

July 14, 1964

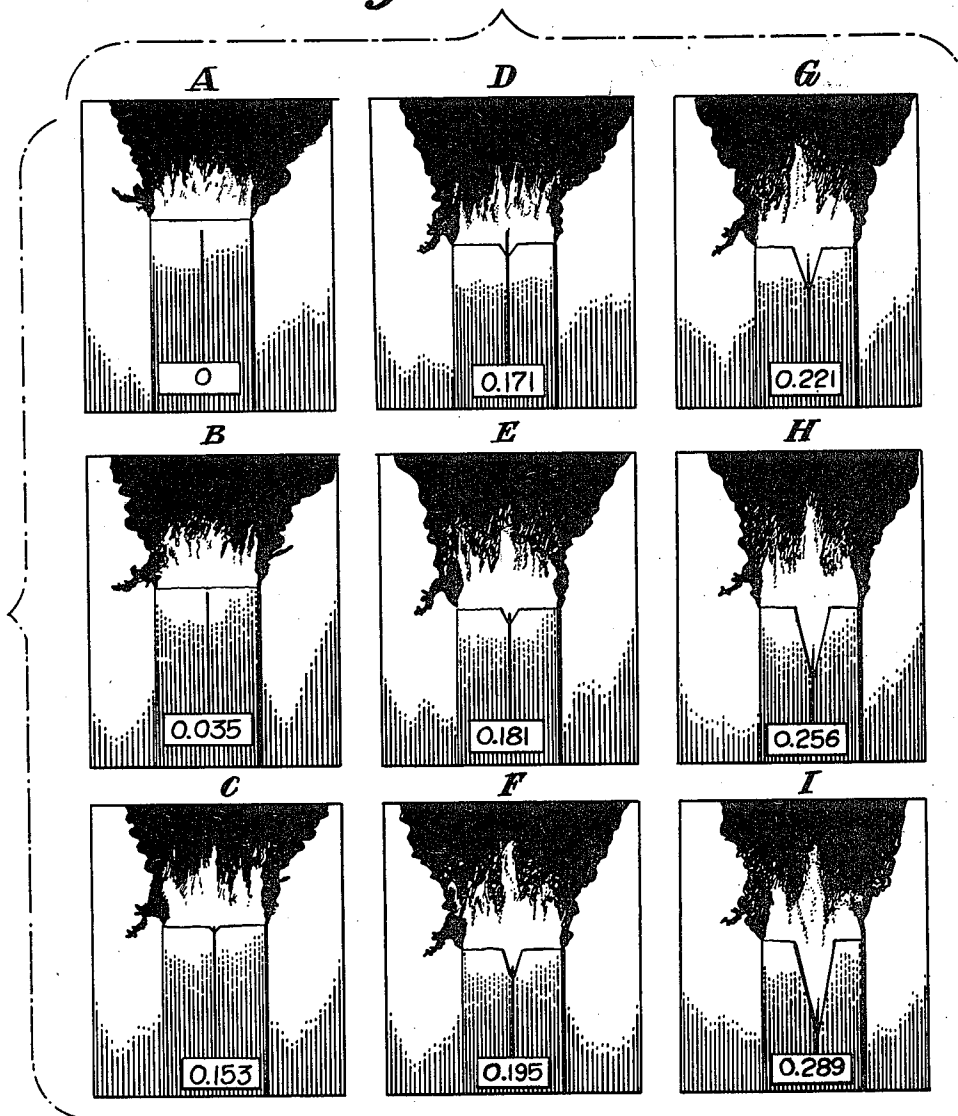
K. E. RUMBEL ET AL
PROPELLENT GRAINS

3,140,663

Filed June 9, 1955

7 Sheets-Sheet 1

Fig. 1.



INVENTORS
KEITH E. RUMBEL,
MELVIN COHEN,
ROBERT G. NUGENT and
ARCH C. SCURLOCK
BY *Martha L. Ross*
AGENT

July 14, 1964

K. E. RUMBEL ET AL

3,140,663

PROPELLENT GRAINS

Filed June 9, 1955

7 Sheets-Sheet 2

Fig. 2.

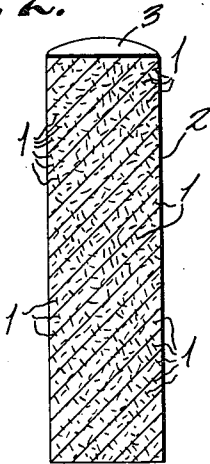


Fig. 3.

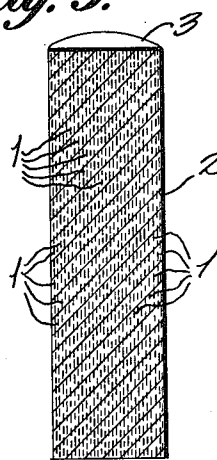


Fig. 4.

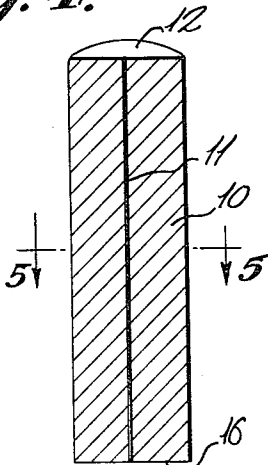


Fig. 5.

