrically operated propellant to rapidly vibrate the polar molecules to increase a temperature of the electrically operated propellant above the thermal ignition threshold; supplying the microwave energy as the electrical input to the electrically operated propellant to accumulate and then discharge electric charge in the form of dielectric breakdowns into randomly oriented local currents that exhibit a local current density J above the electrical ignition threshold thereby satisfying

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the ignition condition and thereby igniting and sustaining ignition of an ignition surface as the electrically operated propellant burns, wherein the metal particles and polar molecules reduce an amount of the microwave energy otherwise required to satisfy the ignition condition and to sustain the burning of the electrically operated propellant, wherein combustion of the ignited electrically operated propellant generates the gaseous byproduct that pressurizes the combustion chamber; varying a phase or frequency of the microwave energy such than an anti-node of the microwave energy tracks the ignition surface as an attenuation zone regresses; and extinguishing the electrically operated propellant by interrupting the microwave energy while the electrically operated propellant is subject to pressure less than the self-sustaining threshold pressure.

These and other features and advantages of the invention will be apparent to those skilled in the art from the following detailed description of preferred embodiments, taken together with the accompanying drawings, in which:

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is an illustration of a gas generation system using microwave ignition of an electrically operated propellant;

FIGs. 2a and 2b are illustrations of an electrically operated propellant with polar molecule and conductive particle additives and microwave stimulation of the propellant to produce dielectric heating and dielectric breakdowns to ignite an ignition surface;

FIGs. 3a and 3b are illustrations of the gas generation system with varying depths of the attenuation zone in the electrically operated propellant based on the concentration of conductive particles;

FIGs. 4a and 4b are illustrations of the gas generation system with varying depths of the attenuation zone in the electrically operated propellant based on the operating frequency of the microwave energy;

FIG. 5 is an illustration of an embodiment of a rocket motor using microwave ignition of an electrically operated propellant;

FIG. 6 is a diagram illustrating the ignition, throttling and extinguishing of the electrically operated propellant by the microwave source; and

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FIGs. 7a and 7b are embodiments of a phase-controlled microwave source and a linear actuator for the electrically operated propellant to position the anti-node of the microwave energy at the ignition surface of the electrically operated propellant.

DETAILED DESCRIPTION OF THE INVENTION

The present invention provides for microwave ignition of electrically operated propellant. Microwave ignition overcomes the issue of "burn back" exhibited by various electrode configurations. Microwave ignition is scalable to combust greater propellant mass to support larger gas generation systems.

Referring now to Figures 1, 2a and 2b, a gas generation system **10** includes a source **12** (e.g. a magnetron) configured to generate microwave energy **14** in a defined microwave band between 0.3 GHz and 300 GHz, a mass of electrically operated propellant **16** and a combustion chamber **18**. Typically, the walls of the chamber around the mass of propellant are impermeable to the microwave energy and the far wall opposite the mass is permeable to the microwave energy. The microwave band is generally a narrow band above a center frequency Fc. The band is typically at most +/- 10% of Fc and more typically +/- 5% of Fc. In certain embodiments, Fc lies between 1 and 10 GHz.

The electrically operated propellant **16** may be any formulation of constituent elements in which an ignition condition of the propellant is defined by satisfying both a thermal ignition threshold and an electrical ignition threshold. To ignite the propellant, the temperature of the propellant must exceed the thermal ignition threshold and the current density J must exceed the electrical ignition threshold.

The base electrically operated propellant **16** includes a combination of constituent elements including an oxidizer **20**, a fuel **22**, and a binder **24**. The oxidizer provides oxygen required to burn the fuel. The binder provides a structural material to bind the fuel and oxidizer. The binder itself is a fuel. Additional fuel may or may not be required. The additional fuel may be a metal-based fuel such as aluminum magnesium or a polymer-based fuel such as Polyvinyl alcohol (PVA) and Polyvinylidene fluoride (Kynar).

To facilitate microwave ignition, the base electrically operated propellant is modified to reduce the amount of microwave energy required to satisfy both the thermal

and electrical ignition conditions. Without such modification to the formulation, microwave ignition while theoretically possible would be impracticable.

The base electrically operated propellant may often include an additive containing polar molecules such as H_20, glycerol, dimethul sulfoxide (DMSO), n-butanol, ethanolamine or 2-ethoxyethanol to mix the constituent elements of the propellant. The polar molecules are then removed during the baking process. This process may be modified by either increasing the original concentration of the polar molecules or changing the baking process such that a concentration of polar molecules **26** remain suspended in the final cured electrically operated propellant. For example, the polar molecule additive may constitute approximately 5 to 40 percent of the mass of the cured electrically operated propellant.

A polar molecule has a net polarity **28** as a result of the opposing charges (i.e. having partial positive and partial negative charges) from polar bonds arranged asymmetrically. Water (H_20) is an example of a polar molecule since it has a slight positive charge on one side and a slight negative charge on the other. The dipoles do not cancel out resulting in a net polarity. If the bond dipole moments of the molecule do not cancel, the molecule is polar. For example, the water molecule (H_20) contains two polar O-H bonds in a bent (nonlinear) geometry. The bond dipole moments do not cancel, so that the molecule forms a molecular dipole with its negative pole at the oxygen and its positive pole midway between the two hydrogen atoms.

The base electrically operated propellant may include conductive particles in the form of the metal-based fuel. Alternately, one or more additives including conductive particles **30** (e.g., metals such as tungsten, magnesium, aluminum ... or non-metals such as graphene or carbon nanotubes) may be suspended within the propellant. The conductive particles increase the conductivity of the propellant by acting as a free source of electrons **32**. The fuel may comprise a metal fuel such as aluminum or magnesium selected for their IR emittance or heat absorbance properties. The additive may be, for example, gold or tungsten selected for their electrical properties to provide free electrons. The non-fuel additives typically have higher conductivity and provide more free electrons. The conductive additive may constitute approximately 5 to 40 percent of the mass of the

electrically operated propellant.

As shown in Figure 2b, in an ignition condition, incoming microwave energy **14** includes both a magnetic field **B 33** an electric field **E 34** within an attenuation zone **36** of the propellant that oscillate at the microwave frequency. The electric field **E 34** penetrates an attenuation zone **36.** The remaining bulk **37** of the propellant is a region of little to no absorption. The electric field **E** causes the free electrons **32** to accumulate at conductive particles **30** of high potential **35** and be discharged in the form of dielectric breakdowns through the other constituents of the propellant to conductive particles **30** of low potential **39**. The charge follows a path of least resistance between conductive particles. These discharges form randomly oriented local currents **38** that exhibit local current densities J that exceed an electrical ignition threshold. The net bulk current across the attenuation zone will be near zero. The randomness of the local discharges largely cancels. There might be a small bias current from the front to the back of the attenuation zone on account of a natural gradient in the amount of energy coupled to the material. Because signal attenuation (absorption) is a percentage of the available microwave power, the signal gets absorbed most rapidly at the front surface.

