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Applications of Ultra-Powerful Pulsed Waterjet Generated By Electrodischarges

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ABSTRACT

A brief description of an ultra-powerful low-frequency pulsed waterjet machine is given. The machine has been manufactured after extensive theoretical and experimental research and development work in the laboratory. The forced pulsed waterjet is generated by a rapidly expanding plasma (very high temperature steam) which is formed as consequence of deposition of electrical energy between a pair of electrodes in a nozzle. The electrical energy is stored in a capacitor bank. The maximum energy stored in the bank of the latest machine is 100 kJ at a voltage of 22 kV.

Recently, the machine has been tested for several possible applications, ranging from rupture of metallic plates to dismantling (neutralization) of explosives which are contained in a variety of enclosures (metal and plastic pipes, spheres, etc.). Its potential for neutralization of landmines has also been evaluated. This paper includes: (1) features of this and earlier machines, (2) recent theoretical results based on CFD (computational fluid dynamics) analysis, and (3) highlights of the experiments investigated. These experiments have shown that the maximum energy and voltage required are in the neighbourhood of only 20 kJ and 10 kV respectively. This has clearly indicated that the machine will be quite compact in size, easily portable and manoeuvrable which are vital, particularly for security/rescue applications.

1.0 NOMENCLATURE

C: Capacitance of the capacitor, μF (Microfarad)
E_o: Maximum energy stored in the capacitors, kJ = $CV_o^2/2$
E: Energy deposited in the nozzle, kJ
i, I: instantaneous and mean current, amp
V_o: Maximum voltage of the capacitor, Volt
V: Voltage at the tip of the electrode in the nozzle, Volt
t: Discharge time

2.0 BACKGROUND

As explained in great detail by Vijay (Ref. 1; this publication cites more than 100 references on the topic of pulsed waterjet), the hydrodynamic phenomena accompanying electric discharges in quiescent liquids at atmospheric pressure have been known for more than a century. Yutkin (Ref. 2), and later, Naugolnykh and Roii (Ref. 3) have given extensive details on electric discharges in water and how they can be harnessed for practical applications, for example, metal forming. An electric discharge in a liquid at atmospheric pressure is known to cause the formation of a strong shock wave and a plasma bubble that could attain a maximum diameter of 10 mm in about 1 μs. The pressure in the plasma bubble can reach 2000 MPa (Ref. 2) or more, depending on the power of discharge (= voltage **x** current). The interest in the technique for a variety of applications stems from the fact that these shock waves and the bubbles are sources of high power, the processing of materials is clean, and can be controlled precisely (a definite advantage compared to explosives). However, the proposition to use the electrical discharges to generate ultra-powerful pulsed waterjet (***EDPWJ***) is fairly new (Ref. 1).

Basically, when sufficient electrical energy at an appropriate voltage is discharged rapidly between a pair of electrodes in a nozzle, water breaks down to form a plasma (Refs. 1, 5 to 8). The result is: (i) formation and propagation of an initial shock wave (Refs. 7 and 8), (ii) formation of a pulsed waterjet produced by the rapidly expanding plasma (Refs. 5 and 6), and (iii) cavitation (water vapor) bubble which is basically the plasma bubble itself cooled by rapid expansion (hard to visualize). The shock wave formed at the point of discharge propagates in both directions, viz., to the left and right of electrodes (see Fig. 1). While the wave travelling towards the right accelerates the fluid, that travelling towards the left decelerates it and can damage the pump. However, it is possible, with the proper disposition of a reflector, not only to prevent this from happening, but also to reflect the wave back towards the nozzle exit so as to contribute to the overall acceleration of the fluid (Ref. 8). The theoretical work reported by Atanov and his co-workers (Ref. 4), among others (Ref. 1), has lent further support to the technique. However, hardly any experimental data exist to prove the viability of the concept. This is not surprising because, as discussed below, despite the simplicity of the concept, there are a number of serious problems that need to be taken into consideration. It is shown here that such a machine is possible, and is now ready for a wide variety of applications.

3.0 THE EVOLUTION OF EDPWJ MACHINES

3.1 Basic Components

The basic components of an **EDPWJ** machine are depicted in Fig. 1. The machine consists of: (1) a capacitor bank with the associated high-voltage (HV) power supply and controls (switches for charging, discharging, dump circuit for safety, etc.), and (2) the nozzle-electrode assembly with or without a pump. As the discharge time (τ) is very short ($\approx$ 100 μs), the frequency of the pulses depends on the rate at which the capacitor bank in the electrical assembly (called here "electrical pulsed power system - **EPPS**") can be charged (akin to a battery charger). In the latest machine described below, the frequency is of the order of 0.2 Hz (that is, 12 waterjet pulses can be generated per minute). The water in the nozzle could be quiescent (similar to a conventional water canon) or flowing, driven by a low pressure pump ($\leq$ 20 MPa). An attractive feature of the **EDPWJ** machine is that the **EPPS** can be placed at a very large distance from the nozzle because they are connected by a coaxial electrical cable (for sturdiness, it could be a coaxial insulated steel rod).

The purpose of the pump will be described later.

3.2 The Original (First Generation) EDPWJ

The very first machine designed and fabricated from scratch to establish the proof of the principle of the **EDPWJ** technique is shown in Fig. 2. The major goal of the machine, as it was funded by a consortium of mining companies, was to investigate the feasibility of preweakening of hard rocks. The details, the problems associated with it, and the results obtained are fully described by Vijay, et. al (Ref. 5). Although it was quite bulky and clumsy (see, for instance, the jumble of cables connected to the electrodes in the nozzle in Fig. 2), results obtained with it were quite encouraging. This work not only confirmed the proof of the principle, but also brought to attention several serious problems associated with the technique that needed to be solved. The major problems were: (1) premature failure of electrical insulating materials, (2) undesirable arcing (sparks; also called tracking) at several locations, including the **EPPS** itself, and (3) the effects of EMP (electromagnetic pulse generated by the high-transient current accompanying the discharge; also called EMI - electromagnetic interference) on other equipment and personnel. It was indeed a learning machine which established the ground rules for further work.

