

April 14, 1964

K. E. RUMBEL

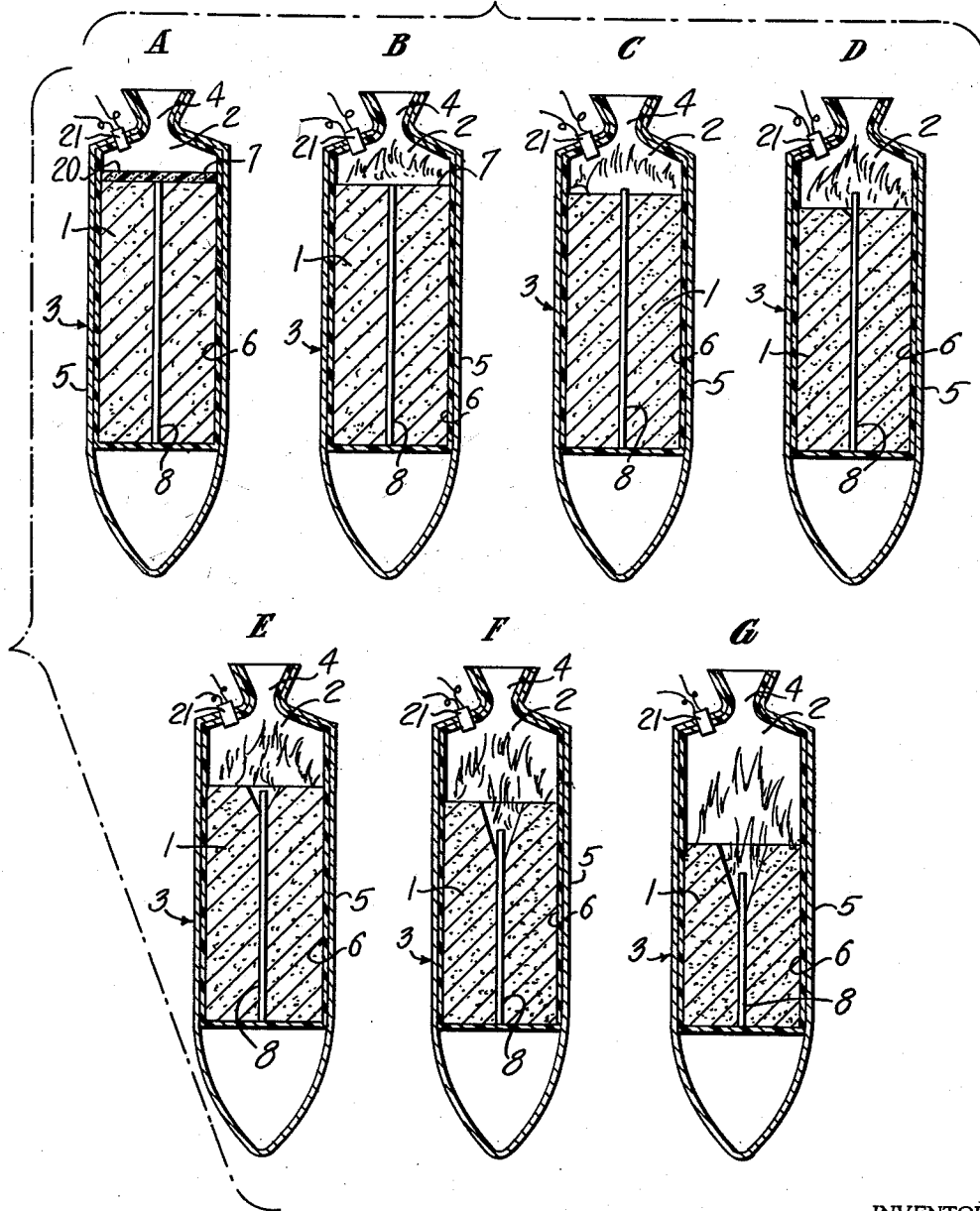
3,128,706

MONOPROPELLANT GRAINS

Filed April 17, 1959

4 Sheets-Sheet 1

Fig. 1.



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Fig. 2.

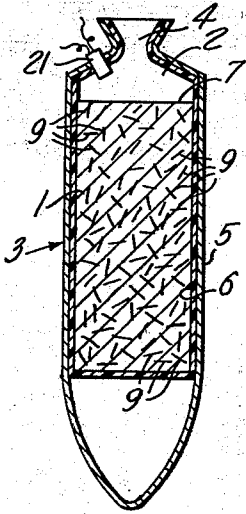


Fig. 3.

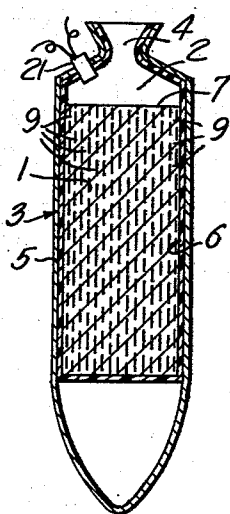


Fig. 4.

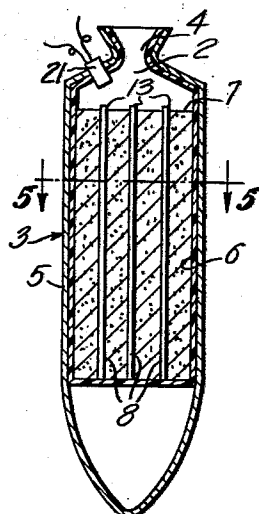


Fig. 5.

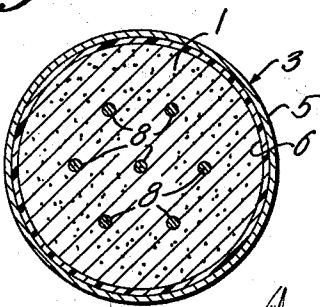


Fig. 6.

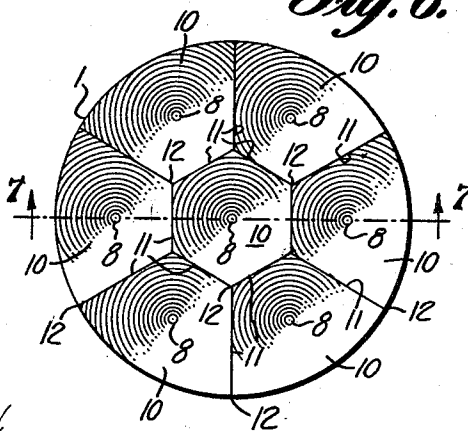
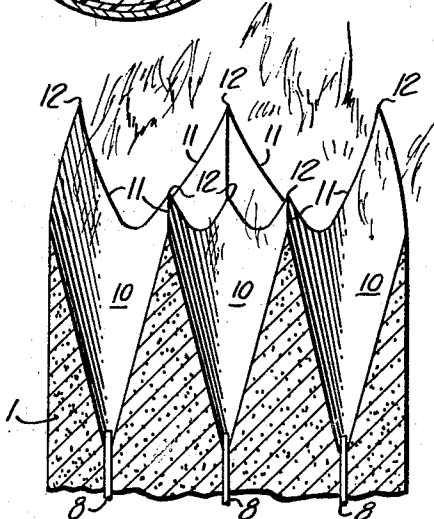


Fig. 7.



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Fig. 8.

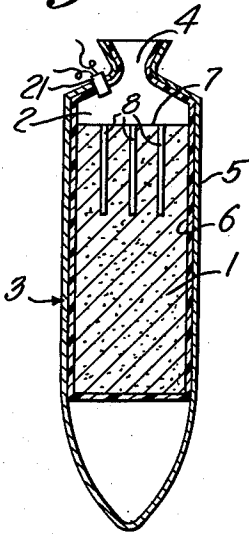


Fig. 9.

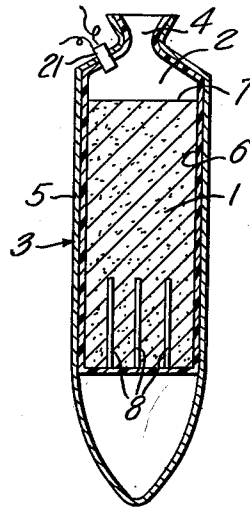


Fig. 10.

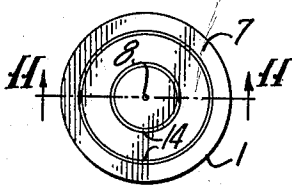


Fig. 11.

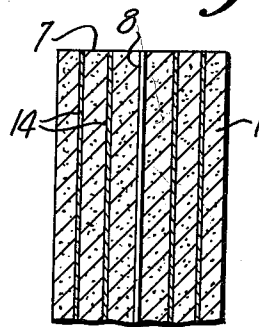


Fig. 12.

