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(54) HYPER-PRESSURE PULSE EXCAVATOR

HYPERDRUCKPULSBAGGER

EXCAVATRICE À IMPULSIONS À HYPERPRESSION

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Description

BACKGROUND

1. Field of the Invention

[0001] The present invention relates to non-explosive mining techniques for mining operations.

2. Description of the Related Art

[0002] Non-explosive mining techniques offer an alternative to the increasing costs associated with explosive excavation. Explosive excavation is a cyclic process requiring several steps: blast holes are drilled into a rock face, explosive charges are loaded into the blast holes, the surrounding area is evacuated, the explosives are detonated, and the area is ventilated and cleared. Explosive excavation incurs significant costs associated with security and environmental damage, such as the generation of toxic gases.

[0003] Mechanized non-explosive mining may be carried out with fewer personnel and reduce the security and environmental costs of high explosives. This approach also increases processing efficiency by allowing selective mining of the ore veins. Mechanical impact hammers can be used to excavate hard rock, but the process is slow; the hammers and support equipment are very heavy and the impact tools wear out quickly.

[0004] Another example of mechanized non-explosive mining is an impact piston water cannon, in which compressed air drives a heavy piston that impacts and pushes a quantity, or slug, of water. The water slug impacts the rock face to cause erosion and excavation. While impact piston devices have been shown to generate high pressures, their use in commercial excavation work has been limited due to the significant wear on the pistons and cylinders of the devices. Further, the mechanical system that must be maneuvered at the rock face is prohibitively bulky.

[0005] As an alternative to an impact piston cannon, a compressed water cannon designed for hard rock mining is described in "A Hydraulic Pulse Generator for Non-Explosive Excavation," by Kolle, J. J., in Mining Engineering, July 1997, pg. 64-72. The compressed water cannon comprises a heavy pressure vessel charged to very high pressures (100-400 MPa, or 14,500-60,000 psi). At these pressures, the water is substantially compressed and stores a considerable amount of energy. After charging, the water is discharged through a fast-opening valve, which causes the resulting pulse of water to impact the rock face. Discharge of a 100 to 400 MPa pulse onto the face of hard rock will have little or no effect in rock fragmentation. To perform rock fragmentation, the compressed water cannon nozzle must be inserted and discharged into a pre-drilled blast hole. Discharge of the pulse into the blast hole generates tensile stresses in the rock and allows effective excavation. The productivity and flexibility of this approach, called bench blasting, is limited because drilling is the most time-consuming aspect of the operation.

[0006] As reported by Mauer, W. C. in Advanced Drilling Techniques, pg. 302-348, Petroleum Publishing Inc., 1980, hyper-pressure pulses that are over 1 GPa, or 145,000 psi, have been shown to efficiently excavate hard rock by cratering, eliminating the need for a pre-drilled blast hole. Accordingly, it would be desirable to enable a compressed water cannon to be employed without the need for a pre-drilled blast hole.

[0007] US4074858 discloses a high pressure pulsed water jet apparatus and process. The apparatus includes a high pressure pulsed water jet apparatus operable in a vertical, horizontal or angled position comprising: a cylindrical high pressure chamber having a nozzle in communication therewith at one end and a substantially watertight plug at the other end; a cylindrical low pressure chamber having one end adjacent said other end of said high pressure chamber and the other end of said low pressure chamber adapted for receiving in substantially watertight relation one end of a power piston rod providing the output of a thrust generator means having a substantially flat thrust pattern; a coupler piston coupled to said power piston rod adapted for substantially watertight reciprocal movement within said low pressure chamber; a cylindrical ram coupled to said coupler piston and having a liquid passage therethrough along its long axis adapted to reciprocate within said high pressure chamber and through said plug in substantially watertight relation, a check valve preventing intake of water to said passage at one end maintained within said high pressure chamber, the other end of said liquid passage in communication with the volume between said coupler piston and said other end of said low pressure chamber; and pressure means for maintaining liquid in said other end of said low pressure chamber.

SUMMARY OF THE INVENTION

[0008] In accordance with the present invention, the problems above are addressed with a hyper-pressure water cannon. Aspects of the present invention are recited by the appended independent claims.

[0009] The hyper-pressure water cannon, or pulse excavator, is able to discharge fluid pulses at extremely high velocities to fracture a rock face in excavation applications. A compressed water cannon can be used to generate hyper-pressure pulses by discharging the pulse into a straight nozzle section which leads to a convergent tapered nozzle. The water cannon design is relatively compact, and the pulse generator can readily be maneuvered to cover the face of an excavation as part of a mobile mining system. As an alternative, the pulse could be generated by a propellant gun.

[0010] Hyper-pressure pulse excavation, or cratering, is an application of the water cannon that eliminates the need for drilling a blast hole. The high-velocity water pulse is discharged into a combination straight and tapered nozzle that can amplify the peak pulse pressure by a factor of 10 or more.

BRIEF DESCRIPTION OF THE DRAWINGS

[0011] Various aspects and attendant advantages of one or more exemplary embodiments and modifications thereto will become more readily appreciated as the same becomes better understood by reference to the following detailed description, when taken in conjunction with the accompanying drawings, wherein:

FIG. 1A illustrates a cross-sectional schematic view of a complete hyper-pressure pulse excavator 100 including an electrical trigger, vent valve assembly 150, pressure vessel 110, and two-part nozzle assembly (120 and 132);

FIGS. 1B-1E illustrate the hyper-pressure pulse excavator 100 in various stages of preparing to fire a water pulse;

FIGS. 2A-2C illustrate exemplary measurements for various sizes of the hyper-pressure pulse excavator 100;

FIGS. 3A-3C show nozzle inlet pulse measurement charts based on a 230 MPa discharge from the exemplary embodiment shown in FIG. 2A;

FIG. 4 illustrates the process of unsteady flow acceleration of a water pulse through straight and tapered nozzle sections;

FIG. 5A-5C illustrate the hyper-pressure outlet pulse measurement charts; and

FIG. 5D shows a chart displaying an exemplary exponentially convergent tapered nozzle profile.

FIG. 5E shows a chart displaying the internal pressure profiles inside an exponentially tapered nozzle at three locations of the fluid pulse.

DETAILED DESCRIPTION

[0012] It is to be understood that the invention is not limited in its application to the details of construction and the arrangement of components set forth in the following description or illustrated in the drawings. The invention is capable of other embodiments and of being practiced or of being carried out in various ways. Also, it is to be understood that the phraseology and terminology used herein is for the purpose of description and should not be regarded as limiting. The use of "including," "comprising," or "having" and variations thereof herein is meant to encompass the items listed thereafter and equivalents thereof as well as additional items. Unless limited otherwise, the terms "connected," "coupled," and "mounted," and variations thereof herein are used broadly and encompass direct and indirect connections, couplings, and mountings. In addition, the terms "connected" and "coupled" and variations thereof are not restricted to physical or mechanical connections or couplings.

[0013] FIG. 1A illustrates a schematic of an exemplary hyper-pressure pulse excavator 100, shown after firing a water pulse. The pulse excavator 100 includes a pressure vessel 110 and a two-part nozzle assembly, which includes a straight nozzle section 120 and a tapered nozzle section 132 within a nozzle housing 130. The pressure vessel 110 includes a supply tube 112, a poppet sleeve 114, a sleeve port 116, and a poppet 118. When poppet 118 is closed, it sits against poppet seat 119 at the end of pressure vessel 110. When the poppet 118 is opened, or pushed away from the poppet seat 119, the poppet 118 and poppet seat 119 together act as a dump valve, and pressurized fluid in the pressure vessel 110 is discharged into the straight nozzle section 120. The junction of the pressure vessel 110 and the straight nozzle section 120 includes an opening connected to an air compressor 126 and a second opening connected to a metering pump 122 and a gel supply 124. The electrical subsystem of the pulse excavator 100 includes a push button switch 170, arm light 172, arm switch 174, relay switch 176, and the solenoid valve 180 (including battery power for the solenoid).

[0014] Fluids within the hyper-pressure pulse excavator 100 build to extremely high pressures and must be discharged very quickly to effectively crater rock. Additionally, an excavating tool such as the pulse excavator 100 should not be so unwieldy and large as to prevent moving the tool around the rock face. Off-the-shelf valve systems offering suitable performance in both size and speed for such operation are typically not available. Instead, as shown in FIG. 1A, a series, or system, of cascading valves leading to the pressure vessel 110 can be used. Each subsequent stage handles progressively larger volumes and pressures, and the final stage opens the poppet 118 in the pressure vessel 110. While FIG. 1A shows an exemplary series of cascading valves, different types and arrangements of valves may be used to operate the poppet 118 in the pressure vessel 110.

[0015] The series of cascading valves includes the solenoid valve 180, the hydraulic pump return valve 146, the pressurized water supply valve 184, and the vent valve assembly 150. In operation, the accumulator 140, return tank 142, and hydraulic pump 148, and isolator piston 144 serve to maintain a pressure on the vent valve assembly 150 until the solenoid valve 180 can open. In the discharged state after firing, the hydraulic pump return valve 146 is open, resulting in water pressure from pressurized water supply 182 moving the isolator piston 144 to its upper position. The hydraulic pump 148 is also shown with a return tank 142 and an accumulator 140. Additionally, the pressurized water supply valve 184 is open, and the solenoid valve 180 to the tank 178 is closed and unarmed. Additional details of the valve operation can be seen in U.S. Patent No. 5,000,516 to Kolle, entitled "Apparatus for rapidly generating pressure pulses for demolition of rock having reduced pressure head loss and component wear," issued March 19, 1991.

[0016] In a preferred embodiment of the invention, the pulse excavator 100 further includes a vent valve assembly 150. The vent valve assembly 150 includes a vent valve housing 158 with vent valve vents 160. Although the pressurized water supply valve 184 is open, the vent valve piston 156 in the vent valve housing 158 is not pressurized to a sufficient level to tightly hold the poppet 154 against its seat 152. The vent valve assembly 150 is connected to the supply tube 112 of the pressure vessel 110. An ultra-high pressure pump 162 with a water inlet 164 is also coupled to the vent valve assembly.