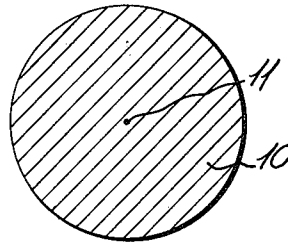


Fig. 6.

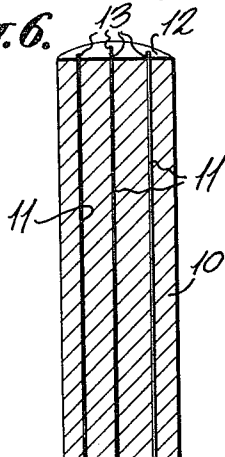
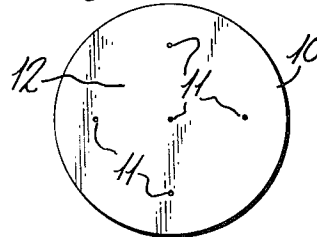


Fig. 7.



INVENTOR

KEITH E. RUMBEL,
MELVIN COHEN,
ROBERT G. NUGENT^{2nd}
ARCH C. SCURLOCK

BY

Martha L. Ross

AGENT

July 14, 1964

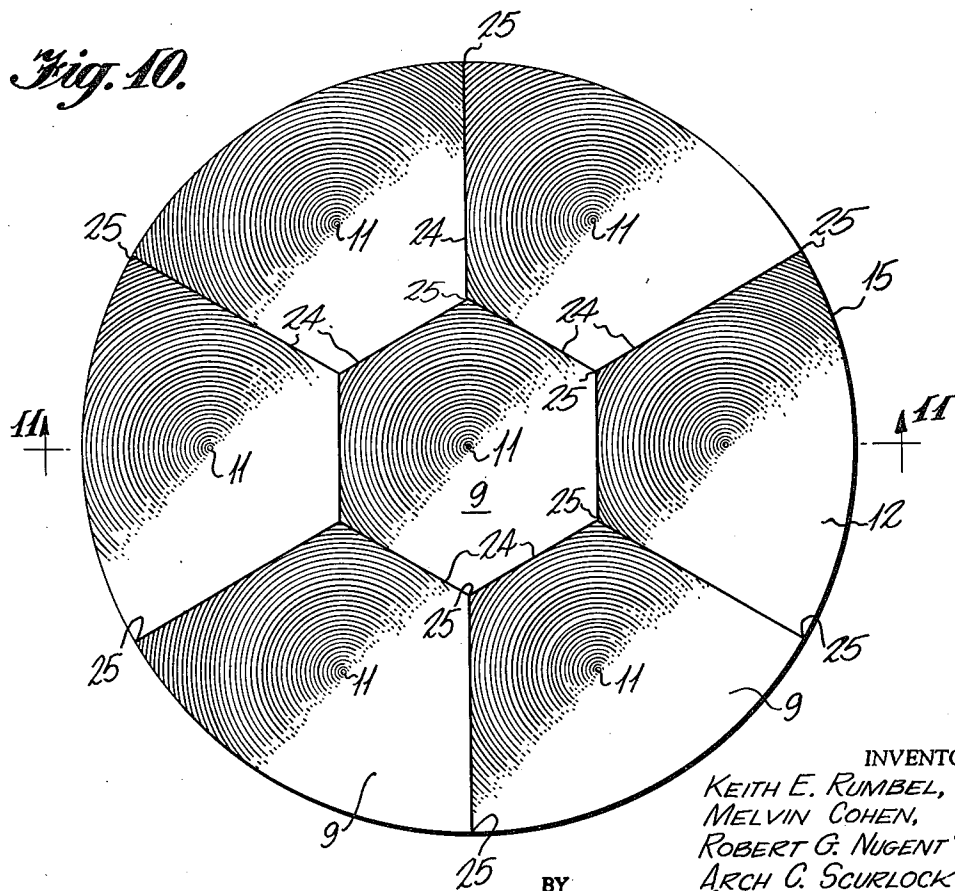
K. E. RUMBEL ET AL

3,140,663

PROPELLANT GRAINS

Filed June 9, 1955

7 Sheets-Sheet 3



July 14, 1964

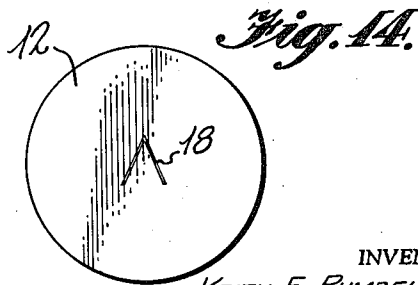