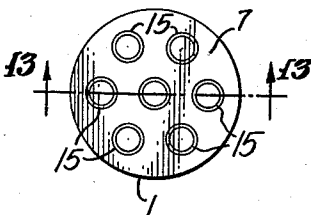
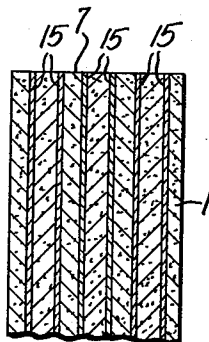


Fig. 13.



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Fig. 14.

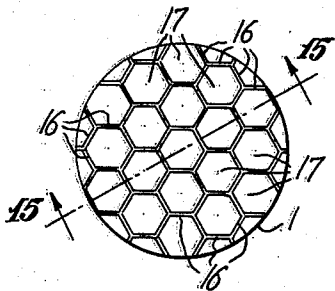


Fig. 15.

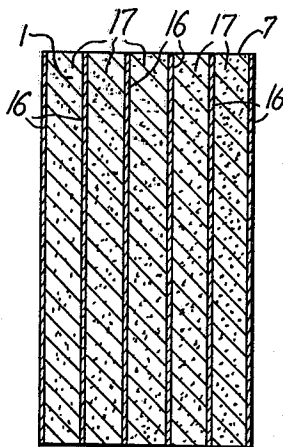


Fig. 16.

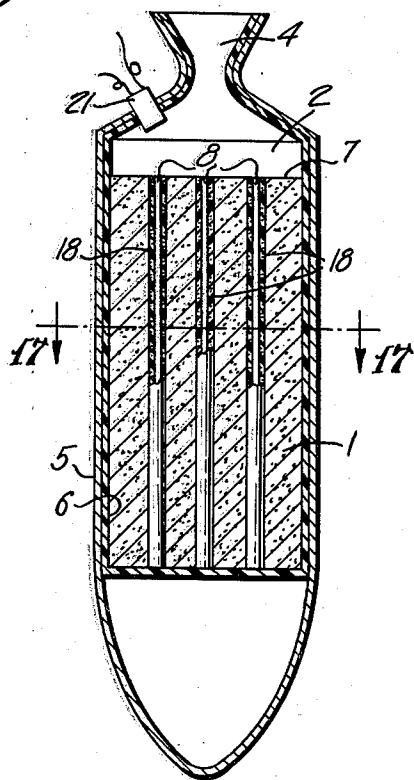
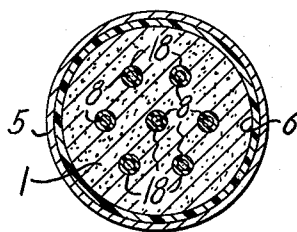


Fig. 17.



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MONOPROPELLENT GRAINS

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23 Claims. (Cl. 102—98)

This invention relates to new semi-solid, end-burning, propellant grains of high mass burning rate for use in gas generator devices to produce high energy gases for such purposes as producing thrust and power.

There have recently been developed semi-solid or plastic monopropellant compositions which, though capable of continuous flow at ordinary temperatures under pressure, are sufficiently cohesive to retain a formed shape. Such monopropellants have hitherto been employed to generate high energy gases by continuously extruding the plastic composition from a storage chamber into a combustion chamber and burning the leading face of the advancing column of monopropellant in the combustion chamber.

The semi-solid monopropellants, which can comprise any cohesive, shape-retentive, self-oxidant compositions which burn to produce high energy gases, possess many of the advantages of solid propellants, such as high density, relatively low heat and shock sensitivity, good stability, storageability for long periods without deterioration, freedom from leakage, and low corrosiveness and toxicity. They also eliminate certain of the disadvantageous characteristics of solid propellants. Solid propellant grains must be cast and cured at elevated temperature and frequently under high pressure. This is a hazardous, time-consuming and expensive operation. The cast and cured grain must, furthermore, be completely free from even minute cracks or fissures which might cause it to shatter under pressure or vibrational stresses in the combustion chamber and thereby provide large, unscheduled and uncontrollable burning surfaces resulting in explosion of the motor or gas generating device. Many solid propellants tend to become excessively brittle at low ambient temperatures and thereby subject to fracture.

The plastic monopropellant, on the other hand, requires no curing and needs only to be mixed in suitable mixing equipment uniformly to distribute the components of the composition, and is then ready to be introduced into the propellant chamber of the gas generating device, as for example, by extruding it into the propellant chamber and subjecting it to sufficient pressure to compact the extruded material (preferably under vacuum to eliminate air bubbles) into a continuous mass. The fluidity of the compositions under stress makes the compacting pressures minimal and eliminates any fissures, which, once formed in a solid propellant grain either at the time of manufacture or subsequently, makes it completely useless.

The plastic monopropellants, instead of being burned in a combustion chamber as an extrusion from a fuel chamber, can be introduced in toto directly into the combustion chamber and burned there as an end-burning grain, namely, as a grain which burns progressively only from one end. The term "grain" has hitherto generally been employed to define a mass or body of solid propellant. It is employed herein also to define a mass or charge of the plastic or semi-solid monopropellant because of its cohesive, shape-retentive characteristics.

An end-burning grain, however, ordinarily does not provide sufficient burning surface area to produce an adequate mass rate of gas generation. In the case of solid propellant grains, this situation can be compensated for by such expedients as perforations, cruciform shaping and the like, which provide increased burning surface area. Such shaping is not practically feasible with plastic monopropellants because of their semi-solid nature.

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Perforations made in the body of the mass would, after a substantial period of storage or under the stresses of handling and transportation, tend to lose shape or even to close because of creep of the monopropellant material.

The object of this invention is to provide semi-solid, shape-retentive, end-burning monopropellant grains which can be introduced into the combustion chamber of a gas-generating device, such as a rocket or gas turbine and burned therein at greatly increased effective mass burning rates to produce a mass rate of gas generation which is sufficiently high for substantially any desired application, including high-thrust rockets.

Another object is to provide semi-solid, shape-retentive, end-burning monopropellant grains which can be burned in the combustion chamber of a gas-generating device at increased mass burning rates which can be effectively controlled within limits.

Still another object is to provide semi-solid, shape-retentive, end-burning propellant grains which possess many of the advantages of solid propellant grains and eliminate certain of their disadvantages, such as curing requirements and fissuring.

Other objects and advantages will become obvious from the following detailed description.

In the drawings, in which like parts in the several figures are identified by the same reference character:

FIGURE 1 comprises a diagrammatic series of longitudinal sectional views through a rocket motor showing a plastic monopropellant charge or grain in the combustion chamber and the effect of a metal wire, embedded in the grain and longitudinally disposed normal to the initial burning surface, on the burning characteristics of the end-burning charge.

FIGURE 2 is a longitudinal section showing a random dispersion of short lengths of wire in a plastic monopropellant grain.

FIGURE 3 is a longitudinal section showing a plastic, monopropellant grain containing embedded therein a dispersion of longitudinally oriented short lengths of wire.

FIGURE 4 is a longitudinal section showing a plastic, monopropellant grain containing embedded therein a plurality of continuous wires.

FIGURE 5 is a cross-sectional view taken along lines 5—5 of FIGURE 4.

FIGURE 6 is a plan view showing the plastic monopropellant grain of FIGURE 4 at burning equilibrium.

FIGURE 7 is a sectional view taken along lines 7—7 of FIGURE 6.

FIGURES 8 and 9 are longitudinal sectional views of other embodiments of the invention.

FIGURE 10 is a plan view of a plastic, monopropellant grain containing embedded therein a continuous, axially-embedded wire and continuous, concentric tubular metal conductors.

FIGURE 11 is a sectional view taken along line 11—11 of FIGURE 10.

FIGURE 12 is a plan view showing a bundle of tubular metal heat conductors embedded in a plastic, monopropellant grain.

FIGURE 13 is a sectional view taken along lines 13—13 of FIGURE 12.

FIGURE 14 is a plan view showing a metal heat conductor in the form of a honeycomb embedded in a plastic monopropellant grain.

FIGURE 15 is a sectional view taken along lines 15—15 of FIGURE 14.

FIGURE 16 is a longitudinal section showing longitudinal coated wires embedded in a plastic, monopropellant grain.

FIGURE 17 is a cross-sectional view taken along lines 17—17 of FIGURE 16.

Broadly speaking, my invention comprises embedding

metal heat conductors in the plastic monopropellant grain in such manner that the entire surface of that portion of the metal which lies within the body of the plastic monopropellant grain is in intimate contact with the propellant matrix. The metal heat conductor can be dispersed in the propellant matrix in the form of discontinuous short wires or filaments which are at least about 0.08 in. long. Preferably it is continuous and oriented longitudinally in the plastic grain in the direction of flame propagation, namely, in a plane normal to the initial ignition surface of the grain.

