# COMPRESSED-WATER PULSE GENERATORS AND APPLICATIONS

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## ABSTRACT

A compressed-water pulse generator consists of a heavy-walled pressure vessel equipped with a fast-opening discharge valve. At ultra-high-pressure - UHP>100 MPa - water has significant compressibility, allowing storage and discharge of energetic pulses from a compact tool. Pulse generators with discharge energies from 1 kJ to 250 kJ have been built and tested. The UHP pulses may be further accelerated through a tapered nozzle to generate hyper-pressure pulses with stagnation pressures of over 1 GPa. Heavy pulse generators have applications in civil engineering including rock blasting, concrete demolition and soil foundation improvement. Smaller systems can be used for manufacturing applications including hydro-forming, metal punching, joining and surface treatment.

## INTRODUCTION

Continuous UHP jetting systems operating at 200 to 400 MPa have found widespread acceptance for industrial cutting and cleaning applications. At these extreme pressures the diameter and range of a continuous UHP jet is quite limited. Impulsive jet systems can provide larger jets and much higher instantaneous power levels. When properly applied, pulsed jets can also generate much higher dynamic pressures. Figure 1 shows an engineering prototype, compressed-water, hydraulic pulse generator. Energy is stored in this device by compressing water to ultra-high pressure. At a pressure of 300 MPa, water is compressed about 10% and the 1.8-liter tool shown has a charge energy of 30 kJ.

The fundamental operating principles of the compressed-water pulse generator are described here, followed by a discussion of a new application to metal forming.