The electric field **E** also causes the polar molecules **26** to vibrate rapidly (the net polarity **28** tries to switch with the electric field **E** but cannot move fast enough), which produces dielectric heating to raise the temperature of the propellant above a thermal ignition threshold in the attenuation zone. Ignition typically occurs around 200 C for most propellants.

In this ignition condition, an ignition surface **40** of the attenuation zone ignites and burns as the zone regresses without igniting the remaining bulk of the propellant to generate gaseous byproducts **42** that pressurize a combustion chamber. The dielectric heating and dielectric breakdowns occur throughout the attenuation zone but most strongly at the ignition surface **40** because of signal attenuation causing it to ignite first. The thermal and electrical ignition thresholds may be satisfied throughout the attenuation zone but need only be satisfied at the ignition surface. The burn rate and regression of the burning propellant means that only the surface will burn as the propellant regresses. Burn back should not be a problem.

In different embodiments, to satisfy both the thermal ignition threshold and the electrical ignition threshold the polar molecules and conductive particles each constitute at least 5% of the mass of the electrically operated propellant. Furthermore, the additives and their relative concentrations are typically selected so that at least 5% of the microwave energy coupled to the propellant is absorbed by the polar molecules for dielectric heating and discharged in dielectric breakdowns. More typically, 70 – 90% of the energy is directed to dielectric heating and 10-30 % to dielectric breakdowns.

In an embodiment, the electrically operated propellant **16** is formulated to exhibit a self-sustaining threshold pressure at which the propellant once ignited cannot be extinguished and below which the propellant can be extinguished by interruption of an electrical input. Sawka's hydroxyl-ammonium nitrate (HAN) based propellant (US 8,857,338) exhibits a threshold of about 150 psi. Villarreal's perchlorate-based propellant (US 8,950,329) can be configured to exhibit a threshold greater than 200, 500, 1,500 and 2,000 psi. In an extinguishment condition, combustion of the propellant is turned off by interrupting of the microwave energy as long as the chamber pressure has not exceeded this threshold.

In an embodiment, the electrically operated propellant **16** comprises an oxidizer such as an ionic perchlorate-based oxidizer of approximately 50 to 90 percent of the mass of the electrically operated propellant, a binder of approximately 10 to 30 percent of the mass of the electrically operated propellant, a metal or polymer based fuel of approximately 5 to 30 percent of the mass of the electrically operated propellant, a metal additive of approximately 5 to 40 percent of the mass of the electrically operated propellant, said metal additive acting as a free source of electrons to increase the conductivity of the propellant and a polar molecule additive of approximately 5 to 40 percent of the mass of the electrically operated propellant. The electrically operated propellant is configured to ignite and extinguish according to the respective application and interruption of microwave energy. The electrically operated propellant has a self-sustaining threshold pressure at which pressure the propellant once ignited cannot be extinguished and below which the propellant can be extinguished by interruption of the microwave energy.

Referring now to Figures 3a-3b and 4a-4b, a penetration depth **50** of an attenuation

zone **52** in a propellant **54** is by convention defined as the depth at which $1/e^2$ ($\cong$13%), where e is base of the natural log, of a signal energy **56** at center frequency Fc from a source **58** remains assuming an anti-node (peak) **60** is positioned at an ignition surface **62**. These peaks of amplitude, called anti-nodes, are the points at which energy is transferred into the propellant most rapidly. The desired penetration depth **50** may depend on such factors as the grain size of the propellant, the size of a rocket motor engine, thrust requirements. The penetration depth **50** may vary as the propellant regresses to accommodate initial ignition conditions versus ongoing burn or changing thrust requirements. A remaining bulk **64** of the propellant is a region of little to no absorption.

In general, the penetration depth is a function of the nature and concentration of the polar molecules and conductive additive and the microwave frequency Fc. As shown in Figures 3a-3b, the more absorbing or the greater the concentration of either additive the shallower the penetration depth **50**. The concentration may be varied throughout the propellant to change the depth of the attenuation zone as the propellant burns and regresses. As shown in Figures 4a-4b, the lower the frequency (longer the wavelength) the shallower the penetration depth **50**. The frequency may be varied to change the depth of the attenuation zone as the propellant burns and regresses.

Referring now to Figures 5 and 6, an embodiment of a rocket motor **100** includes a source **102** (e.g. a magnetron) configured to generate microwave energy **104** in a defined microwave band between 0.3 GHz and 300 GHz. A mass of electrically operated propellant **106** is contained in a microwave impermeable case **108**. A microwave permeable wall **110** defines a combustion chamber **112** to which a surface **114** of the propellant is exposed. A nozzle **116** is coupled to the combustion chamber to exhaust high-pressure gas **118** to produce thrust. A controller **120** is configured to control source **102** to set and possibly vary the amplitude and frequency of microwave energy **104** to control the burn rate, hence the thrust.

In an ignition condition, controller **120** configures source **102** to generate microwave energy **104** at a frequency Fc and of sufficient amplitude **122** such that the polar heating component **124** and local current density J component **126** in an attenuation zone **127** exceed their respective thermal ignition threshold **128** and electrical ignition threshold

130 at surface **114** to ignite and burn the surface. Burning of the propellant produces the high-pressure gas **118** at a chamber pressure Pc **132**.

In a throttle condition, controller **120** may throttle the burn rate, hence chamber pressure **132** and the resulting thrust up and down based on mission requirements. This would typically be done by varying the amplitude **122** of the of the microwave energy. Alternately, the controller may alter the frequency or phase of the microwave energy to vary the amount of energy coupled to the propellant.

In an extinguishment condition, provided the chamber pressure Pc **132** has not exceeded a self-sustaining threshold pressure **134** of the electronically operated propellant, the controller **120** may extinguish combustion of the propellant by interrupting the microwave energy. The controller may re-ignite the propellant by satisfying the ignition condition.

As long as the self-sustaining threshold pressure **134** is not exceeded, the controller **120** can turn the ignition of the propellant on and off at will. When combined with the high self-sustaining threshold pressures provided by Villareal's formulation, the controller has the flexibility to deliver a dynamic and controllable thrust profile such as might be used to control the motion and displacement of a vehicle or the rate and duration of the inflation of an automotive airbag.

As previously discussed, the peaks of amplitude of the microwave energy, called anti-nodes, are the points at which the microwave energy is transferred into the propellant most rapidly. As such, it is generally desirable to position the anti-node at the ignition surface at ignition and maintain that position as the propellant burns. For conciseness, the reference numbers used in Figure 5 are used here for like elements.

Referring now to Figure 7a, in an embodiment, controller **120** modulates the phase **140** (or frequency) of the microwave energy **104** is modulated such that an anti-node **142** tracks the position of the ignition surface **114** as the attenuation zone **127**, hence surface **114** regresses. This can be done open-loop based on a priori knowledge of the burn rate and regression of the propellant or closed-loop using a sensor to detect the position of surface **114** or rate of regression

Referring now to Figure 7b, in an embodiment, an actuator **150** displaces the

propellant **106** to hold the ignition surface **114** in place at a fixed anti-node **152** of the microwave energy. The actuator may comprise one or more springs, a linear actuator, a screw drive, hydraulic pistons or high-pressure gas and valves. The high-pressure gas in the chamber may be partially diverted behind the propellant to assist the actuator.