The heat conductor can be any metal having a substantially higher thermal diffusivity than the plastic monopropellant. It can be used in any suitable form, as, for example, wire of any cross-sectional shape, such as circular, rectangular or oval, thin strips which are flat or bent into shapes such as wedges or tubes of any cross-sectional shape, such as circular, rectangular or hexagonal. Although much of the following description will, for convenience of illustration, be given in terms of the use of wire, it will be understood that similar results are obtained with metal heat conductors of other shapes as aforesaid.

The metal heat conductor, because it has a considerably higher thermal diffusivity than that of the propellant material or its gaseous combustion products, effects a very rapid heat transfer from the high temperature combustion gases in the flame zone to propellant in the grain zone adjacent to the wire and to the burning surface, so that the flame propagates rapidly along the metallic heat conductor. As a result, the burning surface propagates along the wire at a much higher rate than the normal linear burning rate of the plastic monopropellant, with concomitant involution and greatly increased burning surface area and mass rate of gas generation. The wire is at the apex of the recess formed by the involuted burning surface.

FIGURE 1 illustrates diagrammatically the burning phenomenon which occurs when a metal wire is longitudinally embedded in the plastic monopropellant matrix in a plane normal to the initial burning surface. For illustrative purposes, the plastic monopropellant grain 1 is shown in the combustion chamber 2 of rocket motor 3, equipped with a restricted nozzle 4, through which the gases generated by the burning plastic monopropellant vent at high velocity to produce thrust. The plastic monopropellant grain, which is in intimate contact with the motor wall 5, coated with a layer of insulation 6, is inhibited against burning except on ignition surface 7. Wire 8 is longitudinally embedded in the plastic monopropellant grain in intimate contact throughout with the propellant matrix. In FIGURE 1-A, plate 20 is a disc of solid propellant, which functions both to ignite the initial ignition surface 7 of the plastic monopropellant and as a means for preventing flow of the plastic monopropellant under the stresses of handling and transportation or under the stress of its own weight during extended periods of storage at attitudes conducive to such creep.

After ignition of the solid propellant plate by igniter 21, the initial plane burning surface 7 of the plastic grain is ignited, as shown in FIGURE 1-B, and the plastic monopropellant burns at its normal burning rate until a portion of the wire protrudes beyond the burning surface into the hot combustion gases, as shown in FIGURE 1-C. The exposed wire is heated to a high temperature by the hot gases and this heat is then conducted by the wire into the plastic monopropellant adjacent to the wire and to the burning surface. Burning then proceeds rapidly along the wire. The burning surface adjacent to the wire involutes to form a cone with the wire at its apex, as shown in FIGURES 1-D, 1-E, 1-F and 1-G. Involution continues until an equilibrium is reached where the angle of the vertex of the flame zone at the wire, and thus the burning rate along the wire remains substantially constant, as shown in FIGURES 1-F and 1-G. Propaga-

tion of the burning surface continues at a high rate along the wire and the rate of gas generation is greatly increased by the large increase in burning surface produced by involution along the wire.

The burning phenomenon, as discussed above and illustrated in FIGURE 1, occurs only when the wire is embedded in intimate contact with the monopropellant matrix. Any spacing of the wire from the propellant matrix, as for example, such as would be produced by stringing a longitudinally perforated grain on a trap wire, results only in the establishment of a burning surface in the interior of the grain which ignites and then burns progressively away from the wire in an outward direction normal to the perforation and the wire at the normal linear burning rate of the monopropellant. The wire, in such a case, would not function to cause involution and an increase in the mass burning rate or mass rate of gas generation.

As aforementioned, before the flame actively propagates along the wire, a short length of the metal heat conductor must protrude into the burning zone in order that the wire be heated to a sufficiently high temperature to provide the necessary heat transfer along its path to effect involution of the burning surface. The length of protrusion varies with different metals and is determined by such factors as the thermal diffusivity and melting point of the particular metal. In general, the higher the thermal diffusivity, the shorter is the length of exposed wire required before involution occurs. For effective action, therefore, the wire must be of sufficient length both to provide for the initial exposure in the flame zone and for propagation of the flame for some distance into the unburned propellant in which it is embedded. In general, the minimum wire length required to achieve appreciable increase in the mass burning rate is about 0.08 to 0.1 inch and, preferably, about 0.2 inch.

Substantial increases in mass burning rate are obtained by dispersing short lengths of wire in the plastic monopropellant matrix. Dispersion of the wire can be accomplished, for example, by mixing the short lengths of wire into the propellant composition prior to loading it into the combustion chamber of the gas-generating device. The wires in the plastic monopropellant grains prepared in this manner generally assume a more or less random pattern as shown in FIGURE 2, where metal wires 9 are embedded in the plastic monopropellant matrix 1. Somewhat improved results, in terms of increased burning rate, can be achieved by orienting the dispersed short wires in the direction of flame propagation, namely substantially normal to the initial burning surface 7, as shown in FIGURE 3.

As aforesaid, the wire dispersed in the propellant matrix must be at least 0.08 in. long to provide sufficient length for initial exposure into the flame zone and flame propagation along the wire. In general, the longer the wire, the larger is the effective increase in mass burning rate. Wires of 0.2 in. length, for example, produce higher mass burning rates than 0.1 in. wires. To some extent wire lengths will be determined by the size of the plastic monopropellant grain. In the case of large grains, for example, wires 2 in. long or longer can be incorporated.

The amount of discontinuous wire introduced into the propellant matrix is not critical, although this is one of the factors which determines the specific increase in mass burning rate obtained. The addition of even a very small amount effects some increase. In most cases, it is desirable to add at least about 0.5% and, preferably, at least about 1% by weight of the propellant to obtain appreciable results. In general, the larger the amount of wire of a given length added, the higher will be the effective burning rate. However, since the addition of the short wires involves the introduction of substantially inert material into the plastic monopropellant, thereby decreasing the gas generating potential, in practice the amount in-

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corporated will be controlled to a considerable extent by this factor. The dispersed wires are too large to function effectively as a fuel component in the propellant composition and, thereby to increase heat release and specific impulse as in the case of finely-divided powdered metals. For this reason, it will generally be undesirable to add more than about 5 to 10% of the metal by weight of the plastic monopropellant, although in some cases larger amounts may be feasible.

Although substantial increases in effective mass burning rate can be achieved by the dispersion of discontinuous, short wires in the plastic monopropellant matrix, greatly improved performance is obtained with the use of continuous wire or other heat conductor longitudinally disposed in the direction of flame propagation, namely, normal to the initial burning surface, as shown in FIGURE 1. Increases in burning rate of the plastic monopropellant grain which are several-fold greater than that obtained with dispersed, discontinuous, short lengths of wire can be obtained in this way with the use of considerably smaller proportions of metal. Apparently the reason for the large disparity in performance stems from the fact that, in the case of the discontinuous wires, the flame, after initial exposure of one end of the wire into the combustion zone, propagates rapidly with involution of the burning surface along each short length, but is slowed substantially to the normal burning rate of the propellant material when it must bridge the gap between the end of one wire and an adjacent wire. With a continuous metal heat conductor, the flame continues to propagate rapidly and uninterruptedly through the entire length of the desired burning distance. Another advantage of the continuous wire is that it requires the introduction of a minimum amount of inert material.

In many cases, particularly where the propellant grain has a relatively large cross-sectional area, it is desirable to embed a plurality of continuous wires (or otherwise shaped heat conductors) at spaced intervals as shown in FIGURES 4 and 5. If a plastic monopropellant grain, which is short relative to its width, contains only a single wire, such as shown in FIGURE 1, the peripheral portion of unburned propellant remaining when burning has progressed the full length of the wire may be considerably larger than desirable. This can be avoided by introducing a plurality of wires as shown in FIGURES 4 and 5. The use of a plurality of wires also provides a reinforcing element for the plastic monopropellant to eliminate flow under accelerative stresses.

It is frequently desirable to achieve equilibrium, namely the point at which the involuted burning surface area and, consequently, the mass rate of gas evolution, becomes constant, as quickly as possible.

The use of a plurality of wires, as shown in FIGURE 4, greatly increases the rapidity with which the equilibrium burning surface can be established. In the case of a single wire, the area of the burning surface presented by the involuting cone and the depth of the coned recess continues to increase until the flaring end of the cone intersects the peripheral edge of the plastic monopropellant grain, at which point equilibrium is established, or until burning reaches the end of the wire, as, for example, in the case of a plastic monopropellant grain which is short relative to its width. The mass rate of gas evolution continues to increase until the surface area of the cone becomes constant. Such high progressivity can be advantageous for some applications but not where rapid establishment of a constant burning surface is desirable.