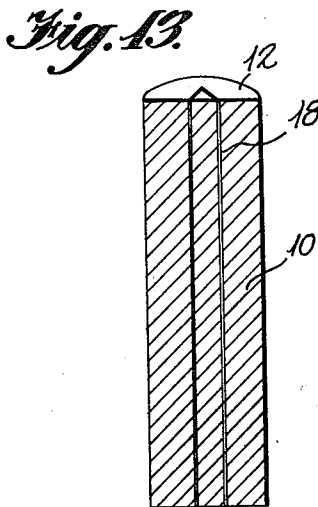
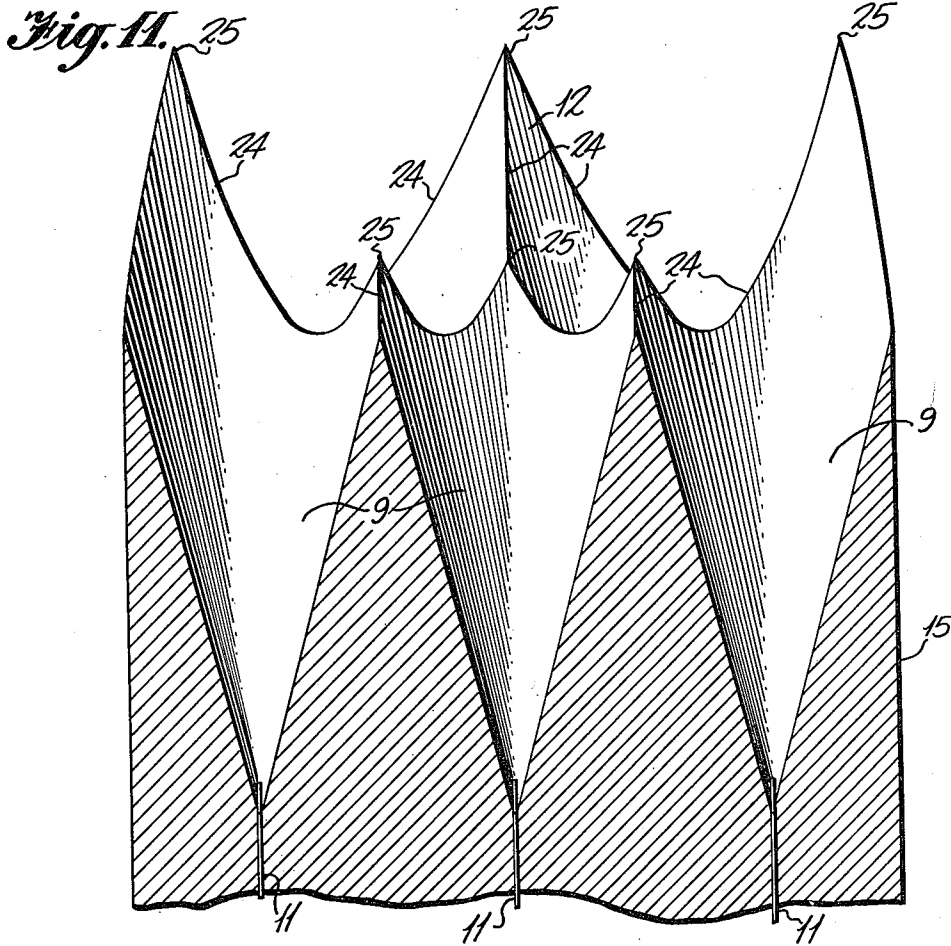
K. E. RUMBEL ETAL

3,140,663

PROPELLENT GRAINS

Filed June 9, 1955

7 Sheets-Sheet 4



INVENTORS

KEITH E. RUMBEL,
MELVIN COHEN,
ROBERT G. NUGENT and
ARCH C. SCURLOCK

BY

Martha L. Ross

AGENT

July 14, 1964

K. E. RUMBEL ET AL

3,140,663

PROPELLENT GRAINS

Filed June 9, 1955

7 Sheets-Sheet 5

Fig. 12.

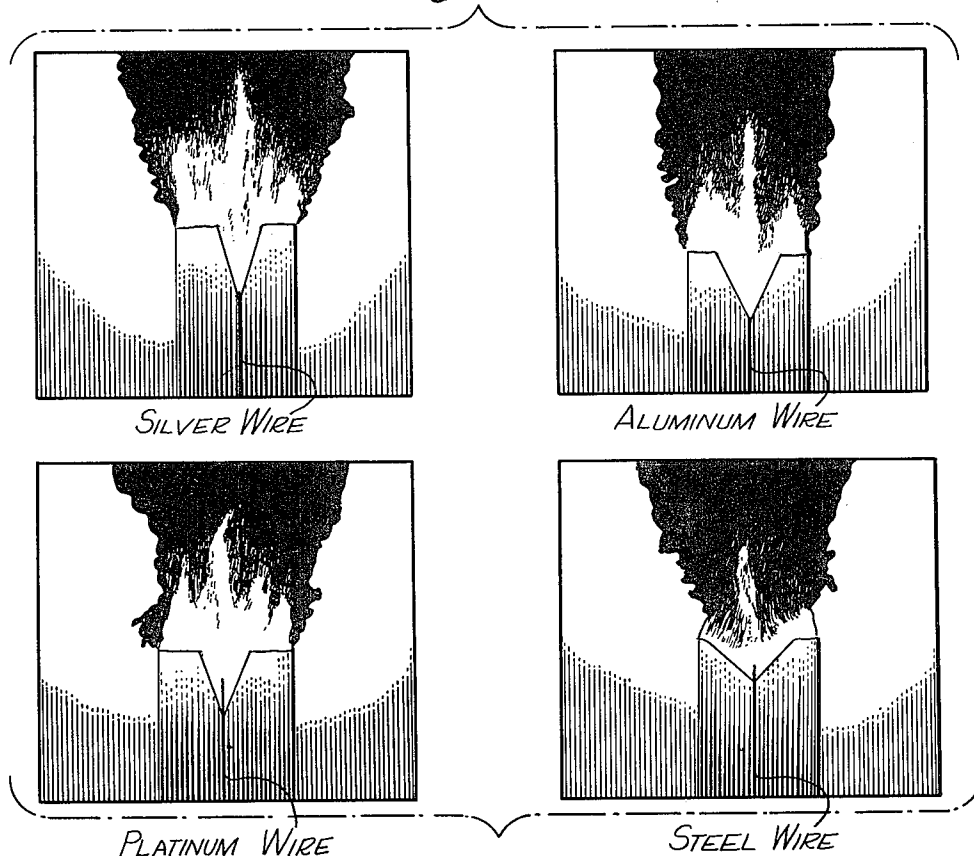


Fig. 15.