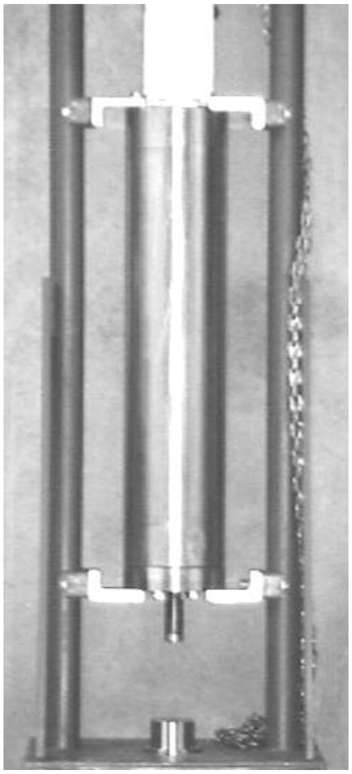

**Figure 1. Engineering prototype, 30 kJ, 1.8-liter pulse generator. (Pressure vessel length is 1-m.)**

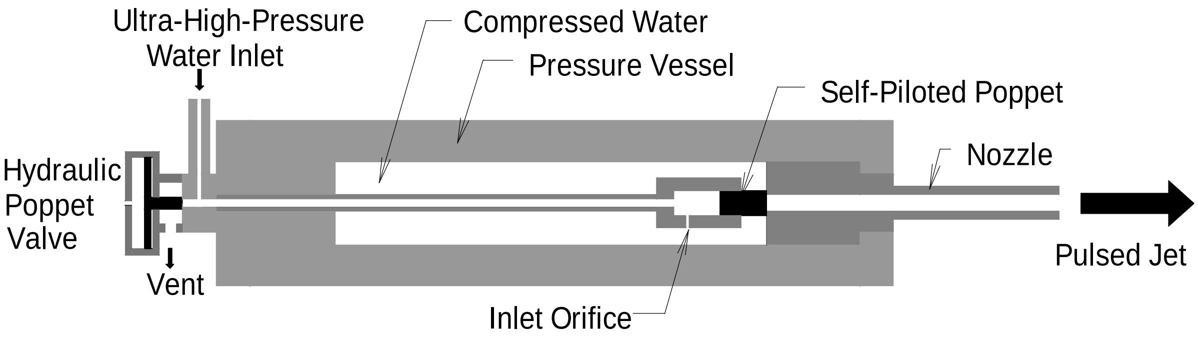

**Figure 2. Compressed-water pulse Generator operating principles.**

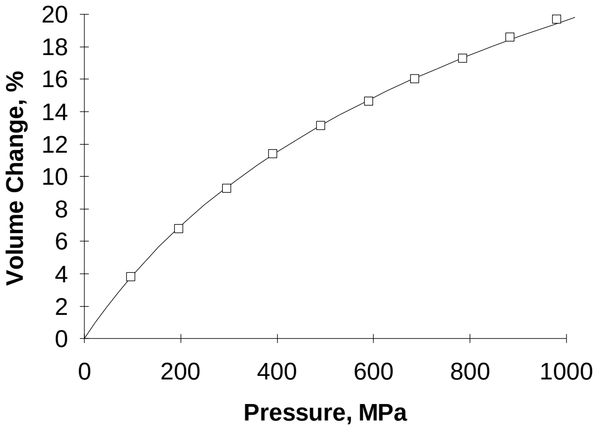

**Figure 3. Compression of water.**

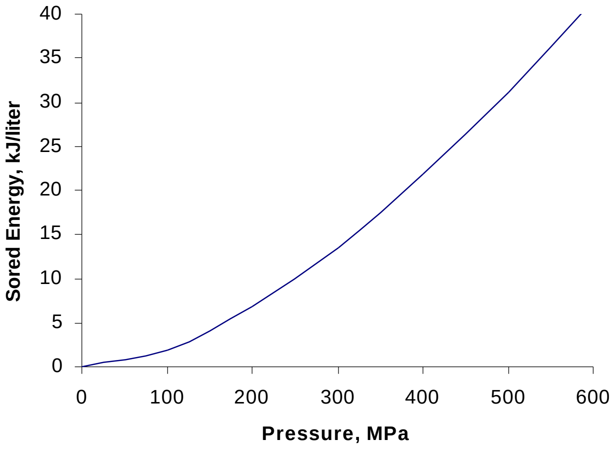

**Figure 4. Stored energy in a 1-liter water-filled pressure vessel.**

## OPERATING PRINCIPLES

The operating principles of the engineering prototype pulse generator are shown in Figure 2. The pulse generator consists of a heavy-walled pressure vessel that is equipped with a fast-opening discharge valve. In this configuration the valve is an unbalanced poppet. The poppet is actuated by venting a chamber behind the poppet that normally holds it closed. Consistent repeated pulses may be generated at a cycle rate of 1 Hz with conventional ultrahigh-pressure pumps. These tools may also be charged at a low rate using a small air-driven intensifier pump.

### Water Compression and Stored Energy

The energy stored in a water-filled pressure vessel can be calculated from an equation of state, which provides the relationship between pressure and volume. Since pressurization occurs rapidly, we assume an adiabatic process. The Tate equation of state for water (Glenn 1974) relates the density, $r$, to the pressure $P$, by

$$\frac{r}{r_o} = \left(1+\frac{P}{aK_w}\right)^a , \qquad (1)$$

where $r_o$ is the initial density, taken as 998.23 kg/m$^3$ at 1 bar, and a temperature of 20 °C; $K_w$ = 2.196 GPa is the adiabatic bulk modulus of water under the same conditions and $a$ = 0.13986) is a constant. This relationship is shown in Figure 3 along with data from Bridgeman (1911) on the compression of water. The average density of fluid in a rigid vessel with volume $V_o$ is related to the volume of fluid pumped into the vessel by

$$\frac{r}{r_o} = \frac{V}{V_o} , \qquad (2)$$

which is also the form of the equation of state. The pressure/volume relationship can be obtained by solving equations (1) and (2);

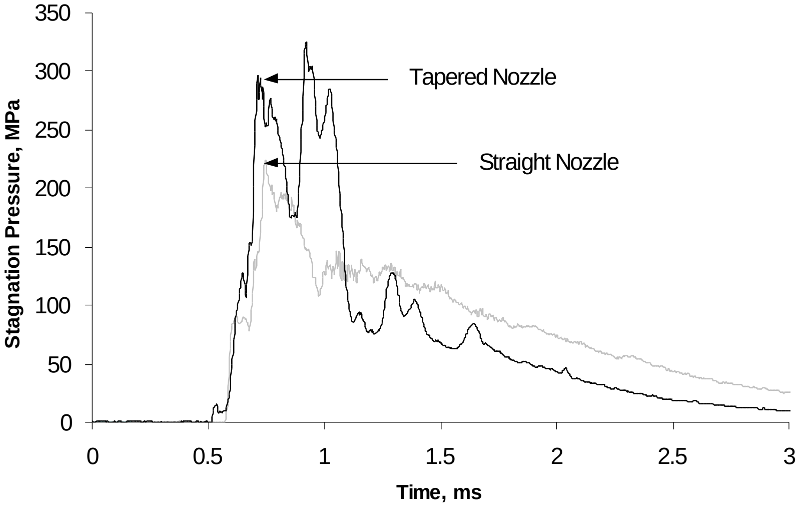

**Figure 5. Free jet stagnation pressure profiles: 300 MPa discharge, standoff = 10 mm.**

$$P = aK_w\left[\left(\frac{V}{V_o}\right)^{1/a} - 1\right]. \qquad (3)$$

The energy stored by pumping an increment of volume at pressure $P$ is $dW = PdV$ and the total stored energy is

$$\begin{aligned} W &= \int_{V_o}^{V_v} PdV \\ &= aK_w \int_{V_o}^{V_v}\left[\left(\frac{V}{V_o}\right)^{1/a} - 1\right]dV \qquad (4) \\ &= aK_w\left[\frac{V_v^{1+1/a} - V_o^{1+1/a}}{\left(1+\frac{1}{a}\right)V_o^{1/a}} - \left(V_v - V_o\right)\right]. \end{aligned}$$