Where a plurality of continuous wires are used, the involuted cones incident to each wire soon intersect at their flaring ends and the equilibrium burning surface area is more quickly reached. Although the equilibrium cone angle is the same as for a single wire, the depth of the recessed cones is shorter in the case of a plurality of wires, so that overall burning surface area is not in actuality increased.

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FIGURES 6 and 7 show diagrammatically the burning surface at equilibrium of the plastic monopropellant grain of FIGURES 4 and 5 produced after initial ignition of surface 7 and after burning has proceeded along the seven spaced wires 8 with concomitant involution until the equilibrium cone angle has been reached. The cones 10 flare out from the wires 8 exposed at the apex of each and intersect each other and the periphery of the plastic monopropellant grain 1 to form inwardly curved ridges 11 and apical points 12.

The equilibrium state can also be established more rapidly by exposure of the wires a short distance beyond the initial ignition surface. In FIGURE 1, the wire terminates at the initial burning surface 7. As aforesaid, upon ignition, the grain will burn for a short distance at the normal rate of the propellant material itself until a short length of the wire protrudes into the hot combustion gas zone. When the protruding end of the wire becomes sufficiently hot to initiate propagation of the flame along the wire, the mass burning rate will increase rapidly until the equilibrium maximum is reached. To initiate flame propagation along the wire more rapidly, the wires can be embedded in such a way that the ends protrude beyond the ignition surface, as shown by exposed wire ends 13 in FIGURE 4.

For many gas generating applications, it is essential that a high burning rate be maintained throughout combustion. This requirement can be satisfied by extending the continuous heat conductor for substantially the entire distance of flame propagation as shown in FIGURES 1, 4, 11, 13, 15 and 16. There are some cases, however, where a very high impulse is required for only a portion of the combustion cycle as, for example, until a propelled object is air-borne, after which the rate of combustion gas production can be reduced. Such a requirement can be met by limiting the length of the metal heat conductor so that it extends in the direction of flame propagation only as far as it is desired to obtain the high rate of burning conferred by the conductor. After burning has proceeded along the full length of the conductor, combustion then continues at the normal linear burning rate of the monopropellant to the end of the grain. FIGURE 8 shows such a configuration.

In other applications, it may be desirable to employ a plastic monopropellant grain which progresses from a relatively low initial impulse to a high impulse. In such case, the longitudinal metal heat conductor can be embedded in the plastic grain at a predetermined point spaced from the initial ignition surface. Such a configuration is illustrated in FIGURE 9.

As aforesaid, the metal heat conductor, though conveniently used in the form of wire, can also be employed in the form of continuous strips which can be flat or bent into other desired shapes, such as a V shape or tube. The effect on mass burning rate is substantially similar to that obtained with wires, with involution of the burning surface occurring along the heat conductors regardless of shape. The burning surface along metal heat conductors which are substantially wider than they are thick, assumes the configuration of a trough of V shape cross section rather than the cone incident to a wire. The various expedients for hastening the establishment of the equilibrium burning surface, discussed above in connection with the use of wires, can be used, such as use of a plurality of the conductors and protrusion from the initial ignition surface.

Tubular metal conductors longitudinally embedded in the plastic propellant matrix are particularly suitable for my purpose because they provide a reinforcing structural element within the body of the plastic grain which substantially eliminates any tendency for the plastic monopropellant to flow or slump under accelerative or vibrational stress during combustion. The tubular heat conductors can be of any suitable cross-sectional shape, such as circular or polygonal, and can be arranged in any de-

sired pattern, so long as they extend longitudinally in the direction of flame propagation.

FIGURES 10 and 11 show a concentric tubular arrangement of metal heat conductors 14 and an axial wire 8. Tubular conductors 14 and wire 8 are embedded in plastic propellant matrix 1 in such manner that they extend longitudinally in a direction normal to initial ignition surface 7.

The metal heat conductors can also be embedded in the plastic monopropellant matrix as a bundle of individual, longitudinally disposed tubes 15, as shown in FIGURES 12 and 13.

FIGURES 14 and 15 show, embedded in the plastic monopropellant matrix 1, a metal heat conductor in the form of a skeletal framework 16 forming longitudinal tubular passages 17 normal to initial ignition surface 7, the tubular passages being of hexagonal cross section. Such a honeycomb made of a heat conducting metal provides maximum structural reinforcement for the plastic monopropellant and is particularly desirable for use with monopropellant compositions which tend to flow under relatively low applied pressures above ambient.

The increase in mass burning rate and, thereby, in the mass rate of gas generation varies with the particular metal used as the heat conductor. The properties of the metal which are apparently involved in determining its efficacy are its thermal diffusivity and its melting point. The higher the thermal diffusivity of the metal, the more rapidly it conducts the heat to the unburned portion of propellant and the more rapid is the burning rate along the wire. Silver, for example, which has a high thermal diffusivity of 1.23 cm.²/sec. at 650° C. effects a somewhat greater increase in burning rate than copper, which has a thermal diffusivity of 0.90 cm.²/sec. at 650° C., and a considerably greater increase than platinum, which has a thermal diffusivity of 0.35 cm.²/sec. at 650° C. Higher melting points also increase efficacy of the metal. Aluminum, for example, melts at a much lower temperature than copper and despite a somewhat higher thermal diffusivity (0.94 cm.²/sec. at 650° C.) increases burning rate along the wire to a considerably lesser degree. Tungsten, which has about the same thermal diffusivity (0.67 cm.²/sec. at 650° C.) as magnesium (0.66 cm.²/sec. at 650° C.) but a much higher melting point, is considerably more effective in increasing burning rate. Apparently the higher the melting temperature of the wire, the longer is the length of the wire which projects into the flame zone, thereby providing a greater area for heat transfer from the hot combustion gases to the wire. Decreasing rates of heat transfer by the metallic conductor result in increasing cone angles at the apex. The larger the cone angle, the shallower is the cone and the less is the available burning surface area with concomitant reduction in effective or mass burning rate.

Metal alloys can be employed advantageously in some cases, particularly where the alloying serves to increase melting point without adversely affecting thermal diffusivity to any substantial extent.

The efficacy of metals such as silver and copper, which have high thermal diffusivity but relatively low melting points, can be enhanced appreciably by plating with a metal of high melting point such as chromium, and the like. The high-melting metal provides a shell in which the lower-melting core, even though molten, is supported to provide a continuous path of low thermal resistance from the flame zone to the propellant. Generally speaking, where the plating metal has a substantially lower thermal diffusivity, the coating is desirably relatively thin, as for example in the order of up to about 0.001 inch and preferably less. Thick coatings may, otherwise, provide sufficient thermal resistance to radial heat transfer to counterbalance the advantage gained by raising the effective melting temperature of the heat conductor.

The thickness of the wire or other metal heat conductor is not critical inasmuch as the increase in effective

burning rate is due to the higher thermal diffusivity of the metal relative to the propellant material. The thickness of the metal conductor does, however, influence to some degree the extent of burning rate increase. For example, the greatest increases generally are obtained with wires having a thickness of about 2 to 10 mils, although large increases are also obtained with both thinner and thicker wires. In the case of metal heat conductors which, in their cross-sectional dimensions are considerably wider than they are thick, such as metal strips or tubes, it appears to be the smaller dimension, namely the thickness, which affects the degree of burning rate increase. One of the practical considerations which may, to some extent, determine the thickness of the wire or other heat conductor, is the undesirability of introducing such large amounts of inert material as substantially to decrease the gas-generating potential of the plastic monopropellant. From this point of view, a maximum heat conductor thickness of about 50 mils and preferably about 30 mils is desirable.

In addition to increasing the mass burning rate and rate of gas generation, the embedded conductors can be employed effectively to reduce the pressure exponent of the plastic monopropellant, namely, the response of its linear burning rate to changes of pressure. It is a general characteristic of propellants that burning rate increases with increased pressure, the degree of increase varying with the particular propellant composition. Propellants which are highly sensitive in this respect are generally undesirable. Above a certain thickness, which varies with the particular metal and the propellant material, the metal heat conductors effect a marked decrease in the pressure exponent.

The embedded bare metal heat conductors make possible increases in effective burning rate which are as high as three to five fold. This is an enormous improvement as compared with the burning rate of the plastic monopropellant grain without such embedded metal conductors. However, fairly definite limits in mass burning rate increases obtainable by incorporation of the bare metal are set by the physical characteristics of the metal, namely its thermal diffusivity and melting point.

There are situations, as, for example, in the field of rocketry, requiring for optimum performance both the high loading density obtainable with the end-burning, plastic, monopropellant grains and even higher effective mass burning rates than those made possible by the embedding of the bare metal heat conductors.