[0017] FIG. 1B shows the system ready to fire a water, or water-based, pulse. The fluid pulse may comprise water, or may comprise water with additives, or may comprise water with additives, the additives comprising salt or polymer. The pressurized water supply valve 184 is closed. The hydraulic pump return valve 146 of the hydraulic pump 148 is closed, and the hydraulic pump 148 has been actuated, pressurizing the top of the isolator piston 144 with oil, water, or another fluid. The other side of the isolator piston 144 contains water. When the top of the isolator piston 144 is pressurized, the left side of the vent valve piston 156 is pressurized, causing the vent valve piston 156 to push against and hold the vent valve poppet 154 against the vent valve poppet seat 152. The ultra-high pressure pump 162 is then actuated and used to charge the pressure vessel 110 through the supply tube 112 into the cavity between the poppet sleeve 114 and poppet 118 within the pressure vessel 110. This pressurization pushes the poppet 118 against its seat 119 at the outlet of the pressure vessel 110, closing the fluid path to the straight nozzle section 120. With the poppet 118 seated against the straight nozzle section 120, the sleeve port 116 is exposed, allowing water to flow into the pressure vessel 110 through the supply tube 112. As more water is pumped into the pressure vessel 110, the pressure within the pressure vessel 110 builds, typically to 100 to 400 MPa.

[0018] In parallel, the air compressor 126 may supply compressed air to the straight nozzle section 120. This helps to empty the straight nozzle section 120 and tapered nozzle section 132 of any residual water (for example, from the previous water pulse firing). In one embodiment, a small volume of a gelled fluid 125 such as agar, polyacrylamide, or bentonite gel may be metered using the metering pump 122 from into the straight nozzle section 120 immediately below the poppet seat 119. This precharges the straight nozzle section 120 with the gelled fluid 125, allowing the gelled fluid 125 to be on the leading edge of the fluid pulse when the pulse excavator 100 fires. This gelled fluid may also be weighted with a substance such as salt to increase its density. The arm switch 174 electrical circuit is then armed, the air valve of the air compressor 126 is closed, and the system 100 is ready to fire.

[0019] FIG. 1C illustrates the start of the firing sequence. The push button switch 170 is closed or depressed, causing the relay switch 176 to close and the solenoid valve 180 to open. As the solenoid valve 180 opens, the isolator piston 144 moves down at constant pressure. The opening time of the solenoid valve 180 is preferably very short, such as on the order of 100 milliseconds so, but there is a limit to the opening speed of solenoid valves. The isolator piston 144 and accumulator 140 assembly give the solenoid valve 180 time to open fully by maintaining pressure on the vent valve poppet 154 before the isolator piston 144 reaches the end of its travel. As soon as the isolator piston 144 reaches the end of its travel, the left side of the vent valve piston 156 is depressurized, and the ultra-high pressure on the face of the vent valve poppet 154 causes it to open.

[0020] FIG. 1D illustrates the continuation of the firing sequence, with the vent valve poppet 154 fully open. This depressurizes the water in the supply tube 112 and the volume of water in the cavity between the poppet 118 and poppet sleeve 114 in the pressure vessel 110. Because the section area of the poppet 118 is larger than the seal area of the poppet seat at the base of the straight nozzle section 120, a large force lifts the poppet 114 from its seat. The poppet 118 opens very quickly, acting like a fast-opening dump valve and discharging the compressed water from the body of the pressure vessel 110. Once the poppet 118 is open, the water contained in the pressure vessel 110 begins accelerating through the straight nozzle section 120. As mentioned above, if gel has been metered out into the straight nozzle section 120, the gel slug is also pushed by the accelerating water pulse. The gel slug and water slug are pushed through the straight nozzle section 120 as well as the nozzle housing 130, as shown in FIG. 1E. The nozzle housing 130 contains a tapered nozzle section 132, which tapers from the diameter of the opening of the straight nozzle section 120.

[0021] Due to the unsteady flow phenomenon, the gel and water slugs are extruded though the tapered nozzle section 132 at extremely high velocities. The process of unsteady flow acceleration is illustrated in FIG. 4. When a fluid pulse moving at uniform velocity, U_o, enters a tapered nozzle, the leading edge of the pulse accelerates (U_e), while the trailing edge of the pulse slows (U_b). The velocities can be calculated for a given nozzle profile based on the principles of continuity of momentum and volume. If no gel is used, then the water will be at the leading edge of the pulse. In a preferred embodiment of the invention, the tapered section 132 is exponential.

[0022] Due to the extreme pressures generated in employing this technique, nozzle wear and fatigue of the cannon body are concern for long-term operation. The tapered nozzle section 132 is preferably fabricated from a hard erosion-resistant material such as hardened steel or carbide. This material may be held by a nozzle housing 130 made of high strength steel. The two part construction of the tapered nozzle allows the use of hard, erosion-resistant materials that may have low tensile strength. Conversely, the tapered nozzle can be fabricated from one part if a sufficiently high strength steel is used.

[0023] FIGS. 2A-2C illustrate exemplary dimensional measurements for various sizes of the hyper-pressure pulse excavator 100. The productivity of hyper-pressure pulse excavation can be expressed in terms of specific energy, which is the ratio of the pulse energy to the volume of rock removed. Increasing the scale of the system increases efficiency substantially, since the specific energy required for breaking is inversely proportional to the rock fragment size. As described above, impact piston cannons provide a means of generating hyper-pressure pulses, but the mechanism for these devices is very bulky and generates large reaction forces. Further, as also described above, their use in commercial excavation work has been limited due to the significant wear on the pistons and cylinders of the devices. The compressed water cannon as described herein can provide the similar pressure levels more efficiently. As described above, the pulse excavator 100 uses the system of cascaded valves to build to sufficient pressure levels. In a smaller embodiment, such as the one seen in FIG. 2A, alternate valve systems, such as a hand valve or a large solenoid valve, may be used. This may allow the pulse excavator 110 to be operated with a single- or dual-level valve system. For larger embodiments, such as the ones seen in FIGS. 2B and 2C, single- or dual-level valve systems will likely not provide the performance required for operation. Additionally, the cascaded valve system allows for smaller valves to be used at the various stages, further allowing for the use of smaller batteries to actuate the solenoid valve 180.

[0024] The specifications for the exemplary embodiment shown in FIG. 2A of the compressed water cannon for use in hyper-pressure pulse excavation are as follows:

- 1.8-liter internal volume;
- 15 kJ @ 240-MPa charge pressure; and
- 12.7-mm-diameter discharge nozzle.

[0025] The operating pressure of the pressure vessel 110 alone is limited by practical considerations to 100-400 MPa (14,500-60,000 psi). However, the pressure required to effectively break harder rock requires fluid pulses with stagnation pressures above 2 GPa (300,000 psi). As mentioned above, the straight nozzle section 120 and tapered nozzle section 132 are used to amplify the velocities of fluid pulses to achieve the stagnation pressures required to effectively break rock. The diameter of the straight nozzle section 120 may be equal to the diameter of the discharge valve of the pressure vessel 110. The diameter of the straight nozzle section 120 is smaller than the diameter of the pressure vessel 110 bore-typically, around 20% to 30% of the bore is preferred, though the range could be 10% to 50%.

[0026] The length of the straight nozzle section 120 is determined by observing the discharge characteristics of the pressure vessel 110 without the nozzle section attached. FIG. 3A shows the observed stagnation pressure from a water pulse discharged from the exemplary embodiment shown in FIG. 2A (without the attached nozzle) when the pressure vessel 110 is charged to 230 MPa versus time. Note that the peak stagnation pressure is substantially less than the charge pressure of 230 MPa. Further, the rise time of the pressure release is very fast, on the order of 1-2 ms. The fast rise time is facilitated by the presence of the fast-opening dump valve, such as the poppet valve 118. FIG. 3B shows the velocity of the pulse as a function of pulse length as calculated from the stagnation pressure profile. A uniform-velocity slug of water is needed to generate a hyper-pressure pulse in a tapered nozzle section 132. In practice, the velocity of water exiting the cannon valve varies continuously, however a pulse of about 0.5 m length with a velocity of over 500 m/s is generated. The kinetic energy of the pulse rises linearly up to around 0.5 m and then increases at a lower rate. The velocity is slow as the valve opens, peaks after the valve is opened, and then drops as the cannon decompresses. A straight nozzle section 120 accumulates the water in the leading edge of the pulse and allows the higher-velocity fluid to catch up, forming a uniform-velocity slug. Once the slug velocity starts to drop, the slug will stretch and break up.

[0027] Based on a measurement of the discharge pressure of the pressure vessel 110 at 230 MPa, the velocity of the water pulse can be measured against the length of the pulse. To reach efficiencies, pulse velocity and length should be maximized. For the pressure vessel 110 of the exemplary embodiment shown in FIG. 2A, a pulse length of 0.5 meters was chosen based on the chart shown in FIG. 3B. The point representing the pulse length of 0.5 meters in FIG. 3B was selected as maximizing both pulse velocity and length because the pulse velocity begins to decrease more substantially after the pulse length of 0.5 meters. Accordingly, the length of the straight nozzle section 120 was set at 0.5 meters. The final volume of the straight nozzle section 120 may be preferably between 2-10% of the volume of the pressure vessel 110.

[0028] Given a 20 inch long (i.e., roughly 0.5 meter) slug with a diameter of 1.3cm (0.5 inch), the tapered nozzle parameters may be determined. As mentioned above, the tapered nozzle section 132 accelerates the leading edge of the pulse to hyper velocity through unsteady flow dynamics. Given a convergent tapered nozzle 132 with an arbitrary profile, it is possible to calculate the velocity of the slug of water everywhere as the slug is extruded though the taper by solving the equations for continuity of volume and momentum. This may be determined using a numerical simulation of these continuity equations for various nozzle profiles. The internal pressure along the length of the nozzle can also be calculated from the local acceleration. The details of this calculation are described in Glenn, Lewis A. (1974) "On the dynamics of Hypervelocity liquid jet impact on a flat rigid surface," Journal of Applied Mathematics and Physics (ZAMP), vol. 25.