3.3 The Second Generation EDPWJ

Based on the experience gained from the first machine, the second prototype was constructed for further investigation (Fig. 3). The details of this machine, and the extensive results obtained with it have been reported by Vijay, et. al (Ref. 6). The capacitor bank in this machine was designed to store 20 kJ at 40 kV. The components of the **EPPS**, namely, the capacitors, rail-gap switch (to dump the stored electrical energy into the electrode gap in the nozzle), the gas cylinders (SF_6 gas was required in the rail-gap switch to initiate current carrying arc), valves, trigger unit, etc., were contained in a commercial steel cabinet to protect them against the EMP. Likewise, the operating console consisting of HV power supply and the controls (simply pushing the buttons on the front panel performed the tasks required, for instance, charging the capacitors) were enclosed in a shielded metal cabinet. As shown in Fig. 4, the nozzle-electrode-cable assembly was considerably improved, eliminating all the undesirable sparks. Although this machine was elegant compared to the 1^{st} machine, its overall size was almost 4 - m^3. It was used quite successfully to obtain several important sets of data (velocity of the jet, fracture of materials exposed to the pulsed waterjet, etc.). However, some damaging effects of EMP and several problems with the insulators still persisted. The lessons learnt from this machine were invaluable in designing the latest pre-commercial prototype described below.

3.4 The Third (Most Recent) Generation EDPWJ

This pre-commercial prototype was built based on the extensive work done with the previous machines and also considerable theoretical work (Refs. 7 and 8). A conceptual layout of the machine is shown in Fig. 5, and its general views are depicted in Fig. 6. The **EPPS**, completely enclosed in the shielded metal cabinet, consists of: HV power supply and its control unit, two capacitors (each rated to store 50 kJ of electrical energy), two ignitron switches (one for each capacitor connected in parallel), current bus (see Fig. 5) and a trigger generator (to fire the ignitron switches). This machine is very versatile with a maximum capacity of 100 kJ at 22 kV designed for a variety of applications in mind, although the major goal (for which it is funded), is for the removal of undesirable growth in chemical reactors and other systems (discussed later). As the overall size of the machine is 1.04 X 0.762 X 1.22 - m (see Fig. 6), and the weight is 360 kg, the machine is considered to be compact and light. Furthermore, as shown in Fig. 5, the **EPPS** need not be in the vicinity of the work area. The length of the cable that connects the EPPS to the electrodes in the nozzle (which remains in the work area) could be as long as 50 - m. As such, it could be loaded on to a truck, and depending on the application, can be charged from the alternator in the truck itself. Another important point is, as discussed below, all the results obtained to date indicate that the electrical energy need not be more than 20 kJ. Therefore, it is quite possible to reduce the overall size and weight even further (say, 0.25 - m^3 and 150 kg) so that it can be transported on a light truck to the site of the job (as discussed later, for security/rescue operations this feature is quite attractive).

In fabricating this machine careful attention was paid to eliminate all the problems observed in the earlier machines. For example, Fig. 7 shows that all the exposed metallic surfaces were completely isolated from each other either by coating with high dielectric coating material or, using Mylar or other insulators. While taking useful measurements (such as voltage, current, etc.), repeated observations were made of the inside of the cabinet of the **EPPS** to make sure that there were no arcs formed from one conductor to another. Despite the high voltages involved, the **EPPS** has been designed to be completely fool-proof (for example, unless all the doors are closed, it will not be possible to charge the capacitors). As the cabinet has been completely shielded, there was no effect of EMP on the electronic components of the **EPPS**. Other steps taken to eliminate the effects of EMP consisted of using completely shielded conduit to connect the cables from the **EPPS** to the nozzle, proper grounding of both the **EPPS** and the nozzle, etc. In order to make sure that these steps have been effective in eliminating the harmful effects of EMP, tests have been conducted (including field demonstrations) in the presence of some delicate devices (for example, a pacemaker). As there has been no damage to these devices, it is believed that the EMP is no longer a threat. Nonetheless, further work is in progress to get the machine certified to meet the specifications of FCC or, other international regulatory bodies (Ref. 9).

4.0 THEORETICAL ANALYSIS (COMPUTATIONAL FLUID DYNAMICS ANALYSIS)

As explained by Vijay and his co-workers (Refs. 7 and 8), the phenomena accompanying the rapid discharge of electrical energy in the gap width of electrodes in the nozzle are quite complex, and are not easily amenable to mathematical analysis (see also, Ref. 5). Therefore, while investigating the first two machines, computational fluid dynamics (CFD) codes were developed to: (1) understand the physics of the flow accompanying the discharge, and (2) guide the design of the nozzle, especially the inner profile and other geometrical parameters (Ref. 7). The results predicted from these codes were quite useful. For example, the initial study showed the development and propagation of shock waves in quiescent water in the nozzle, resulting in the formation of a pulse of water (Ref. 7). In the second study (Ref. 8), attempt was made to obtain more quantitative predictions. Some of the important predictions were: (1) the influence of the reflected shock wave on the pulsed jet, and (2) effect of the rate of energy release on the magnitude of impact pressure on the target, etc. For instance, the analysis indicated that for a rate of release of 1.0 kJ/µs, the magnitude of impact pressure could be as high as 4,000 MPa on a target located at a standoff distance of 150 - mm.

The major objectives for the continuation of CFD analysis were:

- To examine how far upstream of the nozzle exit the electrodes must be located in order to confine the sparks generated by the discharge (see Fig. 8) right within the nozzle. From the standpoint of safety, the emergence of sparks to outside of the nozzle will be totally unacceptable. The arcing, as shown in Fig. 8, must be ignored (this was caused by the alligator clips used for connecting the voltage probe to the electrodes; such probes will not be used in a practical situation).
- To revise the code for predicting the realistic variation of target pressure with time, using a new equation for the rate of electrical energy release, as close as possible, to the actual discharge shown

in Fig. 9 (the total energy deposited is the product of measured current and voltage). In the previous codes the rate of release of energy was assumed to be constant.

The observations from the CFD study were:

- When the location of the electrode plane was changed from 20.5 mm to 43 mm upstream from the nozzle exit, the peak impact pressure decreased from 1,250 to 1,106 MPa (by 12%). Considering the importance of preventing the appearance of sparks outside of the nozzle, this deterioration in performance was deemed to be acceptable. After implementing this step, sparks outside of the nozzle have not been observed. Nonetheless, this is under constant observation.
- Several peaks in the impact pressure occur (Fig. 10), basically following the trace of the discharge current (Fig. 9), although the times do not exactly match (probably due to the simplifications used in the CFD code). While the first peak produces an impact pressure of 1250 MPa, the last three peaks are of the order of 700 MPa. These results are encouraging in the sense that multiple pressure peaks, occurring one after another (with respect to time), will accelerate the process of fragmentation of the target. Although it is not possible to validate these predictions experimentally, unless the impact phenomena are observed using high-speed photography, the fact that multiple samples staggered one over the other are penetrated by the pulsed jet (see below), somewhat lends support to their occurrence.