A considerably greater increase in mass burning rate of the plastic monopropellant grain can be obtained by coating the bare metal heat conductor with a solid self-oxidant composition having a higher linear burning rate than the plastic monopropellant matrix before embedding it therein. The solid, self-oxidant coating must adhere in intimate contact with the metal, and the metal coating, after introduction into the plastic monopropellant grain, must be in intimate contact throughout with the propellant matrix for the same reasons discussed above in connection with the bare metal heat conductors.

The increase in mass burning rate and rate of gas generation obtained by coating the metal heat conductors with a solid, self-oxidant composition of higher burning rate than that of the plastic propellant matrix can be several times greater than that obtained with the bare metal conductor. The extent of the increase appears largely to be determined by the relative burning rates of the matrix and the coating, the higher the burning rate of the coating relative to the matrix, the greater generally being the increase in mass burning rate of the plastic monopropellant grain. Thus, within maximum limits imposed by available maximum burning rates of suitable self-oxidant coating compositions, the mass burning rate of the plastic monopropellant grain can be tailored to desired levels above that obtainable with the bare metal conductor. The self-oxidant coating also possesses the

additional advantage of improving pressure exponent to an even greater extent in some cases than the bare metal alone.

In some applications, it is advantageous to employ end-burning plastic monopropellant grains having mass burning rates, adjustable to any desired level, which are substantially higher than that of the propellant matrix but not as high as those ordinarily obtained by incorporation of the base metal heat conductor. Such controllable, intermediate mass burning rates can be achieved by coating the bare metal conductor with a solid, self-oxidant coating, as aforesaid, except that the self-oxidant coating composition has a substantially lower linear burning rate than that of the plastic monopropellant matrix. Thus, the choice or proper formulation of a self-oxidant coating having a sufficiently lower burning rate than the propellant matrix makes possible controlled tailoring of mass burning rate to substantially any desired level intermediate that of the normal burning rate of a given plastic propellant matrix and the burning rate of the same matrix containing the same bare metal heat conductor embedded therein.

By "self-oxidant coating composition" as employed in this specification and claims is meant a composition which contains within itself oxygen available for combustion of a fuel component of the composition. This oxygen can be present in the form of an oxidizing agent which provides oxygen for the combustion of a separate fuel component, such as an organic fuel or a finely divided metal, or it can be present in the form of compounds which contain sufficient oxygen available for substantial internal combustion of oxidizable portions of the molecule.

For effective, efficient and reliable action, it is desirable that the coating composition adhere to the metal heat conductor in the form of a continuous, homogeneous film, which, preferably is sufficiently elastic or non-brittle not to chip or crack. This can generally be accomplished by employing active components which themselves impart these characteristics or by incorporating a binder which serves both to hold the active components together in a homogeneous mixture and to impart suitable coating properties.

Coating compositions having different burning rates suitable for different propellant applications can readily be formulated by proper selection of fuel and oxidizer components, by varying the concentrations of the fuel and oxidizer, by the incorporation of catalysts which influence the burning rate, by increasing or decreasing the particle size of certain types of fuels, such as powdered metals, or of certain types of oxidizing agents, such as solid inorganic oxidizers, and the like. The suitability of a given coating composition for use with a particular metal conductor and a particular plastic monopropellant matrix to obtain a desired burning rate can readily be determined by the preparation and burning of test grains or strands by methods well known to those skilled in the art.

The solid coating compositions can comprise, in whole or in part, compounds which are internally oxidant, namely, contain sufficient molecularly combined oxygen available for substantial internal oxidation of carbon and hydrogen components of the molecule, such as nitrocellulose, nitroglycerin, nitrotoluene and the like. Good coating compositions can be prepared by gelatinizing nitrocellulose with an internally oxidant plasticizer, such as nitroglycerine, or with an other suitable organic plasticizer which is inert, namely not internally oxidant. Examples of suitable organic plasticizers include triacetin, the various phthalates such as diethyl phthalate, dibutyl phthalate, dioctyl phthalate, di-(methoxyethyl) phthalate, methyl phthalyl ethyl glycolate, ethyl phthalyl ethyl glycolate and butyl phthalyl butyl glycolate, sebacates such as dibutyl and dioctyl sebacates, adipates such as dioctyl adipate and di-(3,5,5-trimethylhexyl) adipate, glycol esters

of higher fatty acids, organic phosphate esters such as tributoxyethyl phosphate, and the like.

Burning rate of such coating compositions can be controlled within limits by choice of the particular internally oxidant compound or compounds, varying the concentration of such compounds in an inert plasticizer, incorporation of an external oxidizing agent where the internally combined oxygen is not sufficient for complete oxidation of the carbon and hydrogen components of the molecule or where an inert plasticizer is employed in whole or in part.

Coating compositions comprising a fuel, which requires an external source of oxygen for combustion, and an oxidizing agent are particularly suitable since they make possible the formulation of compositions having a wide range of burning rate. The fuel can be any readily oxidizable material including organic fuels, finely divided metals, carbon, silicon and the like employed alone or in combination.

We have found that coating compositions containing finely divided metal as the fuel component are especially good. Any metal which forms stable compositions with an oxidizing agent at ordinary temperatures and which forms oxides that are stable at elevated temperatures, can be employed for our purpose. The finely divided metal fuel is particularly effective where high propellant burning rates are desired. Finely divided metal fuels characterized by substantially higher exothermic heats of reaction than carbon when oxidized to carbon monoxide generally provide compositions having higher burning rates than the propellant matrix. Such metals include, for example, Al, Be, B, Ca, Ce, Mg, Si, Ti, V, Zn and the like. Finely divided metals having substantially low to moderate exothermic heats of oxidation, such as Cu, Fe, Ni, Mn, Cr and the like can be employed as fuels where the effective propellant burning rate desired is intermediate that of the propellant matrix alone and that obtained with the same uncoated metal heat conductor.

The finely divided metal fuel and the requisite oxidizing agent can be formulated into a suitable, homogeneous coating composition by admixture with a suitable binding agent which imparts adequate film-forming properties and adherency when the composition is applied to the metal heat conductor. Preferably, the binder is an oxidizable organic material. In such case, the binder can also serve as a fuel component in addition to the metal although it is not essential that sufficient oxidizer be incorporated to oxidize all of the metal and organic fuel or binder. Suitable organic binders which provide desirable coating properties and which can also serve as fuels include, for example, organic polymers such as cellulose esters, cellulose ethers, vinyl polymers, acrylates and methacrylates, phenolaldehydes, urea-formaldehydes, polyamides, and the like; natural and synthetic rubber; natural resins; organic silicones such as dimethyl siloxane; bituminous materials such as pitch and asphalt; and the like.

In the case of the synthetic polymers, it is frequently desirable to incorporate a non-volatile organic plasticizer to improve the workability and film-forming properties of the plastic and the physical properties of the coating in terms, for example, of reduced brittleness and increased adherency. The organic plasticizer can also serve as a fuel component in the coating composition. Any organic plasticizer which is compatible with the polymer and imparts the desired physical properties can be used. Plasticizers which are suitable for the various polymers include, for example, phthalates such as dimethyl phthalate, diethyl phthalate, dibutyl phthalate, dioctyl phthalate, di-(methoxyethyl) phthalate, di-(ethoxyethyl) phthalate, methyl- and ethyl-phthalyl pycolate, butyl phthalyl butyl glycolate, sebacates such as dibutyl and dioctyl sebacate, adipates such as dioctyl adipate, acetates such as glyceryl triacetate, butylene glycol diacetate and cresyl glyceryl diacetate, glycol esters of higher fatty acids, citrates such as triethyl citrate and acetyl tri-

ethyl citrate, organic phosphate esters such as tri-butoxyethyl phosphate and trimethyl phosphate, maleates such as methyl maleate, propionates such as diethylene glycol propionate, and the like.

Organic materials can be employed very effectively as the sole fuel component in combination with an oxidizing agent. Any readily oxidizable organic material can be used for the purpose including for example, synthetic and natural polymers, natural and synthetic rubber, bituminous material such as pitch and asphalt, waxes, carbohydrates and the like. In general, it is preferable to employ organic fuels which possess, in addition, good bonding, film-forming and coating properties such as various organic polymers and rubber, both natural and synthetic. Synthetic polymers which are particularly good include, for example, vinyl polymers such as polyvinyl chloride, fatty acid cellulose esters such as cellulose acetate, cellulose ethers such as ethyl cellulose, acrylate and methacrylate esters, polyamides and the like. The polymers are preferably employed with suitable nonvolatile organic plasticizers, illustrative examples of which have been set out above.

Burning rate of coating compositions containing organic material as the sole type of fuel is determined largely by the particular material selected, the specific oxidizing agent employed and the amount and particle size of the oxidizer. Generally speaking, other factors being constant, increasing burning rates are obtained with increasing concentrations of oxidizer up to stoichiometric levels.