[0029] A numerical analysis indicates that the exemplary compressed water cannon tool from FIG. 2A can produce a compressed water pulse that is 300-mm in length, traveling at a velocity of about 520 m/s, as shown FIG. 5A. The theoretical profile agrees reasonably well with the observed profile shown in FIG. 3B. The theoretical velocities of the leading and trailing edges (shown as U_e and U_b, respectively) of this water slug as it moves through the tapered nozzle are shown in Figure 5B. The leading edge accelerates to over 2000 m/s, while the trailing edge decelerates. The peak velocity drops rapidly, to under 1000 m/s after 200 μsec. In this time the leading edge of the pulse will travel 0.4 m (16 in.). The nozzle should be located at a fraction of this distance from the target to maximize effectiveness. The velocity profiles may be calculated by assuming that the water is an incompressible fluid, although water is compressible at such velocities. The peak velocity of the discharged jet may be limited by the speed of sound in water (around 1500 m/s), which may limit the peak velocities to values lower than those shown in Figure 5B. The compressed water pulse will convert to a 2-GPa pressure spike in a 150-mm-long convergent tapered nozzle, as shown in FIG. 5B, with 80% energy conversion above 1 GPa, as shown in FIG. 5C.

[0030] An example of the internal pressure profiles inside an exponentially tapered nozzle at three locations of the pulse is provided in FIG. 5E. The internal pressure builds as the pulse enters the tapered section. The peak pressure occurs at the moment that the pulse reaches the exit of the nozzle. The peak internal pressure is less than 1 GPa (145,000 psi) which is within the capacity of the nozzle materials available. In a preferred embodiment of the invention, the nozzle comprises a carbide inner section that is pressed into a sleeve to provide a preload on the carbide. Those skilled in the art will understand that a composite nozzle of this type provides higher internal pressure capacity than a monobloc nozzle.

[0031] The cross-sectional area of the tapered nozzle section 132 is denoted as A(x), and it decreases exponentially along the length of the tapered nozzle section 132, which is denoted as *x*. The relationship between the length and cross-sectional area of the tapered nozzle section 132 is shown according to the following exponential equation:

$$A(x) = A_i \exp\left(\frac{-x\ln(R)}{l_t}\right)$$

In this equation, R is the inlet/outlet area ratio; and l_t is the total length of the tapered nozzle section 132. An example of a nozzle profile is as shown in FIG. 5D, which is derived from the data in the following Table 1.

	Length, cm (in.)	Diameter, cm (in.)
Straight	51 (20)	1.27 (0.500)
Taper	0 (0)	1.27 (0.500)
	5 (2)	1.09 (0.429)
	10 (4)	0.937 (0.369)
	15 (6)	0.803 (0.316)
	20 (8)	0.691 (0.272)
	25 (10)	0.592 (0.233)
	31 (12)	0.508 (0.200)

[0032] An exponential tapering is used for the tapered nozzle section 132, as opposed to a linear tapering, to prevent the tapered section from being blown off from the pressure release during a firing. An external nut may be used to clamp the tapered nozzle section 132 to the straight nozzle section 120. This nut may be attached with a torque of about 3000 Nm (2000 ft-lbf). Based on the configuration of the straight nozzle section 120 and tapered nozzle section 132, a water cannon may be converted into the hyper-pressure water cannon 100 suitable for use in excavation applications.

The pressurized fluid in the pressure vessel 110 may be charged to a pressure between 100 MPa to 400 MPa.

The diameter of the straight section 120 may be equal to the inlet diameter of the convergent tapered section 132.

The length of the convergent tapered section 132 may be 30% to 200% of the length of the straight section 120.

The outlet diameter of the convergent tapered section 132 may be 10% to 50% of the diameter of the inlet diameter of the convergent tapered section 132.

The diameter of a taper profile of the convergent tapered section 132 may decrease exponentially across the length of the convergent tapered section 132. The present method of producing a fluid jet pulse with discharge velocity of 1 to 2 km/s, may comprise precharging the elongated straight nozzle section 120 with a gelled fluid.

In the present method of producing a fluid jet pulse with discharge velocity of 1 to 2 km/s, the dump valve 118,119 may be opened within 20 ms.

[0033] Although the concepts disclosed herein have been described in connection with the preferred form of practicing them and modifications thereto, those of ordinary skill in the art will understand that many other modifications can be made thereto. Accordingly, it is not intended that the scope of these concepts in any way be limited by the above description.

Claims

1. A hyper-pressure water cannon system (100) for producing a fluid pulse comprising:

   a pressure vessel (110) configured to couple to a source (164) of pressurized fluid, the pressure vessel (110) comprising a dump valve (118,119); and
   a nozzle (120,132) comprising a straight section (120) and a convergent tapered section (132), the nozzle (120,132) coupled to the pressure vessel (110) after the dump valve (118,119),
   wherein pressurized fluid discharged from the pressure vessel (110) by the dump valve (118,119) increases in velocity as it travels through the nozzle (120,132), wherein the internal volume of the straight section (120) is between 2% to 10% of the internal volume of the pressure vessel (110).

2. The hyper-pressure water cannon (100) of claim 1, wherein the fluid pulse comprises one of: water, water with additives, and water with additives comprising salt or polymer.

3. The hyper-pressure water cannon (100) of claim 1, further comprising:

   a compressor (126) coupled to the base of the nozzle (120,132),
   wherein the compressor (126) discharges air into the nozzle (120,132) after the pressurized fluid travels through the nozzle (120,132).

4. The hyper-pressure water cannon (100) of claim 1, further comprising:

   a metering pump (122) coupled to the base of the nozzle (120,132),
   wherein the metering pump (122) discharges a metered supply of gelled fluid into the nozzle (120,132).

5. The hyper-pressure water cannon (100) of claim 1, wherein:
   the diameter of a taper profile of the convergent tapered section (132) decreases exponentially across the length of the convergent tapered section (132).

6. The hyper-pressure water cannon (100) of claim 1, wherein the cross-sectional area of the taper profile is derived from the equation:

$$A(x) = A_i \exp\left(\frac{-x \ln(R)}{l_t}\right)$$

   wherein A(x) is the area of the cross-section of the taper profile at a given length x,
   wherein l_t is the total length of the convergent tapered section of the nozzle,
   wherein R is the ratio of the inlet area of the convergent tapered section to the outlet are of the convergent tapered section.

7. The hyper-pressure water cannon (100) of claim 1, wherein the diameter of a taper profile is modeled based on a series of linear approximations to an exponential equation with an asymptote at the outlet of the convergent tapered section (132).

8. The hyper-pressure water cannon (100) of claim 1, wherein the dump valve (118,119) is a piloted poppet valve (118,119).

9. The hyper-pressure water cannon (100) of claim 8, wherein the piloted poppet valve (118,119) is opened through a series of cascading valves by a solenoid valve (180).

10. The hyper-pressure water cannon (100) of claim 9, wherein the piloted poppet valve (118,119) is coupled to an accumulator.

11. A method of producing a fluid jet pulse with discharge velocity of 1 to 2 km/s, comprising:

   charging a pressure vessel (110) to 100 to 400 MPa with a water-based fluid;
   releasing the water-based fluid though a discharge passage with a dump valve (118,119);
   directing the flow of the water-based fluid into an elongated straight nozzle section (120); and
   directing the flow of the water-based fluid into an elongated convergent tapered section (132), wherein the internal volume of the straight section (120) is between 2% to 10% of the internal volume of the pressure vessel (110).

12. The method of claim 11, further comprising:
   purging the elongated straight nozzle section (120) and the elongated convergent tapered nozzle section (132) by introducing compressed air at the inlet of the elongated straight nozzle section (120).

13. The method of claim 11, further comprising:
   excavating a rock surface by directing the water-based fluid at the rock surface.

14. The method of claim 13, wherein the nozzle exit is located at a range of zero to ten times the diameter of the nozzle exit from the rock face.

15. The method of claim 11, wherein:
   the dump valve (118,119) is opened through a series

of cascading valves by a solenoid valve (180).

Patentansprüche

1. Hyperdruckwasserkanonensystem (100) zur Erzeugung eines Flüssigkeitspulses, umfassend:

   einen Druckbehälter (110), der dafür konfiguriert ist, mit einer Quelle (164) von Druckflüssigkeit verbunden zu werden, wobei der Druckbehälter (110) ein Ablassventil (118, 119) umfasst; und
   eine Düse (120, 132) umfassend einen geraden Abschnitt (120) und einen sich kegelförmig verjüngenden Abschnitt (132), wobei die Düse (120, 132) mit dem Druckbehälter (110) nach dem Ablassventil (118, 119) verbunden ist,
   worin Druckflüssigkeit, die aus dem Druckbehälter (110) vom Ablassventil (118, 119) ausgetragen wird, an Geschwindigkeit gewinnt, während sie sich durch die Düse (120, 132) bewegt,
   worin das Innenvolumen des geraden Abschnitts (120) zwischen 2 % bis 10 % des Innenvolumens des Druckbehälters (110) beträgt.

2. Hyperdruckwasserkanone (100) nach Anspruch 1, worin der Flüssigkeitspuls eines von folgenden umfasst: Wasser, Wasser mit Additiven und Wasser mit Additiven umfassend Salz oder Polymer.

3. Hyperdruckwasserkanone (100) nach Anspruch 1, ferner umfassend:

   einen Kompressor (126), der mit der Basis der Düse (120, 132) verbunden ist,
   worin der Kompressor (126) Luft in die Düse (120, 132) austrägt, nachdem sich die Druckflüssigkeit durch die Düse (120, 132) bewegt.

4. Hyperdruckwasserkanone (100) nach Anspruch 1, ferner umfassend:

   eine Dosierpumpe (122), die mit der Basis der Düse (120, 132) verbunden ist,
   worin die Dosierpumpe (122) eine dosierte Zufuhr von gelierter Flüssigkeit in die Düse (120, 132) austrägt.

