

Nov. 5, 1963

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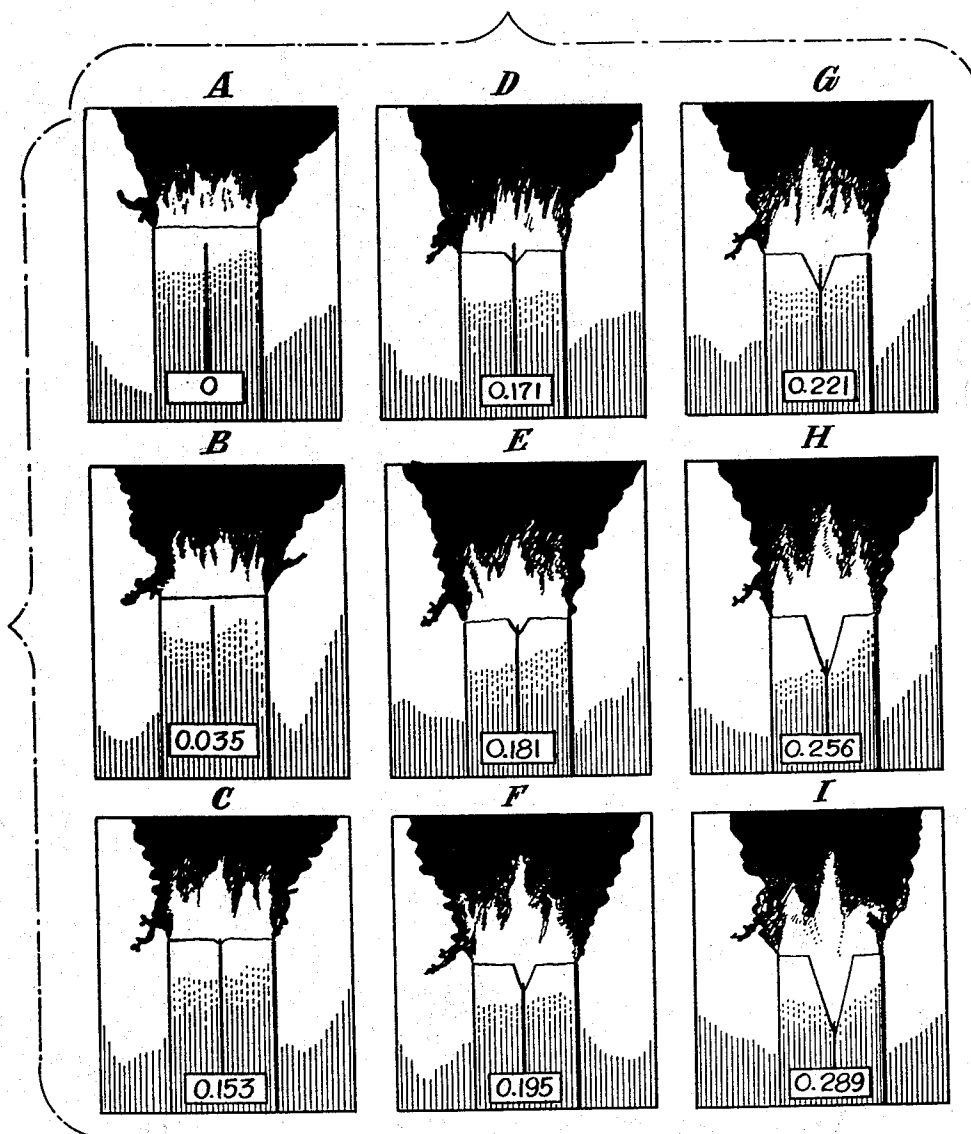
3,109,374

PROPELLENT GRAINS

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Fig. 1.



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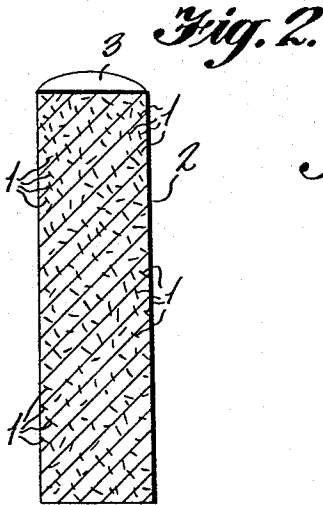
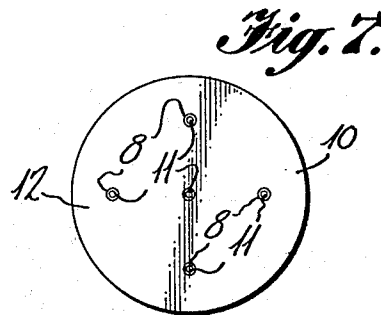
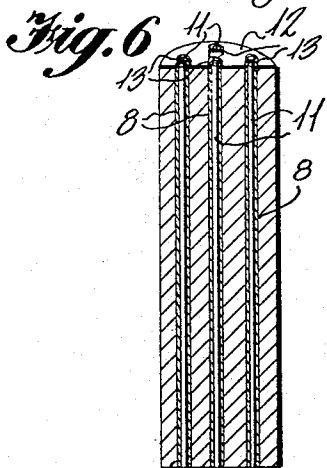
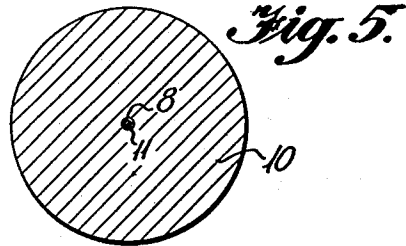
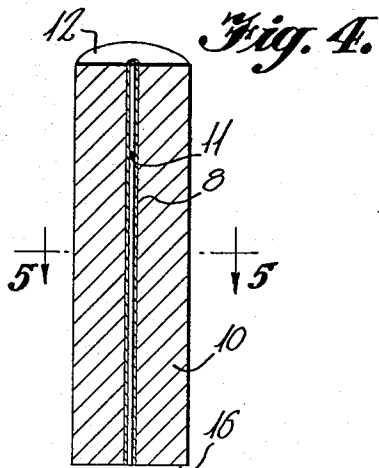
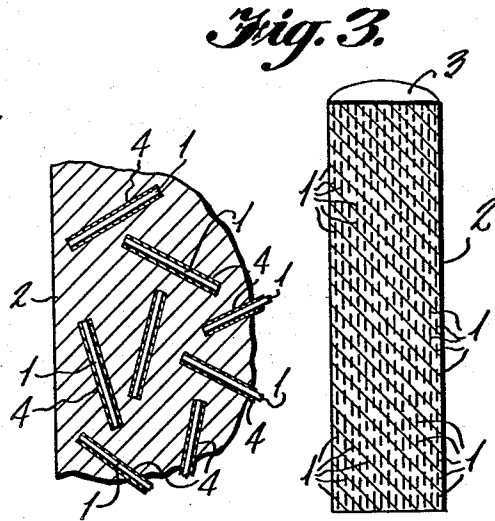


Fig. 2.nd



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Fig. 8.

