

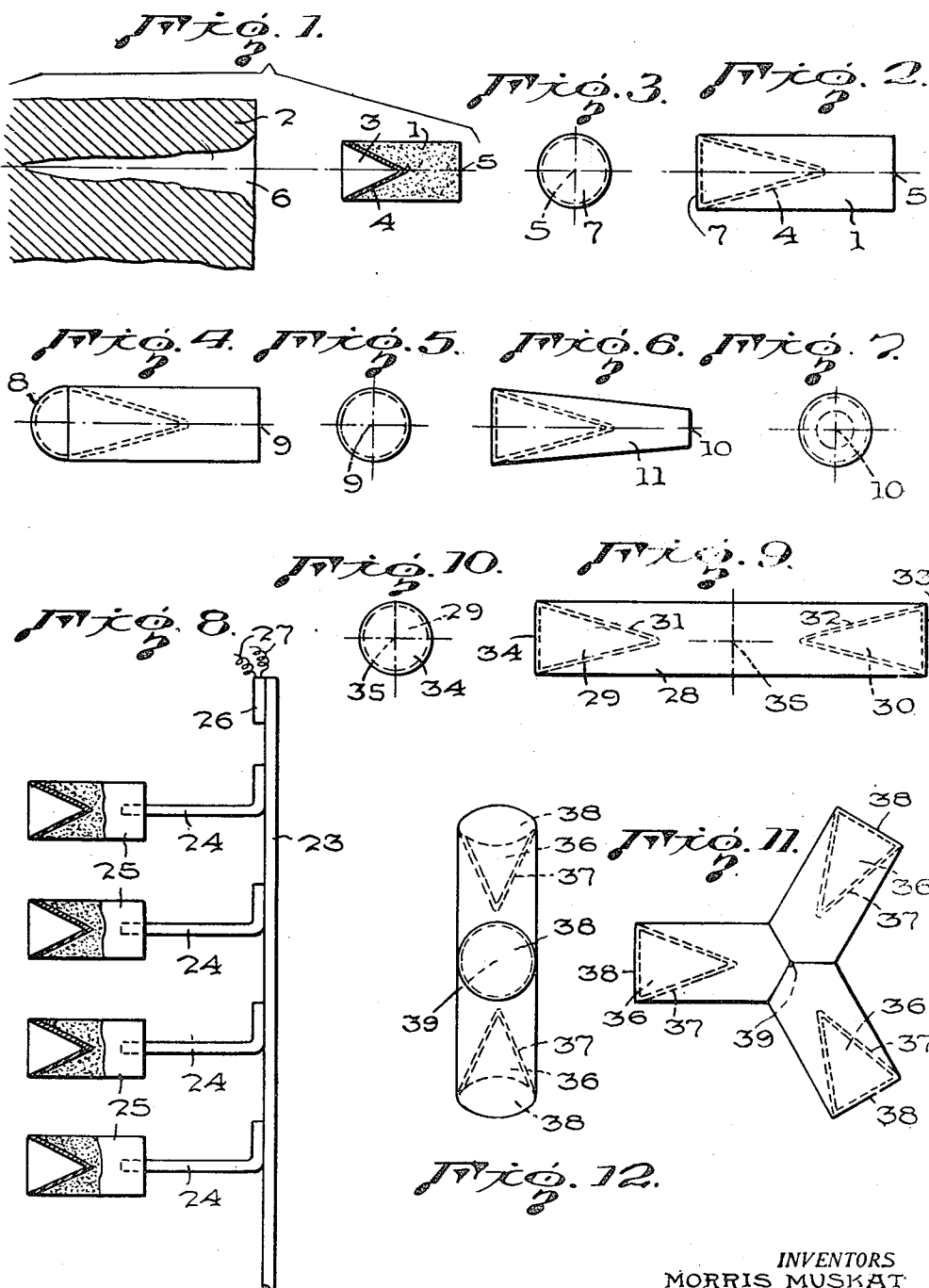
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M. MUSKAT ET AL
APPARATUS FOR PERFORATING WELL
CASINGS AND WELL WALLS