5. Hyperdruckwasserkanone (100) nach Anspruch 1, worin:
   der Durchmesser eines Kegelprofils des sich kegelförmig verjüngenden Abschnitts (132) über die Länge des sich kegelförmig verjüngenden Abschnitts (132) exponentiell abnimmt.

6. Hyperdruckwasserkanone (100) nach Anspruch 1, worin sich die Querschnittsfläche des Kegelprofils aus der folgenden Gleichung ableitet:

$$A(x) = A_i \exp\left(\frac{-x\ln(R)}{l_t}\right)$$

   worin *A(x)* die Fläche des Querschnitts des Kegelprofils bei einer gegebenen Länge x ist,
   worin l_t die Gesamtlänge des sich kegelförmig verjüngenden Abschnitts der Düse ist,
   worin *R* das Verhältnis der Einlassfläche des sich kegelförmig verjüngenden Abschnitts zur Auslassfläche des sich kegelförmig verjüngenden Abschnitts ist.

7. Hyperdruckwasserkanone (100) nach Anspruch 1, worin der Durchmesser eines Kegelprofils auf Basis einer Reihe von linearen Annäherungen an eine Exponentialgleichung mit einer Asymptoten am Auslass des sich kegelförmig verjüngenden Abschnitts (132) modelliert wird.

8. Hyperdruckwasserkanone (100) nach Anspruch 1, worin das Ablassventil (118, 119) ein vorgesteuertes Tellerventil (118, 119) ist.

9. Hyperdruckwasserkanone (100) nach Anspruch 8, worin das vorgesteuerte Tellerventil (118, 119) durch eine Reihe von Kaskadenventilen von einem Magnetventil (180) geöffnet wird.

10. Hyperdruckwasserkanone (100) nach Anspruch 9, worin das vorgesteuerte Tellerventil (118, 119) mit einem Speicher verbunden ist.

11. Verfahren zum Erzeugen eines Flüssigkeitsstrahlpulses mit einer Austragsgeschwindigkeit von 1 bis 2 km/s, umfassend:

    Füllen eines Druckbehälters (110) auf 100 bis 400 MPa mit einer wasserbasierten Flüssigkeit;
    Abgeben der wasserbasierten Flüssigkeit durch einen Austragskanal mit einem Ablassventil (118, 119);
    Richten des Flusses der wasserbasierten Flüssigkeit in einen länglichen geraden Düsenabschnitt (120); und
    Richten des Flusses der wasserbasierten Flüssigkeit in einen länglichen sich kegelförmig verjüngenden Abschnitt (132), worin das Innenvolumen des geraden Abschnitts (120) zwischen 2 % bis 10 % des Innenvolumens des Druckbehälters (110) beträgt.

12. Verfahren nach Anspruch 11, ferner umfassend: Ausblasen des länglichen geraden Düsenabschnitts (120) und des länglichen sich kegelförmig verjüngenden Düsenabschnitts (132) durch Einführen von Druckluft am Einlass des länglichen geraden Düsenabschnitts (120).

13. Verfahren nach Anspruch 11, ferner umfassend: Ausheben einer Gesteinsoberfläche durch Richten der wasserbasierten Flüssigkeit auf die Gesteinsoberfläche.

14. Verfahren nach Anspruch 13, worin sich der Düsenaustritt in einem Bereich vom null- bis zehnfachen Durchmesser des Düsenaustritts von der Gesteinsoberfläche befindet.

15. Verfahren nach Anspruch 11, worin: das Ablassventil (118, 119) durch eine Reihe von Kaskadenventilen von einem Magnetventil (180) geöffnet wird.

Revendications

1. Un système de canon à eau à hyperpression (100) destiné à produire une impulsion de fluide comprenant :

un récipient sous pression (110) configuré pour s'accoupler à une source (164) de fluide sous pression, le récipient sous pression (110) comprenant une vanne de décharge (118, 119) ; et une buse (120, 132) comprenant une section rectiligne (120) et une section effilée convergente (132), la buse (120, 132) étant accouplée au récipient sous pression (110) après la vanne de décharge (118, 119),
dans lequel le fluide sous pression déchargé du récipient sous pression (110) par la vanne de décharge (118, 119) augmente en vitesse à mesure qu'il circule à travers la buse (120, 132), dans lequel le volume interne de la section rectiligne (120) est compris entre 2% et 10% du volume interne du récipient sous pression (110).

2. Le canon à eau à hyperpression (100) selon la revendication 1, dans lequel l'impulsion de fluide comprend : soit de l'eau, soit de l'eau avec des additifs, soit de l'eau avec des additifs comprenant un sel ou un polymère.

3. Le canon à eau à hyperpression (100) selon la revendication 1, comprenant en outre :

un compresseur (126) accouplé à la base de la buse (120,132),
dans lequel le compresseur (126) décharge de l'air dans la buse (120,132) après que le fluide sous pression a circulé à travers la buse (120,132).

4. Le canon à eau à hyperpression (100) selon la revendication 1, comprenant en outre :

une pompe de dosage (122) accouplée à la base de la buse (120,132),
dans lequel la pompe de dosage (122) décharge une quantité mesurée de fluide gélifié dans la buse (120, 132).

5. Le canon à eau à hyperpression (100) selon la revendication 1, dans lequel :

le diamètre d'un profil effilé de la section effilée convergente (132) diminue exponentiellement sur toute la longueur de la section effilée convergente (132).

6. Le canon à eau à hyperpression (100) selon la revendication 1, dans lequel l'aire de section transversale du profil effilé est dérivée de l'équation :

$$A(x) = A_i \exp\left(\frac{-x \ln(R)}{l_t}\right)$$

où *A(x)* est l'aire de la section transversale du profil effilé à une longueur donnée x,
où l_t est la longueur totale de la section effilée convergente de la buse,
où *R* est le rapport de l'aire d'entrée de la section effilée convergente à l'aire de sortie de la section effilée convergente.

7. Le canon à eau à hyperpression (100) selon la revendication 1, dans lequel le diamètre d'un profil effilé est modélisé sur la base d'une série d'approximations linéaires r selon une équation exponentielle avec une asymptote à la sortie de la section effilée convergente (132).

8. Le canon à eau à hyperpression (100) selon la revendication 1, dans lequel la vanne de décharge est une soupape champignon pilotée (118, 119).

9. Le canon à eau à hyperpression (100) selon la revendication 8, dans lequel la soupape champignon pilotée (118, 119) est ouverte par le biais d'une série de soupapes en cascade par une électrovanne (180).

10. Le canon à eau à hyperpression (100) selon la revendication 9, dans lequel la soupape champignon pilotée (118, 119) est accouplée à un accumulateur.

11. Un procédé de production d'une impulsion de jet de fluide avec une vitesse de décharge comprise entre 1 et 2 km/s, consistant à :

charger un récipient sous pression (110) à entre 100 et 400 MPa avec un fluide à base d'eau ;
décharger le fluide à base d'eau par le biais d'un

passage de décharge avec une vanne de décharge (118, 119) ;
diriger l'écoulement du fluide à base d'eau dans une section de buse rectiligne allongée (120) ; et
diriger l'écoulement du fluide à base d'eau dans une section effilée convergente allongée (132),
dans lequel le volume interne de la section rectiligne (120) est compris entre 2% et 10% du volume interne du récipient sous pression (110).

12. Le procédé selon la revendication 11, consistant en outre à :
purger la section de buse rectiligne allongée (120) et la section de buse effilée allongée (132) en introduisant de l'air comprimé à l'entrée de la section de buse rectiligne allongée (120).

13. Le procédé selon la revendication 11, consistant en outre à :
creuser une surface rocheuse en dirigeant le fluide à base d'eau vers la surface rocheuse.

14. Le procédé selon la revendication 13, dans lequel la sortie de buse est située dans une plage comprise entre zéro et dix fois le diamètre de la sortie de buse, de la face rocheuse.

15. Le procédé selon la revendication 11, dans lequel : la vanne de décharge (118, 119) est ouverte par le biais d'une série de soupapes en cascade par une électrovanne (180).