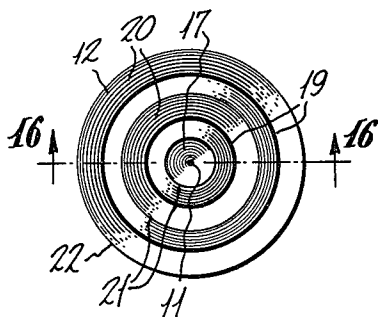
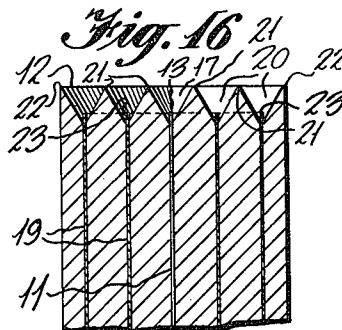


Fig. 16.



INVENTORS

KEITH E. RUMBEL,

MELVIN COHEN,

ROBERT G. NUGENT and

ARCH C. SCURLOCK

BY

Martha L. Ross

AGENT

July 14, 1964

K. E. RUMBEL ETAL

3,140,663

PROPELLENT GRAINS

Filed June 9, 1955

7 Sheets-Sheet 6

Fig. 17.

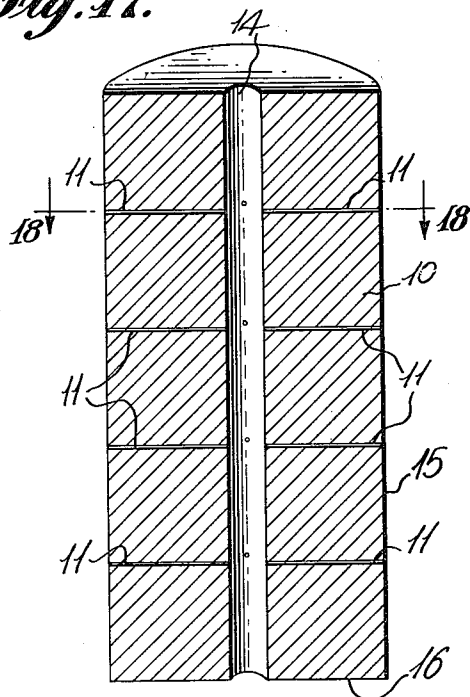


Fig. 18.

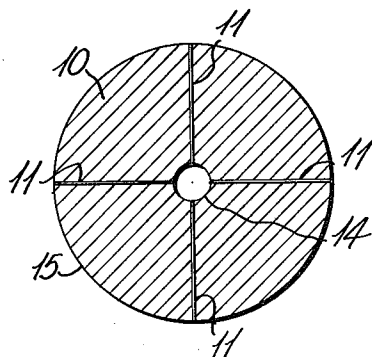


Fig. 19.

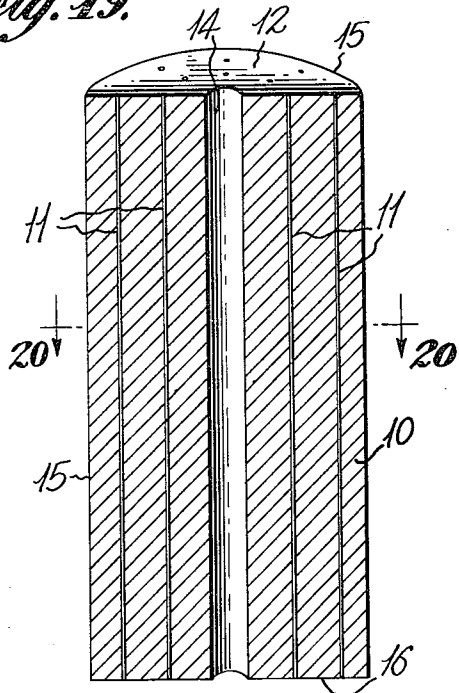
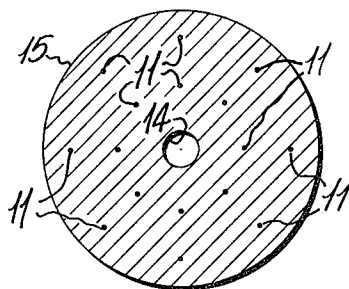


Fig. 20.



INVENTORS

KEITH E. RUMBEL,

MELVIN COHEN,

ROBERT G. NUGENT

BY *Martha L. Ross* ^{2nd} ARCH G. SCURLOCK
AGENT

July 14, 1964

K. E. RUMBEL ETAL

3,140,663

PROPELLENT GRAINS

Filed June 9, 1955

7 Sheets-Sheet 7

Fig. 21.