Figure 4 shows the stored energy in a 1 liter pressure vessel as a function of pressure.

### Pulsed Jet Stagnation Pressure

Figure 5 illustrates a free jet stagnation pressure profile generated when a 200 MPa pulse is discharged through a straight and tapered discharge nozzle. The straight nozzle has a diameter of 13-mm (0.5”) while the tapered nozzle has a discharge diameter of 5-mm (0.2”). The peak stagnation pressure is observed to be only about half of the water cannon charge pressure. The pulse magnitude is increased by accelerating the flow through the tapered nozzle. In this case a stagnation pressure amplification of 50% is obtained.

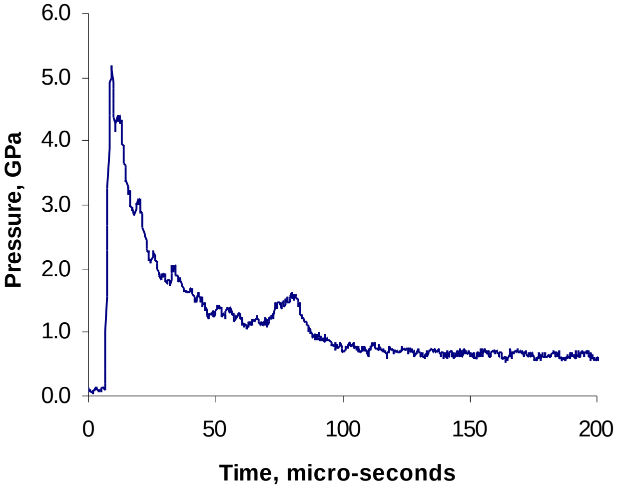

**Figure 6. Shock pressure due to jet impact in a closed conduit.**

The stagnation pressure of a pulsed jet can be further amplified by holding the discharge nozzle against a rigid workpiece to produce a water hammer effect. Figure 6 shows a 5 GPa shock generated from the impact of a 240 MPa pulse in a closed, tapered conduit. The shock pressure is over twenty times the free jet pressure.

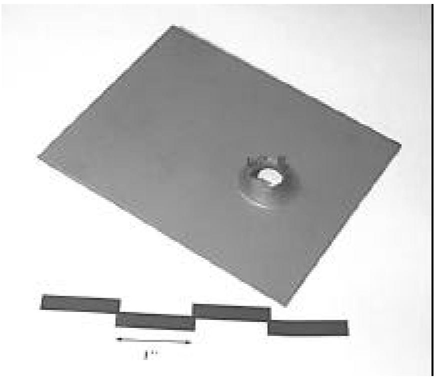

**Figure 7. 0.1”-thick steel sheet pierced with a 20 kJ pulsed water jet**

## METAL-FORMING APPLICATIONS

The shock pressures obtained by directing the jet pulse into a closed conduit are high enough to cause plastic flow in a variety of metals including aluminum and sheet steel Figure 7 shows a 0.1” thick steel sheet that has been pierced by a 20 kJ water jet. Potential applications include hole punching, hydro-forming and clinch bonding and surface peening (Kollé 1998a). In the following, we focus on techniques for pulse bonding sheet metal components.

Pressures Required for Pulse Bonding

Fluid jet pulse bonding requires stagnation pressures which are high enough to cause plastic deformation of the alloys being joined. The pressure required can be estimated from an analysis of the shear stress in an elastic half-space beneath a stagnating jet. The stress distribution beneath an area of uniform pressure, $P$, distributed over a circular area of radius $a$, can be determined by superimposing the Boussinesq solution for stress beneath a point load (Timoshenko and Goodier 1970). The shear stress distribution beneath the center of the pressurized area is shown in Figure 8. In this case, the maximum shear stress has a magnitude of $t_{max} = 0.33P$ at $z = 0.6a$.