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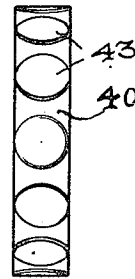
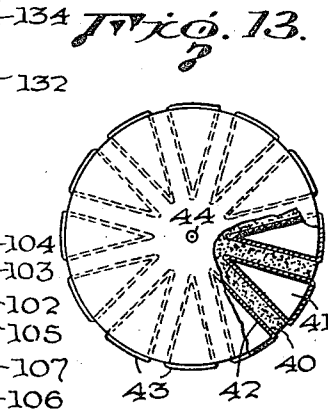
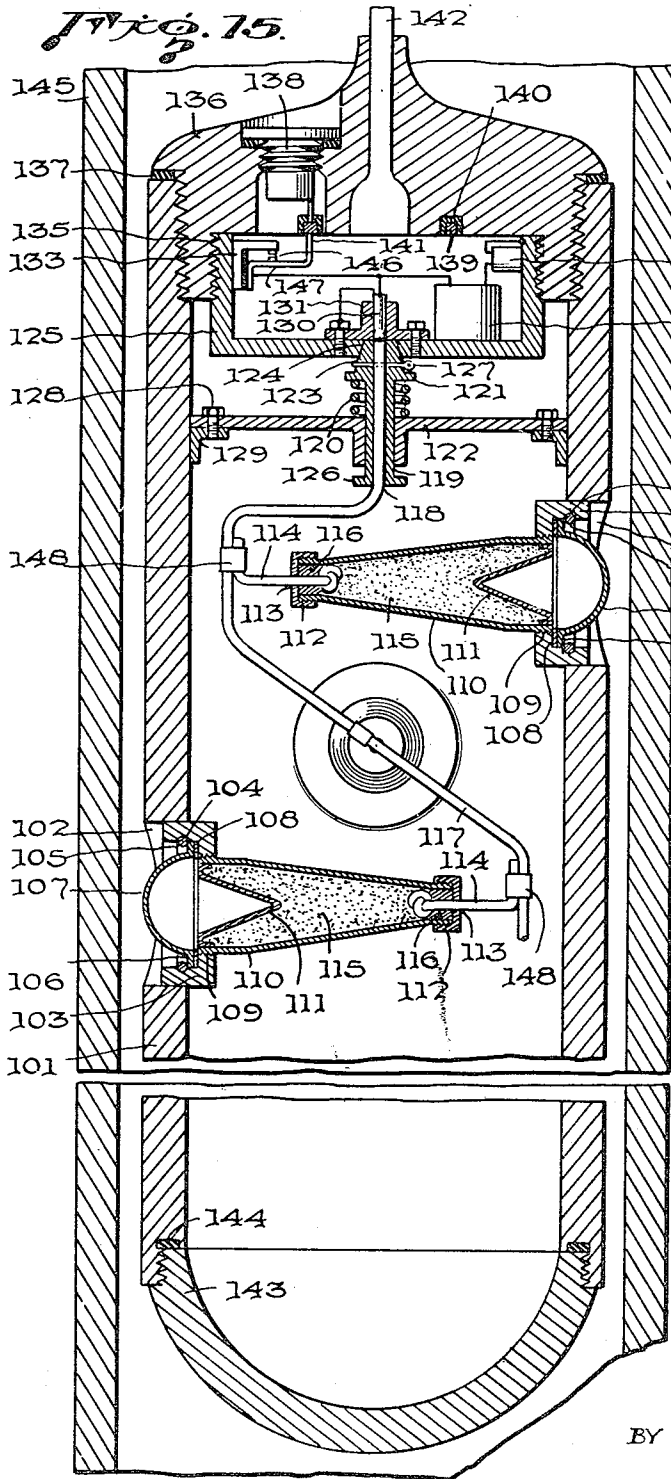
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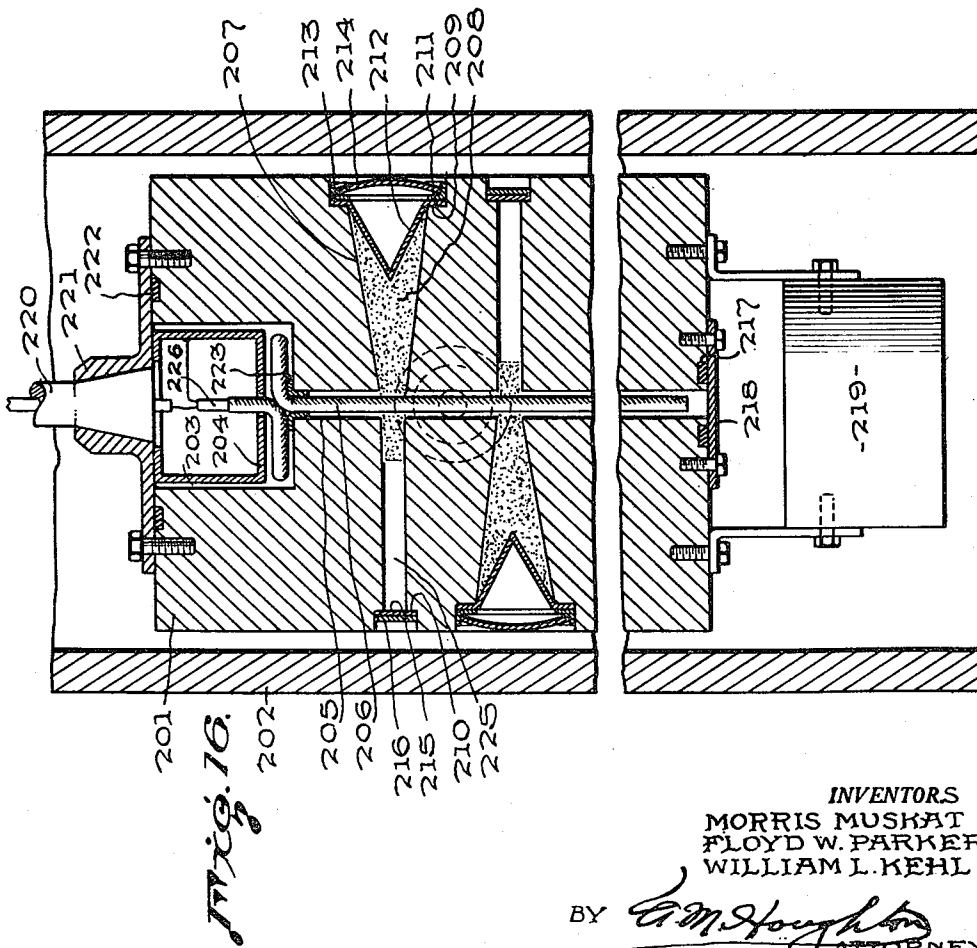
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UNITED STATES PATENT OFFICE

2,494,256

APPARATUS FOR PERFORATING WELL CASINGS AND WELL WALLS

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This invention concerns a new and useful apparatus for perforating pipe, which apparatus is particularly advantageous for use in limited confines such as well bores. In particular it concerns apparatus for employing specially shaped and specially disposed explosive charges for perforating well casing.

This invention is based upon the cutting action of a special type of explosive jet. This jet is the resultant effect of shaping the high explosive charge so that its end provides a concave surface facing the object to be penetrated, and in which, moreover, this concave surface is lined with an inert material such as a metal, ceramic or plastic. Such shaped and lined charges are very effective in creating holes in solid objects including steel, rock, cement, etc. The holes created are of considerable depth and diameter, although these may be varied over an appreciable range by varying the calibre of the explosive charge, its distribution and composition, the geometry of the concave shaped surface, the material and thickness of the liner, and the stand-off distance between the forward end of the charge and the target. We have utilized this effect in the apparatus of this invention useful for perforating and cutting operations in boreholes.