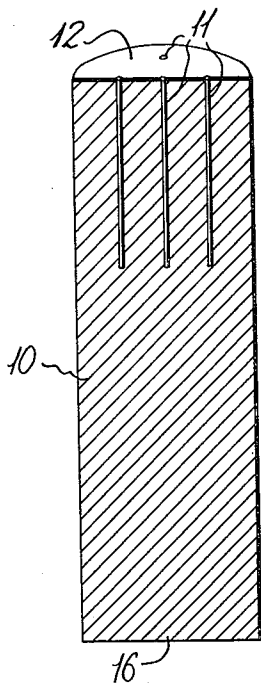
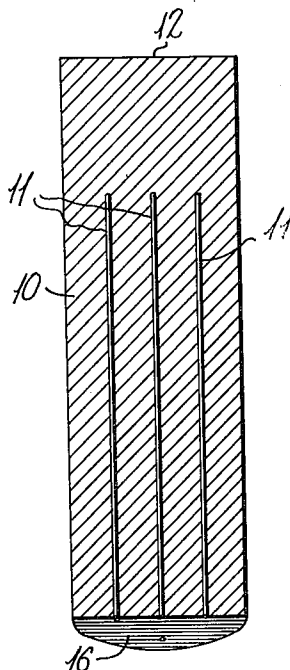


Fig. 22.



INVENTOR

KEITH E. RUMBEL,
MELVIN COHEN,
ROBERT G. NUGENT and
ARCH C. SCURLOCK

BY

Martha L. Ross
AGENT

1

3,140,663

PROPELLENT GRAINS

Keith E. Rumbel, Falls Church, Va., Melvin Cohen, Washington, D.C., Robert G. Nugent, Alexandria, Va., and Arch C. Scurlock, Washington, D.C., assignors to Atlantic Research Corporation, Alexandria, Va., a corporation of Virginia

Filed June 9, 1955, Ser. No. 514,254
15 Claims. (Cl. 102-98)

This invention relates to new and improved propellant grains having greatly 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 that have been obtained 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 propellents, combined with other expedients for increasing burning surface, such as perforations, provides a considerably higher rate of gas evolution than could hitherto be achieved.

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

2

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

In the drawings:

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 wire.

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

FIGURE 4 is a sectional perspective showing a solid, end-burning grain with a single continuous 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 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 comprises duplications of high speed motion picture frames.

FIGURE 13 is a sectional perspective of another embodiment.

FIGURE 14 is a plan view of the grain of FIGURE 13.

FIGURE 15 is a plan view of a solid end-burning grain containing a continuous, axially-embedded wire and continuous, concentric tubular metal heat conductors and having a preshaped ignition surface.

FIGURE 16 is a cross-section taken along line 16-16 of FIGURE 15.

FIGURE 17 is a sectional perspective of a perforated grain with radially disposed continuous wires.

FIGURE 18 is a transverse cross-section taken along lines 18-18 of FIGURE 17.

FIGURE 19 is a sectional perspective of a perforated grain with longitudinally disposed continuous wires.

FIGURE 20 is a cross-section along line 20-20 of FIGURE 19.

FIGURES 21 and 22 are sectional perspectives of still other embodiments of our invention.

We have found that effective or mass burning rate can be greatly increased by embedding within the propellant grain a metallic heat conductor in the form, for example, of fine wire, filaments, strips and the like, so that the entire surface of that portion of the metal which lies within the body of the propellant grain is in intimate contact with the propellant matrix. The metal heat conductor may be 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 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 rate of propagation of the burning surface along the metallic

heat conductor is many times the normal propellant burning rate.

The heat conductor can be any metal having a substantially higher thermal diffusivity than the propellant material. It can be used 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 aforesaid 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.

We have observed that when a metal wire is embedded in a solid propellant, and the grain ignited, the propellant burns at its normal burning rate until a portion of the wire protrudes beyond the burning surface into the hot combustion gases. The exposed wire is heated to a high temperature by the hot gases and this heat is then conducted by the wire into the unburned portion of the propellant. Burning then proceeds rapidly along the wire. The burning surface adjacent to the wire recesses to form a cone with the wire at its apex. The recessing continues until an equilibrium point 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. Propagation of the burning surface continues at a high rate along the wire. The rate of gas evolution is greatly increased by the large increase in burning surface produced by recessing along the wire.

FIGURE 1 illustrates graphically the burning phenomenon which occurs when a metal wire is embedded in solid propellant. The series shown are duplications 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. All surfaces except the end burning surface were inhibited. 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 the recessing of the burning surface. Thereafter, as shown in frames D-I, the burning surface propagates rapidly along the wire with continued recessing until the angle subtended by the equilibrium burning surface and the wire becomes established and remains 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.

As aforementioned, before active propagation of the flame along the wire will occur, 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 ignite the unburned propellant along its path. The length of protrusion varies with the particular metal and is determined by such factors as the thermal diffusivity and melting point of the particular metal. Table I shows the exposure lengths of wires of different metals embedded in a solid propellant comprising polyvinyl chloride, dibutyl sebacate and ammonium perchlorate.

TABLE I

	Silver	Copper	Aluminum
Wire diameter, inches.....	0.005	0.005	0.005
Burning pressure, p.s.i.....	1,015	1,015	1,015
Exposure length of wire to initiate propagation of flame along wire, inches.....	0.035	0.047	0.052

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, we have found that 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.