Plastic yielding will initiate when the shear stress is about half the plastic flow strength, $s_p$, (which can be defined as the average of the yield strength and the ultimate strength). Plastic yielding will initiate when $P_{si} = 1.5\ s_p$ and the boundary of the plastic strain region will extend from the surface to a depth of $2.5a$ at a mean pressure $P_{sp} = 5\ s_p$. Values for these two pressures are listed in Table 1 for a range of aluminum alloys. These represent a range of pressures required to induce plastic flow in a half space. Comparison with Figure 6 shows that all of these alloys may be easily formed with a pulsed jet.

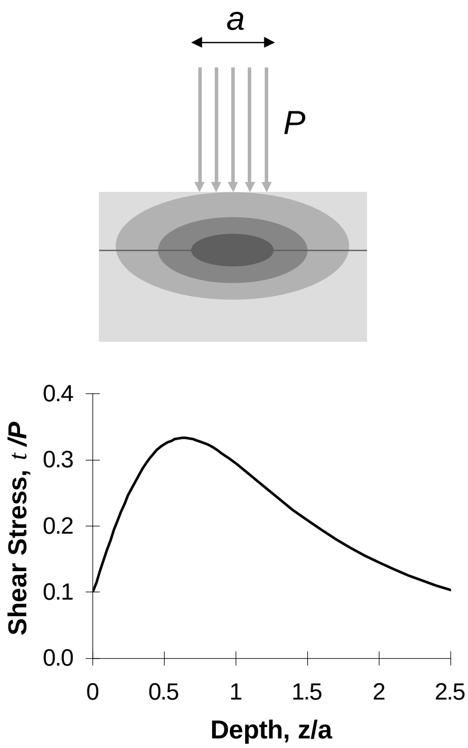

**Figure 8. Shear stress distribution in an infinite half space beneath a uniform pressure over a circular area.**

**Table 1. Plastic flow limits for some common aluminum alloys**

| Material | $s_{UTS}$, MPa | $P_{sp}$, MPa | $P_{sp}$, MPa | Elongation, % |
|---|---|---|---|---|
| 2036 – T4 | 340 | 510 | 1700 | 28 |
| 5182 – T4 | 275 | 413 | 1375 | 24 |
| 6009 – T4 | 220 | 330 | 1100 | 25 |
| 7050 – T76 | 507 | 761 | 2535 | 8 |
| 7075 – T6 | 534 | 801 | 2670 | 11 |
| Annealed | 165 | 248 | 825 | 17 |