This invention may be used to make holes in the casing of a well, such casing usually consisting of one or more strings of steel pipe with cement between them and also between the outer pipe and the formation wall. Such holes or perforations are made for the purpose of allowing fluid to enter the well so that the fluid may be brought to the surface. Heretofore the formation of such holes has been accomplished by means of "gun perforating" equipment, which utilizes the penetrating ability of high speed bullets to form holes in the casing and surrounding material. Since the length of the barrel through which the bullet is accelerated is limited by the diameter of the casing to be perforated, the speed and hence the penetrating ability of gun perforating bullets, is severely restricted. This invention utilizes the penetrating ability of a properly shaped and lined high explosive charge to produce holes through the casing, thus eliminating the need for a gun barrel. The invention may be used to perforate any pipe of which only the inside is accessible.

It is accordingly an object of this invention to provide an improved apparatus for perforating the casing of a borehole.

Another object of this invention is to provide

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apparatus for perforating the casing of a borehole by use of a shaped high explosive charge. Another object of this invention is to provide apparatus for producing several casing perforations simultaneously either by use of a single high explosive charge which produces multiple holes, or by simultaneously detonating several charges, each of which produce one or more holes.

Another object of this invention is to provide apparatus which achieves such high powers of penetration through the steel casing that residual energy is available to produce additional penetration in the cement and surrounding rock.

Another object of this invention is to provide a well casing perforating means employing the penetrating effect of an explosive jet.

It is also an object of this invention to provide a method of perforating the well casing and surrounding cement and rock which is substantially free from the disadvantage of forming burrs on the inside of the casing around the hole made through the casing.

It is still another object of this invention to provide a method of perforating the well casing and the cement and rock surrounding it which does not leave an impermeable slug in the hole produced, which slug might otherwise seal the hole against the fluids in the formation perforated and hence defeat the purpose of the perforation.

These and other useful objects may be accomplished by the apparatus of our invention as described in this specification, of which the accompanying drawings form a part, and in which:

Fig. 1 shows the form and disposition of the explosive used by our invention and the hole produced thereby;

Figs. 2 and 3 show how the lined cavity may be covered to exclude extraneous material;

Figs. 4 and 5 show another shape which the cover to the lined cavity may take;

Figs. 6 and 7 show another shape which the explosive cartridge may take;

Fig. 8 shows a manner of connecting a number of explosive cartridges to a length of explosive fuse for producing a number of perforations substantially simultaneously;

Figs. 9 and 10 show a form of the explosive cartridge useful for simultaneously producing two perforations having directions 180° apart;

Figs. 11 and 12 show a form of the explosive cartridge useful for simultaneously producing three perforations having directions 120° apart;

Figs. 13 and 14 show a form of the explosive

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cartridge useful for producing twelve perforations having directions 30° apart;

Fig. 15 shows a cross section of a well apparatus for perforating well casing by means of shaped charges; and

Fig. 16 shows a cross section of an expendable well apparatus for perforating well casing by means of shaped charges.

In the apparatus of our invention the explosive is not projected as a bullet but is merely placed statically at a certain distance from the target. The effect of the explosive is to create a hole in the target by virtue of a specially shaped and lined cavity in the end of the explosive facing the target. The target is not shattered. Virtually the whole penetrating power of the explosive used arises from the effect of the cavity plus liner formed in the end of the explosive facing the material to be penetrated. This fact is apparently closely related to what has been previously known in the explosives art as the Munroe effect. While there are theories for this effect, it basically represents purely an empirical discovery. The theory suggests the possibility that an explosive jet of very high velocity is formed opposite the cavity and this jet has a strong penetrating or cutting effect. The nature of the jet may be controlled and its efficiency augmented by placing inert non-explosive materials in the cavity as liners.

Fig. 1 represents a longitudinal cross-sectional view of a high explosive charge 1, and a medium 2 which is to be penetrated. An essential feature of the specially shaped high explosive charge used for the purpose specified above is the presence of a cavity 3 in the end of the charge facing the material to be penetrated. Another essential feature is the presence of a solid liner 4 on the inner surface of the cavity. The liner 4 may be metal, ceramic material, or plastic; in fact any non-explosive material may be used. When such a charge is detonated from a point on the axis of the charge such as indicated by 5, a hole 6 is formed in the target material in the direction of the axis of the cavity 3. The dimensions of the hole produced depend on the shape and dimensions of the cavity 3; the kind, amount, and distribution of high explosive in the charge 1; the nature of the confinement of the charge; the material, dimensions, and physical properties of the liner 4; the distance between the base of the cavity 3 and the surface of the target material 2; and the nature of the target material. By making proper selections of the above variables, the hole can be made to penetrate large distances into the target material.

The liner 4 has the effect of greatly enhancing the penetrating power of the cavity charge, even though the latter already is much more effective than a straight-ended charge. For example, among numerous results of our experiments we have found that a high explosive charge 1½" dia., 4" long, and having a 45° unlined cavity, formed a hemispherical cavity 1½" diameter and approximately ¾" deep. Under otherwise identical conditions, when the cavity was lined with a steel cone, the hole made in the target was more than 3" deep, with an entry diameter 1⅞".

Even much more striking contrasts can be achieved by suitably varying other important parameters of the cavity liner, such as the cone angle, liner material, liner weight, and standoff from the target. It is true that the unlined cavity will give approximately the same target hole volume as the lined cavity, but the depth of the

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penetration is very much greater with the lined charge. The reason for this appears to be that the high explosive forms, from the cone material, a fine spray or jet which has very high penetrating power. The material of the cavity liner 4 may be metallic, for example, steel, aluminum, brass, lead, copper; or it may be ceramic; or glass; or of plastic composition. The cavity 3 need not of necessity be conical, but may be pyramidal, hemispherical, parabolic, or may have other equivalent shapes.