Substantial increases in burning rate are obtained by dispersing short lengths of wire in the propellant matrix. Dispersion of the wire can be accomplished, for example, by mixing the short lengths of wire with the propellant material prior to extrusion or casting. The wires in propellant grains prepared in this manner generally assume a more or less random pattern as shown in FIGURE 2 where metal wires 1 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 involution 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 wires 1 are embedded in propellant grain 2 having initial burning surface 3.

The wires dispersed in the propellant matrix must 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, as aforesaid. Wires of 0.2 in. length produce higher burning rates than 0.1 in. lengths of wire of the same diameter. Some additional improvement can be obtained by further increasing the length of the dispersed 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, wires 2 inches 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 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 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

5

be undesirable to add more than about 5 to 10% by weight of the propellant although, in some cases, larger amounts may be feasible.

Table II summarizes the results obtained by incorporation of short lengths of copper wire into a propellant comprising polyvinyl chloride, dibutyl sebacate and ammonium perchlorate. In B, one percent of copper chromite was added to the propellant mix as a burning catalyst. The grains were solid, end-burning strands as shown in FIGURE 2. Measurements were taken at 1000 p.s.i.

TABLE II

Amount wire added, percent	Length of wire, inch	Diameter of wire, inch	Burning rate, in./sec.	Percent increase in burning rate	Pressure exponent
----------------------------	----------------------	------------------------	------------------------	----------------------------------	-------------------

A

None	-----	-----	0.54	-----	0.45
1	0.2	0.003	1.23	128	0.45
2	0.1	0.003	1.03	91	0.38
1	0.1	0.003	0.825	53	0.45

B

None	-----	-----	0.82	-----	0.40
1	0.1	0.003	1.22	49	0.36
2	0.1	0.003	1.42	73	0.40
2	0.2	0.003	1.72	110	0.40
2	0.1	0.005	1.10	34	0.41

Although substantial increases in effective burning rate can be achieved by the dispersion of discontinuous, short wires in the propellant matrix, we have found that vastly improved performance is obtained with the use of continuous wire which is longitudinally disposed in the desired direction of flame propagation. 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 obtained 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 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 as shown by the arrow 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 may 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 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 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 wire to form a cone with the wire at its apex. As the flame proceeds along the 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, 75

6

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 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 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 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 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. We have found that establishment of equilibrium can be hastened in several ways.

The use of a plurality of wires as shown in FIGURES 6 and 7 increases greatly the rapidity with which the equilibrium burning surface area can be accomplished. In the case of a single wire, the burning surface presented by the recessing 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. When a plurality of continuous wires is used, the recessed 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 wires a short distance beyond the initial ignition surface. In FIGURE 4, the wire terminates at the initial burning surface 12. 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 gases. When the protruding end of the wire 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 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. In some cases such exposed wire ends may cause practical difficulties because they may be broken off during handling of the propellant grains. This can be obviated by indenting the ignition surface as for example in the form of cones 9 or other depressions into which the wire protrudes, as shown in FIGURES 8 and 9.

We have also found that recessing the ignition surface adjacent to the wires, preferably in the form of cones, with the wire exposed at the apex, as shown in FIGURES 8 and 9, hastens establishment of the equilibrium burning surface area. Any degree of preconcaving 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 sur-

face 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 so 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 wires 11. The cones 9, which flare out from the wire exposed at the apex of each, intersect each other and with 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 and the particular propellant material. The cone angle, for example, varies with the thermal diffusivity of the particular metal, as will be seen below. These factors can readily be determined by those skilled in the art and the particular grain ignition surface designed accordingly.

Table III shows the enormous increase in effective burning rate obtained by embedding a continuous metal wire in the propellant grain. The propellents employed in these burning tests were end-burning grains with an axially embedded, continuous wire normal to the initial burning surface and longitudinally disposed in the direction of flame propagation substantially as shown in FIGURE 4. The solid propellant material comprised 12.44% polyvinyl chloride, 12.44% dibutyl sebacate, 74.63% ammonium perchlorate, and 0.49% stabilizer. The wire in each case was 5 mils in diameter.

TABLE III

Wire	Burning Rate Along Wire (in./sec.)	Ratio of Burning Rate Along Wires to Standard Rate ¹	Properties of the Metal	
			Thermal Diffusivity at 650° C. (cm. ² /sec.)	Melting Temperature (° C.)
Silver.....	2.65	5.3	1.23	960
Copper.....	2.32	4.6	0.90	1083
Tungsten.....	1.82	3.6	0.67	3370
Platinum.....	1.46	2.9	0.35	1755
Aluminum.....	1.16	2.3	0.94	660
Magnesium ²	0.96	1.9	0.66	651
Steel ³	0.80	1.6	0.064	1490

¹ Normal burning rate of the propellant material=0.50 in./sec.

² A square filament cut from 0.005-inch magnesium sheet was used.

³ Music wire.

⁴ Est.

As shown in Table III, the increase in burning rate of the propellant 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. effected an increase in burning rate of 430% whereas platinum with considerably lower thermal diffusivity of 0.35 cm.²/sec. at 650° C. increased the burning rate by 190%. Higher melting points also increase efficacy of the metal as can be seen by a comparison of copper and aluminum. Aluminum melts at a

much lower temperature than copper 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.

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. This is graphically illustrated in FIGURE 12 which shows duplications of photographs taken during burning of propellant strands containing axially embedded continuous wires of silver, aluminum, platinum and steel.