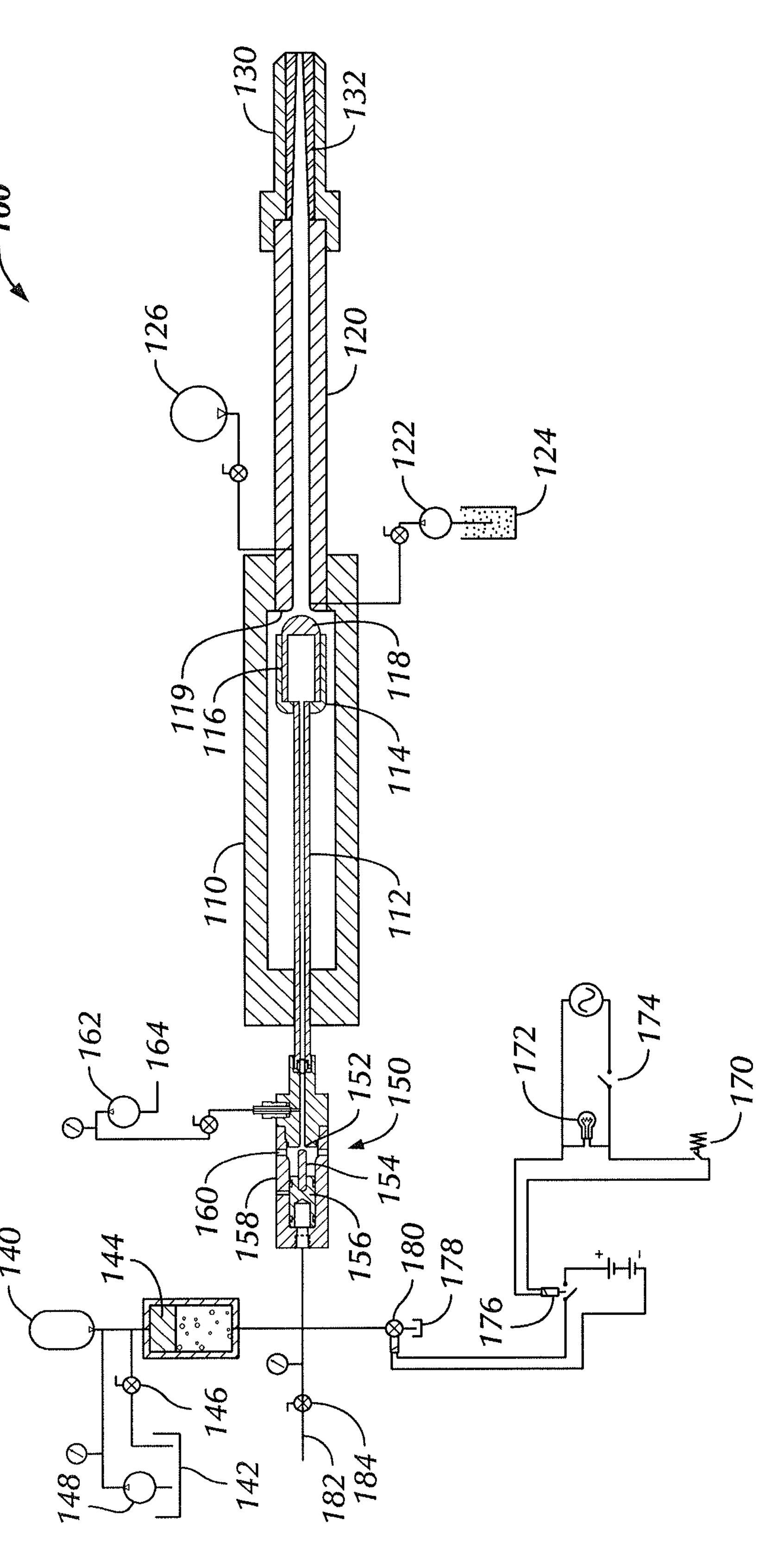

100
130
132
126
120
122
124
119
116
118
114
110
112
162
164
152
150
160
154
158
156
172
174
170
140
144
180
178
176
146
142
148
182
184

FIG 1A

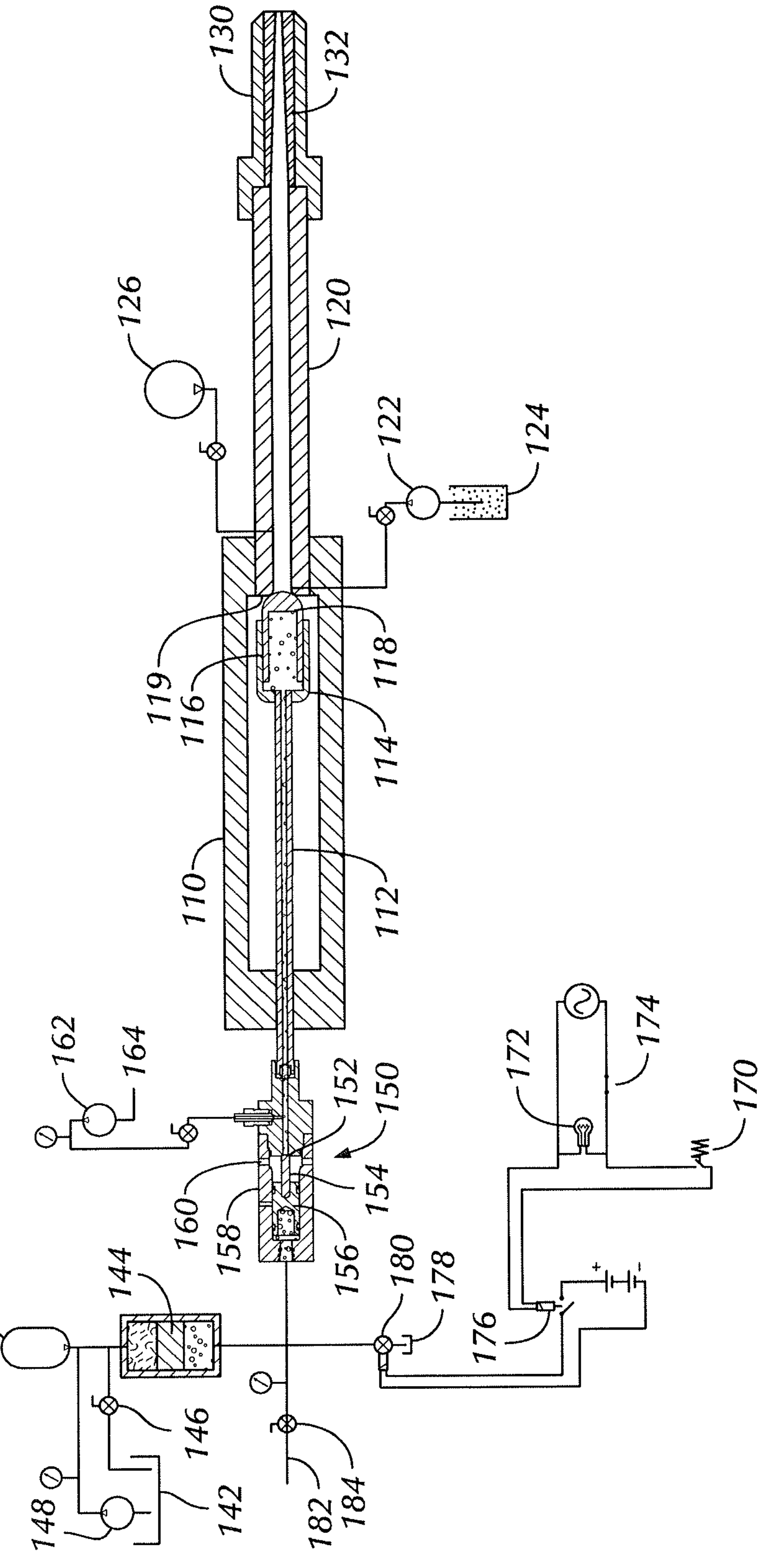

100
130
132
126
120
122
124
119
116
118
114
110
112
162
164
152
150
160
154
158
156
140
144
180
178
176
172
174
170
146
142
148
182
184

FIG 1B

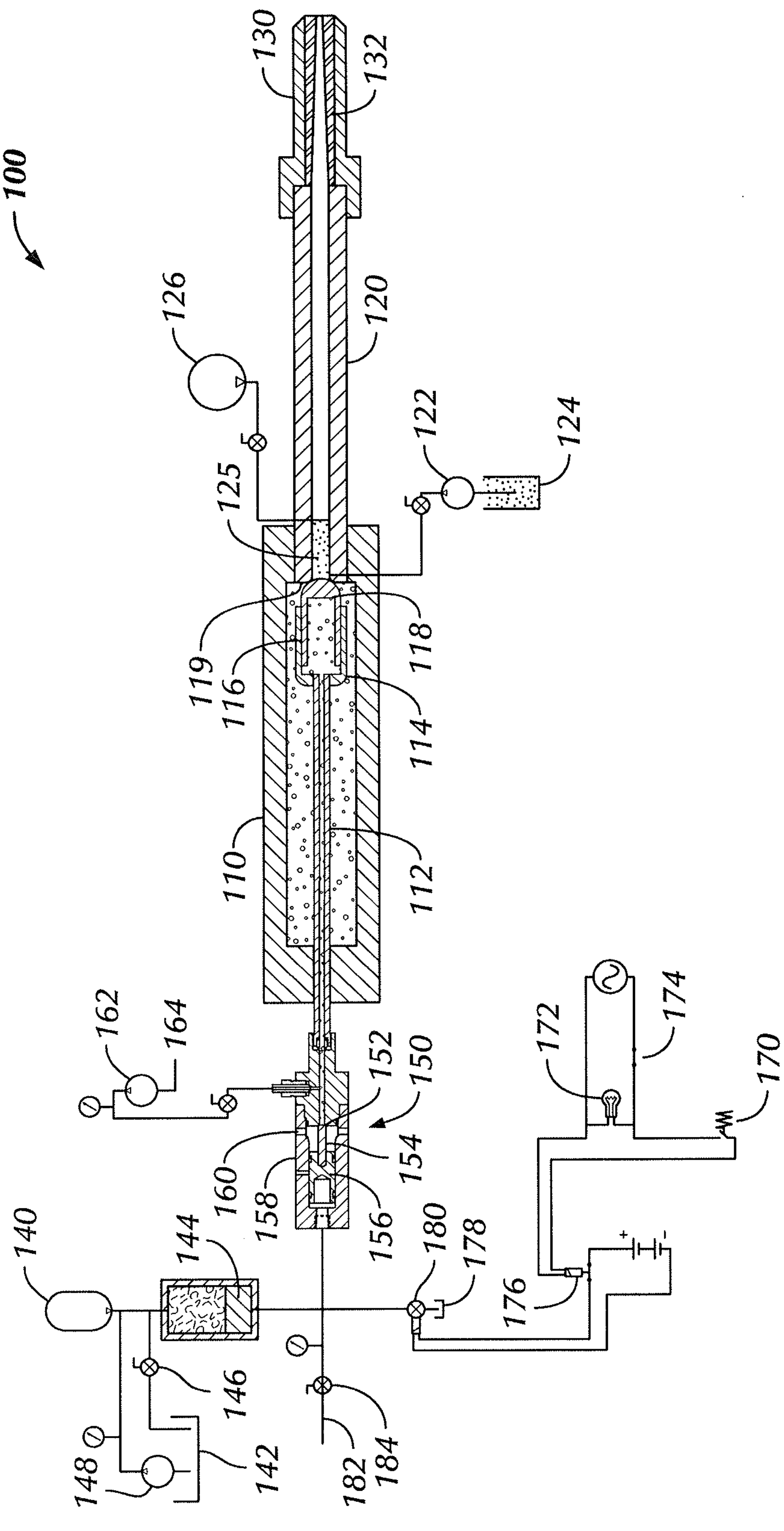

100
130
132
126
120
125
122
124
119
116
118
114
110
112
162
164
152
150
160
154
158
156
172
174
170
140
144
180
178
176
146
148
142
182
184