Material of appreciable density within the cavity greatly diminishes the penetrating action of the charge merely because it prevents formation of the jet. When any dense material is some distance from the base of the cavity it is equivalent to a corresponding amount of the target in the path of the penetrating jet. In either case the residual penetration is greatly reduced. Therefore material of appreciable density, for example water, must be excluded from the cavity, since the presence of such matter within the cavity greatly diminishes the penetrating action of the cavity charge. Thus, for work in liquids, the base of the cavity is provided with a suitable cover to prevent any liquid entering the cavity. The nature of the material surrounding the charge also influences the hole formation performance considerably. An otherwise unconfined charge in a well would effectively be confined by any fluid present in the well. Thus, if unconfined shots are to be made in a fluid filled well, the charges may be placed in a suitably designed container which prevents the fluid from surrounding the charges.

The high explosive may be of any type such as pentolite, tetryl, T. N. T., etc., and may be augmented by any suitably chosen booster explosive. For example, tetryl could be used as a booster for pentolite, since the former is more sensitive to shock than the latter. The choice of high explosive material must be governed by the conditions under which it is to be used as is generally the case in any explosive application.

Fig. 2 shows a side view of an explosive cartridge similar to Fig. 1 but having a cover 7 over the cavity to keep out extraneous material such as water. The cover 7 may be of similar material as the liner 4 and may be an integral part thereof or it may be of any convenient material of sufficient strength.

Fig. 3 shows an elevation of the explosive cartridge of Fig. 2 illustrating a circular cross section, but other shaped sections such as square or hexagonal ones may be used as well. Detonation of the charge 1 illustrated in Figs. 2 and 3 is made at a point 5 at the base of the charge on its center line.

Fig. 4 shows a side view of an explosive cartridge having a hemispherical cover 8 over a conical liner and cavity, and Fig. 5 shows an elevation thereof. Such hemispherical or dome-shaped covers are better able to withstand external fluid pressure and are therefore useful when the cartridge is immersed in a fluid to a considerable depth as in a fluid filled well. The cartridge shown in Figs. 4 and 5 is also detonated at a point on its axis at the base, indicated by point 9.

Figs. 6 and 7 show side view and elevation respectively of another possible shape which may be used for the high explosive charge 11. This shape is somewhat more efficient in that this design can produce a given hole with a smaller quantity of explosive than the shape shown in Figs. 2 and 4. Detonation of this shape charge

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is made at a point on the axis at the rear of the charge, as indicated by 10.

In perforating well casing the target arrangement encountered will usually consist of from one to three strings of steel casing with cement between the casing strings and between the outermost strings and the surrounding formation rock. As a general rule, the depth of penetration increases as the density of the target material decreases and the hole diameter increases as the tensile strength of the material decreases.

In perforating well casing it is usually desirable to make a series of perforations more or less simultaneously. Fig. 8 shows an arrangement for this purpose whereby several shaped high explosive charges may be detonated simultaneously. To a trunk line of explosive fuse 23 such as primacord or cordeau, a number of branch lines 24 are led to the specially shaped charges 25. The entire assembly is supported by a properly designated device and lowered into the wall. The trunk line 23 may be detonated by means of a detonator 26, which may be fired by a suitable mechanism. For example, the detonator may be of the current sensitive type with electrical lead wires 27 leading to the surface. By applying a proper voltage to these leads the detonator is fired and it in turn initiates the detonation of the trunk line. The detonation of the trunk line is then propagated to each branch line and in turn to the cavity charges 25. Since the speed of detonation in known types of explosive fuse is extremely high (for example, the speed of detonation of primacord is 6200 meters per sec.), the delays encountered in the detonation of the shaped high explosive charges are so small as to be negligible, and the detonations of the charges can be considered to be simultaneous. Thus a number of perforations may be made simultaneously through the casing and into the rock formation by use of this apparatus.

Another manner of simultaneously producing two holes is by the use of the special shape of high explosive charge illustrated in Figs. 9 and 10. In this case the explosive material 28 has two oppositely directed cavities 29 and 30. The cavities may be lined with liners 31 and 32, and closed by covers 33 and 34. Detonation of the charge shown in Figs. 9 and 10 is initiated at the midpoint of the axis, as at the point indicated by 35, and produces hole forming jets in the two directions 180° apart and opposite the cavities. Obviously such a charge would be supported in a hole in a transverse position, its length being adjusted so as to allow the proper stand-off distance between each end of the explosive stick and the wall of the casing. The covers 33 and 34 may have extensions so as to exclude well fluid from between the end of the cavity and the wall of the borehole.

Figs. 11 and 12 show a shape of high explosive cartridge for simultaneously making three holes on axes 120° apart. In this case there are three cavities 36 on axes 120° apart, each cavity having a liner 37 and cover 38. Detonation is initiated at the center point 39. The geometrical symmetry of the shape shown in Figs. 11 and 12 may be extended to one producing any desired number of holes.

Thus Figs. 13 and 14 show a shape of high explosive for simultaneously producing twelve holes. This shape consists of a continuous disk of explosive material 40, having around its outer surface cavities 41 with liners 42, the cavities

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being protected by covers 43. In this case detonation is initiated at the midpoint 44.

As another means of obtaining a multitude of simultaneous perforations one may use a cylindrical column of high explosive, whose surface is provided with a number of lined cavities of desired distribution and spacing. Virtually simultaneous perforations are obtained when detonation is initiated by means of an explosive fuse passed through the center of the cylinder.