5.0 EXPERIMENTAL RESULTS

5.1 General Remarks

The overall experimental program consists of: (1) measuring the influence of all electrical parameters (duration of discharge, rate of energy release, electrode gap resistance, etc.) on the characteristics of the pulsed waterjet produced by the discharge, (2) influence of the hydrodynamic operating parameters (static pressure in the nozzle, nozzle diameter, etc.), (3) operating parameters (traverse speed, standoff distance, etc.), and (4) properties of materials exposed to the jet. As some of these results have already been published (Ref. 7), in this paper only highlights of some of the potential applications are given.

5.2 Fragmentation Results

The pulsed waterjet produced by the electrical discharge can be used for any application that requires fragmentation of the target material. Some of these are: annihilation of bombs or explosives (Ref. 10), hydro-demolition, removal of unwanted growth in chemical reactor vessels, pipelines, etc. The requirements for handling explosive materials for safe disposal are quite stringent as dictated below (Source: Explosives Disposal & Technology Section of the military):

- Deconstruction of metal, plastic, paper, etc.
- Must be portable (preferably to be lifted by two people).
- 120 Volt recharge capability, preferably from the vehicle alternators.
- Water must be re-usable.
- Cone type filter to remove debris in water.
- Enclosed unit with a scalable option for a portable incinerator.
- Superwater compatible (this is to increase the effective and safe standoff distance, Ref. 11).

5.2 Bombs, Landmines, Etc.

As shown in Fig. 11, bombs and other explosive devices come in various shapes and sizes. The enclosures can be made from paper, fibrous materials, metal (generally cast iron with wall thickness as high as 6.35 - mm), plastic (brittle or ductile). The explosive material can itself be in liquid, powder or solid form..

In order to investigate the feasibility of penetrating the walls of the containers and to attack the explosive material, several tests were conducted using thin sheets of stainless steel (each 0.076 - mm thick), aluminum (0.7 - mm thick), hard rock material (Minnesota black granite) and plexiglass (each 12.5 - mm thick), etc. The results of penetration and fragmentation of these materials are depicted respectively in Figs. 12, 13 and 14. Fig. 12 shows a 1 - m high plexiglass tube in which several samples could be placed one over the other. For these tests, the nozzle contained only quiescent water (≈0.25 litre). For many safe disposal operations (Ref. 10), minimum use of water is absolutely important. Figure 12 clearly shows the penetration of aluminum sheet at a discharge voltage of only 10 kV (capacitor energy = 20.6 kJ). The penetration and total rupture of several stainless steel samples (placed one over the other - not one at a time) are depicted in Fig. 13. More recently a total of seven samples have been ruptured at the same voltage and energy (10 kV & 20.6 kJ). Results obtained on the confined (to avoid free edge effects) discs of rock and plexiglass are shown in Fig. 14. The pulsed waterjet first penetrated and broke the plexiglass disc, and then the rock sample which was placed over it, the voltage being 6 - 8 kV (energy = 7.4 - 13.2 kJ).

With this background data, tests were conducted on pipes containing sand to simulate the explosive material (as required by the military). The results are shown in Fig. 15. In the ductile plastic pipe, the jet made a hole large enough to wet and flush out some of the sand. The brittle pipe (akin to cast iron), on the other hand,, shattered into several pieces, the voltage and energy being once again of the order of 8 kV and 13.2 kJ respectively. These results are now in the hands of the military (security operations) for thorough evaluation.

With respect to neutralization of landmines, a consultant (a recently retired general of the army with expertise in landmine disposal) was engaged to evaluate the potential of the technique as it offers many advantages. Referring to Fig. 5, these are:

- The **EPPS** can be located on an armored vehicle almost 50 - m away from the location of a landmine.
- The cable connecting the EPPS to the nozzle could be a long (50 - m) solid insulated co-axial rod.
- The nozzle itself can be as far as 1 - m (probably 5 - m with the use of superwater, Ref. 11) from the landmine.
- The technique uses a small quantity of water - the nozzle can be easily refilled after each shot.

The conclusions from the consultant's report are (Ref. 10):

- The advantage of the technique is the reduced consumption of water when compared to more conventional waterjet technologies.
- High destructive force combined with the compactness of the size are suitable for the application.
- Typically, mined areas are left undisturbed, which means the most are overgrown by wild vegetation that impedes movement, let alone detection; thus, portability is useful.
- Mined roads present different problems, although much easier to deal.
- There may be a niche application for this technology in road mine clearing. This would be the case if the technique could be shown to save time, provide or improve safety, deal equally well with

various type of pavements and soils, and be effective at neutralising the landmines.

With the results on the fracture of pipes and other materials in hand, the consultant is now working to put together a pilot project, the first step being developing a "typical mission day" which would be used to estimate the logistical requirements of the system (the number of operators, size of the vehicle, etc.).

5.3 The Removal of Chemical Growth

Figure 16 shows general views of typical chemical growth (for want of a better word, these are simply called chemical resins) that occur in many chemical industries including gas pipelines. Such growth hinders normal operation of the equipment, and in the case of reactor vessels, can pose danger to the environment by releasing toxic gases to the atmosphere as the pressure inside the vessel builds up. Currently, the reactors are normally shut down for a period of time during which the growth is removed by mechanical scraping (with hammer and chisel), or more recently using rotating ultra-high pressure ($\geq$250 MPa) waterjets. The rates of removal are low, or as one contractor stated, it does not really matter just as long as the debris is removed.

Tests are in progress to investigate the feasibility of using **EDPWJ** to remove such debris. Preliminary tests using bricks to simulate the chemical growth have yielded highly encouraging results (Fig. 17), once again, at voltages of the order of only 10 kV. Figure 18 shows the result of one of the tests conducted on samples received from a chemical plant (aluminum smelting plant). The sample, as shown in Fig. 16 (B), was embedded in a concrete matrix to simulate the *in situ* stresses that exist on the walls of the reactor vessels. Water at tap pressure ($\approx$ 0.5 MPa) was used to aid the removal of the material as it would flow through the cracks, micro and macro fractures generated by the impact of a single pulse of water. These fractures are clearly visible in Fig. 18, and the average diameter of the hole is about 25.4 - mm. As the discharge time was very short ($\approx$ 100 µs), the actual rate of removal of the growth would depend on the charging time of the capacitor bank (faster the better). For the conditions shown in Fig.18 the removal rate for one shot was approximately 0.06 m^3/hr. Obviously increasing the voltage from 6 to 10 kV, and employing slightly higher pressure water ($\approx$ 10 - 20 MPa) would augment the removal rates. At this voltage and stored energy ($\approx$20 kJ), the machine would be quite compact, and would offer many advantages, particularly in view of the fact that no ultra-high pressure water pumps would be required.