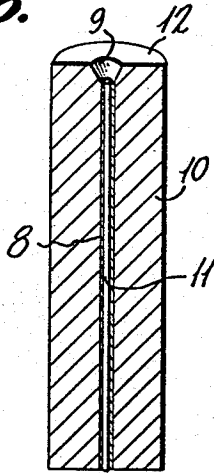


Fig. 9.

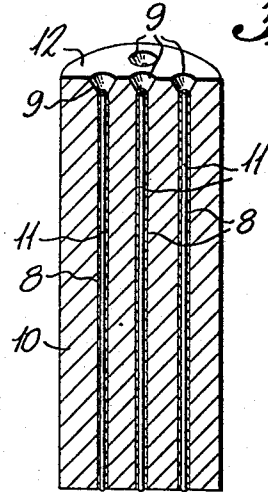
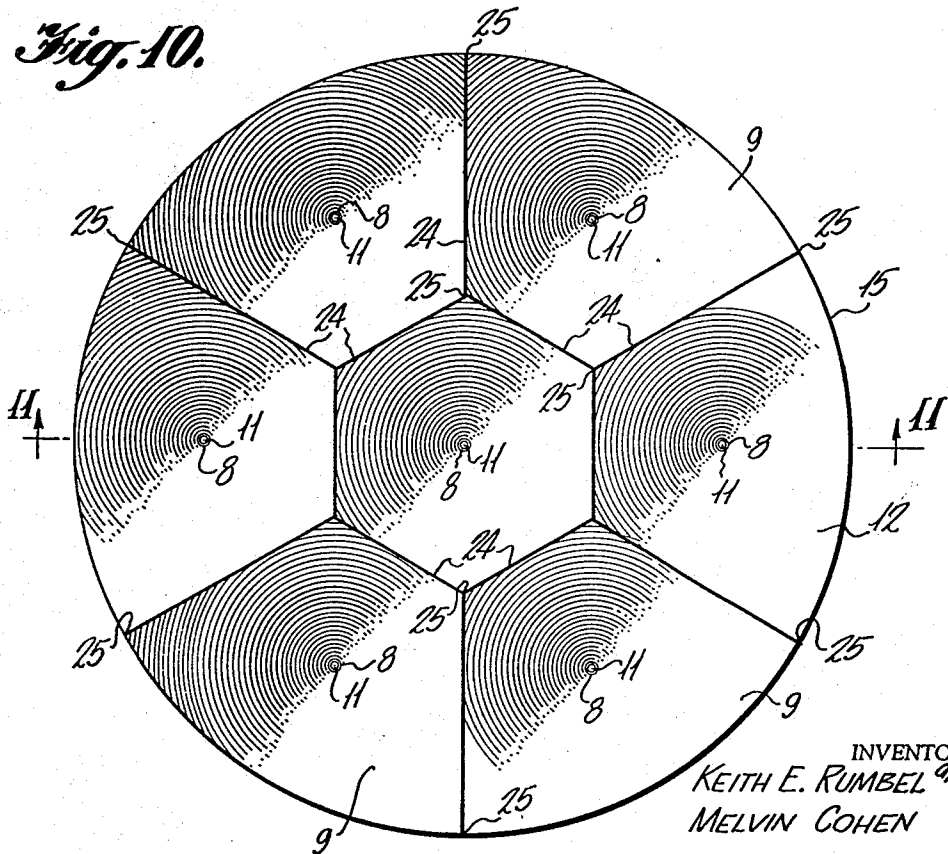


Fig. 10.



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Fig. 11.

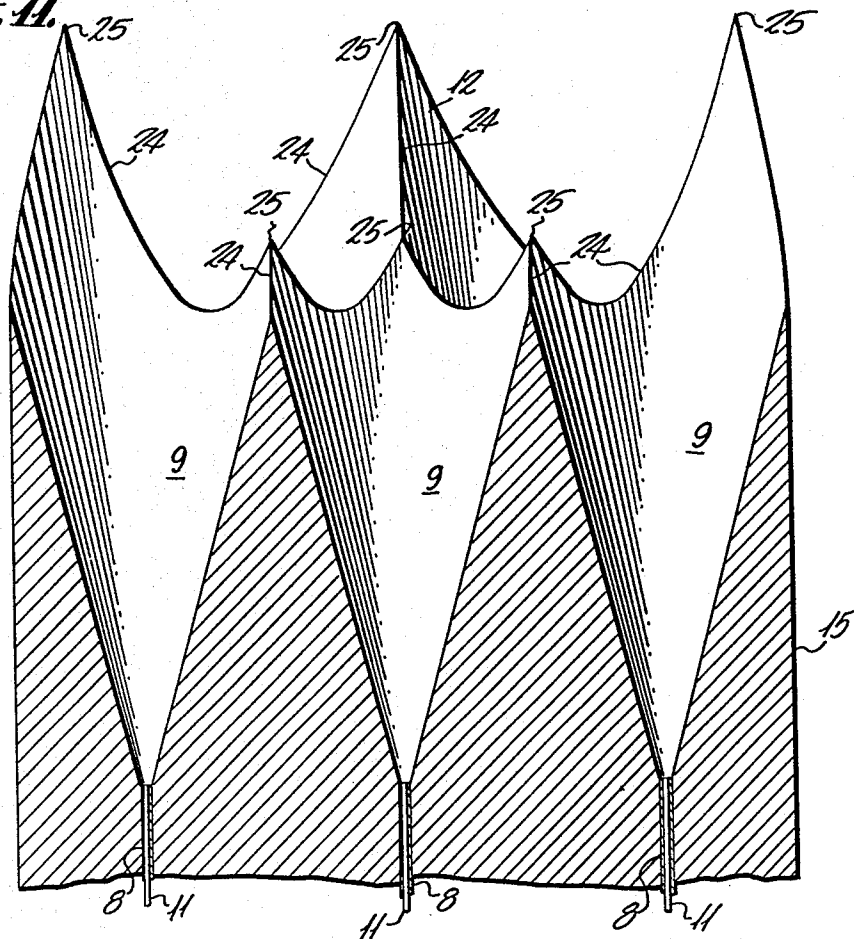


Fig. 12.