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.

We have also found that 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. We have obtained additional increases in effective burning rate of 5% and more by plating silver and copper wires with 0.00025 and 0.0005 inch coatings of chromium. These results were obtained by burning strands of the polyvinyl chloride propellant afordescribed containing the continuous plated wires axially embedded substantially as shown in FIGURE 1.

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.

We have observed that at pressures of 600 p.s.i. and higher, the pressure exponent of the burning rate along the wire or other metal heat conductor is decreased by an increase in conductor thickness. Above a certain thickness, which varies with the particular metal and propellant material, the pressure exponent becomes even less than that of the propellant itself. Thus the use of continuous wires embedded in the propellant grain affords a means not only of considerably increasing the effective burning rate but also of simultaneously improving the pressure exponent. Where improvement in pressure exponent is an important consideration, wires of greater thickness can be used although the considerable increase in effective burning rate is somewhat less than the maximum obtainable. In certain applications, it may be desirable to obtain maximum possible burning rate and the wire species and thickness can be chosen to effectuate this.

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 mills will probably be desirable in most cases.

Table IV summarizes burning test results obtained respectively with continuous copper, silver, tungsten and molybdenum wires embedded in end-burning grains substantially as shown in FIGURE 4. The propellant material comprised 12.44% polyvinyl chloride, 12.44% dibutyl sebacate, 74.63% ammonium perchlorate, and 0.49% stabilizer. Measurements were made at a pressure of 1000 p.s.i. The results show the large increase in effective burning rate achieved by use of the continuous embedded wires, the effect of varying wire diameter and the improvement in pressure exponent with increasing wire diameter. For example, the 3-mil copper wire increased effective burning rate by 411% as compared with the burning rate of the propellant alone and also gave a considerable improvement in pressure exponent. With the 10 mil copper wire, effective burning rate increase, while not quite so large, was almost 3-fold and pressure exponent was reduced from 0.43 to 0.20. The trends were similar for the other metals tested. As was to be expected, maximum increases in effective burning rate obtained with tungsten and molybdenum were appreciably less than those obtained with copper and silver because of the considerably lower thermal diffusivities of the former two metals, although, to some extent their lower thermal diffusivity was offset by their high melting points.

TABLE IV
COPPER

Wire diameter, inch	Burning rate, in./sec.	Increase in burning rate, percent	Pressure exponent
None	0.46	-----	0.43
0.001	1.12	142	0.75
0.002	1.80	291	0.58
0.003	2.35	411	0.35
0.005	2.20	378	0.31
0.007	2.10	357	0.21
0.010	1.78	287	0.20
SILVER			
None	0.44	-----	0.45
0.001	0.81	84	0.87
0.003	1.80	309	0.60
0.005	2.20	400	0.40
0.007	1.86	323	0.45
0.010	2.08	370	0.15
TUNGSTEN			
None	0.46	-----	0.46
0.001	1.10	140	0.75
0.003	1.63	254	0.40
0.005	1.55	237	0.33
MOLYBDENUM			
None	0.45	-----	0.43
0.003	1.30	189	0.40
0.005	1.50	234	0.32
0.011	1.28	184	0.19

The embedded metal heat conductors are effective regardless of the specific nature or composition of the propellant although the specific increase 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 external oxidizer, such as the polyvinyl chloride propellant previously described, Thiokol, polystyrene and polyester type propellants and the like, with single and double-

base nitrocellulose propellents, pressed ammonium nitrate propellents etc. Table V illustrates the efficacy of a continuous 5-mil copper wire in end-burning propellant grains of different composition.

TABLE V

Propellant	Burning pressure, p.s.i.	Burning rate without wire	Burning rate along wire	Increase in burning rate, percent
A-----	1,975	0.046	0.17	270
B-----	1,015	0.29	1.16	300

A—Polyvinyl chloride 12.5%; dibutyl sebacate 12.5%; ammonium nitrate 75% (3450/6900 r.p.m. grinds in ratio of 1:1); plus 0.5% added stabilizer.
B—Nitrocellulose (12.6% N) 52.1%; nitroglycerin 39.2%; diethyl phthalate 6.6%; 2-nitrodiphenylamine 2.1%; Candelilla wax 0.01%.

Example I

A solid, cylindrical, end-burning propellant grain 1.9 inches in diameter was cast containing 19 copper wires of 7 mil diameter. The wires, which were spaced at intervals through the propellant matrix and positioned normal to the initial burning surface, were longitudinally disposed and continuous throughout the length of the grain. The propellant material was a solid plasticized polyvinyl chloride gel comprising polyvinyl chloride, dibutyl sebacate, ammonium perchlorate and a stabilizer. A 9-inch section of the grain was static-fired at ambient temperature and a pressure of 850 p.s.i. Effective burning rate was 2.7 in./sec. as compared with the normal burning rate of the propellant material itself of 0.68 in./sec. The increase in effective burning rate was of the order of 297%.

As aforementioned, the metal heat conductor, though conveniently used in the form of wire, can also be employed in the form of continuous thin 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 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 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 wires, can be employed with thin, wide conductors, such as protrusion from the ignition surface, and pre-troughing the ignition surface adjacent the heat conductor.