6.0 CONCLUSIONS

A powerful forced pulsed waterjet machine based on the rapid discharge of electrical energy within a nozzle has been designed, fabricated and tested for several commercial and military (demining and other) applications. The conclusions from the material presented herein are:

- All the results obtained to date indicate that voltage and stored energy would be in the vicinity of 10 kV and 20 kJ respectively.
- For a given application, the machine would be quite small in size and weight facilitating transportability and manoeuverability.
- The machine would not require very high pressure ($\geq$ 20 MPa) pumps.
- The machine shows a great promise for demining and other similar applications.
- The EMP, once the machine is certified, would no longer be a threat to personnel or other equipment in the vicinity.

- Theoretical analysis (CFD) generally supports the experimental observations. However, further work is required to improve both the CFD code and validation by experimental data.

7.0 ACKNOWLEDGMENTS

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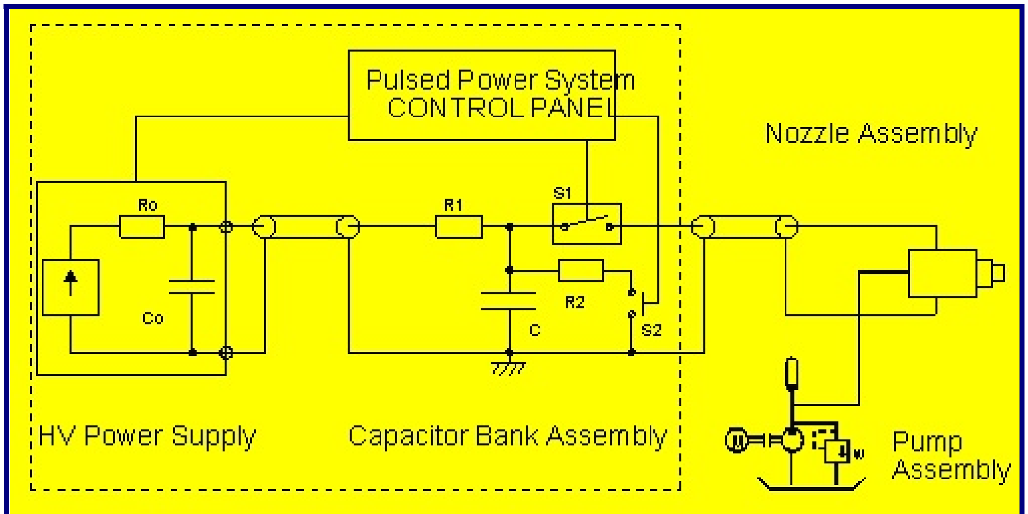

Fig. 1. A typical diagram of the electrodischarge system consisting of electrical pulsed power system with controls, a nozzle assembly in which electrical energy is discharged and water supply (with or without a pump).

Fig. 2. The original (1st generation) electrical pulsed power system (EPPS) fabricated from scratch to investigate the feasibility of generating pulsed waterjet. Maximum stored electrical energy = 5 kJ at 40 kV.

Fig. 3. A general view of the 2nd generation EPPS. Maximum stored electrical energy = 20 kJ at 40 kV.

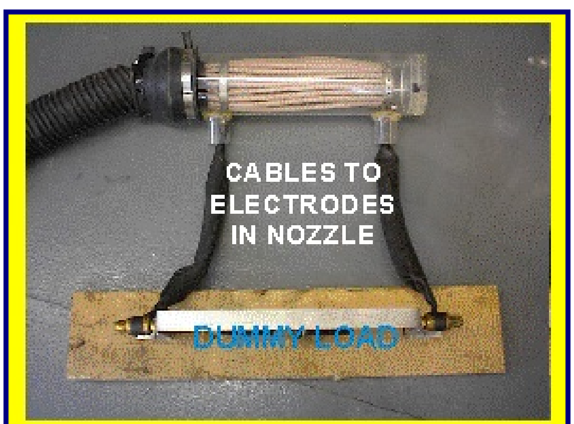

Fig. 4. Current configuration of the cables from the EPPS to the electrodes in the nozzle (dummy load is for measurements).

Fig. 5. A schematic sketch of the layout the most recent (3rd generation) electrodischarge machine for generating ultra-powerful pulsed waterjet. Maximum stored electrical energy = 100 kJ at 22 kV. Overall size ≈ 25% of the machine shown in Fig. 3.