Fig. 15 is a diagrammatical cross-section of one type of apparatus employing the above mentioned shaped charges for purposes of perforating casing in a well bore. This embodiment is designed so that the main body of the device will be recoverable after the shots have been fired. In Fig. 15 numeral 101 represents a steel cylinder which contains a number of openings 102 within each of which a ring 103 has been welded or otherwise attached in such a manner as to provide a seal against exterior hydrostatic pressures. Each ring 103 contains a groove 104 which accommodates a split lock-ring 105 which holds the flange 106 of a metal cap 107 against a gasket 108 which forms a pressure-tight seal and prevents the influx of well fluids into the interior of the cylinder 101. The ring 103 also contains threads 109 which engage similar threads on the member 110. The member 110 contains and is attached to a conical charge liner 111 by any convenient method such as soldering, threading, friction, etc. Member 110 is also provided with a cap 112 which is attached by means of threads. A hole 113 in the cap 112 allows for the passage of a length of explosive fuse 114. The end of the explosive fuse 114 is embedded within and at the end of an approximately conical high explosive charge 115 bounded by the charge liner 111, the member 110 and the cap 112, or by some sort of packing material 116 such as putty occupying the space near the cap 112. The length of explosive fuse 114 is joined to a trunk-line of explosive fuse 117 which extends from the lower-most charge (not shown) to the upper portion of the cylinder 101 and into the hole 118 in the piece 119. A coil spring 120 situated between a shoulder 121 on the piece 119 and a supporting member 122 tends to force the conical end 123 of the member 119 upward into the conical socket 124 of the fuze-chamber 125. A flange 126 limits the upward travel of the piece 119. A pin 127 is provided to hold the end of the explosive fuse 117 in place. The supporting member 122 is provided to guide and hold piece 119 and is attached to the cylinder 101 by means of the bolts 128 and the bracket 129 or by any other suitable means. The fuze-chamber 125 contains an electrically actuated detonator 130 held in close proximity to the end of the explosive fuse 117 by the piece 131. One lead from the detonator is grounded to the wall of the fuze-chamber whereas the other is connected to a clock mechanism 132 and to a switch 133. One terminal of a battery 134 is connected to the clock mechanism 132 and the other is grounded to the fuze-chamber 125. Threads 135 are provided to fasten the fuze-chamber 125 on the end piece 136 which seals the upper end of the cylinder 101 from influx of well fluids by virtue of the gasket 137. End piece 136 contains a pressure-sensitive switch 138 which is connected electrically with a metallic ring 139. Conducting ring 139 is electrically insulated from the end piece 136 by the insulating material 140 and is in electrical contact with switch 133 through the brush 141. A wire line

142 is attached to the end piece 136 in such a way that well fluids do not enter the interior of the perforator. The wire line 142 allows the entire assembly to be lowered into and withdrawn from a well bore. Another end piece 143 is screwed to the lower end of cylinder 101 and forms a fluid tight seal by virtue of the gasket 144.

The charges 115 are formed by casting, pressing, or otherwise filling the member 110 with an appropriate explosive. For example, 50-50 pentolite may be molten and readily cast into such a container by pouring through the opening provided in 110 and allowing the explosive to cool. The end of a piece of explosive fuse 114, such as primacord, is embedded in the explosive as shown in the figure in such a way that detonation of the explosive fuse will propagate to the charge 115. For example, a knot in the end of a length of primacord inserted beneath the surface of a molten pentolite charge, and held in place until the charge solidifies, is adequate to transmit detonation from the primacord to the pentolite charge. In cases where the elevated temperature existing in a well is high enough to cause melting of the explosive charge 115, a suitable packing material 116 such as putty can be used to prevent loss of explosive through the opening 113, or an explosive with a higher melting point may be used, or the temperature of the interior of the perforator can be kept below the melting point of the explosive by using an appropriate cooling medium.

The assembly of the perforator is accomplished in the following way: An explosive filled charge unit is threaded into the lowermost ring 103 by means of slots or lugs attached to the large end of member 110 and an appropriate tool. The gasket 108 and the metal cover 107 are placed in position and the split lock-ring 105 is inserted into the groove 104 to hold the cap 107 against the gasket 108. The protruding length of explosive fuse 114 is attached to the trunkline 117 of explosive fuse by a sleeve 148 which may be crimped in place with an appropriate tool. The remaining charge units are then placed in the same manner, attaching the explosive fuse protruding from each charge to the trunkline of explosive fuse as indicated. The upper end of the trunkline is then inserted through the hole 118 and the supporting member 122 is placed in position as shown. The surplus explosive fuse is then drawn through the hole 118, the pin 127 is inserted to hold the explosive fuse in place, and the surplus explosive fuse is removed by cutting it flush with the end of piece 119.

The clock mechanism 132 is set to complete the circuit to the detonator 130 after a chosen time interval. The fuze-chamber 125 is then threaded into end piece 136, the latter then threaded into cylinder 101 forcing the piece 119 to compress the spring 120 keeping the end of the fuse 117 and the detonator 130 in contact. End piece 143 can be threaded into the lower end of cylinder 101 at any time. When all of the component parts of the perforator are assembled, the perforator is lowered to the desired depth in the well by means of the wire line 142. At the predetermined time, the clock mechanism 132 connects the electrically actuated detonator 130 in series with the battery 134. The firing of the detonator initiates a detonation wave in the explosive fuse which is rapidly propagated down the trunkline 117 and down each branchline 114 and thereby into each charge 115. The detonation of each charge 115 provided with a properly shaped liner

111 and having no dense matter in the concave region of the liner, produces a hole through the casing 145 and into the surrounding formation. The speed of propagation of the detonation wave down the trunkline 117 is so rapid that the charges may be assumed to be detonated simultaneously.