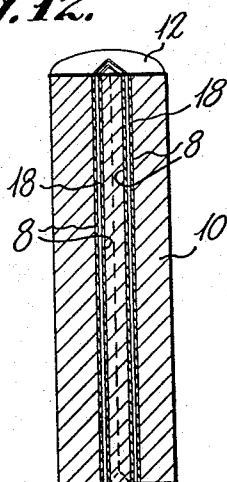
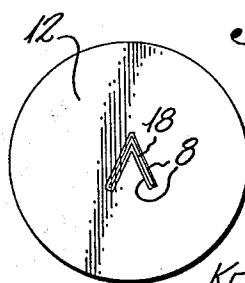


Fig. 13.



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Fig. 14.

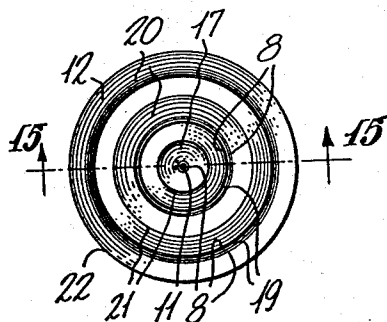


Fig. 15.

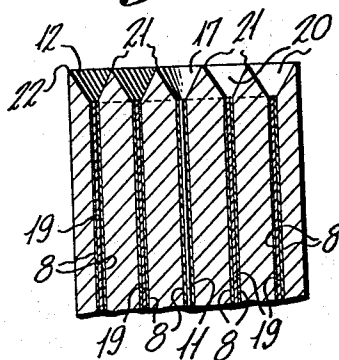


Fig. 16.

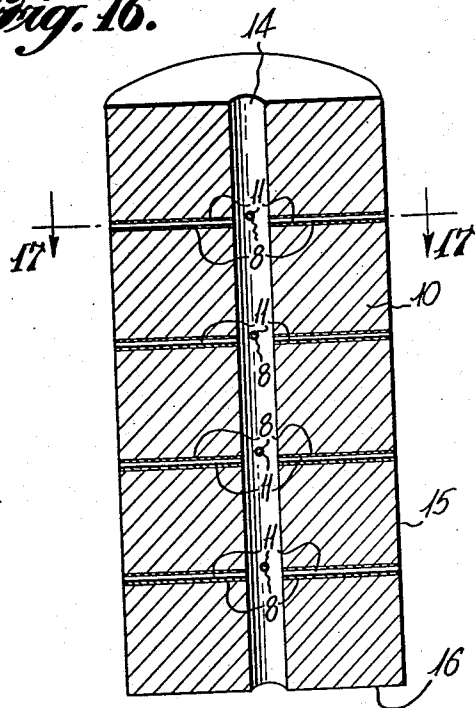
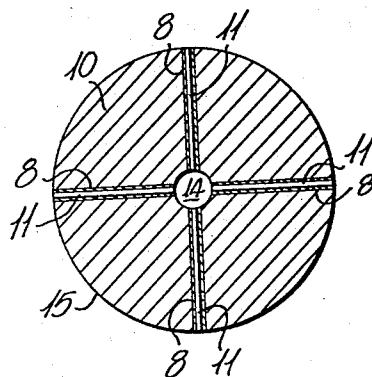


Fig. 17.



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Fig. 18.

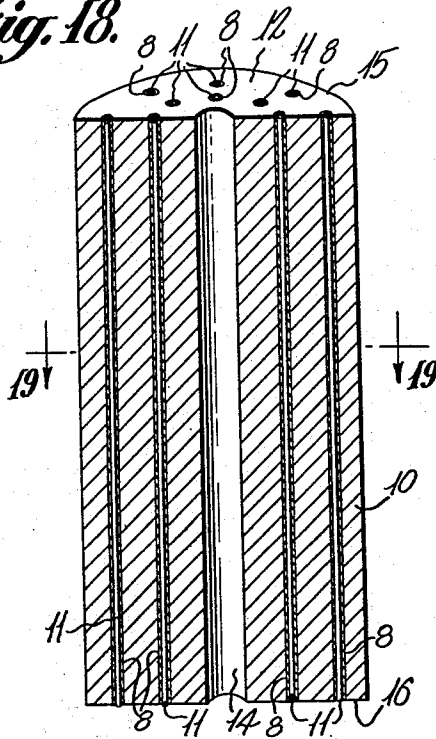


Fig. 19.

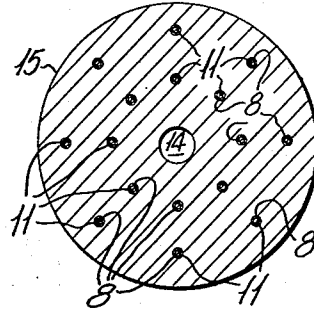


Fig. 21.

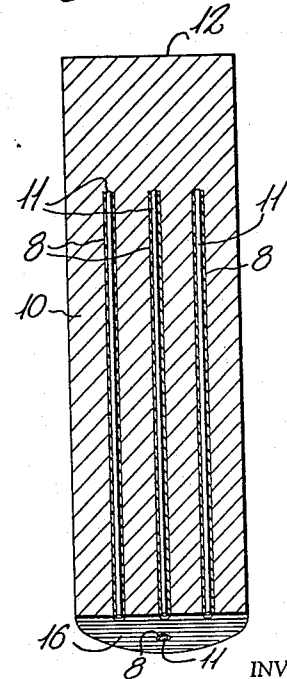
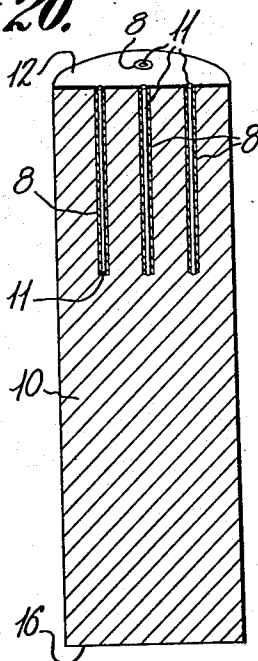


Fig. 20.



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PROPELLENT GRAINS

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Filed Dec. 7, 1956, Ser. No. 627,071
18 Claims. (Cl. 102-98)

This invention relates to new and improved solid propellant grains characterized by controlled increased effective burning rates.

There is an ever-growing requirement, as for example, in the field of rocketry, for the development of propellant grains which provide increased propulsive performance. One way of accomplishing this is to increase the loading density; that is, to fill a greater fraction of the rocket motor chamber volume with the propellant grain. In so doing, however, an adequate rate of generation of propulsive gases must be maintained. Although solid end-burning grains are notable for their high loading density, their use in propulsive devices, as for example, solid-propellant rockets, has been limited by a low rate of generation of propulsive gases. The rate of generation of propulsive gases is proportional to the product of the propellant burning rate and the burning surface area. Although there are various expedients which can be employed to increase the burning rate of the propellant material, the propellant burning rates obtained by modification of the propellant compositions hitherto have not been sufficient to permit the general use of solid end-burning propellant grains.