While several illustrative embodiments of the invention have been shown and described, numerous variations and alternate embodiments will occur to those skilled in the art. Such variations and alternate embodiments are contemplated, and can be made without departing from the spirit and scope of the invention as defined in the appended claims.

What is claimed is:

1. A gas generation system, comprising:

a combustion chamber;

a source configured to generate microwave energy in a defined microwave band between 0.3 GHz and 300 GHz and to provide said microwave energy as an electrical input;

an electrically operated propellant in which an ignition condition of the electrically operated propellant is defined by satisfying both a thermal ignition threshold and an electrical ignition threshold, wherein said electrically operated propellant has a self-sustaining threshold pressure at which the electrically operated propellant once ignited cannot be extinguished and below which the electrically operated propellant can be extinguished by interruption of the electrical input in an extinguishment condition, said electrically operated propellant further including:

one or more conductive additives including conductive particles suspended within the electrically operated propellant that increase a conductivity of the electrically operated propellant; and

one or more polar additives including polar molecules suspended within the electrically operated propellant,

wherein the one or more conductive additives and the one or more polar additives reduce an amount of the microwave energy otherwise required to satisfy the ignition condition and to sustain combustion of the electrically operated propellant; and

a controller configured to control the source such that in the ignition condition, the microwave energy accumulates electric charge in the electrically operated propellant in an attenuation zone, with said electric charge being discharged in the form of dielectric breakdowns between the conductive particles through the electrically operated propellant such that a local current density J surpasses the electrical ignition threshold, and wherein in the ignition condition, the microwave energy also rapidly vibrates the polar molecules to increase a temperature of the electrically operated propellant in the attenuation zone to surpass the thermal ignition threshold, whereby the controller controls the source such that the electrical ignition threshold and the thermal ignition threshold are met only at an ignition surface of the attenuation zone whereby

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only the ignition surface is ignited without igniting a remaining bulk of the electrically operated propellant, to thereby generate gaseous byproducts that pressurize the combustion chamber while maintaining a combustion chamber pressure of the combustion chamber at less than the self-sustaining threshold pressure,

wherein the controller is further configured to control the source to vary a phase or frequency of the microwave energy such that an anti-node of the microwave energy tracks the ignition surface as the attenuation zone regresses, and

wherein in the extinguishment condition the source interrupts generation of the microwave energy to interrupt the electrical input and extinguish the electrically operated propellant.

2. The gas generation system of claim 1, wherein the defined microwave band is a center frequency Fc between 0.3 GHz and 300 GHz plus or minus at most 10 % of the center frequency.

3. The gas generation system of claim 2, wherein the center frequency Fc is between 1 and 10 GHz.

4. The gas generation system of any one of claims 1 to 3, wherein the conductive particles include metal particles that provide fuel for the electrically operated propellant.

5. The gas generation system of any one of claims 1 to 4, wherein said conductive particles constitute at least 5 % by mass of the electrically operated propellant and said polar molecules constitute at least 5 % by mass of the electrically operated propellant.

6. The gas generation system of any one of claims 1 to 5, wherein said one or more conductive additives and said one or more polar additives are configured such that at least 5 % of the microwave energy coupled into the electrically operated propellant is discharged in dielectric breakdowns and at least 5 % is absorbed by the polar molecules to satisfy the electrical ignition threshold and the thermal ignition threshold, respectively.

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7. The gas generation system of any one of claims 1 to 6, wherein a depth of the attenuation zone varies as the attenuation zone regresses.

8. The gas generation system of any one of claims 1 to 7, further comprising a nozzle coupled to the combustion chamber to exhaust the gaseous byproducts to produce thrust.

9. The gas generation system of any one of claims 1 to 8, wherein said self-sustaining threshold pressure is at least 500 psi.

10. The gas generation system of claim 9, wherein the electrically operated propellant comprises:

at least 50 by mass an ionic perchlorate-based oxidizer;

10 to 30 percent by mass a binder;

5 to 30 percent by mass a metal or polymer based fuel;

5 to 40 percent by mass a metal additive; and

5 to 40 percent by mass the polar molecules.

11. The gas generation system of any one of claims 1 to 10, wherein the ignition surface burns as the attenuation zone regresses.

12. The gas generation system of any one of claims 1 to 11, wherein the conductive particles provide a source of free electrons for the dielectric breakdowns.

13. A method of generating gaseous byproduct to pressurize a combustion chamber, the method comprising:

providing an electrically operated propellant in which an ignition condition of the electrically operated propellant is defined by satisfying both a thermal ignition threshold and an electrical ignition threshold, said electrically operated propellant having a self-sustaining threshold pressure of at least 200 psi at which the electrically operated propellant once ignited cannot be extinguished and below which the electrically operated propellant can be extinguished

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by interruption of an electrical input, said electrically operated propellant including metal particles and polar molecules suspended within the electrically operated propellant to reduce an amount of energy supplied by the electrical input required to satisfy the ignition condition;

supplying microwave energy as the electrical input to the electrically operated propellant to rapidly vibrate the polar molecules to increase a temperature of the electrically operated propellant above the thermal ignition threshold;

supplying the microwave energy as the electrical input to the electrically operated propellant to accumulate and then discharge electric charge in the form of dielectric breakdowns into randomly oriented local currents that exhibit a local current density J above the electrical ignition threshold thereby satisfying the ignition condition and thereby igniting and sustaining ignition of an ignition surface as the electrically operated propellant burns, wherein the metal particles and polar molecules reduce an amount of the microwave energy otherwise required to satisfy the ignition condition and to sustain the burning of the electrically operated propellant,

wherein combustion of the ignited electrically operated propellant generates the gaseous byproduct that pressurizes the combustion chamber;

varying a phase or frequency of the microwave energy such than an anti-node of the microwave energy tracks the ignition surface as an attenuation zone regresses; and

extinguishing the electrically operated propellant by interrupting the microwave energy while the electrically operated propellant is subject to pressure less than the self-sustaining threshold pressure.

14. The method of claim 13, wherein the self-sustaining threshold pressure is at least 500 psi, wherein the electrically operated propellant comprises a perchlorate-based oxidizer.