The danger of an unintentional explosion may be reduced by several safety devices. To prevent any such premature detonation, the detonator is grounded through the contact 146 of the switch 133 at all times while the fuze-chamber is not attached to the end piece 136. Thus, if in adjusting the clock mechanism, or at any other time, the full voltage of the battery 134 should be accidentally applied to the ungrounded terminal of the detonator, the current would be bypassed through the contact 146 of switch 133 to ground. On threading the fuze-chamber 125 into the end piece 136, another grounding circuit is completed through the brush 141, the ring 139, and the pressure-sensitive switch 138. The depression of the contact arm 147 which holds the brush 141 by the ring 139 breaks the contact 146. The grounding circuit through the pressure-sensitive switch 138 remains closed, however, until the perforator unit is lowered to a predetermined depth in the well at which the hydrostatic pressure is sufficient to open switch 138. The clock mechanism is set to connect the battery 134 to the ungrounded terminal of the detonator 130 for a short interval at a predetermined time. If for any reason the detonator fails to fire, the perforator can be withdrawn with safety since the clock will have broken the connection of the detonator lead with the battery and will have connected it to ground. Furthermore, the pressure-sensitive switch will again close when the hydrostatic pressure falls and the contact 146 again closes as the fuze-chamber is being removed.

The interior of the perforator shown in Figure 15 is maintained fluid tight to provide an expansion chamber for the gases resulting from the explosive in order to prevent damage to the casing and excessive shattering of the surrounding formation, and also to eliminate the necessity of providing pressure tight fuze-chambers and charge cases.

Instead of the apparatus of Figure 15 the vehicle for any desired group of shaped charges may alternatively simply be an expendable inert cylinder of material such as wood, plastic, etc., in which pockets are provided for the insertion of shaped charge units of desired number, spacing, and distribution. Figure 16 shows a diagrammatic cross section of such an expendable type of apparatus employing shaped charges for the purpose of perforating casing in a well bore. This embodiment is designed so that everything but the supporting cable will be expended in the well bore at the time it is fired, so that only the cable needs to be withdrawn from the well bore after firing.

The main body 201 of the perforator consists of an inert material such as wood, plastic, or cement, in the form of a cylinder to fit inside the well casing 202. A cavity 203 is drilled centrally in one end of the main body 201 to provide a space for the fuze-chamber 204 which contains suitable provisions for making the unit safe for handling and yet make it operable at the desired depth in the well bore. From the bottom of the cavity 203 a cylindrical hole 205 is drilled axially along the entire length of the body 201, and is of such size that a length of explosive fuse 206, such as primacord, may be inserted into its full length. Other cavities 207 are drilled diametrically

through the main body 201 to hold the shaped charges of high explosive 208. These cavities 207 may be spaced both radially and vertically in any way desired. For example, they can be arranged in a helical pattern around the cylindrical main body 201, with one or more cavities in a given horizontal plane. Or, they can be arranged one above the other, with one or more cavities in any given horizontal plane, and with almost any desired vertical separation between horizontal planes. Each single cavity is of a shape formed by the junction at or near the axis of the body 201 of a small cylindrical section 225 and a coaxial expanded cavity 207 of conical, cylindrical or other equivalent shape, as shown in Fig. 16.

Each cavity 207 and 225 is counterbored at the outer end to provide square shoulders 209 and 210. The shoulder at 209 is a seat for the flange 211 on the conical charge liner 212. A suitable gasket 213 is placed over the flange 211 in such a way that when the sealing disk 214 is pressed down on it and fastened by suitable means, a pressure tight seal is made so that well fluids cannot enter any part of the cavity 207. At the other end of the cavity 207 another gasket 215 and sealing disk 216 are provided to seat against shoulder 210 and prevent well fluids from entering the cavity at this point. A gasket 217 and a sealing disk 218 are provided to prevent well fluids from entering the lower end of central hole 205. A weight 219, for example, a lead mass, is provided at the bottom of the main body 201 in case added weight is necessary to sink the unit in the well fluids.

The entire unit is suspended in the well bore by means of a conducting cable 220. Cable 220 is fastened to the main body of the device 201 by means of a suitable clamp 221, which also makes a pressure tight seal with cable 220 and with the main body 201 by virtue of the gasket 222. This seals the upper end of the device against entrance of well fluids. One conductor of cable 220, which may conveniently be an armored jacket thereof, may make electrical connection with the fuze-chamber 204. The fuze-chamber 204 may contain safety devices in the form of a time switch, pressure actuated safety switch, etc. as is customary in devices of this kind. These have been omitted to simplify the drawing, one conductor of cable 220 being shown connected directly to detonator 226.

In actual practice, the procedure that might be followed in preparing the casing perforator for use, and in using it in the well bore, is as follows. Given the main body 201 with all cavities and counterbores drilled out, the first step is to put the explosive fuse 206 in place in the axial hole 205. A grommet 223 may be inserted if necessary to hold the explosive fuse securely in the hole and to prevent loss of explosive through the hole. The gasket 217 and sealing disk 218 are next put into place over the bottom end of the axial hole 205. The conical liners 212 are inserted into the cavities 207 with the flanges 211 seating against the shoulders 209. Gaskets 213 and sealing disks 214 are next put into place and suitably held. The explosive 208 can now be loaded into the cavities 207 in the region behind the conical liners 212 by inserting the explosive from the small end of the cavities 207 in each case. The method of loading, whether by pouring, pressing, or other means, will be largely dictated by the type of explosive used and by the distributions of the cavities. It is necessary, however, to make sure that the explosive makes good contact everywhere with the exposed surfaces of the conical liners 212, and that poros-

ity of the explosive be reduced to a minimum. Good contact should also exist between the explosive and the explosive fuse 206 where it intersects each cavity 207. The explosive need fill each cavity 207 only to a point somewhat past the explosive fuse, and the remainder of the space may be either left air-filled or filled with an inert material, such as high melting point wax or powder which can be packed into the space. Gasket 215 and sealing disks 216 are next fastened into position over the ends of the cavities 207, and loading is completed. The exposed end of the explosive fuse 206 is then inserted into a properly designed fitting incorporated in the fuze-chamber 204, after which the fuze-chamber is inserted into the cavity provided for it, the surplus explosive fuse coiling in the space beneath the fuze-chamber. The remaining pieces are then attached and the unit is ready to be lowered into the well.