Instead, it has generally been necessary to employ propellant grains having a burning surface area much greater than the grain cross section by resorting to such devices as extensive perforation of the propellant grain, concentric, spaced tubular arrangement of the propellant material, cruciform shapes and the like. Though providing the desired large area of burning surface, these expedients possess the disadvantage of weakening the grain so that the solid-propellant material must meet stringent requirements as to strength and other physical properties, which impose rigid limitations as to the type of material which can be used. In many cases, also, such grains must be provided with special external supporting and bracing structures.

Solid, end-burning grains, on the other hand, possess the strength inherent in a structure which is solid throughout and can be supported externally by the walls of the chamber of use. As compared to perforated grains, operating temperature limits of solid end-burning grains are broader, and propellant materials giving higher impulse can be employed without danger of weakening the physical structure of the grain.

Thus an increase in the effective or mass burning rate of solid end-burning grains which is sufficiently high to bring the rate of gas evolution within the desired range makes possible the use of such grains, with their attendant advantages, for many applications where they could hitherto not have been considered. Furthermore, the use of such rapid-burning propellants, combined with other expedients for increasing burning surface, such as perforations, provides a higher rate of gas evolution than could hitherto be achieved.

The object of this invention is to provide propellant grains having increased effective burning rates.

Another object is to provide propellant grains, the effective burning rates of which can be controlled within limits.

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

In the drawings:

2

FIGURE 1 comprises a series of duplications of high speed motion picture frames.

FIGURE 2 is a sectional perspective of a solid, end-burning grain showing a random dispersion of short lengths of coated wire.

FIGURE 2a is an enlarged fragmentary section of the grain of FIGURE 2 showing the coated wires.

FIGURE 3 is a sectional perspective of a solid, end-burning grain showing a dispersion of short lengths of coated wire which are longitudinally oriented.

FIGURE 4 is a sectional perspective of a solid, end-burning grain with a single, continuous, coated wire.

FIGURE 5 is a transverse cross-sectional view taken along line 5-5 of FIGURE 4.

FIGURE 6 is a sectional perspective showing a solid, end-burning grain with a plurality of continuous coated wires.

FIGURE 7 is a plan view of the grain of FIGURE 6.

FIGURES 8 and 9 are sectional perspective views of other embodiments of our invention.

FIGURE 10 is a plan view of a solid, end-burning grain with preshaped ignition surface.

FIGURE 11 is a cross-sectional view taken along lines 11-11 of FIGURE 10.

FIGURE 12 is a sectional perspective of another embodiment.

FIGURE 13 is a plan view of the grain of FIGURE 12.

FIGURE 14 is a plan view of a solid end-burning grain containing a continuous, axially embedded, coated wire and continuous, concentric tubular, coated metal heat conductors and having a preshaped ignition surface.

FIGURE 15 is a cross-section taken along line 15-15 of FIGURE 14.

FIGURE 16 is a sectional perspective of a perforated grain with radially disposed continuous coated wires.

FIGURE 17 is a transverse cross-section taken along lines 17-17 of FIGURE 16.

FIGURE 18 is a sectional perspective of a perforated grain with longitudinally disposed, continuous, coated wires.

FIGURE 19 is a cross-section along line 19-19 of FIGURE 18.

FIGURES 20 and 21 are sectional perspectives of still other embodiments of our invention.

In co-pending Keith E. Rumbel et al. application, Serial Number 514,254, filed June 9, 1955, it is disclosed that effective or mass burning rate can be greatly increased by embedding within the propellant grain a metal heat conductor in the form, for example, of fine wire, filaments, strips and the like. The heat conductor, which can be any metal having a substantially higher thermal diffusivity or conductivity than the propellant material, is dispersed in the propellant matrix in the form of discontinuous short wires or filaments or, preferably, in the form of a continuous wire or strip oriented longitudinally in the desired direction of flame propagation. The increased burning rate of the propellant grain is due to the fact that the metal heat conductor, having a considerably higher thermal diffusivity or conductivity than the propellant material or its gaseous combustion products, effects rapid heat transfer from the high temperature combustion gases in the flame zone to unburned propellant within the grain so that the flame propagates rapidly along the metallic heat conductor. As a result, the burning surface propagates along the heat conductor at a much faster rate than the normal propellant burning rate; the burning surface recesses to form a cone with the heat conductor at its apex, thereby becoming much larger than normal; and the effective burning rate of the propellant grain is greatly increased. Recessing of the burning surface along the metal heat conductor continues rapidly until an equilibrium point is reached where the

angle of the vertex of the flame zone at the heat conductor, and thus the burning rate along the heat conductor, remain substantially constant. The rate of gas evolution is greatly increased by the large increase in burning surface.

FIGURE 1 illustrates graphically the burning phenomenon which occurs when a metal wire is embedded in solid propellant. The series shown are duplication of frames selected from a high speed motion picture of the actual burning of a propellant strand. A copper wire of 5 mil diameter was embedded axially in a solid propellant strand which was 2 mm. thick, 6 mm. wide and 40 mm. long. The propellant comprised a solid gel consisting of polyvinyl chloride dissolved in plasticizer with a finely divided oxidizer dispersed in the gel matrix. The plasticizer in this case was dibutyl sebacate and the oxidizer finely divided ammonium perchlorate. The embedded wire terminated a short distance from the uninhibited end burning surface. The propellant was burned in a nitrogen atmosphere at 1015 p.s.i.

Elapsed time, with the first frame A at time zero, is indicated at the bottom of each frame. In the first two frames A and B, at zero and 0.035 second elapsed time, the wire is completely below the burning surface and the burning surface is plane. In frame C, at time 0.153 second, the wire projects into the flame zone approximately 0.05 inch and the burning surface is just starting to propagate along the wire with recessing of the burning surface. Thereafter, as shown in frames D—I, the burning surface propagates rapidly along the wire. The angle subtended by the equilibrium burning surface and the wire is quickly established and remains substantially constant. At this point the burning rate along the wire also becomes substantially constant. The rapid increase in burning rate along the wire is clearly shown by a comparison of the burning distances and elapsed time of 0.153 second between frames A and C and the elapsed time of 0.136 second between frames C and I. The large increase in burning surface produced by the recessed cone can also be seen.