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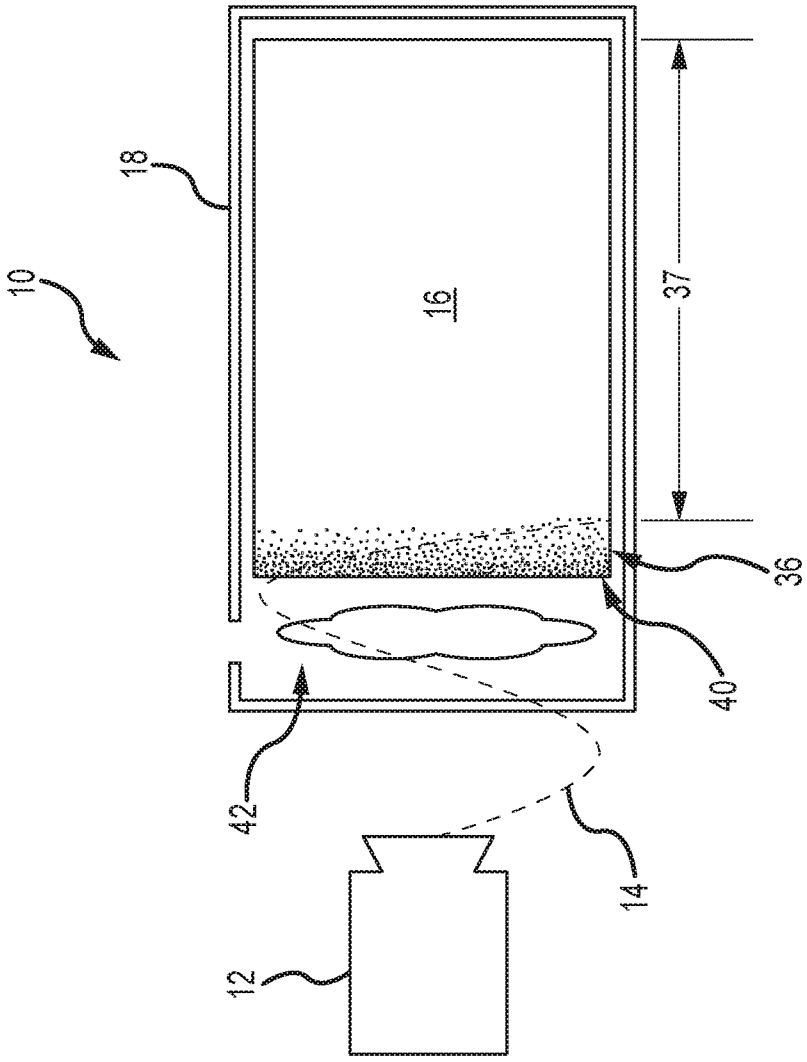
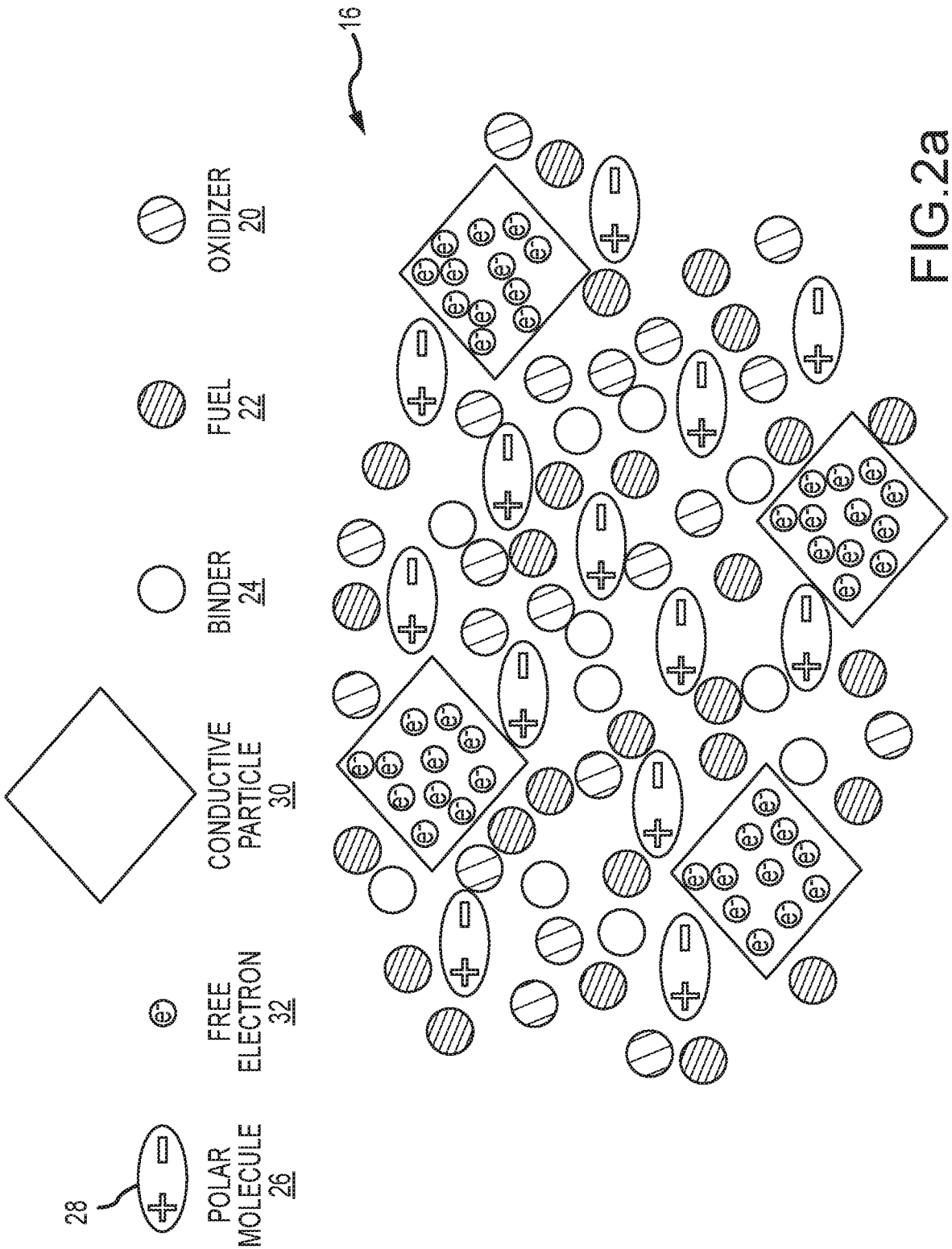


FIG.1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FUEL 22
BINDER 24
CONDUCTIVE PARTICLE 30
FREE ELECTRON 32
POLAR MOLECULE 26
28