After the perforator has been lowered to the desired depth in the well bore and appropriate safety devices in the fuze-chamber have functioned to make the firing mechanism operable when an electrical impulse is received from the surface of the ground, the operator is ready to fire and sends an electrical impulse down the conducting cable 220 and thus initiates detonation of the explosive fuse 206 at the end connected to the fuze-chamber 204. The detonation travels along the explosive fuse and through the explosive charges 208, initiating them one by one in rapid succession. A hole is made through the casing and cement and into the formation opposite each charge 208. The main body 201 of the perforator is destroyed, and the weight 219 will drop to the bottom of the well bore where it will do no serious harm since, being made of lead, or other soft heavy material, there will be no great difficulty in cutting or squeezing it out of the way of any other tools which may subsequently be run down to the bottom of the well. There remains only the conducting cable to withdraw from the hole and it may be used for subsequent operations by attaching another perforating unit to it.

It is to be noted that the form of the perforator units is not to be limited precisely to the arrangement shown or described in Figures 15 and 16. Modifications, such as the use of multiple charges in any horizontal plane as shown in Figures 9 to 14 for producing multiple perforations, instead of the single hole producing charge shown, are within the scope of the invention.

The nature of the holes produced by the charges 115, Figure 15, depends on the shape and dimensions of the cavity liner 111, and on the standoff distance between the base of the liner 111 and the target material which is composed of the cap 107, the casing 145 and the well fluid between them, as well as the cement behind the casing. The depth of penetration into a target increases as the standoff distance increases until the standoff is very large compared to the calibre of the charge. Moreover, with a steel target and a steel liner, a crater is formed at the entry of the target hole which projects beyond the incident face of the target forming what is commonly termed a burr. The removal of such burrs is a desirable but an expensive operation. We have discovered, however, that if steel liners are used and the standoff is reduced to a distance not greater than the calibre of the charge, the formation of the burr does not take place, and the penetration, although somewhat less than the maximum obtainable, is still adequate to form a

hole through the casing and well into the formation beyond.

Many types of liners give rise to so-called slugs, which are solid metal pieces formed from the liner during the detonation of the charge and which frequently enter and plug the target hole after it has been produced. We have discovered that if a steel cone with a thickness ranging from 1% to 3% of the calibre of the charge, is used as a charge liner, the slug which is formed is sufficiently small to pass through the hole in the casing and come to rest deep in the formation where it has a negligible effect on the flow of fluids through the hole.

In addition to the above specifications, we have found that best results are achieved when the apex angle of steel liners lies in the range of 30° to 80° and when the length of the charge, measured from the base of the liner, lies in the range of 1½ to 3 calibres (charge diameters). The diameter of the conical cavity is preferably in the range of 1 or 2 times the thickness of the steel to be penetrated.

Liners of aluminum may be used, and in such case the desirable apex angle and calibre is the same as above specified for steel. The thickness of an aluminum liner should lie in the range of 2% to 6% of the diameter of the conical liner, and the standoff should lie in the range of 0 to 2 calibres.

The above specifications of liner, material and dimensions, and standoff apply not only to the charges of Fig. 15 but also to those of Fig. 16 and wherever such charges are used.

The principles of our inventions may also be employed for making extended cuts in pipe, particularly well pipe or casing, and apparatus for such purpose is disclosed and claimed in our co-pending divisional application Serial No. 129,252, filed November 25, 1949, entitled "Apparatus for cutting and slotting pipe" and assigned to the same assignee as the instant application.

What we claim as our invention is:

1. Apparatus for shooting holes in a well pipe or well wall comprising an explosive charge having a cavity facing the wall of the well, the length of said explosive charge being in the range 1½ to 3 times its diameter, means for supporting and positioning the charge with respect to the well wall and means for initiating the detonation of the explosive charge.

2. Apparatus for shooting holes in a well pipe or well wall comprising an explosive charge having a cavity facing the wall of the well, a steel lining in contact with the explosive in said cavity, means for supporting and positioning the charge with respect to the well wall so that the standoff is less than the diameter of the charge, and means for initiating the detonation of the explosive charge.

3. Apparatus for shooting holes in a well pipe or well wall comprising an explosive charge having a conical cavity facing the wall of the well and a conical steel lining in contact with the explosive in said cavity, said steel lining having a thickness in the range of 1% to 3% of the charge diameter, means for supporting and positioning the charge with respect to the well wall and means for initiating the detonation of the explosive charge.

4. Apparatus for shooting holes in a well pipe or well wall comprising an explosive charge having a cavity facing the wall of the well, an aluminum lining in contact with the explosive in said cavity, means for supporting and position-

ing the charge with respect to the well wall so that the standoff is less than twice the diameter of the charge, and means for initiating the detonation of the explosive charge.

5. Apparatus for shooting holes in a well pipe or well wall comprising an explosive charge having a conical cavity facing the wall of the well and a conical aluminum lining in contact with the explosive in said cavity, said aluminum lining having a thickness in the range of 2% to 6% of the charge diameter, means for supporting and positioning the charge with respect to the well wall and means for initiating the detonation of the explosive charge.

6. Apparatus for perforating well casing comprising an explosive charge having a conical cavity facing the wall of the well casing, the diameter of said cavity being in the range of 1 to 2 times the thickness of casing wall to be penetrated, means for supporting and positioning the charge with respect to the well casing, and means for initiating the detonation of the explosive charge.

7. Apparatus for perforating well casing comprising a cylindrical housing capable of being inserted into the well casing, top and bottom closures for said housing, means for positioning said apparatus in a well, inwardly extending explosive charges mounted in spaced openings in said housing, said explosive charges having outward facing cavities lined with an inert material, covers over said openings, means for sealing said covers in place, and means for initiating the detonation at a point on the axis at the inside end of said explosive charges.