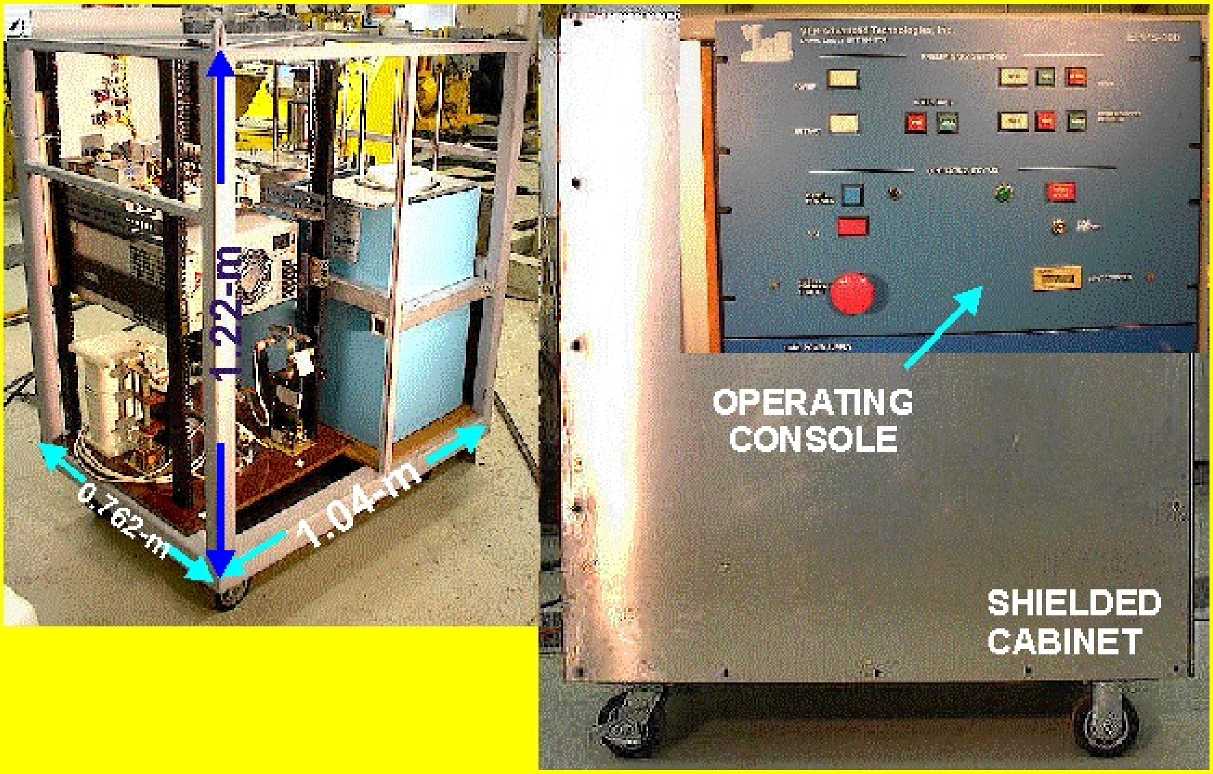

Fig. 6. A general view of the electrodischarge machine the schematics of which is shown in Fig. 5. Overall size < 1-m^3.

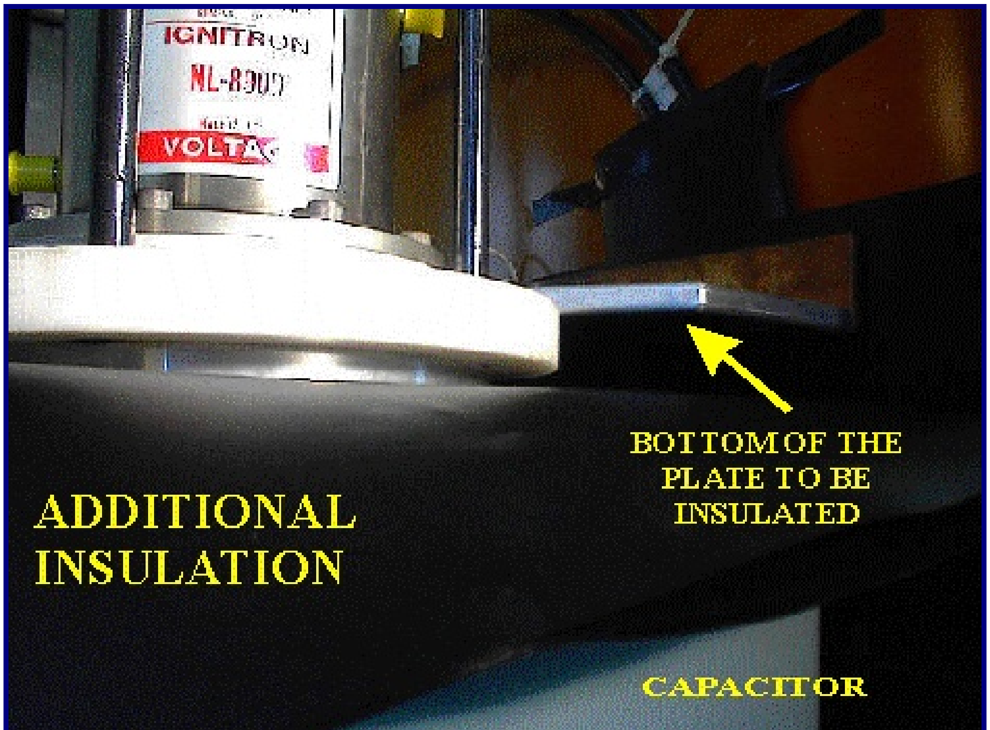

Fig. 7. Potential problem areas (generally caused by internal sparking called tracking) in the EPPS which have been totally eliminated by insulating every single exposed metallic surface.

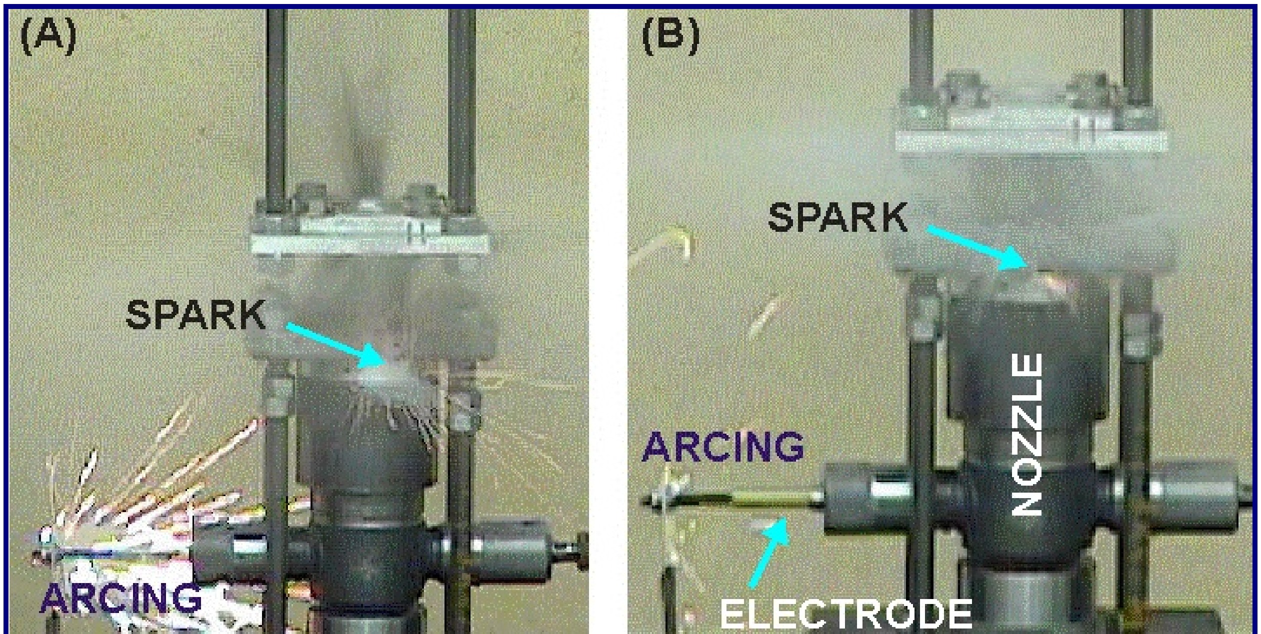

Fig. 8. A general view of the nozzle showing the sparks and the arcing following the discharge of electrical energy in the nozzle at 8 kV.