FIG.2a

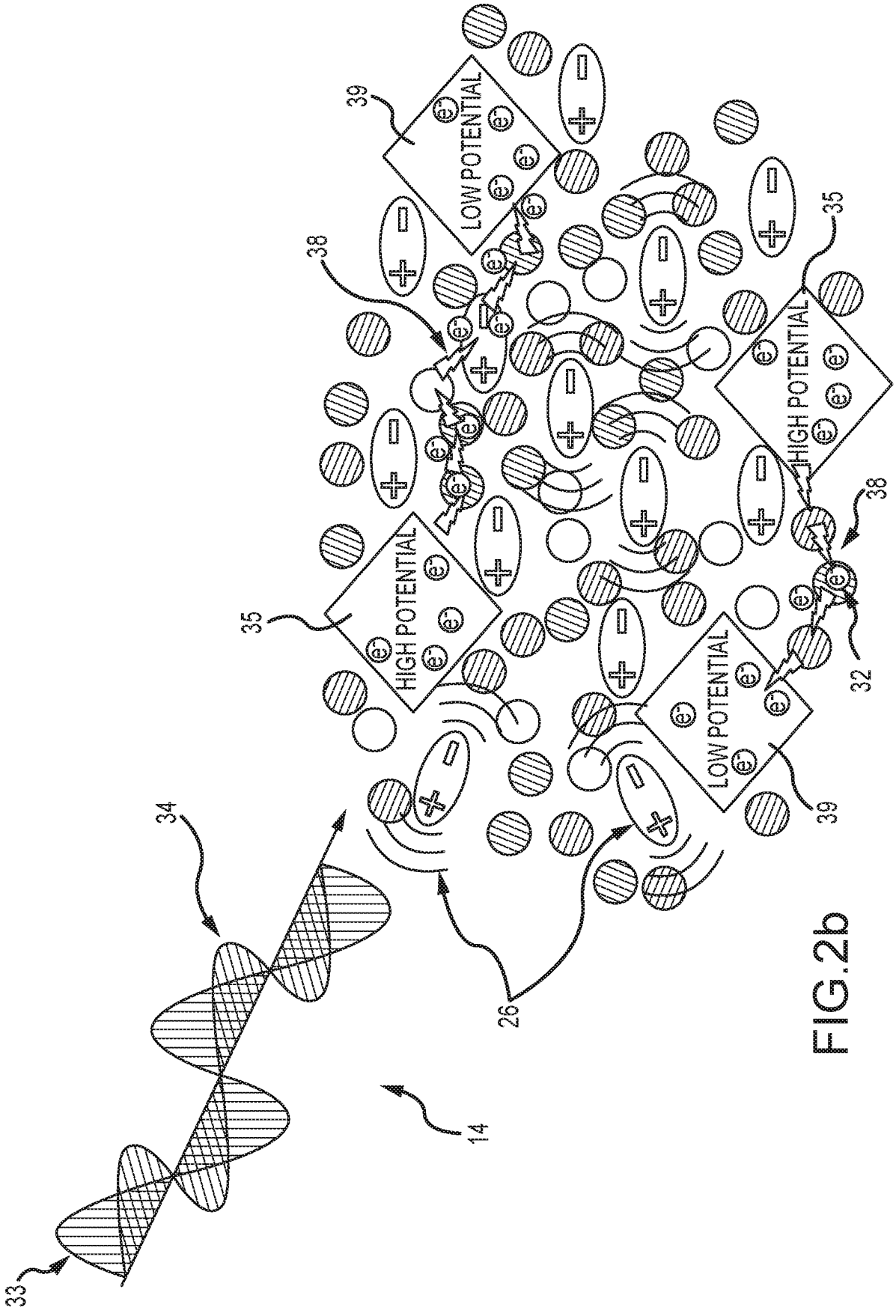

LOW POTENTIAL
HIGH POTENTIAL
HIGH POTENTIAL
LOW POTENTIAL
39
38
35
35
38
32
39
34
33
26
14

FIG.2b

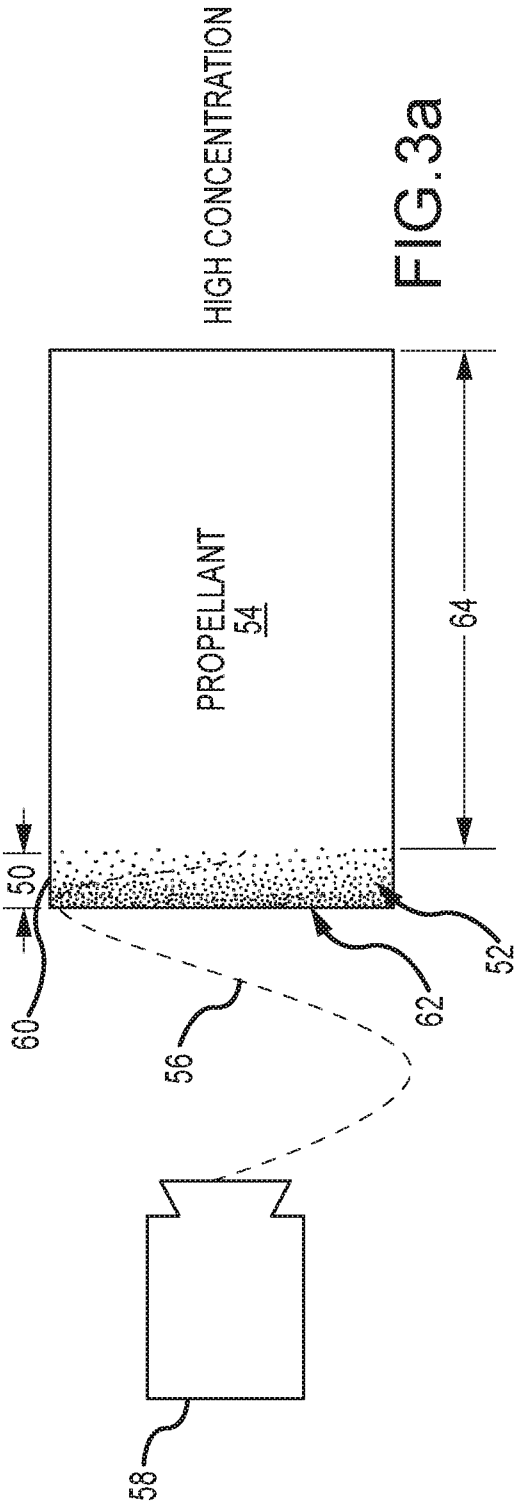
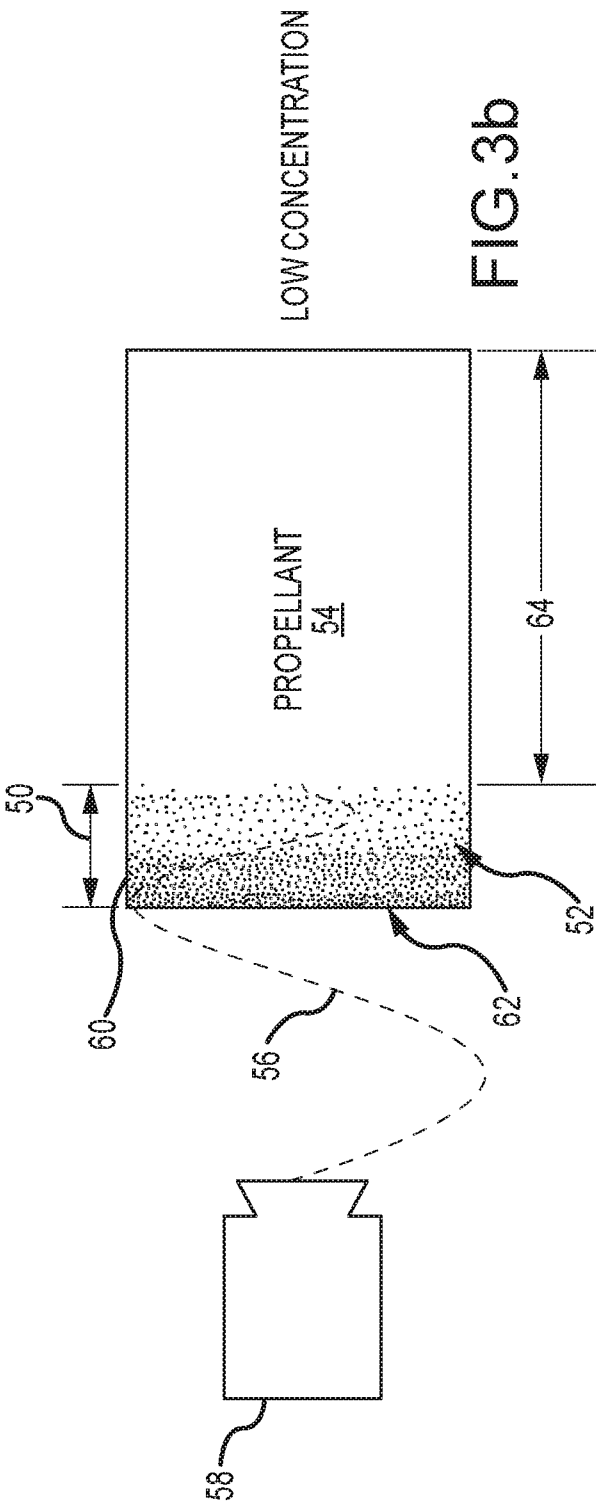