FIG 1C

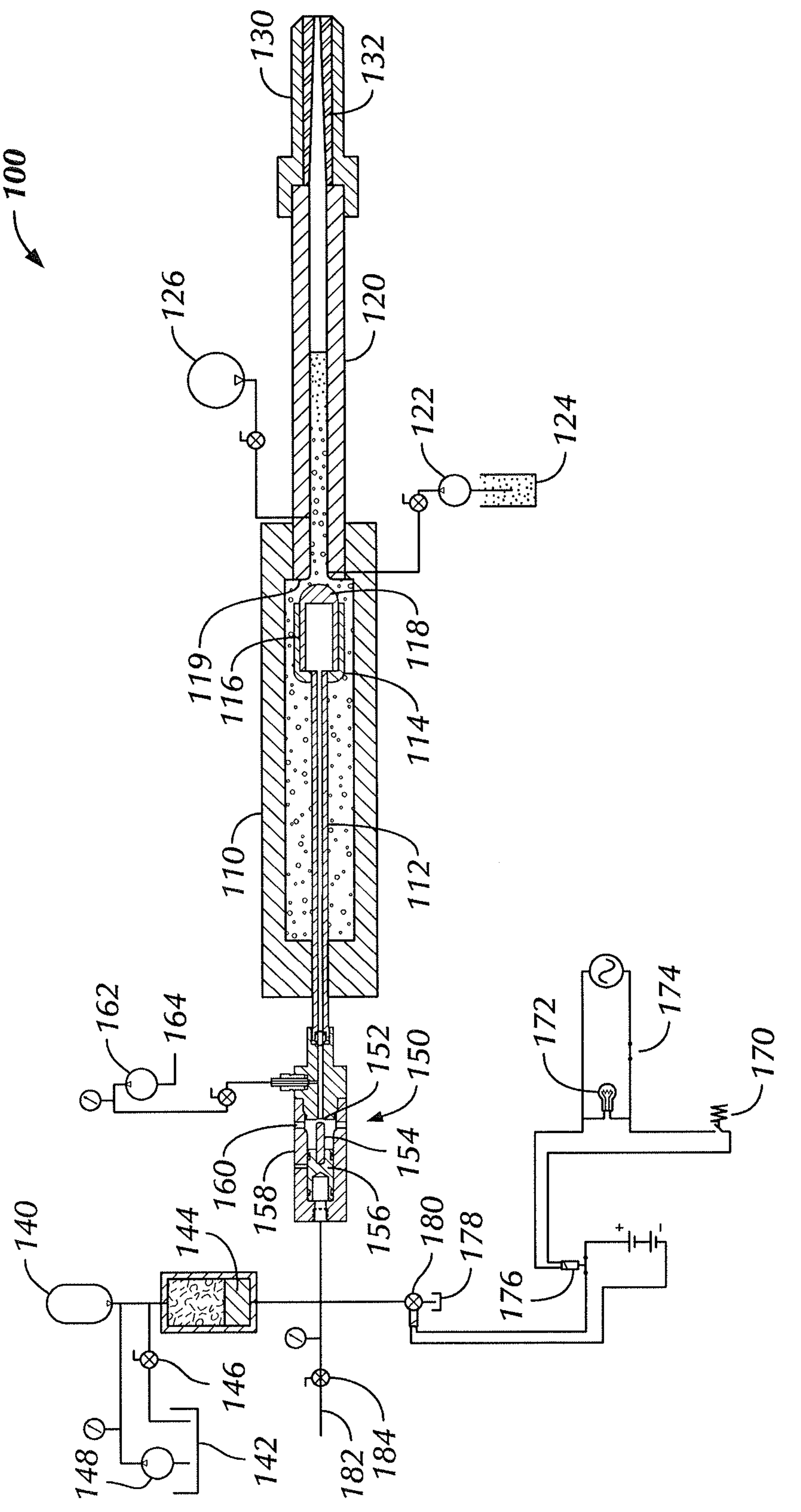

100
130
132
126
120
122
124
119
116
118
114
110
112
162
164
172
174
152
150
170
160
154
158
156
140
144
180
178
176
146
142
148
182
184

FIG 1D

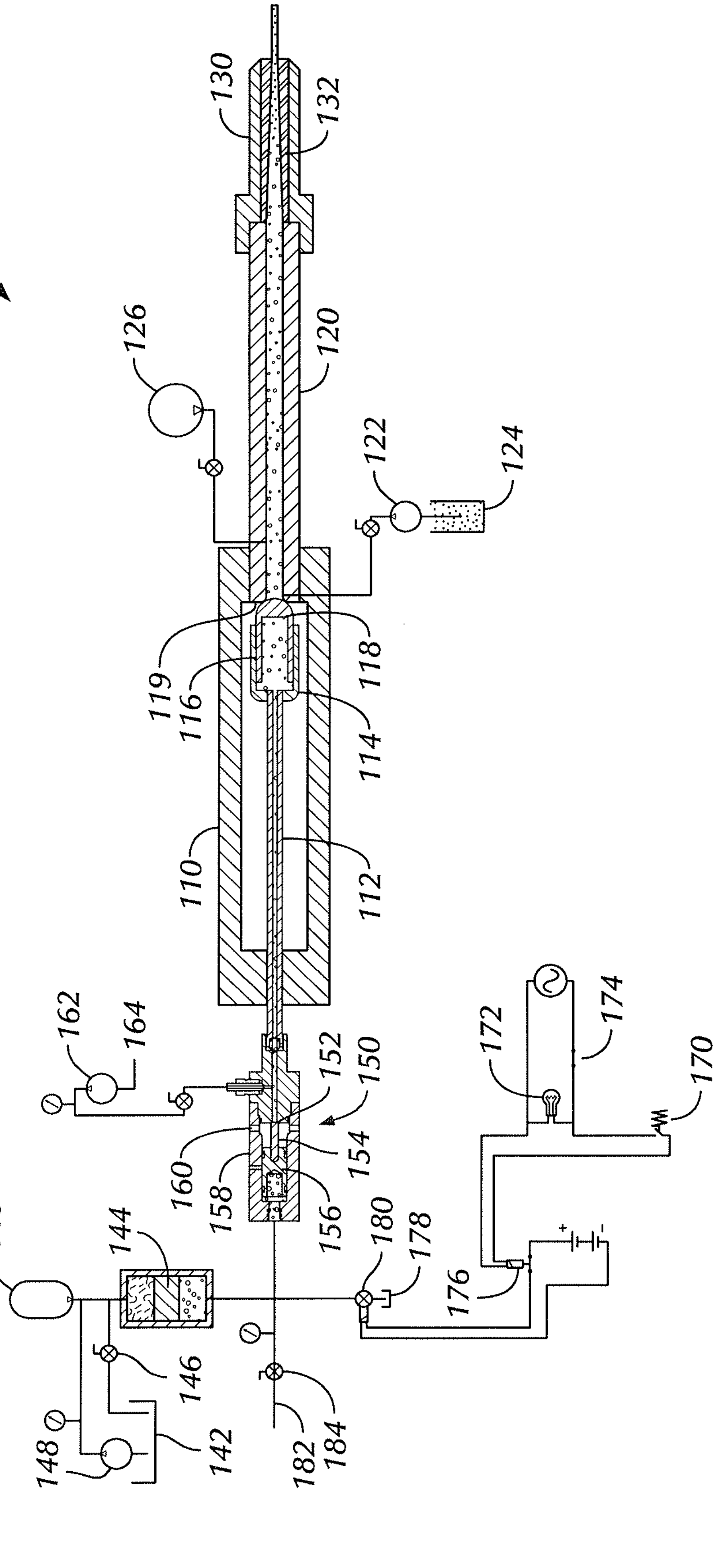

100
130
132
126
120
122
124
119
116
118
114
110
112
162
164
172
174
152
150
170
160
154
158
140
144
156
180
178
176
146
142
148
182
184