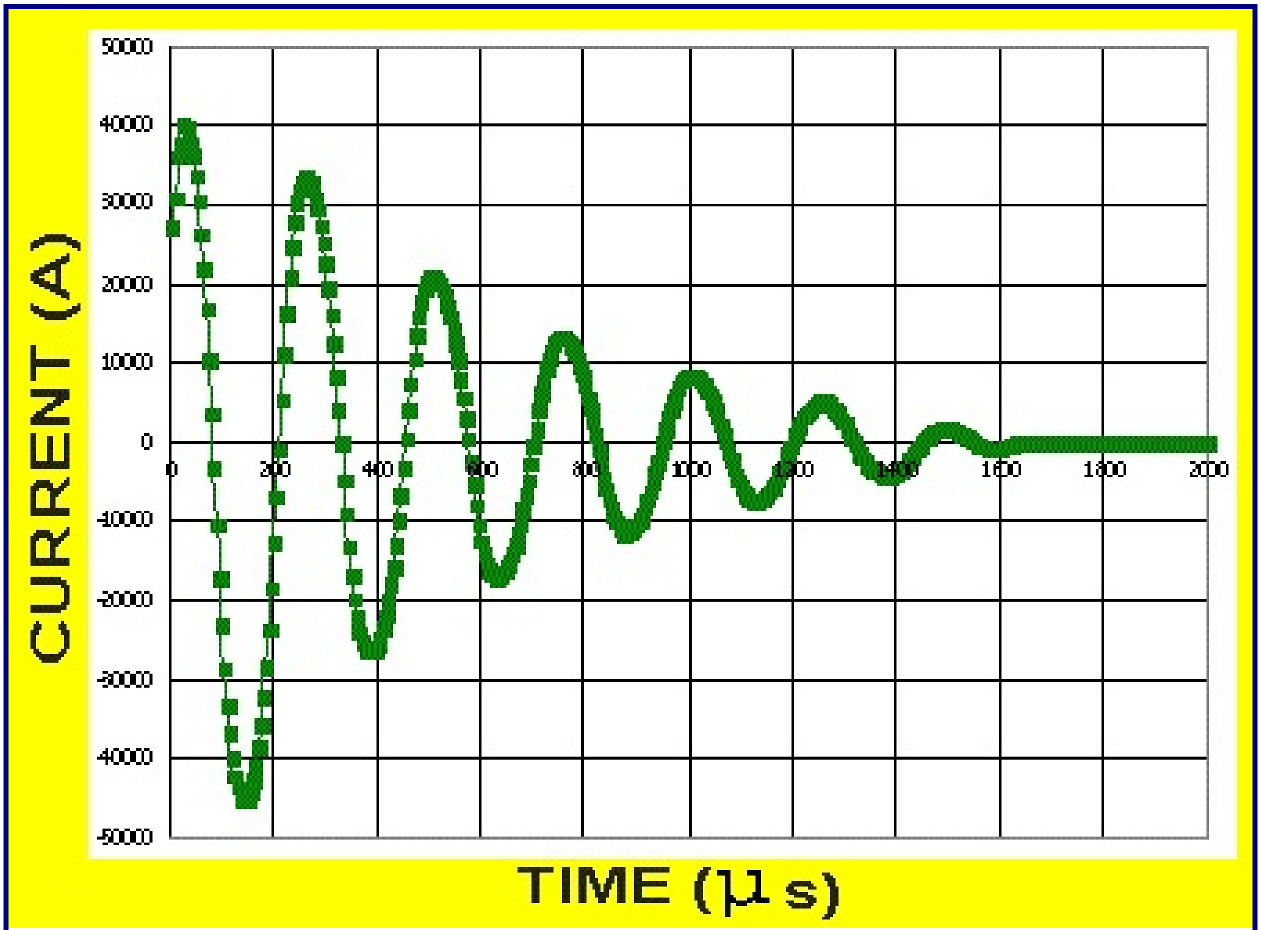

Fig. 9. Plot of total current against time after the discharge of capacitor energy into a dummy load (short circuit). Capacitor Voltage = 6.0 kV

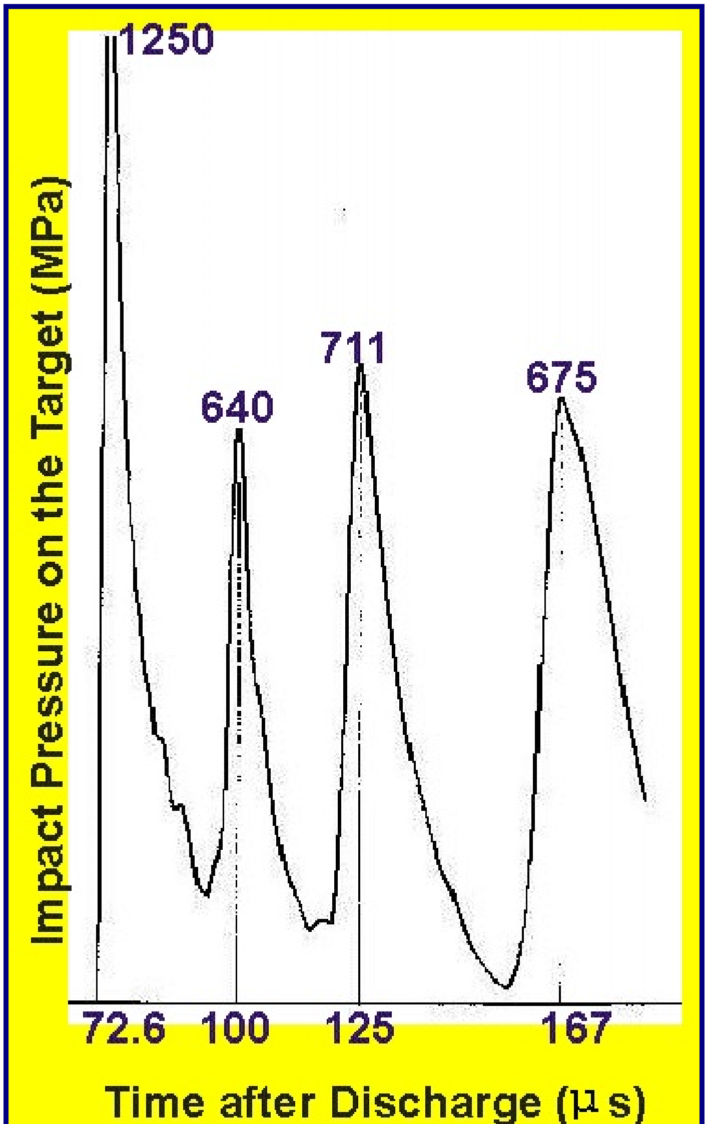

Fig. 10. Plot of impact pressure on the target as a function of time after discharge.