HIGH CONCENTRATION
PROPELLANT
54
64
50
60
56
62
52
58

FIG.3a


LOW CONCENTRATION
PROPELLANT
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64
50
60
56
62
52
58

FIG.3b

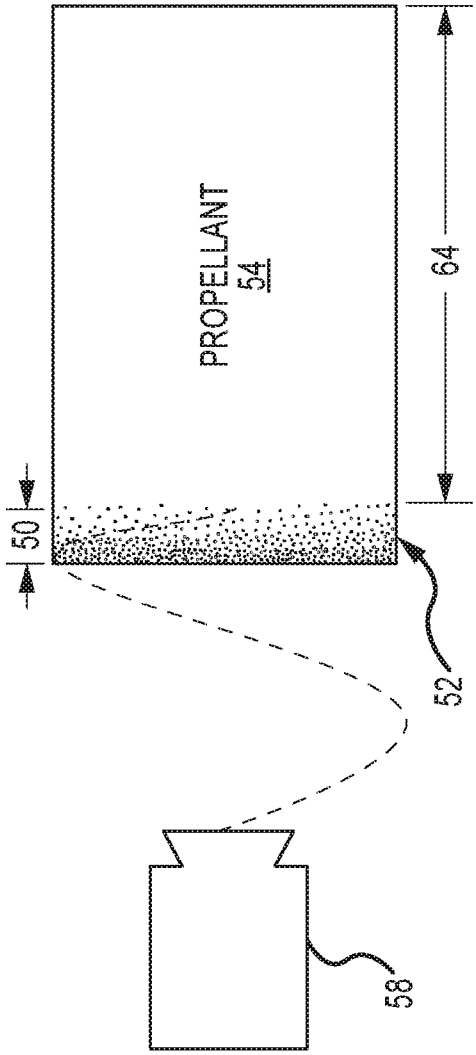

LOW
FREQUENCY
PROPELLANT
54
50
64
52
58

FIG.4a

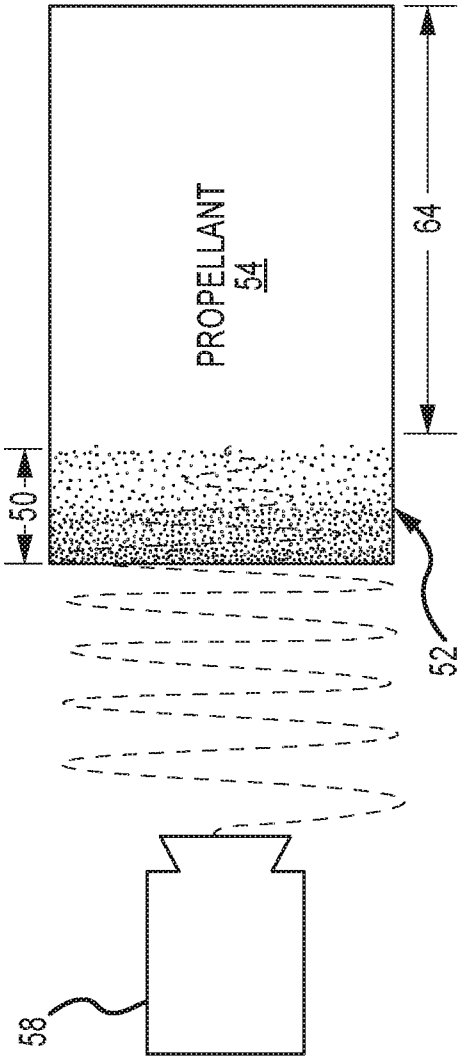

HIGH