The increase in effective or mass burning rate of a given propellant is largely determined by the particular metal used as the heat conductor. The properties of the metal which are apparently involved in determining its efficacy are thermal diffusivity, thermal conductivity and melting point. The higher the thermal diffusivity and conductivity of the metal, the more rapidly it conducts heat to the unburned portion of propellant and the more rapid is the burning rate along the wire. In a particular set of controlled tests, Ag, which has a high thermal diffusivity of 1.23 cm.²/sec. at 650° C., effected an increase in burning rate of 430% whereas Pt, with the considerably lower thermal diffusivity of 0.35 cm.²/sec. at 650° C., increased burning rate by 190%. Higher melting points also increase efficacy of the metal as shown in the same set of tests by a comparison of Cu and Al. Al melts at a much lower temperature than Cu and, despite a somewhat higher thermal diffusivity, increases burning rate along the wire to a considerably lesser degree. Similarly tungsten, which has about the same thermal diffusivity as magnesium 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 transport from the hot gases to the wire.

The effective burning rate obtained with a bare metal heat conductor embedded in a given propellant matrix is largely determined and limited by the physical characteristics of the particular metal, namely its heat diffusivity, heat conductivity and melting point. Some adjustment in burning rate can be accomplished by varying the thickness of the conductor but the range of burning rate obtainable by this expedient is rather small. Tayloring of

the burning rate to a desired level can also be achieved to a limited extent by the use of metal alloys but this poses in many cases practical difficulties in the preparation of suitable alloys.

There are situations where it is advantageous to employ end-burning grains having burning rates which are substantially higher than that of the propellant matrix but not as high as those ordinarily obtained by incorporation of the bare metal heat conductors. It is further preferable that such intermediate burning rates be adjustable to substantially any desired level.

We have discovered that coating the metal heat conductor with a composition which is of substantially lower heat conductivity than the metal and which is inert, namely not self-oxidant, reduces the effective burning rate of the propellant grain relative to that obtained with the given bare metal, thus making possible the manufacture of propellant grains having effective burning rates intermediate the normal burning rate of the propellant matrix and the burning rate of the same matrix containing the same bare or uncoated metal heat conductor similarly embedded therein. This intermediate burning rate can, furthermore, be controlled or adjusted to substantially any desired level by proper choice or formulation of the coating composition in combination with other factors such as thickness of the coating and the particular metal employed as the heat conductor.

Since the inert coating composition, unlike the propellant 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 propellant 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.

Broadly speaking, therefore, our invention comprises embedding within the matrix of a propellant grain a metal heat conductor, such as metal wire, coated with a non-self-oxidant composition having substantially lower heat conductivity than that of the metal and thereby increasing the effective burning rate of the propellant grain to a substantially controlled degree intermediate the normal burning rate of the propellant matrix and the effective burning rate of the matrix containing the same bare metal heat conductor.

The embedded coated metal heat conductors possess another important advantage since they afford a means not only of increasing the effective burning rate of the propellant grain to a controlled degree but also of simultaneously decreasing the burning rate pressure exponent of the grain. In many cases such reduction in pressure exponent is desirable since it decreases sensitivity of the burning rate to changes in pressure.

In the case of embedded bare metal heat conductors, such as wires, at pressures of 600 p.s.i. and higher, the pressure exponent decreases with increase of wire thickness and above a certain thickness, which varies with the particular metal and propellant material, the pressure exponent becomes even less than that of the propellant matrix itself. We have found that the insulating coating generally does not substantially reduce the effectiveness of the metal heat conductor in reducing the pressure exponent and, in fact, in some instances, results in even greater pressure exponent reduction.

The 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. Metal coatings are not suitable for our purpose because of their generally excessive heat conductive properties. 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 for our purpose 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 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 of film-forming properties of the plastic and the physical properties of the coating in terms, for example, of reduced brittleness and increased adherency. 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 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 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.

The thickness of the coating can be varied as desired. In general, the thicker the coating, the greater is the insulating effect.

The metal heat conductor, which is preferably copper or silver, although it can be any other metal having good heat conductive properties, such as Pt, steel, tungsten, Al, Mg and the like, after being coated as aforescribed is embedded within the matrix of the propellant grain so that the entire surface of that portion of the coated metal which lies within the body of the propellant grain is in intimate contact with the propellant matrix. This intimate contact is essential to effectuate the requisite heat transfer from the metal through the coating to the propellant matrix.

The metal heat conductor employed can be in the form of wire of any cross-sectional shape, or thin strips which are flat or bent into shapes such as, for example, tubes, wedges and the like. The strips can be solid or perforated as, for example, in the form of wire screening. The use of wire is our preferred embodiment for the practical reason of its more common availability. Although the following description will 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 aforescribed such as thin strips, tubes, or the like. The term "wire" as employed in this specification and claims refers to elongated metal filaments which are not necessarily circular in cross section but which can also be of other cross-sectional shapes such as rectangular, oval or the like.

It will also be understood that the term "coated" or "coating" as employed hereafter refers to the inert non-self-oxidant, heat-insulating coatings aforescribed.

The over-all burning pattern produced by the coated wire is substantially similar to that produced by a bare wire as shown in FIGURE 1, with the exception that the burning rate along the same coated wire in the same propellant matrix is lower because of the reduction in heat transfer from the metal to the matrix caused by the insulating properties of the coating. Decreased rate of burning along the metal conductor results in an increased cone angle at the apex. The larger the cone angle, the shallower is the cone and the smaller is the available burning surface with concomitant decrease in effective or mass burning rate of the propellant grain. The rate of burning along the metal conductor appears largely to be determined by the characteristics of the particular metal, namely its heat diffusivity, heat conductivity and melting point, and by the insulating effect of the particular coating.

The insulating efficacy of any given coating composition can readily be determined by routine testing in any desired manner as, for example, by the strand-burning technique. In this way, a suitable coating, both in terms of composition and thickness of application can be chosen to produce a desired burning rate which is higher than that of the normal burning rate of the propellant matrix alone but not as high as that achieved with the bare metal conductor.

Before active propagation of the flame along the wire occurs, the matrix burns along the wire at substantially its normal burning rate for a short distance until the metal is heated to a sufficiently high temperature to ignite the propellant along its path. For effective action, therefore, the coated 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 effective burning rate is about 0.08 to 0.1 inch and, preferably, about 0.2 inch.

Where relatively small increase in effective burning rate is desired, as, for example, under 50%, this can be accomplished by dispersing short lengths of coated wire in the propellant matrix. Dispersion can be accomplished, for example, by mixing the short lengths of the coated wire with the propellant material prior to extrusion or casting. The wires in propellant grains prepared in this manner generally assumed a more or less random pattern as shown in FIGURE 2 where metal wires 1 having coating 4 are embedded in propellant grain 2. It will be noted, as shown in the drawing, that a large number of the randomly dispersed wires are at an angle substantially less than 180° relative to the plane of the initial ignition surface. The burning surface regenerates along such angled wires to produce recessing and increased burning surface area. 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. Such a grain is shown in FIGURE 3 where coated wires 1 are embedded in propellant grain 2 having initial burning surface 3.