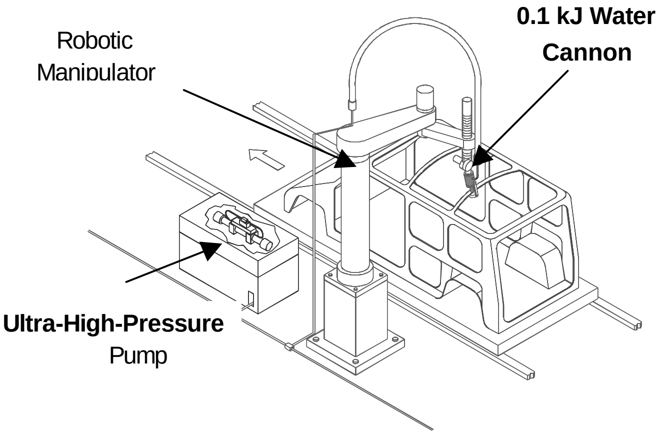

**Figure 9. Pulse bonding of an automotive structure with a robotic manipulator.**

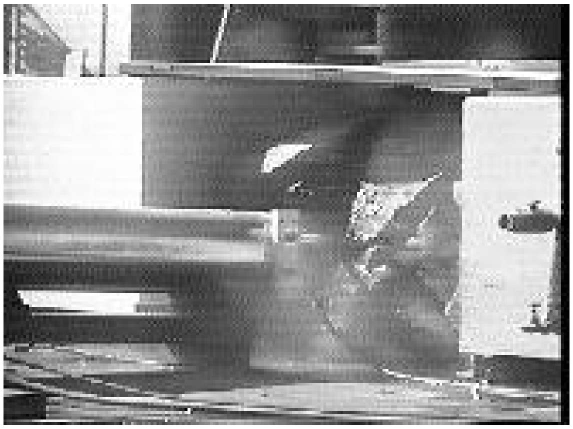

**Figure 10. Rock fragmentation with a 250 kJ pulse generator.**

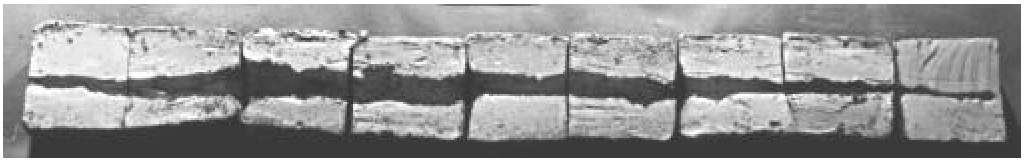

**Figure 11. 1.3 m deep pulsed jet perforation (from left to right) in very stiff clay.**

A light-weight pulse generator could be mounted on a manipulator arm for automated fastening of large structures as illustrated in Figure 9. This figure shows fabrication of an automotive frame structure. A reaction anvil is located behind the workpiece to support the impact load of the pulse generator. Because the bonding load is dynamic, the assembly fixture can be relatively lightweight. Reaction loads on the pulse generator are also small so that a lightweight, robotic manipulator can be used to position the pulse generator. A single pulse generator could be used to fasten material of varying thickness, different materials and form a variety of fastener sizes and shapes.

## CIVIL ENGINEERING APPLICATIONS

Pulse generators were first developed for non-explosive excavation of hard rock (Kollé 1997). Explosive blasting is an efficient process but the transport, storage and handling of high explosives poses a safety hazard. Explosives also generate toxic fumes that can pose a hazard in poorly ventilated areas. Non-explosive blasting with the pulse generator involves discharge into a blind blasthole. The largest water canon built to date has a charge energy of 250 kJ with a 25-mm diameter discharge nozzle. This tool is capable of excavating 0.5 tons of hard rock per blast as seen inFigure 10

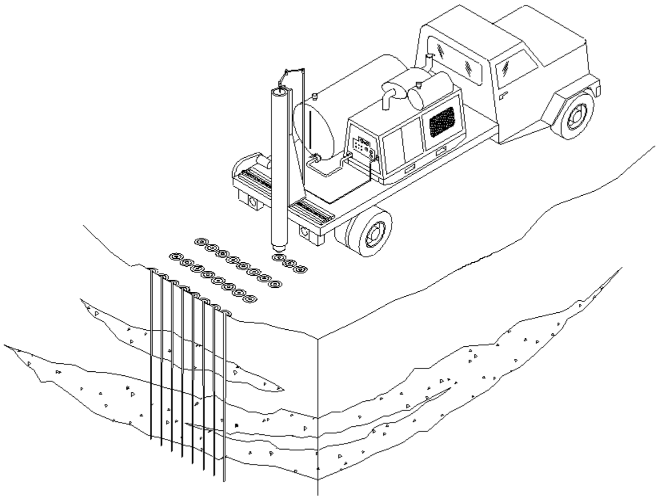

**Figure 12. Truck-mounted soil perforation system.**

The high pressure pulse is also capable of perforating soils to a significant depth (Kollé 1998a). As long as the pulse stagnation pressure is much greater than the soil strength, the jet penetrates in the same way as an explosive shaped charge. Figure 11 shows a pulsed jet penetration into hard clay. Penetration depths of up to 30 m are possible with a large (1MJ) pulsed jet system. These perforations can be used to enhance soil remediation by providing aeration for enhanced extraction pathways. The pulsed jet also compacts the soil providing a new means of improving foundations on loose soils.

The compressed-water cannon can be used to rapidly perforate large volumes of contaminated soil at a cost, which is much lower than conventional drilling. Because penetration occurs by lateral displacement of the soil, no contaminated spoil material is generated at the surface. The water supply, UHP pump and water cannon could all be mounted on a four-wheel-drive truck for surface perforation applications as illustrated in Figure 12. The water cannon can also be deployed in a borehole for lateral perforation in order to enhance the conductivity of groundwater wells. Since the orientation and depth of perforations can be predicted accurately, this approach provides a reliable alternative to hydraulic or pneumatic fracturing.

## CONCLUSIONS

The compressed-water pulse generator provides a powerful tool that extends the range of application of ultra-high-pressure fluid jet systems. Pulsed jets can generate pressures that are an order of magnitude higher than continuous jetting systems and the jet diameter can two orders of magnitude greater.

Smaller systems can be adapted for manufacturing applications. By directing the jet pulse through a tapered nozzle onto a workpiece, it is possible to generate hyper pressure (>1GPa) pulses capable of causing subsurface flow in most common steel and aluminum alloys. A compact, light-weight generator with a pulse energy of 1 kJ, could be used for a variety of applications including sheet metal bonding and other small-scale metal forming applications. The pulse bonding system would be well adapted to robotic manipulation and high speed flexible manufacturing.

Larger water cannon systems have applications for non-explosive excavation, tunneling, foundation soil improvement and environmental remediation of soils.

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