FREQUENCY
PROPELLANT
54
50
64
52
58

FIG.4b

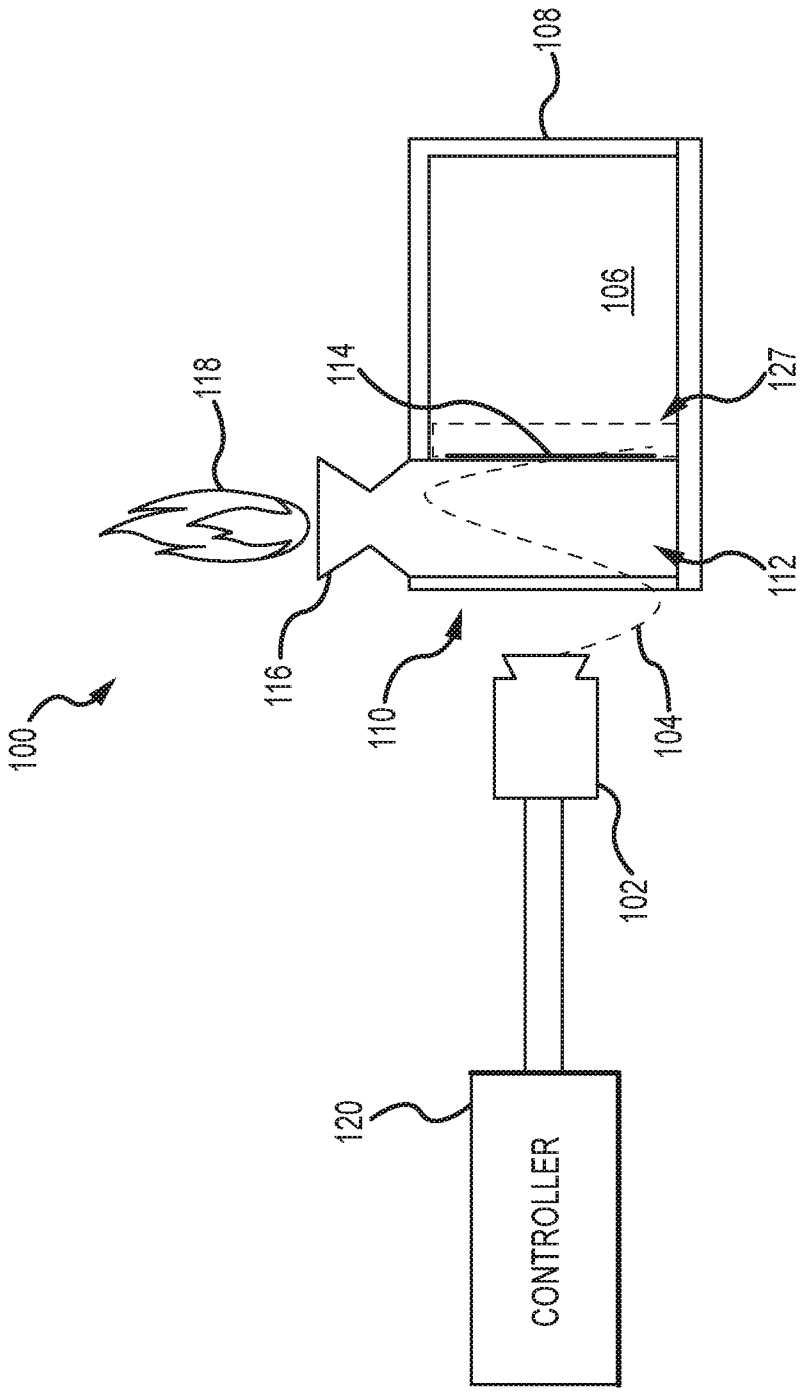


FIG.5

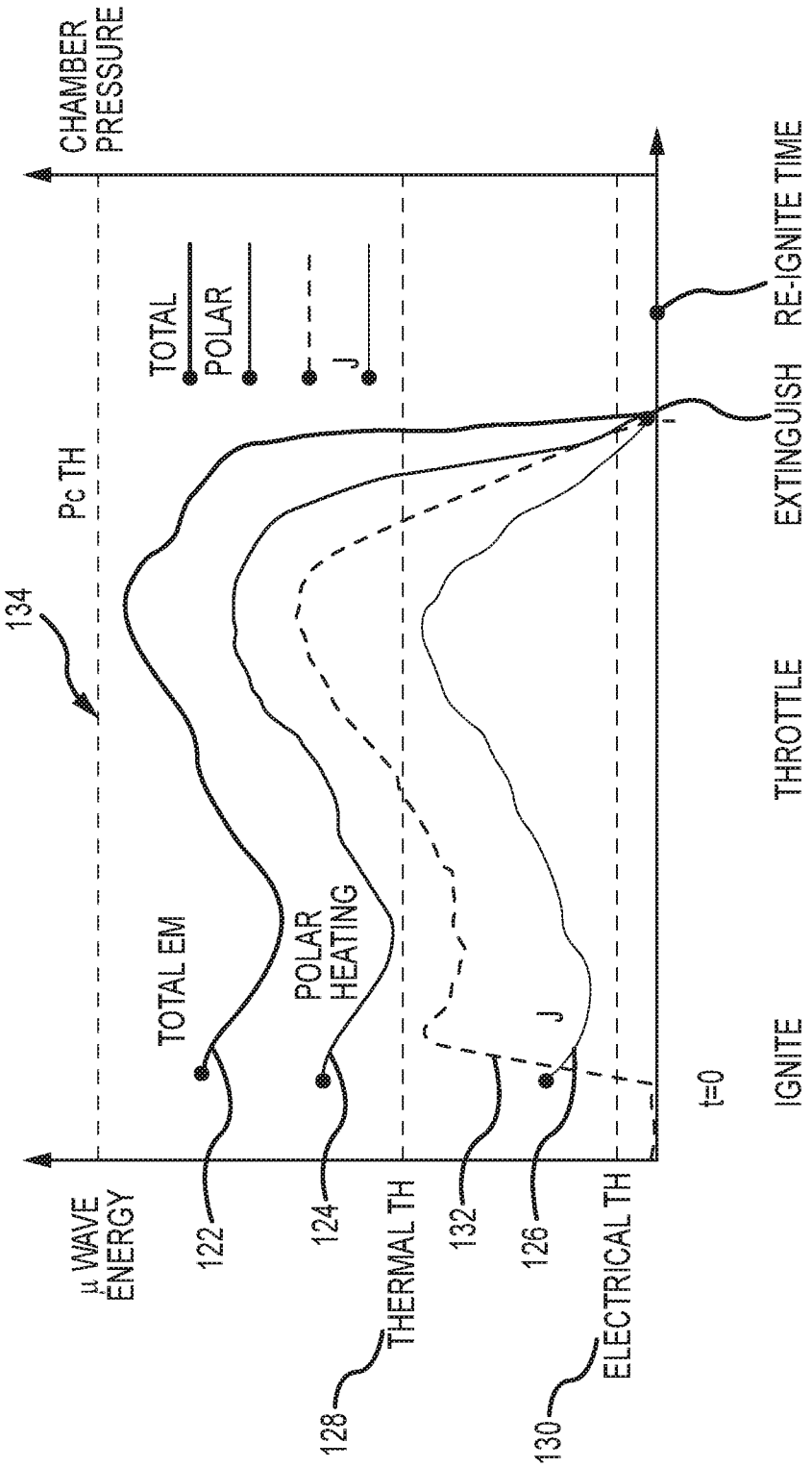

CHAMBER PRESSURE
Pc TH
TOTAL
POLAR
J
134
TOTAL EM
POLAR HEATING
J
μ WAVE ENERGY
122
124
132
126
THERMAL TH
ELECTRICAL TH
128
130
t=0
IGNITE
THROTTLE
EXTINGUISH
RE-IGNITE TIME