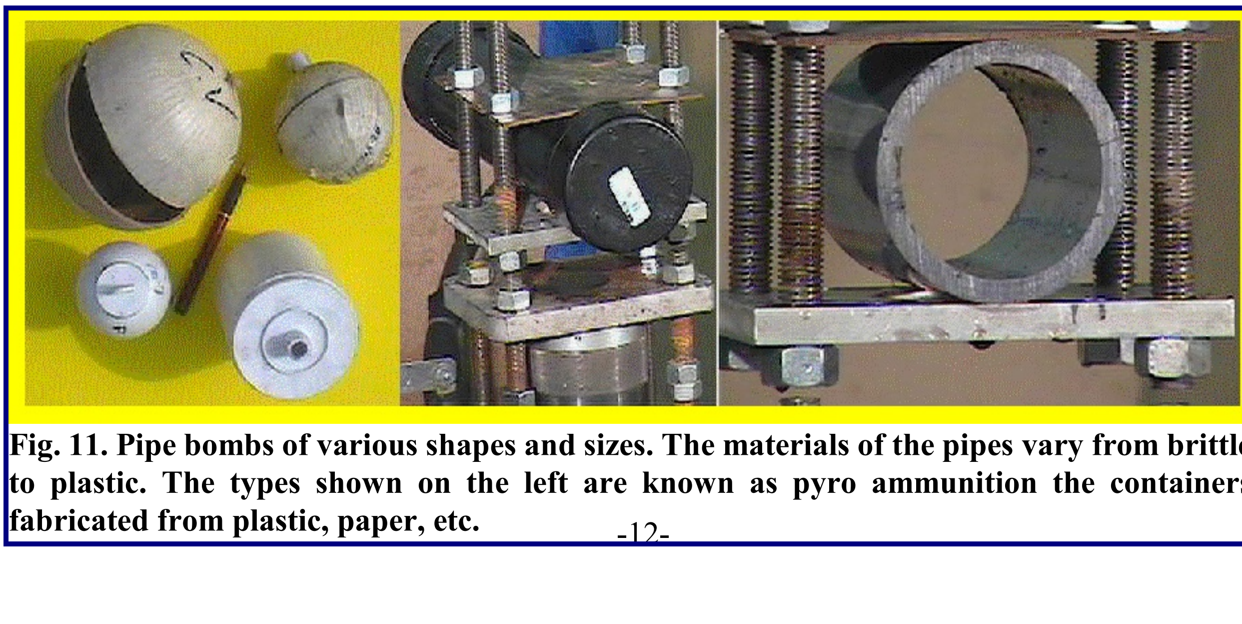
Fig. 11. Pipe bombs of various shapes and sizes. The materials of the pipes vary from brittle to plastic. The types shown on the left are known as pyro ammunition the containers fabricated from plastic, paper, etc.

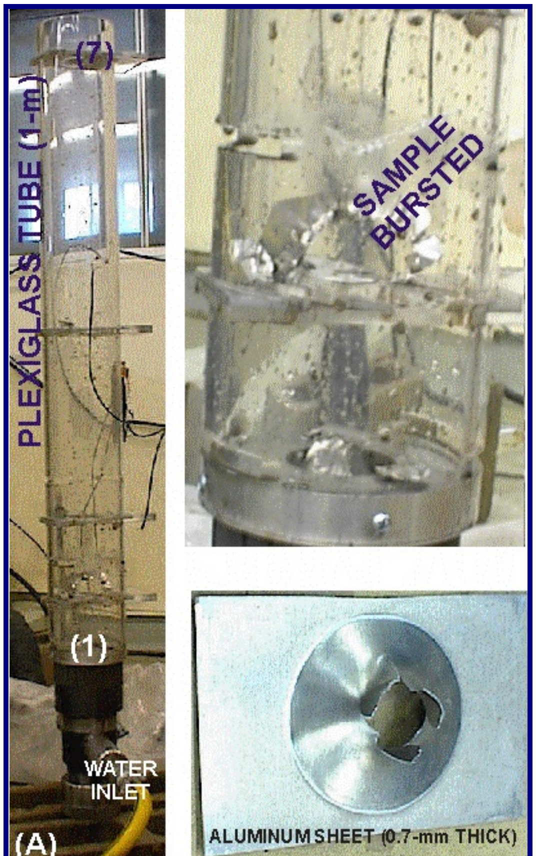

Fig. 12. Experimental set-up to investigate the potential of the pulsed waterjet generate by electrodischarge.

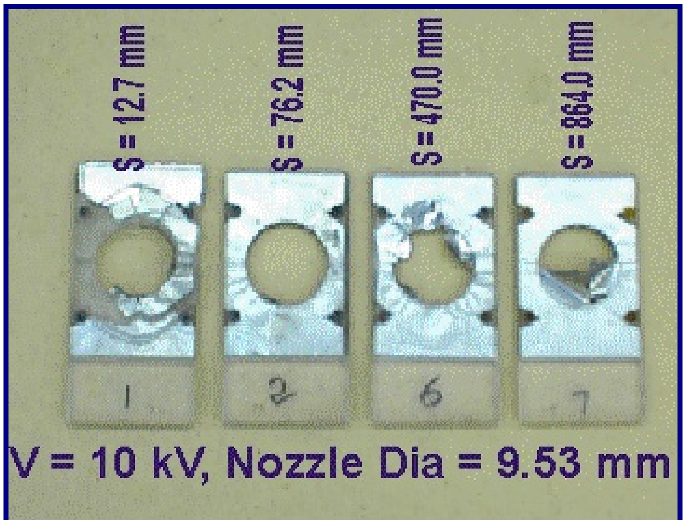

Fig. 13. Stainless steel samples (0.076 mm thick) penetrated by the pulsed waterjet formed by the discharge (placed one over the other, Fig. 12).