FIG 1E

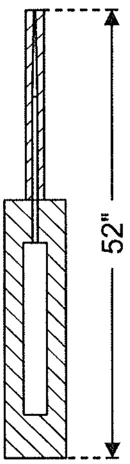


FIG. 2A

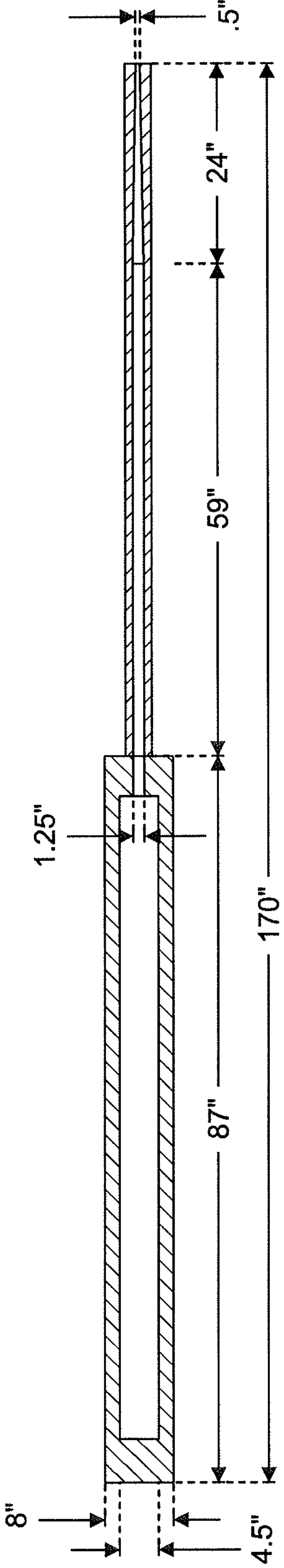


FIG. 2B

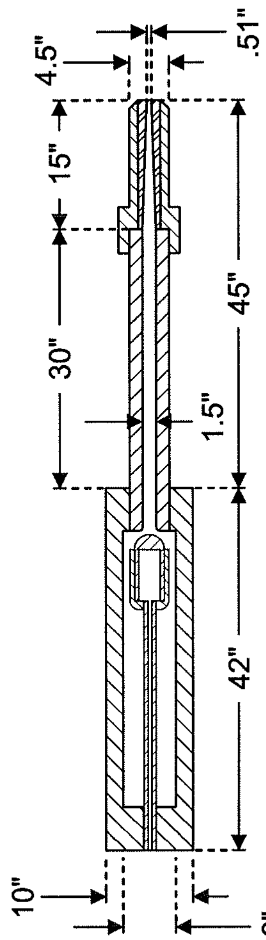
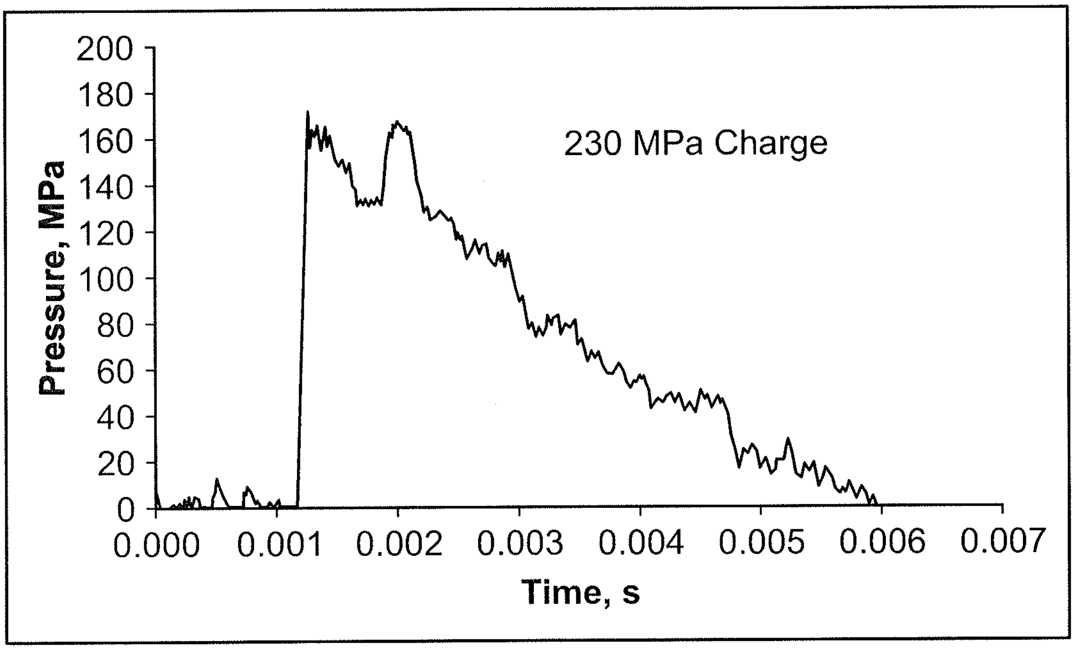
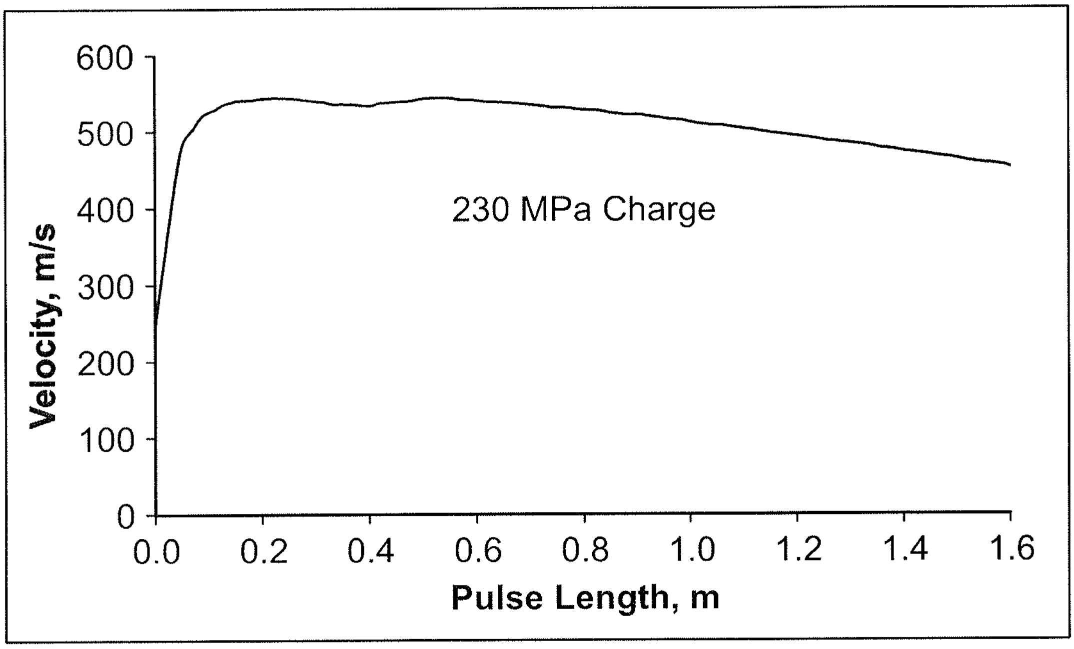


FIG. 2C



200
180
160
140
120
100
80
60
40
20
0
Pressure, MPa
230 MPa Charge
0.000
0.001
0.002
0.003
0.004
0.005
0.006
0.007
Time, s

FIG. 3A



600
500
400
300
200
100
0
Velocity, m/s
230 MPa Charge
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
Pulse Length, m

FIG. 3B

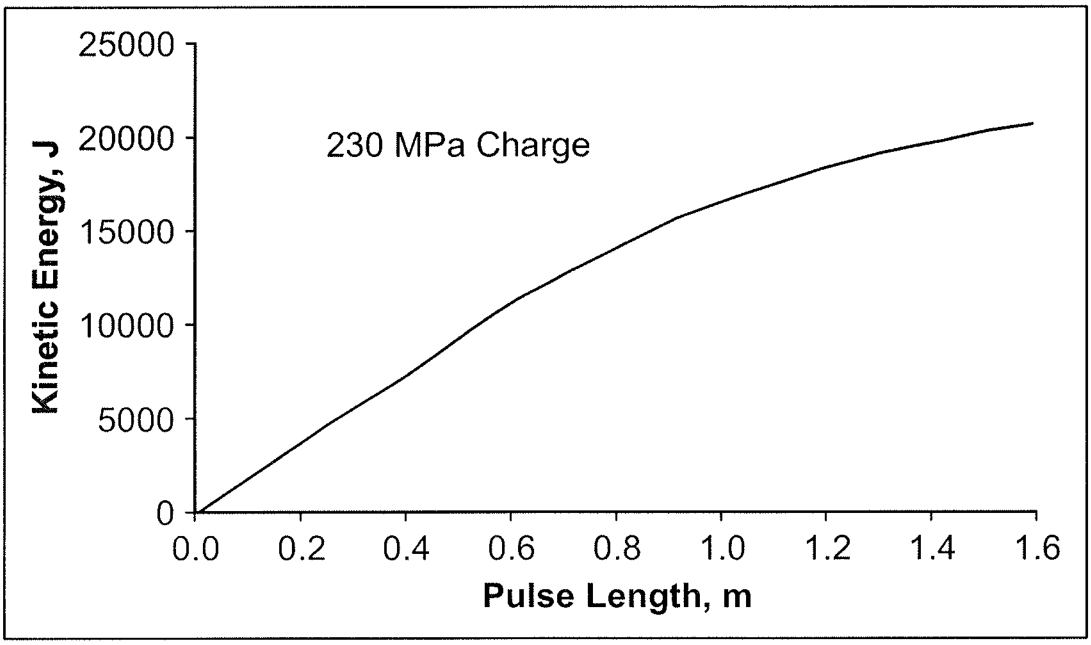

230 MPa Charge
Kinetic Energy, J
25000
20000
15000
10000
5000
0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
Pulse Length, m