FIG.6

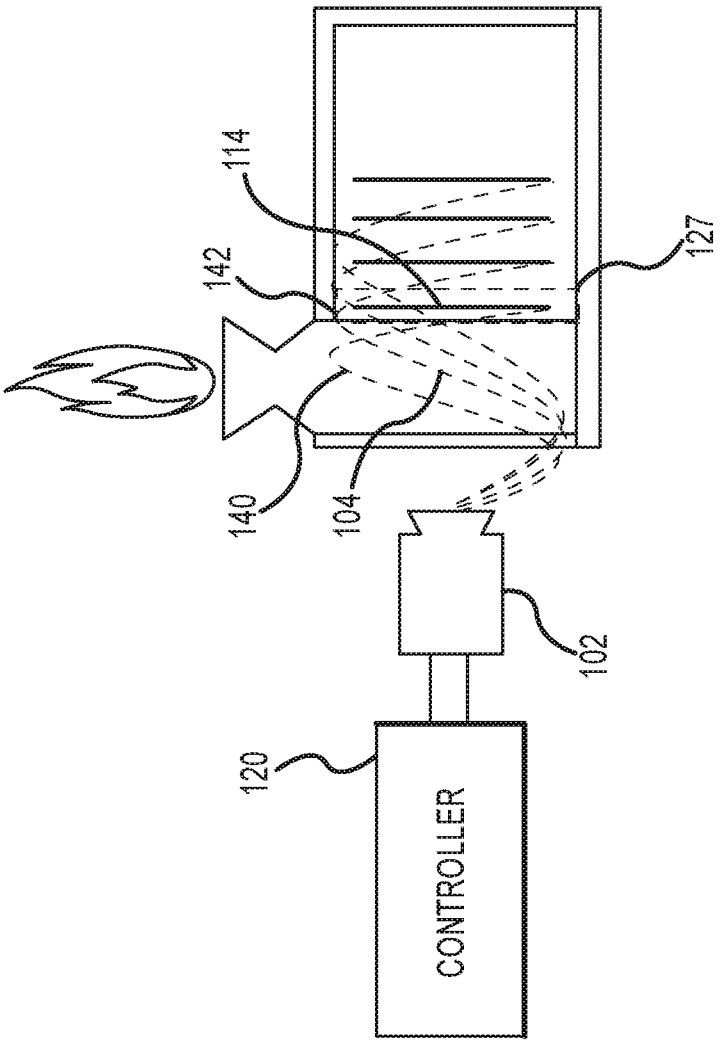


FIG.7a

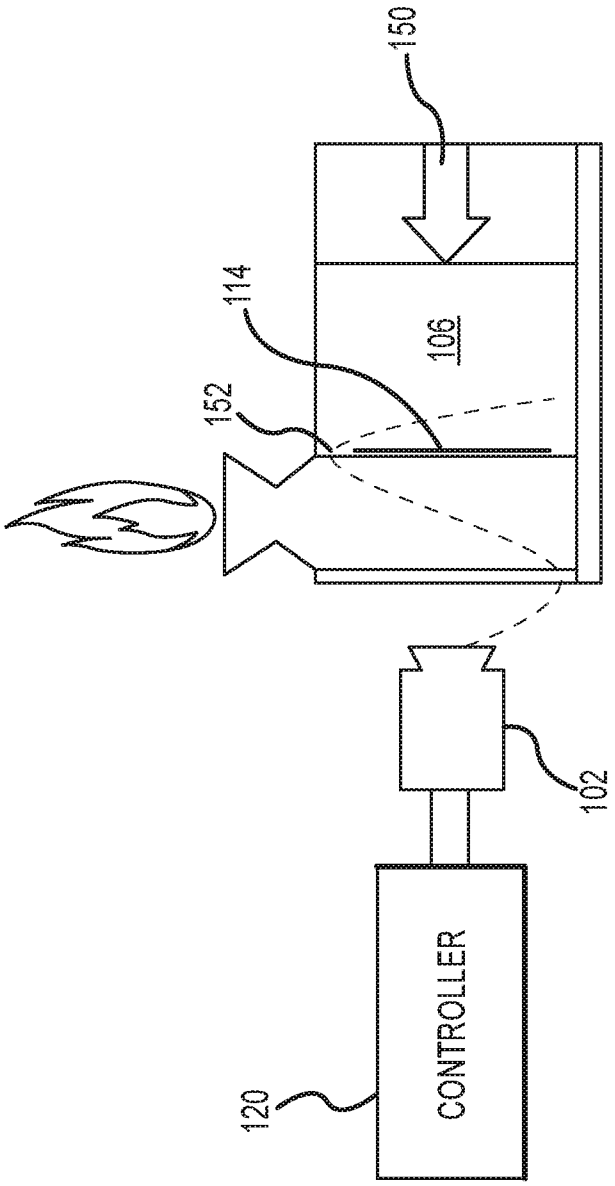
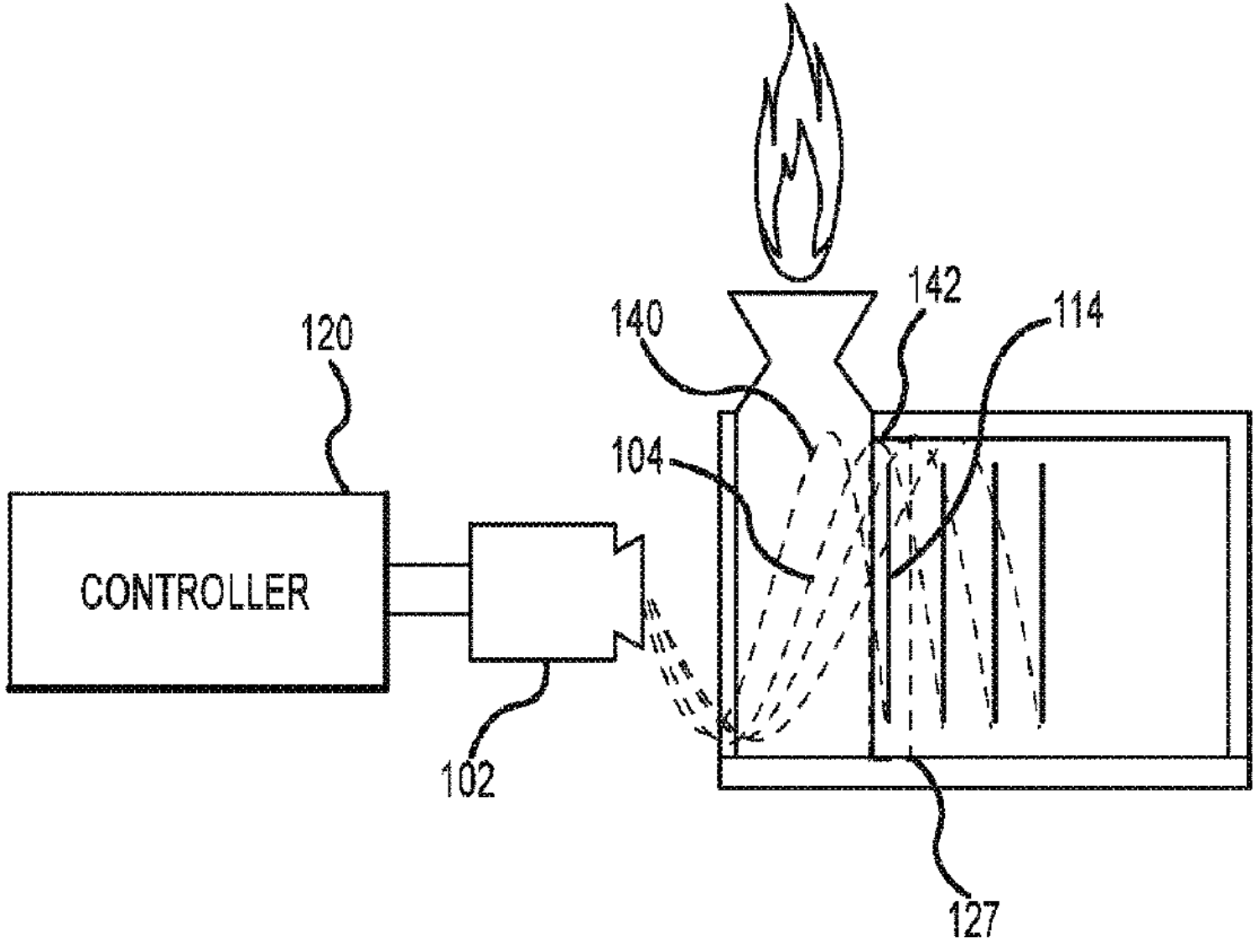


FIG. 7b


120
CONTROLLER
102
140
142
114
104
127