# APPLICATION OF PULSED POWER GENERATED HIGH POWER ULTRASOUND TO WASTE COMMINUTION AND THE RECOVERY OF METALS

**M.P. Wilson[1*], L. Balmer[2], M.J. Given[1], S.J. MacGregor[1], J.W. Mackersie[1], I.V. Timoshkin[1]**

[1] High Voltage Technologies Group, Department of Electronic & Electrical Engineering, University of Strathclyde, Glasgow, UK. (*email: m.wilson@eee.strath.ac.uk; fax: 0141 552 5398)

[2] NRS Technologies Limited, Shrewsbury, Shropshire, UK.

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## Abstract

The disposal of waste materials is an increasing burden on industry across the world. In order to address this problem, the development of viable technologies and recycling paths is required. Often it is necessary to process waste to reduce its size (comminution) or to allow the recovery of high value components entrapped in waste. This paper describes the application of High Power Ultrasound (HPU), generated using pulsed power techniques, to two waste products: glass and stainless steel slag.

## 1 Introduction

HPU is generated when an electrical breakdown, induced by the application of a high voltage pulse with a sub-microsecond rise time, occurs between two electrodes immersed in a working fluid medium such as oil or water. This leads to the formation of a conductive plasma-filled path between the electrodes. Extremely high electrical current (up to tens of kA in the tests performed within the High Voltage Technologies Group) starts to flow through the plasma channel.

The electrical energy, initially stored capacitively, is released into the plasma over tens of microseconds resulting in peak powers of 10 to 100 MW being generated. Such rapid Joule heating of the hot gases leads to the development of a high pressure front at the interface of the spark channel (up to several GPa [5]). This causes the channel to expand in the water with a velocity of 100 to 1000 m/s. This produces a shock wave which separates from the channel, quickly transforming into a high power ultrasound pulse that radiates from the spark discharge [3]. This HPU pulse has pressure amplitude of hundreds of MPa and is extremely wide band due to the very short rise time.

The pressure in the plasma channel at the end of the spark discharge is much higher than the external pressure, $P>>P_0$, and the channel continues to expand after the current in the circuit dies. The channel transforms into a cavity filled with a gas which continues to expand even after the internal pressure becomes lower than the external hydrostatic pressure, $P<P_0$, due to inertia of the surrounding water flow. A rarefaction pressure pulse is radiated in this stage of the bubble development [1].

As the gas-filled cavity generated by the spark discharge reaches its maximum radius, $R_{max}$, the internal pressure becomes much lower than the external hydrostatic pressure, resulting in violent collapse of the bubble and emission of a secondary HPU pulse. Several cycles of expansion and contraction of the gas bubble in the underwater plasma discharge can be observed [2].

Figure 1 shows the dynamics of the cavity radius, electrical energy deposited into the plasma and acoustic energy radiated by the pulsating cavity, generated by the discharge in water in which about 20J of electrical energy has been dissipated in the plasma channel. Calculations have been performed on the basis of the phenomenological approach presented in [4].

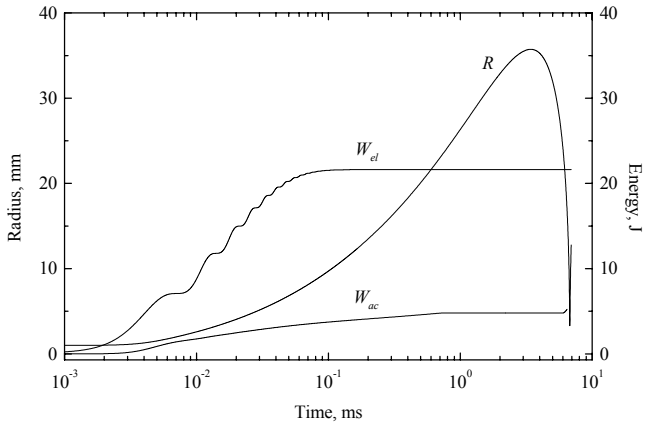


Figure 1: Calculated dynamics of the cavity radius, electrical energy deposited in the spark channel, $W_{el}$, and the acoustic energy, $W_{ac}$, radiated by the pulsating cavity.