The coated wires dispersed in the propellant matrix should be at least about 0.08 in. long to provide sufficient length for initial exposure into the flame zone and flame propagation along the wire. Some additional improvement can be obtained by increasing the length of the dis-

persed wires as, for example, to about 0.5 inch or longer. To some extent wire lengths will be determined by the size of the propellant grain. In the case of large grains, for example, coated wires 2 inches long or longer can be incorporated.

The amount of discontinuous coated wire introduced into the propellant matrix is not critical, although this is one of the factors which determines the specific increase in burning rate obtained. In other words, even the addition of a very small amount will effect 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 quantity of coated 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 propellant, thereby decreasing the gas-generating potential, in practice the amount incorporated will be controlled to a considerable extent by this factor. For this reason, it will generally be undesirable to add more than about 5 to 10% by weight of the propellant although, in some cases, larger amounts may be feasible.

Where the burning rate required is higher than that obtainable with a dispersion of discontinuous, short coated wires, continuous coated wire which is longitudinally disposed in the desired direction of flame propagation should be used. Increases in burning rate of the propellant grain which are several-fold greater than that obtained with dispersed, discontinuous, short lengths of wire can be achieved in this way despite 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 propagates rapidly 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 wire the flame continues to propagate rapidly and uninterruptedly through the entire length of the desired burning distance. Another important advantage of the continuous wire is that it requires the introduction of a minimum amount of inert material, generally no more than a fraction of one percent by weight of the propellant.

FIGURE 4 shows an end-burning grain 10 containing continuous wire 11, having coating 8, axially embedded in the grain. The wire, which is normal to the initial burning surface 12, is disposed longitudinally in the direction of flame propagation and is continuous throughout the distance of flame propagation, in this case the full length of the grain. The surfaces of the grain other than the end burning surface 12 can be inhibited in any desired fashion. FIGURE 5 is a cross-sectional view of the propellant grain shown in FIGURE 4. The mode of burning of such a grain is substantially as shown in FIGURE 1. If desired, end 16 of the grain can be left uninhibited and burning instituted from both ends. The flame then propagates along the coated wire from both ends with doubled rate of gas evolution.

As shown in FIGURE 1, the burning surface of the grain shown in FIGURE 4 recesses as the flame propagates along the coated wire to form a cone with the wire at its apex. As the flame proceeds along the coated wire, the flaring end of the lengthening cone increases in width and encompasses more and more of the cross-sectional area of the grain. If the grain is sufficiently narrow, the cone will eventually encompass the entire width of the grain and rapid burning of all the propellant material will continue until the other end of the coated wire is reached at which point only a small peripheral portion of the propellant material adjacent the end of the wire remains unburned.

In many cases, particularly where the propellant grain has a relatively large cross-sectional area, it is desirable to embed a plurality of continuous coated wires at spaced

intervals as shown in FIGURES 6 and 7. For example, if a grain which is short relative to its width contains only a single coated wire such as shown in FIGURE 4, 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 coated wires as shown in FIGURES 6 and 7.

It is frequently desirable to achieve equilibrium pressure, namely the point at which burning surface area and, consequently, rate of gas evolution, becomes substantially constant, as quickly as possible. Establishment of equilibrium can be hastened in several ways.

The use of a plurality of coated wires as shown in FIGURES 6 and 7 increases greatly the rapidity with which the equilibrium burning surface area can be established. In the case of a single wire, the burning surface presented by the cone continues to increase in area until the flaring end intersects the peripheral edge of the grain or until burning reaches the end of the wire, as, for example, in the case of a grain which is short relative to its width. Rate of gas evolution continues to increase until 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 area is desirable. Where a plurality of continuous coated wires is used, the cones incident to each wire soon intersect at their flaring ends and from this point on, the burning surface area remains constant as the flame proceeds along the wires.

The equilibrium state can also be established more rapidly by exposure of the coated wires a short distance beyond the initial ignition surface. In FIGURE 4, the coated wire terminates at the initial burning surface 12. Upon ignition, the grain will burn along the wire for a short distance at the normal rate of the propellant material itself. When the exposed end of the metal becomes sufficiently hot to initiate propagation of the flame along the wire, the effective or mass burning rate will increase rapidly until an equilibrium maximum is reached. To initiate flame propagation along the wire more rapidly, the coated wires can be embedded in the grain in such a way that the ends of the wire protrude from the ignition surface as shown in FIGURE 6 where wire ends 13 extend for a short distance beyond ignition surface 12. The exposed wire ends can be coated, as shown in FIGURE 6, or can be stripped of the coating or left bare to hasten heating of the metal.

Recessing the ignition surface adjacent to the coated wires, preferably in the form of cones, with the wire exposed at the apex, as shown in FIGURES 8 and 9, also hastens establishment of the equilibrium burning surface area. Any degree of preconing which brings the initial burning surface into a closer approximation of the equilibrium burning surface than an initial plane surface results in more rapid establishment of equilibrium. Thus, equilibrium is more quickly reached by the grains shown in FIGURES 8 and 9 than by the plane surfaced grains shown in FIGURES 4 and 6.

Most rapid establishment of equilibrium burning surface area is obtained by preconing the initial ignition surface so that it has a shaped area which closely approximates or is substantially the same as the equilibrium burning surface area with the result that equilibrium is established almost immediately after ignition. In such a grain design, the angle of the vertex of the recessed cones should closely approximate the equilibrium angle and the cones should intersect with each other and the periphery of the grain at substantially the same points at which they will intersect during burning in the equilibrium state. FIGURES 10 and 11 illustrate an end burning propellant grain having the ignition surface 12 preconed in such a way that it has a shape and surface area which is substantially the same as the equilibrium burning surface as burning proceeds along the seven spaced coated wires 11. The cones 9,

which flare out from the wire exposed at the apex of each, intersect each other and the periphery of the grain 15 to form inwardly curved ridges 24 and apical points 25.

The preshaping of the ignition surface to simulate the equilibrium burning surface of an end-burning grain is determined by such factors as the number and spacing of the continuous wires, the metal of which the wires are made, the thickness of the wire, the particular coating on the wire and the particular propellant material. The cone angle varies, for example, with the thermal diffusivity of the particular metal, the insulating effect of the coating and the burning rate of the propellant matrix. The cone angle for a given combination of factors can readily be determined by those skilled in the art and the particular grain ignition surface designed accordingly.

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 and conductivity 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. One of the practical considerations which may determine, to some extent, 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 propellant. From this point of view, a maximum heat conductor thickness of about 30 to 50 mils will probably be desirable in most cases.

The following tables summarize test data illustrating the controlled, intermediate burning rate achieved by longitudinally embedding a wire coated with a non-self-oxidant, heat-insulating composition as compared with the ballistic properties of the same propellant without an embedded wire and with the same wire uncoated. They also show the marked decrease in pressure exponent.