Burning rates as high as those obtainable with a finely divided metal fuel having a considerably higher exothermic heat of oxidation than carbon to carbon monoxide cannot generally be achieved when an organic material is employed as the sole type of fuel. However, such organic fuel coating compositions for the metal heat conductor can be prepared having substantially higher burning rates than the propellant matrix of the propellant grain with resulting substantially increased mass burning rate of the grain as compared with that obtained with the bare metal heat conductor. Another important advantage of organic fuel coatings lies in the fact that such compositions having lower burning rates than the propellant grain matrix can be easily prepared as, for example, by reducing oxidizer concentration. Application of coatings having lower burning rates than the propellant matrix to the metal heat conductor results in an over-all mass burning rate for the propellant grain which is intermediate that of the matrix alone and that of the matrix containing the embedded bare metal, thus providing effective burning rate control within this area.

Any finely divided oxidizing agent which provides readily available oxygen for combustion of the fuel component of the coating composition can be employed including, for example, ammonium, K, Na and Li chlorates and perchlorates, ammonium, K, Na and Ba nitrates, metal oxides, peroxides or superoxides, such as those of Cu, Fe, Hg, Pb, Mo, Co, Ni, Zn, As, Sb, Sn, Ba, K, Mn and Na, and the like. The inorganic oxidizing salts and oxides are preferred because of their relative stability, organic oxidizing agents such as hexanitroethane, mannitol hexanitrate, cyclotrimethylene trinitramine and the like can also be used if satisfactorily desensitized.

The concentration of oxidizer incorporated in the coating composition is not critical and is determined largely by the requirements of the particular fuel components and the burning rate desired. It can be introduced in some cases in an amount as low as 15 to 20% and as high as 85% or more.

Controllable mass burning rates intermediate those of the plastic monopropellant matrix with and without a given embedded bare metal conductor can also be obtained by coating the metal with a composition which has a substantially lower heat conductivity than the metal and which is inert, namely not self-oxidant. Adjustment of the mass burning rate to any desired intermediate level

can be achieved by proper choice or formulation of the coating composition.

Since the inert coating composition, unlike the plastic monopropellant matrix, is not self-oxidant, namely does not contain within itself oxygen in substantial amounts available for self-combustion, it functions primarily as an insulator which diminishes heat transfer from the metal heat conductor to the plastic monopropellant matrix. The degree to which the heat transfer is reduced is determined largely by the particular insulating properties of the composition and the thickness of the coating.

The insulator coating material can be substantially any non-self-oxidant composition which is characterized by substantially lower heat conductivity than the metal heat conductor and which adheres to the metal in the form of a continuous, homogeneous film. The coating should preferably be sufficiently elastic or non-brittle not to chip or crack.

Coatings which comprise a polymer, at least in part, are especially suitable both because of their insulating properties and their usually excellent film forming ability. Such polymers include, for example, cellulose esters such as cellulose acetate and other fatty acid esters, cellulose ethers such as ethyl cellulose, vinyl polymers such as polyvinyl chloride and polyvinyl acetate, phenolic resins such as the phenol-aldehydes, urea-formaldehydes, polyamides, natural and synthetic rubber, natural resins, silicones such as a dimethyl siloxane, and the like.

In the case of the synthetic polymers, it is frequently desirable to incorporate a non-volatile organic plasticizer to improve the workability and film-forming properties of the plastic and the physical properties of the coating in terms, for example, of reduced brittleness and increased adhesion. Any organic plasticizer which is compatible with the polymer and imparts the desired physical properties can be used. Plasticizers which are suitable for the various polymers include, for example, phthalates such as dimethyl phthalate, diethyl phthalate, dibutyl phthalate, dioctyl phthalate, di-methoxyethyl phthalate, diethoxyethyl phthalate, methyl- and ethyl-phthalyl glycolate, butyl phthalyl butyl glycolate, sebacates such as dibutyl and dioctyl sebacate, adipates such as dioctyl adipate, acetates such as glyceryl triacetate, butylene glycol diacetate and cresyl glyceryl diacetate, higher fatty acid glycol esters, citrates such as triethyl citrate and acetyl triethyl citrate, organic phosphate esters such as tri-butoxyethyl phosphate and trimethyl phosphate, maleates such as methyl maleate, propionates such as diethylene glycol propionate, and the like.

Finely divided solids, such as silica, bentonite, CaCO_3 , asbestos and the like, can be incorporated into the coating composition to influence its insulating properties.

Inorganic coatings, e.g. fused metal oxides, glass or ceramic coatings can also be used. An example of an excellent enamel frit coating is the National Bureau of Standards Ceramic Coating A-418 which, after fusion of a SiO_2 , BaCO_3 , H_3BO_3 , CaCO_3 , ZnO , hydrated Al_2O_3 and ZrO_2 mixture onto the metal conductor, forms an adherent boro-silicate film comprising, by analysis on an oxide basis, SiO_2 , BaO , B_2O_3 , CaO , ZnO , Al_2O_3 and ZrO_2 .

The various coating compositions can be prepared and applied to the metal heat conductor in any desired manner as, for example, by dipping or spraying. In some cases it may be desirable to fluidify the coating prior to application by addition of a volatile solvent which is removed by volatilization after the coating is applied. In some instances, it will be necessary to heat the coated metal to polymerize applied monomeric or partially cured polymeric materials, to dissolve the polymer in plasticizer to form a solid gel, or to fuse the applied materials. Where the coating composition is self-oxidant, any required heating operation should, of course, be carried out at temperatures below ignition temperature.

FIGURES 16 and 17 illustrate a plastic monopropellant grain having embedded therein longitudinally disposed

coated wire heat conductors 8, having coating 13, which can be self-oxidant or non-self-oxidant. Both the self-oxidant and non-self-oxidant coatings can be applied to metal heat conductors of any configuration, such as those illustrated in FIGURES 10, 12 and 14, with results similar to those obtained with the coated wires.

The metal heat conductor, bare or coated as aforescribed is preferably copper, aluminum or silver, although it can be any other metal having good heat conductive properties, such as platinum, steel, tungsten, magnesium and the like.

As aforementioned, the monopropellants employed in this invention are cohesive, shape-retentive materials, which are characterized as plastic or semi-solid because they flow at ambient or normal temperatures under stress or pressure. The cohesive strength for the present mode of use should be substantial, the particular degree being largely determined by the stresses developed in a particular application. For example, the degree of cohesive strength required where the plastic monopropellant grain will be subjected to high accelerative stresses, as in a rocket, is greater than that required where the propellant is burned in a stationary gas generator, such as a gas turbine. Cohesive strength is closely related to tensile strength of the material. In general the minimum desirable tensile strength is about 0.03 p.s.i. and preferably about 0.05 p.s.i.

The fluidity of the plastic monopropellant compositions, as measured by the flow through a circular tube corresponds to an apparent viscosity of 1,000 to 150,000 poises at ambient temperature.

Many different plastic monopropellant compositions tailored to different performance requirements can be made having the aforescribed physical characteristics. The monopropellant composition can, for example, by a double-base type propellant, such as nitroglycerine gelled to the proper semisolid consistency by solution therein of nitrocellulose. Generally, it will comprise a stable dispersion of a finely-divided, insoluble oxidizer in a continuous matrix of an oxidizable liquid fuel which burns to produce large quantities of high energy combustion gases.

The liquid fuel can be any oxidizable liquid, preferably an organic liquid containing carbon and hydrogen. Suitable liquid fuels include hydrocarbons, such as triethyl benzene, dodecane, liquid polyisobutylene, and the like; compounds containing oxygen linked to a carbon atom, as, for example, esters, like di-methyl maleate, diethyl phthalate, dibutyl oxalate, and the like; alcohols, such as benzyl alcohol, triethylene glycol and the like; ethers such as methyl α -naphthyl ether and the like; and many others.

The solid oxidizer can be any suitable, active oxidizing agent which yields an oxidizing element such as oxygen, chlorine or fluorine readily for combustion of the fuel and which is insoluble in the liquid fuel vehicle. Such oxidizers include inorganic oxidizing salts such as ammonium, sodium and potassium perchlorate or nitrate and metal peroxides such as barium peroxide.

The amount of solid oxidizer incorporated varies, of course, with the particular kind and concentration of fuel components in the formulation, the particular oxidizer, and the specific requirements for a given use, in terms, for example, of required heat release and rate of gas generation, and can readily be computed by those skilled in the art. Since the liquid vehicle can, in many instances, be loaded with as high as 80 to 90% of finely-divided solids, stoichiometric oxidizer levels with respect to the fuel components can generally be achieved when desired, as for example, in rocket applications where maximum heat release and specific impulse are of prime importance. In some applications, stoichiometric oxidation levels may not be necessary or even desirable, as, for example, in gas turbines where relatively low combustion chamber temperatures are preferred, and the amount of oxidizer can be correspondingly reduced. Sufficient oxidizer must,

of course, be incorporated to maintain active, gas-generating combustion.