The HPU spark generated pulse, with pressure amplitude of hundreds of MPa, impacts upon the materials being processed and causes their fracturing and fragmentation.

In a homogeneous material, the HPU pulse will induce compression, which causes fragmentation. This can be enhanced if flaws or inclusions are present where induced tensile stress can cause cracks to propagate in the material.

With an inhomogeneous material, reflection of the HPU pulse from the boundaries between regions with differing acoustic

impedances leads to an increase in the tensile stress along these boundaries, causing interfacial spalling and separation. The tensile tail of the strain wave and tensile stresses arising upon the reflection of the shock wave from the interface of different components also causes boundary shattering.

This paper reports on tests performed to establish the relevance of the application of HPU to the processing and recycling of materials such as glass and the slag waste product resulting from stainless steel manufacture.

## 2 Experimental Method

The results reported in this paper have been obtained using treatment chambers based round a point-point electrode gap submerged in water. The gap was broken down using pulses provided by an inverting HV pulsed power supply. The breakdown leads to the production of shock waves and HPU which cause fractures to occur in solids within the treatment chamber [6].

Treatment chambers with volumes up to 6836cm$^3$ were used for comminution and metal recovery. These chambers were capable of processing up to 1kg of glass and 3kg of stainless steel slag. The basic design is shown in Figure 2. The electrodes are situated vertically at the centre of the chamber. The HV electrode consists of a 5mm diameter stainless steel rod encased in a 25mm diameter insulating bushing. The earth electrode consists simply of a 10mm hexagonal nut, fixed directly on to a perforated sheet with a 45% open area (in the form of 1.7mm diameter holes). A detachable collection chamber is mounted below the perforated sheet to gather the comminuted material for analysis

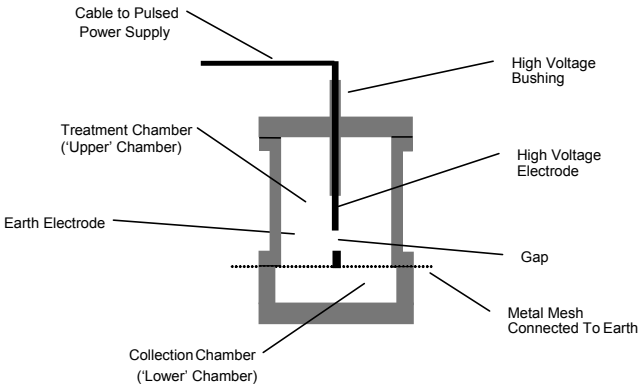


Figure 2: Schematic of test chamber.

The pulsed power supply used in this work was based on a 60nF capacitance which was driven via a 2.5kJ/s capacitor charging unit and switched via a triggered $SF_6$-filled spark gap switch. Charging voltages in the range 30-35kV were utilised, giving expected discharge energies in the range of 27-36.75J. This supply is capable of achieving pulse repetition frequencies up to 60pps. In the results reported in this paper repetition rates of 5-30pps were used, meaning average power inputs from 135W up to a maximum of 1102.5W.

Pulses of 35kV were applied across a 5mm gap to obtain voltage and current waveforms, which showed that the gap typically broke down approximately 14μs after the switch operated. During this time the voltage across the gap decayed to around 32.8kV from its initial value of 35kV. This means that the energy available to the load at breakdown was ~32.3J per pulse with a 35kV charging voltage. The peak current flowing between the electrodes during breakdown has been shown to exceed 5kA.

## 3 Results and Discussion

### 3.1 Tests on Bottle Glass

In order to determine optimum electrical parameters, i.e. pulse energy and pulse repetition rate, to be used for the comminution process, a systematic testing schedule was performed using a 15.5cm diameter chamber with glass as a test material. Glass was chosen as a highly reproducible sample with a market for recycling.

Charging voltages of 30, 32.5 and 35kV were utilised to give expected discharge energies of 27, 31.69 and 36.75J respectively. The lower limit on pulse repetition rate was chosen to be 5pps. This was increased in increments of 5pps up to a maximum of 30pps. Tests were run for all six pulse repetition rates at each chosen charging voltage. In each case the sample chamber was initially loaded with 1kg of bottle glass shards. A standard sample is shown in figure 3.