Table I

	Burning rate at 1,000 p.s.i.a. and 70° F. in./ sec.	Pressure Exponent, 1,000 p.s.i.a. and 70° F.
Propellant Matrix A ¹	0.56	0.51
Matrix A plus 5 mil diameter bare Cu wire.....	2.90	0.24
Matrix A plus 5.5 mil diameter Formvar ² enameled Cu wire.....	0.83	0.29
Matrix A plus 5 mil diameter plain enameled magnet wire ³	1.29	0.14

¹ NH₄ClO₄ 81.96%; polyvinyl chloride 7.75%; dioctyl adipate 9.68%; wetting agent 0.25%; carbon black 0.06%; stabilizer 0.31%.

² Polyvinyl formal combined with an alkyl phenolic resin.

³ Phenolic resin.

Table II

	Burning rate at 1,000 p.s.i.a. and 70° F. in./ sec.	Pressure Exponent 1,000 p.s.i.a. and 70° F.
Matrix B ¹	0.58	0.50
Matrix B plus 5 mil diameter bare Ag wire.....	2.82	0.37
Matrix B plus 5 mil diameter Ag wire with 5 mil thick coating of silicone varnish.....	2.20	0.34
Matrix B plus 5 mil diameter Ag wire with 5 mil thick coating of plasticized poly- vinyl chloride ²	0.99	0.25

¹ NH₄ClO₄ 82.0%; polyvinyl chloride 8.0%; dibutyl sebacate 9.43%; stabilizer 0.32%; wetting agent 0.25%.

² Polyvinyl chloride 85%; dibutyl sebacate 15%.

The embedded coated metal heat conductors are effective regardless of the specific nature or composition of the propellant matrix although the specific change in effective burning rate will vary to some extent according to the specific propellant composition. They can be employed both with composite type propellants which comprise a fuel and an oxidizing agent such as the polyvinyl chloride propellants described above, thiokol, poly-

styrene and polyester type propellants and the like, with single and double base nitrocellulose propellants, etc.

As aforementioned, the metal heat conductor, though conveniently used in the form of wire, can also be employed in the form of continuous thin coated strips which can be flat or bent into other desired shapes such as a V-shape or a tube. The effect on mass burning rate is substantially similar to that obtained with coated wires. The burning surface along metal heat conductors which are substantially wider than they are thick, assumes the configuration of a V-shaped trough rather than the cone incident to a wire. As in the case of wires, a plurality of coated strips or tubes can be employed.

The various expedients for hastening the establishment of the equilibrium burning surface, discussed above in connection with the use of coated wires, can be employed with thin, wide, coated conductors, such as protrusion from the ignition surface, and pre-troughing the ignition surface adjacent the heat conductor.

FIGURES 12 and 13 show a solid, end-burning propellant grain containing a coated V-shaped metal heat conductor 18 which is disposed longitudinally the full length of the grain with one end exposed at the ignition surface 12.

FIGURES 14 and 15 show a concentric tubular arrangement of coated metal heat conductors 19 with a coated wire 11 embedded axially. The ignition surface 12 is preshaped to a configuration which closely approximates the equilibrium burning surface. The flaring ends of coned recess 17 with the central wire at its apex intersects with the circular V-shaped trough 20, which has the first concentric tube at its apex, to form a ridge 21. The outer flaring edge of this trough in turn intersects with the second trough having the outer concentric metal tube at its apex to form a second ridge. The second trough flares out to intersect with the periphery of the grain at 22.

Although the preceding description has been in terms of solid, end-burning grains because of the controlled, increased burning rate and improvement in other properties, such as pressure exponent, obtained with this type of grain, our invention can also be applied very advantageously to other types of propellant grains, such as perforated grains. The incorporation of coated metal wire into the matrix of a perforated grain results in a propellant which burns with extreme rapidity by virtue of the combination of the increased effective burning rate along the coated metal wire and the large initial burning surface provided by the perforations. The wire can be continuous through the distance of flame propagation or can be dispersed through the matrix in the form of short, discontinuous wires. As in the case of end-burning grains, the heat-insulating coatings are effective to control the effective burning rate at levels intermediate that obtained without any wire and that resulting from the use of bare wire.

The continuous coated wire can be positioned in the matrix of the perforated grain in a manner most suitable for the particular application. For example, in the grain shown in FIGURES 16 and 17, the embedded coated wires radiate out from the central perforation 14 which provides the initial burning surface. With the exterior surface 15 inhibited, the flame rapidly propagates peripherally along the wires.

FIGURES 18 and 19 show an end-burning cylindrical grain with central perforation 14 and a plurality of continuous coated wires which are normal to the end-burning surfaces 12 and 16 and run the length of the grain. If both the exterior surface 15 and the surface exposed by the central perforation are inhibited, the flame propagates rapidly along the wires from both ends of the grain. If the central perforation surface is uninhibited, the grain also burns outwardly from the central perforation but propagation of this flame front is considerably slower because of the absence of wire in the direction

of flame propagation. Such grains are particularly suitable for some rocket applications since it makes possible venting of combustion gases produced at the end of the grain adjacent to the closed end of the rocket chamber through the central perforation.

As in the case of solid grains, the heat conductor incorporated into perforated grains can be in the form of coated wires or thin coated strips of metal shaped into any suitable configuration such as wedges, tubes, etc.

For many applications requiring the use of propellant grains, it is essential that a high burning rate be maintained throughout combustion. This requirement can be satisfied by extending the continuous coated heat conductor for substantially the entire distance of flame propagation of the grain, as shown, for example, in FIGURES 4, 6, 8, 9, 12, 16 and 18. There are some cases, however, where a very high rate of gas generation 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 coated 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 of the grain then continues at the normal rate of the propellant grain material.

FIGURE 20 shows a solid, end-burning propellant grain in which the coated heat conducting metal wires 11, which are disposed longitudinally in the direction of flame propagation with one end exposed at ignition surface 12, do not extend the full burning distance of the grain. Burning proceeds from the ignition surface at the high rate induced by the embedded heat conductors until the point at which they terminate within the grain, after which burning continues at the normal rate of the grain composition until the full burning distance of the grain has been traversed at end 16.

It will be understood that the various expedients aforediscussed which can be employed to regulate burning rate, pressure exponent, establishment of equilibrium pressure and the like, such as choice of particular coating compositions, metal species and thickness of the heat conductor, the use of one or a plurality of coated heat conductors, protrusion of the heat conductor from the ignition surface, perforation, etc., can be employed both where the coated heat conductor is continuous substantially throughout the entire burning distance of the grain or where it extends only for a predetermined portion of the burning distance.