FIGURES 13 and 14 show a solid, end-burning propellant grain containing a 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 15 and 16 show a concentric tubular arrangement of metal heat conductors 19 with a 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 protruding central wire at its apex intersects with the circular V-shaped trough 20, which has the first concentric tube protruding 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. The wire end 13 and tube ends 23 protrude from the ignition surface.

Example II

A strip of copper 5 mils thick and 2 mm. wide was bent longitudinally into the shape of a V with an angle of 45°, the flaring sides each being 1 mm. wide. The V-shaped strip was embedded longitudinally in a solid, end-burning polyvinyl chloride propellant grain substantially as shown

11

in FIGURES 13 and 14, which was inhibited on all surfaces except for the end ignition surface. The grain was burned at 1015 p.s.i. Burning rate along the V-shaped strip was 1.35 in./sec. as compared with a burning rate of 0.43 in./sec. for the propellant in the absence of the metal heat conductor. Increase in mass burning rate was 214%.

The large increase in effective burning rate made possible by the incorporation of metallic heat conductors into the propellant matrix, particularly in the form of continuous wires or strips which extend substantially the entire distance of flame propagation, makes practical the use of solid, end-burning propellant grains for many applications, as for example in rocketry, where hitherto their use was impossible. This is of great importance because of their other advantages as compared with perforated grains, such as higher loading density, and greater strength. Propellants of higher impulse can be employed without danger of weakening the physical structure of the propellant grain and wider operating temperatures can be employed.

Although the preceding description has been in terms of solid end-burning grains because of the enormous improvement in burning rate and other properties, such as pressure exponent, of this type of propellant grain, our invention can also be applied very advantageously to other types of propellant grains, such as perforated grains. The incorporation of 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 metal wire and the large initial burning surface provided by the perforations. The wire may be continuous through the distance of flame propagation or may be dispersed through the matrix in the form of short, discontinuous lengths of wire. As in the case of end-burning grains, the continuous wires provide a considerably higher effective burning rate than the discontinuous wire.

The continuous 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 17 and 18, the embedded 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 19 and 20 show an end-burning cylindrical grain with central perforation 14 and a plurality of continuous 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 may be in the form of wires or thin 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 heat conductor for substantially the entire distance of flame propagation of the grain, as shown, for example, in FIGURES 4, 6, 8, 9, 13, 17 and 19. 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

12

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 21 shows a solid, end-burning propellant grain in which the 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 metal species and thickness of the heat conductor, the use of one or a plurality of heat conductors, protrusion of the heat conductor from the ignition surface, perforation, etc., can be employed both where the 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 initial impulse to a high impulse. In such case, the 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 22 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 may be embodied in other forms within the scope of the appended 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 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 of said grain 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 propellant grain.

2. The propellant grain of claim 1 in which the metal heat conductors are metal wires.

3. The propellant grain of claim 1 in which the metal heat conductors have a thin coating of a metal of higher melting point and the entire surface of said metal-coated

metal heat conductors lying within the body of said propellant grain is in intimate, gas-sealing contact with the propellant matrix.

4. The propellant grain of claim 1 in which the ends of the heat conductors are exposed at the ignition surface of the grain.

5. The propellant grain of claim 4 in which the ends of the heat conductors are exposed at the apex of a recess in the ignition surface.

6. The propellant grain of claim 1 in which the metal heat conductors are continuous substantially throughout the entire distance of flame propagation of the propellant 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 metal wires are selected from the group consisting of copper and silver.

9. 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 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 of said grain and being continuously and longitudinally disposed in the direction of flame propagation of the grain substantially throughout the entire distance of flame propagation, the ends of said heat conductors being exposed in the ignition surface of said 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 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. The propellant grain of claim 10 in which the metal heat conductors are metal wire.

12. The propellant grain of claim 11 in which the metal heat conductors are selected from the group consisting of copper and silver.

13. A solid propellant grain, said grain comprising a self-oxidant, solid propellant matrix, the combination 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, the entire surface of said length of said 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 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 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 propellant grain.

14. A rocket grain comprising solid self-combustible propellant material, said grain having an exposed burning surface whereupon the principal ignition of said grain takes place, and a plurality of straight metal wires with diameters in the range of 0.001 to 0.05 inch spatially and completely embedded throughout said propellant material and contiguous therewith, said wires being oriented in a direction generally normal to all of said burning surface and arranged and adapted to increase the burning rate of said propellant material and increase the structural strength thereof.

15. The rocket grain comprising a cylindrical solid self-combustible propellant material of the composite type comprising a major amount of a solid inorganic oxidizing salt and a minor amount of a rubbery binder, said grain having at least one of its ends exposed to form a burning surface whereupon the principal ignition of said grain takes place, and a plurality of straight metal wires with diameters in the range of 0.001 to 0.05 inch spatially and completely embedded throughout said propellant material and contiguous therewith, said wires being oriented in a direction normal to all of said burning surface and arranged and adapted to increase the burning rate of said propellant material and increase the structural strength thereof.

References Cited in the file of this patent

UNITED STATES PATENTS

1,301,381	Buckingham	Apr. 22, 1919
1,530,692	Paulus	Mar. 24, 1925
2,417,437	Nicholas	Mar. 18, 1947
2,519,878	Bjork	Aug. 22, 1950
2,548,926	Africano	Apr. 17, 1951

FOREIGN PATENTS

652,542	Great Britain	Apr. 25, 1951
69,697	Netherlands	Mar. 15, 1952