8. Apparatus for shooting holes in a well pipe or well wall comprising a closed container capable of being inserted into the well and having spaced openings therein, means for positioning said container in a well, inwardly extending explosive charges mounted in the spaced openings of said container, said explosive charges having outwardly facing cavities lined with an inert material, covers over said openings, means for sealing said covers in place, an explosive fuse connecting the inside end of said explosive charges, and means for initiating the detonation of said fuse.

9. Apparatus for perforating well casing comprising a cylindrical housing capable of being inserted into the well casing, top and bottom closures for said housing, means for positioning said apparatus in a well, inwardly extending explosive charges mounted in spaced openings in said housing, said explosive charges having outward facing cavities lined with an inert material, covers over said openings, means for sealing said covers in place, an explosive fuse connecting the inside end of said explosive charges, and means for initiating the detonation of said fuse.

10. Apparatus for perforating well casing comprising a cylindrical housing capable of being inserted into the well casing, top and bottom closures for said housing, means for positioning said apparatus in a well, inwardly extending explosive charges mounted in spaced openings in said housing, said explosive charges having outward facing conical cavities of cone angle between 30° and 80° and lined with an inert material, sealed covers over said openings, an explosive fuse connecting the inside end of said explosive charges, and means for initiating the detonation of said fuse.

11. Apparatus for perforating well casing comprising a cylindrical housing capable of being

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inserted into the well casing, top and bottom closures for said housing, means for positioning said apparatus in a well, inwardly extending explosive charges mounted in spaced openings in said housing, the length of said explosive charge being in the range $1\frac{1}{2}$ to 3 times its diameter, said explosive charges having outwardly facing cavities lined with an inert material, sealed covers over said openings, an explosive fuse connecting the inside end of said explosive charges, and means for initiating the detonation of said fuse.

12. Apparatus for perforating well casing comprising a cylindrical housing capable of being inserted into the well casing, top and bottom closures for said housing, means for positioning said apparatus in a well, inwardly extending explosive charges mounted in spaced openings in said housing so that the distance between the outer end of the charge and the casing is less than the diameter of the charge, said explosive charges having outward facing cavities lined with steel, sealed covers over said openings, an explosive fuse connecting the inside end of said explosive charges, and means for initiating the detonation of said fuse.

13. Apparatus for perforating well casing comprising a cylindrical housing capable of being inserted into the well casing, top and bottom closures for said housing, means for positioning said apparatus in a well, inwardly extending explosive charges mounted in spaced openings in said housing, said explosive charges having outwardly facing conical cavities lined with steel whose thickness is in the range of 1% to 3% of the charge diameter, sealed covers over said openings, an explosive fuse connecting the inside ends of said explosive charges, and means for initiating the detonation of said fuse.

14. Apparatus for perforating well casing comprising a cylindrical housing capable of being inserted into the well casing, top and bottom closures for said housing, means for positioning said apparatus in a well, inwardly extending explosive charges mounted in spaced openings in said housing, so that the distance between the outer end of the charge and the casing is less than twice the diameter of the charge, said explosive charges having outward facing cavities lined with aluminum, sealed covers over said openings, an explosive fuse connecting the inside end of said explosive charges, and means for initiating the detonation of said fuse.

15. Apparatus for perforating well casing comprising a cylindrical housing capable of being inserted into the well casing, top and bottom closures for said housing, means for positioning said apparatus in a well, inwardly extending explosive charges mounted in spaced openings in said housing, said explosive charges having outward facing conical cavities lined with aluminum whose thickness is in the range of 2% to 6% of the charge diameter, sealed covers over said openings, an explosive fuse connecting the inside end of said explosive charges, and means for initiating the detonation of said fuse.

16. A bore hole perforator comprising a body portion adapted to drop into a bore hole, a plurality of radially extending openings therein, an explosive charge removably secured in each of said openings and having a hollow end portion

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directed outwardly thereof, and means for selectively detonating said charges by remote control.

17. A gun for shooting holes in a well pipe or well wall comprising in combination a body having a series of supporting members therein, means for lowering said body in said well, an explosive charge in each member, a substantially conical cavity in the outer end of each charge with the axis of each cavity substantially the same as the axis of its respective charge, a layer of a malleable and ductile metal lining each of said cavities, a cap closing the end of each cavity providing an air space between said cap and said cavity and means for firing said charges substantially simultaneously in a predetermined order.

18. A gun for shooting holes in a well pipe or well wall comprising in combination a body having a series of supporting members therein, means for lowering said body in said well, an explosive charge in each member, a substantially conical cavity in the outer end of each charge with the axis of each cavity substantially the same as the axis of its respective charge, a cap closing the end of each cavity providing an air space between said cap and said cavity and means for firing said charges substantially simultaneously.

19. Apparatus for perforating well casing comprising a hollow sealed housing capable of being inserted in the well casing, said housing defining an expansion chamber, means for positioning said apparatus in a well, an explosive charge mounted within said housing and extending into said expansion chamber, said explosive charge having an outwardly-facing cavity lined with an inert material, and means for detonating said explosive charge.

20. Apparatus for perforating well casing comprising a hollow sealed housing capable of being inserted in the well casing and having an opening therein, said housing defining an expansion chamber, means for positioning said apparatus in a well, an explosive charge mounted opposite said opening in said housing and extending into said expansion chamber, said explosive charge having a cavity facing said opening and lined with an inert material, a cover over said opening, and means for detonating said explosive charge.

21. Apparatus for perforating well casing comprising a hollow sealed housing capable of being inserted in the well casing, said housing defining an expansion chamber, means for positioning said apparatus in a well, an explosive charge mounted within said housing and extending into said expansion chamber, said explosive charge having an outwardly-facing cavity lined with an inert material, a cover over said cavity, and means for detonating said explosive charge.

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