Finely-divided solid metal powders such as aluminum or magnesium, in sizes up to about 50 microns, may be incorporated in the monopropellant composition as an additional fuel component along with the liquid fuel. Such metal powders possess the advantages both of increasing the fuel density and improving the specific impulse of the monopropellant because of their high heats of combustion.

The physical properties of the plastic monopropellant in terms of shape-retentive cohesiveness, tensile strength and thixotropy, can be improved by addition of a gelling agent, such as a polymer, e.g. polyvinyl chloride, polyvinyl acetate, cellulose acetate, ethyl cellulose, or metal salts of higher fatty acids, such as the sodium or magnesium stearates or palmitates. The desired physical properties can also be obtained without a gelling agent by using a liquid vehicle of substantial intrinsic viscosity, such as liquid organic polymers, e.g. liquid polyisobutylene, liquid siloxanes, liquid polyesters, and the like.

The plastic monopropellants are prepared simply by mixing the components in a suitable mixing device and can then be extruded directly into the combustion chamber of the gas generating device under sufficient pressure to make them flow. After introduction into the combustion chamber, relatively light tamping pressures are generally adequate to produce coalescence of the plastic material throughout, thereby eliminating any undesirable interstices within the body of the mass. Loading is preferably carried out under vacuum to prevent the formation of air bubbles. The plastic monopropellants can also be loaded into receptacles, preferably made of a heat insulating material and shaped to conform to the contours of the combustion chamber. The receptacles containing the plastic monopropellant grain can then be introduced into the combustion chamber of the gas generating device. The plastic monopropellants thus eliminate certain of the disadvantages of solid propellants, such as hazardous high temperature, high pressure curing, fissuring and cracking.

The metal heat conductors can be introduced into the plastic monopropellant in a number of ways. Rigid structures, such as tubes or honeycomb can be pushed directly down into the body of the plastic material. Wires can be threaded through the mass. They can also be fixedly positioned in the combustion chamber as, for example, by means of spiders attached to the chamber walls prior to extrusion of the plastic monopropellant into the chamber. A properly designed tamper can then be employed to compact the plastic material down and about the wires.

To prevent any undesirable flow of the plastic monopropellant under the stresses of handling, shipping or certain attitudes during storage, a solid capping plate can be overlaid on the exposed ignition surface of the end-burning grain. Preferably this is made of solid propellant, as shown in FIGURE 1-A, since the plate can then also function as an igniter for the plastic monopropellant.

The following example is given to illustrate the efficacy of a metal heat conductor in increasing the mass burning rate of an end-burning grain made of a plastic or semi-solid monopropellant as aforescribed.

End-burning grains were made of a semi-solid, shape-retentive, monopropellant composition comprising.

Percent by weight

NH ₄ ClO ₄ , 6900 r.p.m. 2TH grind and unground,	
2:1 -----	79.7
Diocetyl adipate-----	12.1
Polyvinyl chloride ¹ -----	8.1
Wetting agent-----	0.1

¹ Gelling agent.

All surfaces were inhibited except for an initial end-burning surface. Burning rate of the grains was 0.55 in./sec. at 1000 p.s.i.a. Pressure exponent was 0.46.

Similar grains were prepared except that a 5-mil diameter silver wire was axially positioned in each grain normal to the initial end-burning surface. Upon ignition, burning occurred with involution along the wire. Burning rate was 2.46 in./sec. at 1000 p.s.i.a. Pressure exponent was 0.43.

Although this invention has been described with reference to illustrative embodiments thereof, it will be apparent to those skilled in the art that the principles of this invention can be embodied in other forms but within the scope of the claims.

I claim:

1. A monopropellant grain which burns progressively from one end which defines the initial ignition surface, comprising a self-oxidant matrix, the combustion of which generates propulsive gases, said matrix being a semi-solid, thixotropic mass having a minimum tensile strength of about 0.03 p.s.i., and being capable of flow under applied pressure at ambient temperature, its maximum apparent viscosity at ambient temperature as measured by its flow through a circular tube being about 150,000 poises, said matrix containing embedded therein elongated metal heat conductor means, said metal heat conductor means being positioned substantially normal to the plane of said initial ignition surface and being continuously and longitudinally disposed in the direction of flame propagation of the grain, said conductor within the body of the grain having a length of at least about 0.2 inch and a maximum metal thickness of about 0.05 inch in at least one transverse direction, the entire surface of said length of said metal heat conductor means lying within the body of the propellant grain and being in intimate, gas-sealing contact with the propellant matrix, the burning surface of said grain after ignition regenerating progressively along said metal heat conductor and, in so doing, forming a recess which is substantially V-shaped in at least one plane with said metal heat conductor at the apex of said recess, thereby forming a recessed surface of substantially larger surface area than that of a plane burning surface, the metal heat conductor means thereby serving controllably to increase the mass burning rate and, thereby, the mass rate of gas generation of said monopropellant grain.

2. The monopropellant grain of claim 1 in which one end of the metal heat conductor means is exposed at said initial ignition surface of the grain.

3. The monopropellant grain of claim 1 in which the metal heat conductor means is longitudinally and continuously disposed for a predetermined distance in the direction of flame propagation of the grain.

4. The monopropellant grain of claim 1 in which said elongated metal heat conductor means forms a longitudinal tubular structure within the body of the grain.

5. The monopropellant grain of claim 4 in which said elongated metal heat conductor means forms a plurality of longitudinal tubular structures within the body of the grain.

6. The monopropellant grain of claim 5 in which said elongated metal heat conductor means comprises a skeletal framework forming longitudinal passages.

7. A monopropellant grain which burns progressively from one end which defines the initial ignition surface, comprising a self-oxidant matrix, the combustion of which generates propulsive gases, said matrix being a semi-solid, thixotropic mass having a minimum tensile strength of about 0.03 p.s.i., and being capable of flow under applied pressure at ambient temperature, its maximum apparent viscosity at ambient temperature as measured by its flow through a circular tube being about 150,000 poises, said matrix containing embedded therein, a plurality of elongated metal heat conductors substantially spaced from each other in the plane transverse to the direction of

flame propagation, said metal heat conductors being positioned substantially normal to the plane of said initial ignition surface and being continuously and longitudinally disposed in the direction of flame propagation of the grain, said conductors within the body of the grain having a length of at least about 0.2 inch and having a maximum thickness of about 0.05 inch in at least one transverse direction, the entire surface of said length of said metal conductors lying within the body of the propellant grain and being in intimate, gas-sealing contact with the propellant matrix, the burning surface of said grain, after ignition, regenerating progressively along each of said metal heat conductors and, in so doing, forming a recess which is substantially V-shaped in at least one plane with each of said metal heat conductors at the apex of said recess, thereby forming a recessed surface of substantially larger surface area than that of a plane burning surface, said metal heat conductors being spaced sufficiently apart to permit said recessing of the burning surface, the metal heat conductors thereby serving to increase the mass burning rate, and, thereby, the mass rate of gas generation of said monopropellant grain.

8. The monopropellant grain of claim 7 in which the metal heat conductors are continuous substantially throughout the distance of flame propagation.

9. The monopropellant grain of claim 7 in which the metal heat conductors comprise a plurality of metal wires.

10. A monopropellant grain which burns progressively from one end which defines the initial ignition surface, comprising a self-oxidant matrix, the combustion of which generates propulsive gases, said matrix being a semi-solid, thixotropic mass having a minimum tensile strength of about 0.03 p.s.i., and being capable of flow under applied pressure at ambient temperature, its maximum apparent viscosity at ambient temperature as measured by its flow through a circular tube being about 150,000 poises, said matrix containing embedded therein elongated metal heat conductor means coated with a self-oxidant solid coating having a normal burning rate different from the normal burning rate of the monopropellant matrix, said coated metal heat conductor being positioned substantially normal to the plane of said initial ignition surface of said grain and being continuously and longitudinally disposed in the direction of flame propagation of the grain, said conductor within the body of the grain having a length of at least about 0.2 inch and a maximum metal thickness of about 0.05 inch in at least one transverse direction, the entire surface of said length of said coated metal conductor lying within the body of the monopropellant grain and being in intimate, gas-sealing contact with the monopropellant matrix, the burning surface of said grain, after ignition, regenerating progressively along said coated metal heat conductor and, in so doing, forming a recess which is substantially V-shaped in at least one plane with said coated metal heat conductor at the apex of said recess, thereby forming a recessed surface of substantially larger surface area than that of a plane burning surface, the coated metal heat conductor means thereby serving controllably to increase the mass burning rate and, thereby, the mass rate of gas generation of said monopropellant grain to a level determined by the particular metal heat conductor and the relative burning rates of the self-oxidant coating and the monopropellant matrix.