In certain applications, it may be desirable to employ a propellant which progresses from a relatively low to a high rate of gas generation. In such case, the coated metal heat conductor can be embedded in the grain at a predetermined point spaced from the initial ignition surface. The spacing can be small or considerable depending on the particular situation. An example of such a grain is illustrated in FIGURE 21 where 12 is the initial ignition surface.

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

We claim:

1. A solid propellant grain, said grain comprising a self-oxidant, solid propellant matrix, the combustion of which generates propellant gases, and having at least one initial exposed ignition surface, said matrix containing embedded therein an elongated metal heat conductor coated with a solid, inert, non-metal 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 propaga-

tion 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 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 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 thereby serving controllably to increase the mass burning rate and, thereby, the mass rate of gas generation of said propellant grain to a level intermediate that of the propellant matrix alone and that of the propellant matrix containing embedded therein the same metal heat conductor uncoated.

2. The propellant grain of claim 1 in which the heat conductor is continuous substantially throughout the distance of flame propagation of the grain.

3. The propellant grain of claim 1 in which the inert coating composition comprises a polymeric material.

4. A solid propellant grain, said grain comprising a self-oxidant, solid propellant matrix, the combustion of which generates propellant gases and having at least one initial exposed ignition surface, said matrix containing embedded therein a plurality of elongated, metal heat conductors coated with an inert, solid, non-metal composition characterized by substantially lower heat conductivity than the metal, said coated metal heat conductors being positioned substantially normal to said initial ignition surface of said grain, being substantially spaced from each other in the plane transverse to the direction of flame propagation, 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 metal thickness of about 0.05 inch in at least one transverse direction, the entire surface of said length of said coated 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 coated metal heat conductors and, in so doing, forming a recess which is substantially V-shaped in at least one plane with each of said coated metal heat conductors at the apex of a recess, thereby forming a recessed surface of substantially larger surface area than that of a plane burning surface, said coated metal heat conductors being spaced sufficiently apart to permit said recessing, the coated metal heat conductors thereby serving controllably to increase the mass burning rate and, thereby, the mass rate of gas generation of said propellant grain to a level intermediate that of the propellant matrix alone and that of the propellant matrix containing embedded therein the same metal heat conductor uncoated.

5. The propellant grain of claim 4 in which the heat conductors are metal wires.

6. The propellant grain of claim 4 in which the metal heat conductors are continuous substantially throughout the distance of flame propagation of the grain.

7. The propellant grain of claim 6 in which the metal heat conductors are metal wires.

8. The propellant grain of claim 7 in which the inert coating composition comprises a polymeric material.

9. The propellant grain of claim 4 in which the ends of the metal heat conductors are exposed at the ignition surface of the propellant grain.

10. The propellant grain of claim 9 in which the ends of the heat conductors are exposed at the apex of a recess in the ignition surface.

11. A solid propellant grain, said grain comprising a self-oxidant, solid propellant matrix, the combustion of which generates propellant gases and having at least one initial exposed ignition surface, said matrix containing embedded therein a plurality of elongated, metal heat conductors coated with an inert, solid, non-metal composition characterized by substantially lower heat conductivity than the metal, said coated metal heat conductors being positioned substantially normal to said initial ignition surface of said grain, being substantially spaced from each other in the plane transverse to the direction of flame propagation, and being continuously and longitudinally disposed for substantially the entire distance 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 metal thickness of about 0.05 inch in at least one transverse direction, the entire surface of said length of said coated metal conductors lying within the body of the propellant grain and being in intimate gas-sealing contact with the propellant matrix, the ends of said metal heat conductors being exposed at said ignition surface, the burning surface of said grain, after ignition, regenerating progressively along each of said coated metal heat conductors and, in so doing, forming a recess which is substantially V-shaped in at least one plane with each of said coated metal heat conductors at the apex of a recess, thereby forming a recessed surface of substantially larger surface area than that of a plane burning surface, said coated metal heat conductors being spaced sufficiently apart to permit said recessing, the coated metal heat conductors thereby serving controllably to increase the mass burning rate and, thereby, the mass rate of gas generation of said propellant grain to a level intermediate that of the propellant matrix alone and that of the propellant matrix containing embedded therein the same metal heat conductor uncoated.

12. The propellant grain of claim 11 in which the ends of the metal heat conductors are exposed at the apex of a recess in the ignition surface of the propellant grain.

13. The propellant grain of claim 12 in which the metal heat conductors are metal wires.

14. A solid propellant grain, said grain comprising a self-oxidant, solid propellant matrix, the combustion of which generates propellant gases and having at least one initial exposed ignition surface, said matrix containing embedded and randomly dispersed therein a plurality of spaced, elongated metal wires having a minimum length of about 0.08 inch and a maximum diameter of about 0.05 inch and coated with an inert, solid, non-metal composition characterized by substantially lower heat conductivity than the metal, the entire surface of said coated metal wires lying within the body of the propellant grain and being in intimate, gas-sealing contact with the propellant matrix, a substantial number of said randomly dispersed, coated wires being at an angle, relative to the plane of said initial ignition surface, which is substantially less than 180°, the burning surface of said grain, after ignition, regenerating progressively along each of said coated 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 coated 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 coated metal wires being spaced sufficiently apart to permit said

recessing of the burning surface, the coated metal wires thereby serving controllably to increase the mass burning rate and, thereby, the mass rate of gas generation of said propellant grain to a level intermediate that of the propellant matrix alone and that of the propellant matrix containing embedded therein the same metal heat conductor uncoated.

15. A solid propellant grain, said grain comprising a self-oxidant, solid propellant matrix, the combustion of which generates propellant gases and having at least one initial, exposed ignition surface, said matrix containing embedded therein elongated metal heat conductor means forming a longitudinal tubular structure within the body of said grain, said metal heat conductor means being coated with an inert, solid, non-metal composition characterized by substantially lower heat conductivity than the metal, 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 coated tubular conductor means within the body of the grain having a length of at least about 0.2 inch and having a maximum, metal wall thickness of about 0.05 inch, the entire surface of said length of said coated 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 coated, tubular, metal heat conductor means and, in so doing, forming a recess which is substantially V-shaped in at least one plane with said coated metal conductor means 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 propellant grain to a level intermediate that of the propellant matrix alone and that of the propellant matrix containing embedded therein the same metal heat conductor uncoated.

16. The propellant grain of claim 15 in which the coated metal heat conductor means forms a plurality of longitudinal tubular structures within the body of the grain.

17. The propellant grain of claim 16 in which the coated metal heat conductor means is continuous substantially throughout the entire distance of flame propagation of the propellant grain.

18. The propellant grain of claim 15 in which the coated metal heat conductor means is continuous substantially throughout the entire distance of flame propagation of the propellant grain.

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