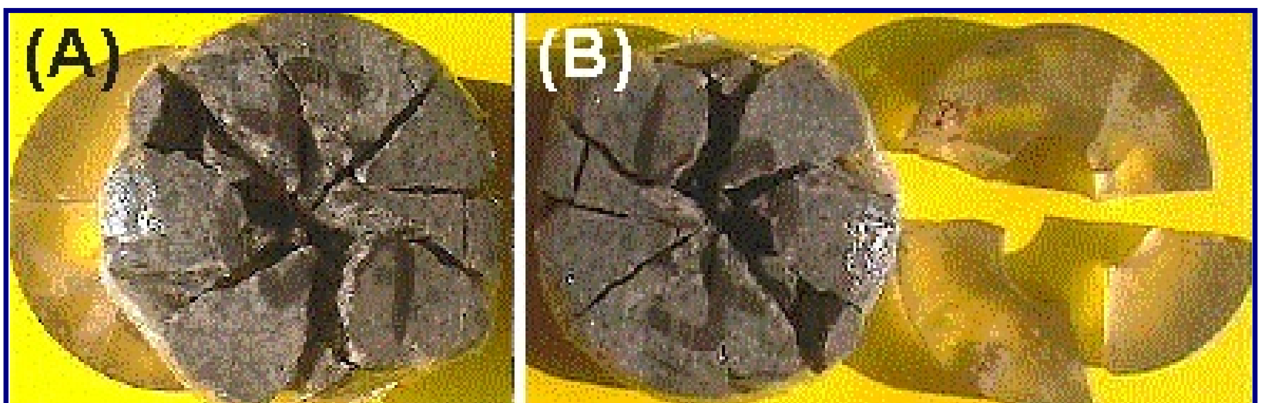

Fig. 14. Discs of plexiglass and black granite (placed over plexiglass: total thickness = 25.4 mm) completely fragmented by the pulsed waterjet. V = 6 to 8 kV.

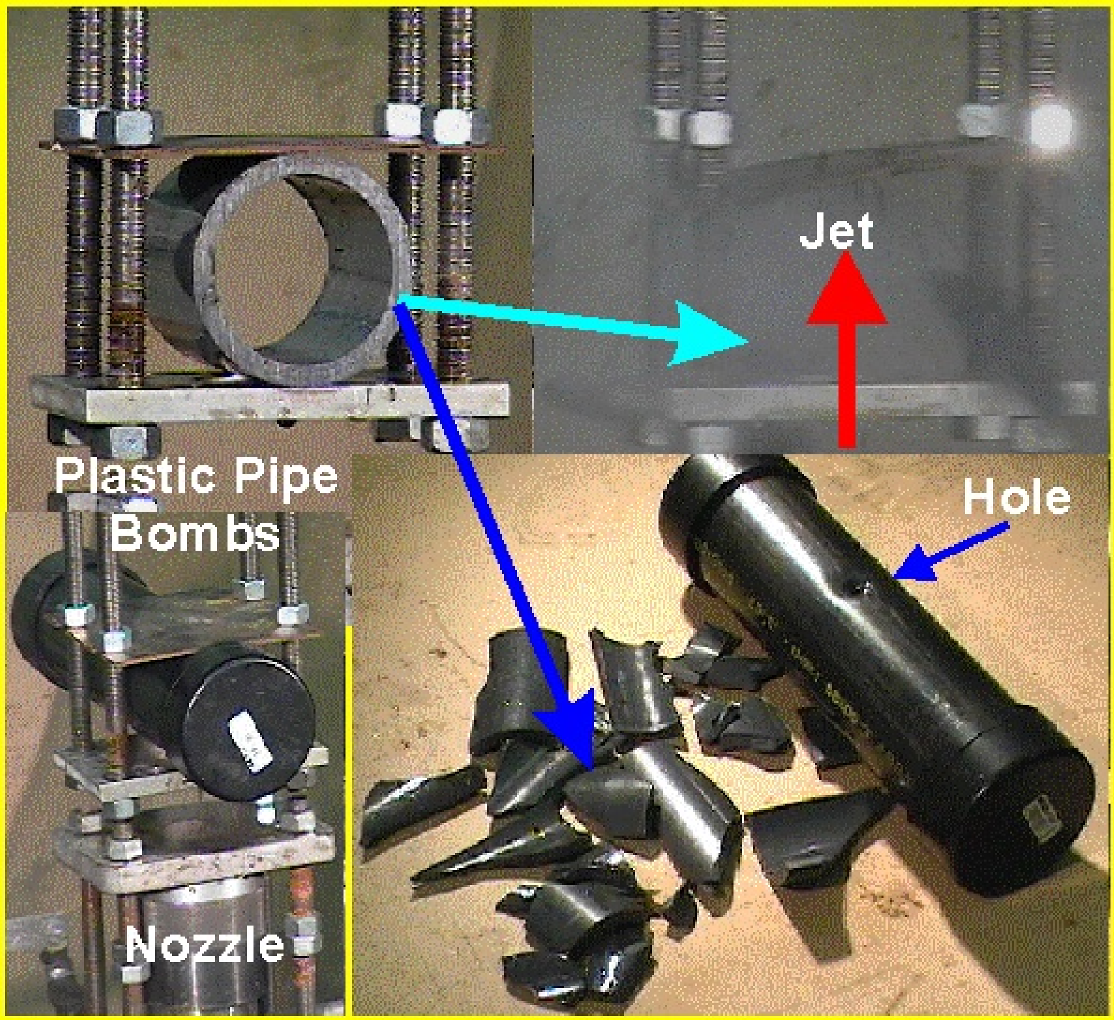

Fig. 15. Simulated tests conducted for neutralizing plastic pipe bombs with the pulsed waterjet. The mode of failure of the bomb was observed to be a function of the property of the material (brittle or ductile). The pipes contained sand.

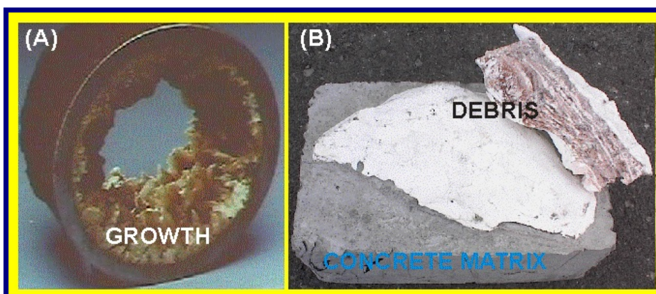

Fig. 16. a general view of the chemical growth in chemical reactor vessels, pipelines, etc. Thickness can be as large as 300 - mm.

Fig. 17. A sample of brick (material to simulate chemical growth) fragmented by the pulsed waterjet generated at a discharge voltage of 10 kV (sample confined between steel plates).

Fig. 18. Hole and fractures made in the chemical resin (unwanted growth) with the pulsed waterjet generated by the discharge. Water pressure = tap water (0.5 MPa), Nozzle diameter = 9.52 mm, Voltage = 6 kV and E_o = 7.4 kJ.