11. The monopropellant grain of claim 10 in which the self-oxidant coating has a higher normal linear burning rate than the monopropellant matrix.

12. The monopropellant grain of claim 10 in which the coated metal heat conductor means comprises a plurality of coated metal wires substantially spaced from each other in the plane transverse to the direction of flame propagation, said wires being spaced sufficiently apart to permit recessing of the burning surface after ignition.

13. The monopropellant grain of claim 10 in which the coated metal heat conductor means is continuous

substantially throughout the distance of flame propagation of the grain.

14. The monopropellant grain of claim 10 in which said coated elongated metal heat conductor means forms a longitudinal tubular structure within the body of the grain.

15. The monopropellant grain of claim 14 in which said tubular structure comprises a skeletal framework forming longitudinal passages.

16. A monopropellant grain which burns progressively from one end which defines the initial ignition surface, comprising a self-oxidant matrix, the combustion of which generates propulsive gases, said matrix being a semi-solid, thixotropic mass having a minimum tensile strength of about 0.03 p.s.i., and being capable of flow under applied pressure at ambient temperature, its maximum apparent viscosity at ambient temperature as measured by its flow through a circular tube being about 150,000 poises, said matrix containing embedded therein elongated metal heat conductor means coated with a solid, inert composition characterized by substantially lower heat conductivity than that of the metal, said coated metal heat conductor being positioned substantially normal to the plane of said initial ignition surface of said grain and being continuously and longitudinally disposed in the direction of flame propagation of the grain, said conductor within the body of the grain having a length of at least about 0.2 inch and a maximum metal thickness of about 0.05 inch in at least one transverse direction, the entire surface of said length of said coated metal conductor lying within the body of the monopropellant grain and being in intimate, gas-sealing contact with the monopropellant matrix, the burning surface of said grain, after ignition, regenerating progressively along said coated metal heat conductor and, in so doing, forming a recess which is substantially V-shaped in at least one plane with said coated metal heat conductor at the apex of said recess, thereby forming a recessed surface of substantially larger surface area than that of a plane burning surface, the coated metal heat conductor means thereby serving controllably to increase the mass burning rate and, thereby, the mass rate of gas generation of said monopropellant grain to a level intermediate that of the monopropellant matrix alone and that of the monopropellant matrix containing embedded therein the same metal heat conductor uncoated.

17. The monopropellant grain of claim 16 in which the coated metal heat conductor means comprises a plurality of coated metal wires substantially spaced from each other in the plane transverse to the direction of flame propagation, said wires being spaced sufficiently apart to permit recessing of the burning surface after ignition.

18. The monopropellant grain of claim 16 in which said coated elongated metal heat conductor means forms a longitudinal tubular structure within the body of the grain.

19. The monopropellant grain of claim 18 in which said tubular structure comprises a skeletal framework forming longitudinal passages.

20. A monopropellant grain which burns progressively from one end which defines the initial ignition surface, comprising a self-oxidant matrix, the combustion of which generates propulsive gases, said matrix being a semi-solid, thixotropic mass having a minimum tensile strength of about 0.03 p.s.i., and being capable of flow under applied pressure at ambient temperature, its maximum apparent viscosity at ambient temperature as measured by its flow through a circular tube being about 150,000 poises, said matrix containing embedded and randomly dispersed therein a plurality of spaced elongated metal wires having a minimum length of 0.08 inch and a maximum diameter of about 0.05 inch, the entire surface of said length of said metal wires lying within the body of the monopropellant grain and being in intimate, gas-

sealing contact with the monopropellant matrix, a substantial number of said randomly dispersed wires being at an angle, relative to the plane of said ignition surface, which is substantially less than 180° , the burning surface of said grain, after ignition, regenerating progressively along each of said metal wires positioned at said angle substantially less than 180° , and, in so doing, forming a recess which is substantially V-shaped in at least one plane, with a wire at the apex of each formed recess, thereby forming a recessed surface of substantially larger surface area than that of a plane burning surface, said metal wires being spaced sufficiently apart to permit said recessing of the burning surface, the metal wires thereby serving to increase the mass burning rate and, thereby, the mass rate of gas generation of said monopropellant grain.

21. In a gas generating device, a combustion chamber containing therein a monopropellant grain which burns progressively from one end which defines the initial ignition surface, comprising a self-oxidant matrix, the combustion of which generates propulsive gases, said matrix being a semi-solid, thixotropic mass having a minimum tensile strength of about 0.03 p.s.i., and being capable of flow under applied pressure at ambient temperature, its maximum apparent viscosity at ambient temperature as measured by its flow through a circular tube being about 150,000 poises, said matrix containing embedded therein elongated metal heat conductor means, said metal heat conductor means being positioned substantially normal to the plane of said initial ignition surface and being continuously and longitudinally disposed in the direction of flame propagation of the grain, said conductor within the body of the grain having a length of at least about 0.2 inch and a maximum metal thickness of about 0.05 inch in at least one transverse direction, the entire surface of said length of said metal heat conductor means lying within the body of the propellant grain and being in intimate, gas-sealing contact with the propellant matrix, the burning surface of said grain after ignition regenerating progressively along said metal heat conductor and, in so doing, forming a recess which is substantially V-shaped in at least one plane with said metal heat conductor at the apex of said recess, thereby forming a recessed surface of substantially larger surface area than that of a plane burning surface, the metal heat conductor means thereby serving controllably to increase the mass burning rate and, thereby, the mass rate of gas generation of said monopropellant grain.

22. In a gas generating device, a combustion chamber containing therein a monopropellant grain which defines the initial ignition surface, comprising a self-oxidant matrix, the combustion of which generates propulsive gases, said matrix being a semi-solid, thixotropic mass having a minimum tensile strength of about 0.03 p.s.i., and being capable of flow under applied pressure at ambient temperature, its maximum apparent viscosity at ambient temperature as measured by its flow through a circular tube being about 150,000 poises, said matrix containing embedded therein elongated metal heat conductor means coated with a self-oxidant solid coating having a normal burning rate different from the normal burning rate of the monopropellant matrix, said coated metal heat conductor being positioned substantially normal to the plane of said initial ignition surface of said grain and being continuously and longitudinally disposed in the direction of flame propagation of the grain, said conductor within the body of the grain having a length of at least about 0.2 inch and a maximum metal thickness of about 0.05 inch in at least one transverse direction, the entire surface of said length of said coated metal conductor lying within the body of the monopropellant grain and being in intimate, gas-sealing contact with the monopropellant matrix, the burning surface of said grain, after ignition, regenerating progressively along said coated metal heat conductor and, in so doing, forming a recess which is sub-

stantially V-shaped in at least one plane with said coated metal heat conductor at the apex of said recess, thereby forming a recessed surface of substantially larger surface area than that of a plane burning surface, the coated metal heat conductor means thereby serving controllably to increase the mass burning rate, and, thereby, the mass rate of gas generation of said monopropellant grain to a level determined by the particular metal heat conductor and the relative burning rates of the self-oxidant coating and the monopropellant matrix.

23. In a gas generating device, a combustion chamber containing therein a monopropellant grain which burns progressively from one end which defines the initial ignition surface, comprising a self-oxidant matrix, the combustion of which generates propulsive gases, said matrix being a semi-solid, thixotropic mass having a minimum tensile strength of about 0.03 p.s.i., and being capable of flow under applied pressure at ambient temperature, its maximum apparent viscosity at ambient temperature as measured by its flow through a circular tube being about 150,000 poises, said matrix containing embedded therein elongated metal heat conductor means coated with a solid, inert composition characterized by substantially lower heat conductivity than that of the metal, said coated metal heat conductor being positioned substantially normal to the plane of said initial ignition surface of said grain and being continuously and longitudinally disposed in the direction of flame propagation of the grain, said conductor within the body of the grain having a length of at least about 0.2 inch and a maximum metal thickness of about 0.05 inch in at least one transverse direction, the entire surface

of said length of said coated metal conductor lying within the body of the monopropellant grain and being in intimate, gas-sealing contact with the monopropellant matrix, the burning surface of said grain, after ignition, regenerating progressively along said coated metal heat conductor and, in so doing, forming a recess which is substantially V-shaped in at least one plane with said coated metal heat conductor at the apex of said recess, thereby forming a recessed surface of substantially larger surface area than that of a plane burning surface, the coated metal heat conductor means thereby serving controllably to increase the mass burning rate and, thereby the mass rate of gas generation of said monopropellant grain to a level intermediate that of the monopropellant matrix alone and that of the monopropellant matrix containing embedded therein the same metal heat conductor uncoated.

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