FIG. 3C

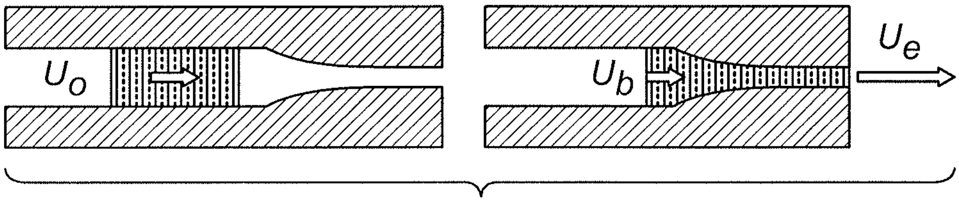

U_o
U_b
U_e

FIG. 4

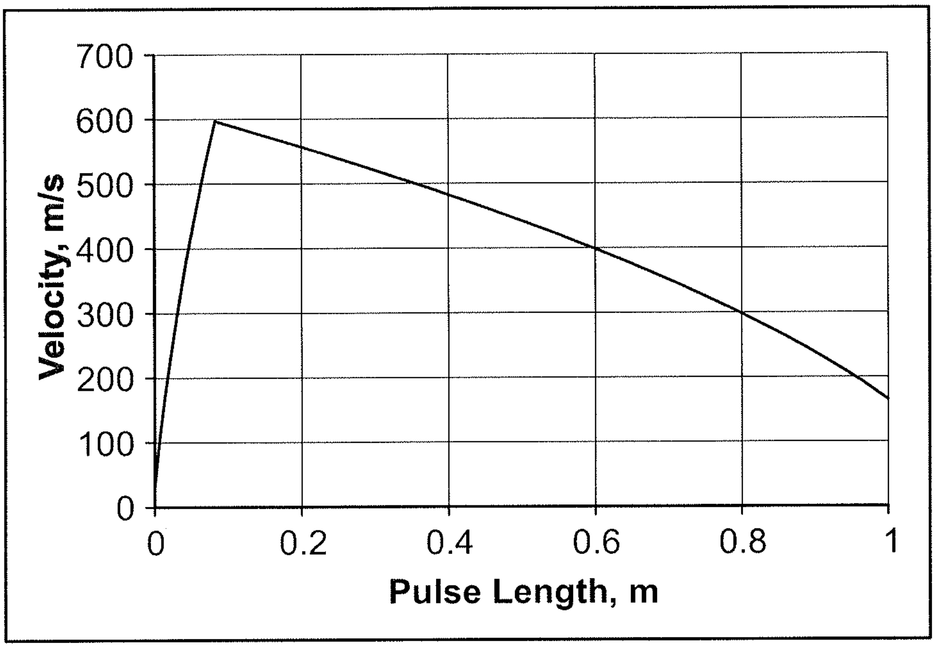

700
600
500
400
300
200
100
0
Velocity, m/s
0
0.2
0.4
0.6
0.8
1
Pulse Length, m

FIG. 5A

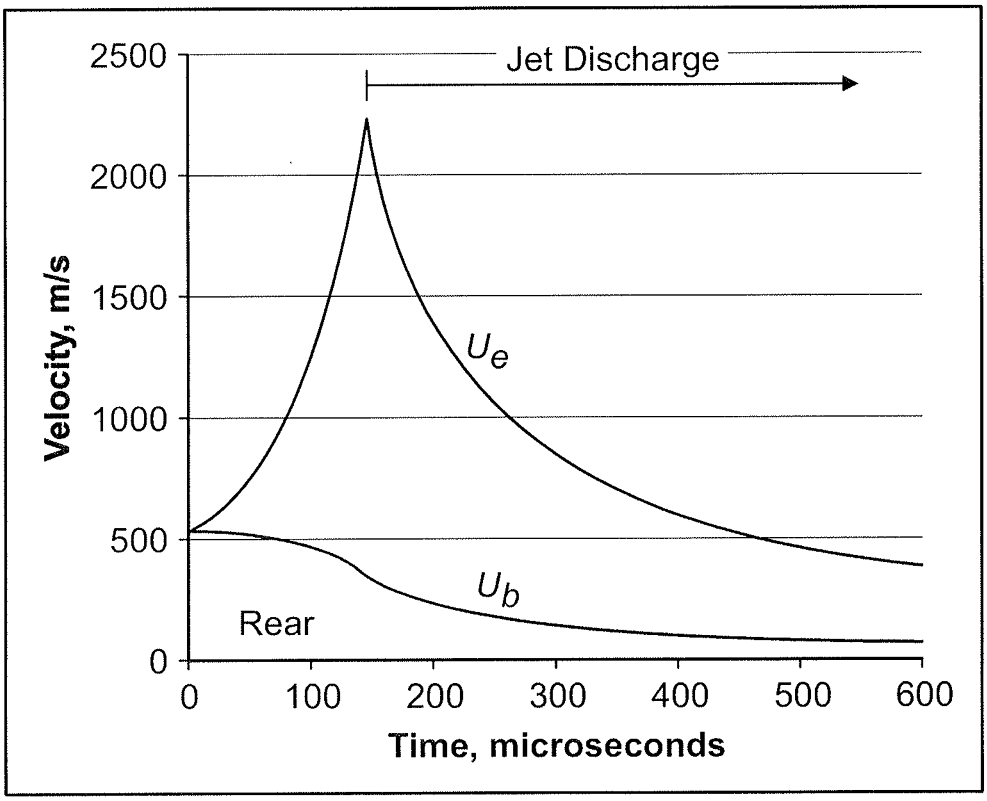

2500
2000
1500
1000
500
0
Velocity, m/s
Jet Discharge
Ue
Ub
Rear
0
100
200
300
400
500
600
Time, microseconds

FIG. 5B

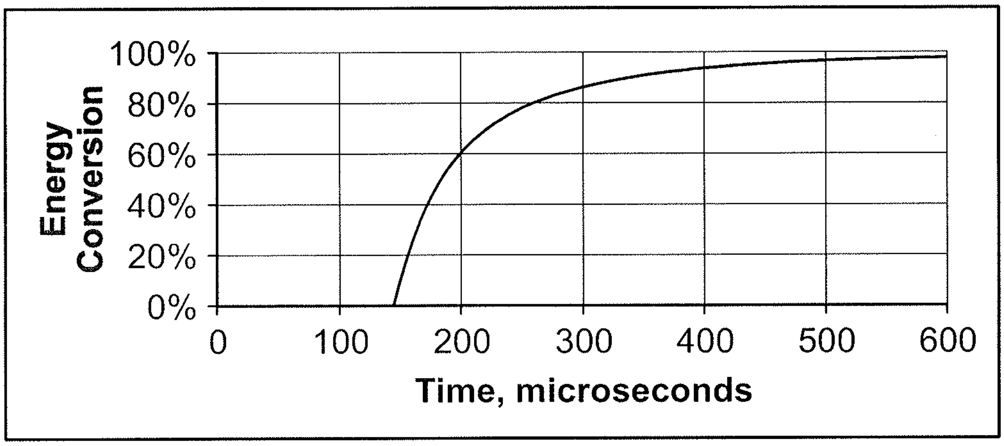

Energy Conversion
100%
80%
60%
40%
20%
0%
0
100
200
300
400
500
600
Time, microseconds

FIG. 5C

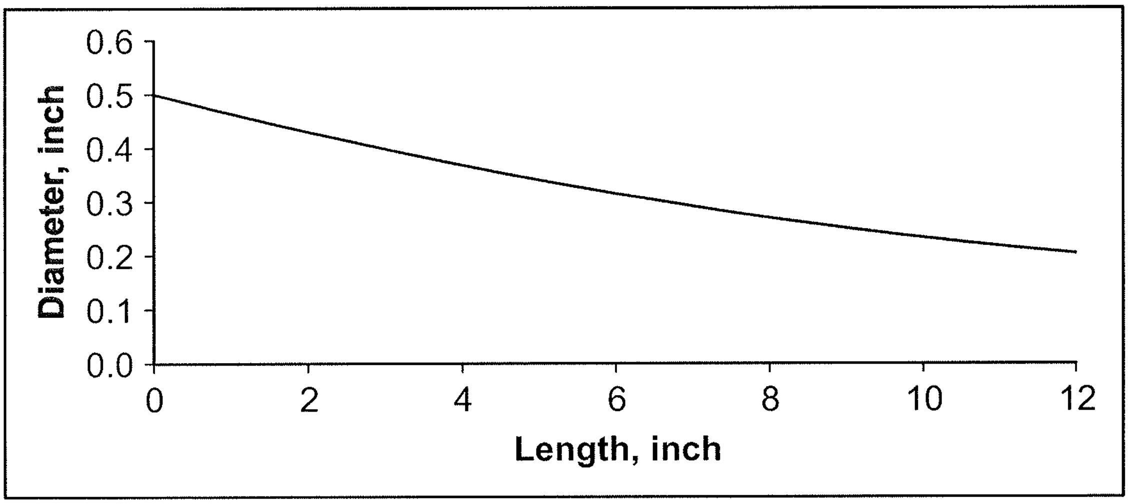
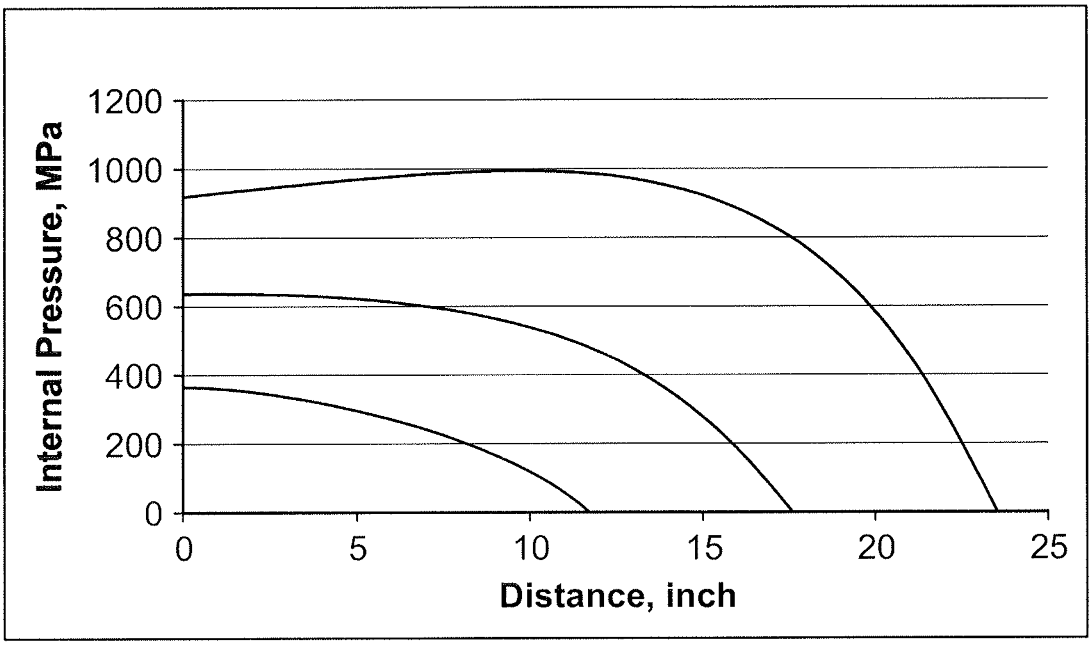

Diameter, inch
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
2
4
6
8
10
12
Length, inch

FIG. 5D



Internal Pressure, MPa
1200
1000
800
600
400
200
0
0
5
10
15
20
25
Distance, inch

FIG. 5E

REFERENCES CITED IN THE DESCRIPTION

Patent documents cited in the description

- US 4074858 A **[0007]**
- US 5000516 A, Kolle **[0015]**

Non-patent literature cited in the description

- **KOLLE, J. J.** A Hydraulic Pulse Generator for Non-Explosive Excavation. *Mining Engineering,* July 1997, 64-72 **[0005]**
- **MAUER, W. C.** Advanced Drilling Techniques. Petroleum Publishing Inc, 1980, 302-348 **[0006]**
- **GLENN ; LEWIS A.** On the dynamics of Hypervelocity liquid jet impact on a flat rigid surface. *Journal of Applied Mathematics and Physics (ZAMP),* 1974, vol. 25 **[0028]**