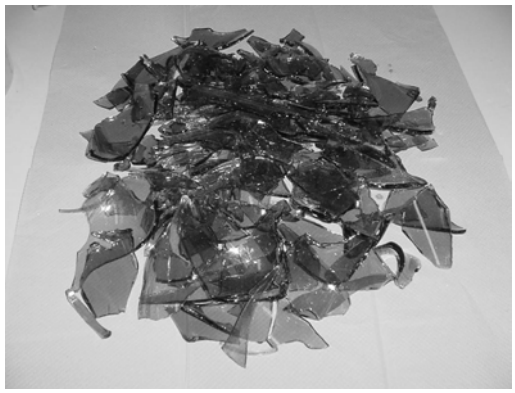

Figure 3: Glass Shards prior to treatment with HPU.

The glass shards were obtained by shattering the glass through mechanical impact. Thicker pieces of glass, i.e. the neck and base, were removed before the sample was placed in the treatment chamber. The average size of the shards was of the order of 20mm.

The material in the treatment chamber was subjected to 60 seconds of HV pulses to generate HPU. Any material in the collection chamber was then removed for drying and weighing, with the material remaining in the upper chamber subsequently treated for a further 60 seconds. This cycle was repeated for 300 seconds in total (i.e. 5 runs) or until the majority of the initial material had passed through the perforated plate to the collection chamber.

After treatment the glass particle size had been reduced to less than 1.7mm. A rounding process had also taken place and the

typical appearance of the glass after processing is shown in figure 4. A series of standard sieves has been used to determine the size distribution of the glass particles after treatment and these results are shown in table 1.

| Particle Size (mm) | Mass (g) | % of Total |
|---|---|---|
| 1.0-1.7 | 65 | 21.9 |
| 0.5-1.0 | 121 | 40.7 |
| 0.3-0.5 | 60 | 20.2 |
| 0.15-0.3 | 35 | 11.8 |
| 0.106-0.15 | 10 | 3.4 |
| <0.106 | 6 | 2.0 |
| **TOTAL** | **297** | **100** |

Table 1**:** Size distribution of glass particles after treatment.

Various tests were performed to examine the influence of the electrical parameters of the impulses applied to the gap on the behaviour of the treatment process.

Figure 4: Appearance of glass after HPU treatment.

Figure 5 shows the cumulative mass of glass processed as the pulse repetition rate was varied between 5 and 30pps. The pulse voltage was 35kV, leading to an expected electrical pulse energy of 36.75J.

At the lowest pulse repetition rate, 5pps, the mass of treated material increased linearly with time. As the pulse repetition rate is raised to 10pps the rate at which the material treated increases and evidence of a saturation effect at longer time periods was observed. For higher pulse rates, >15pps, corresponding increases in the initial treatment rate were observed and the saturation effects at longer treatment times are clearly visible.

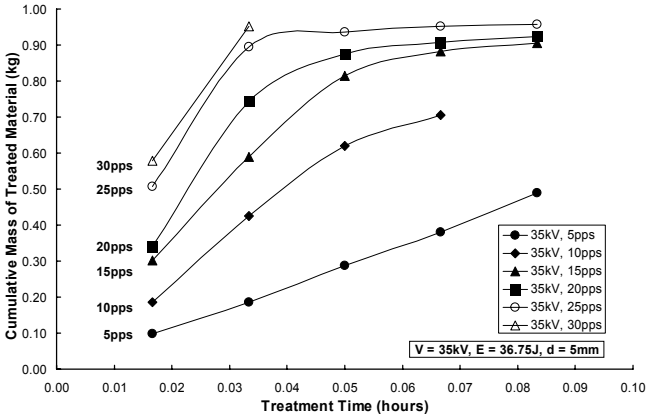


Figure 5**:** Mass of glass treated as a function of time with 36.75J pulses.

The linear relationship between the mass of glass processed and time of treatment observed for the lower pulse rates suggest that the mass of glass processed depends purely on the number of pulses applied to the system, and consequently the number of HPU events which have occurred. The saturation effect observed at the higher pulse rates appears to occur when between 90 and 95% of the glass material originally in the chamber has been treated. At this point the chamber is mostly empty and the efficiency of the process decreases. There are two reasons why the decrease in the processing rate may be occurring. The internal structure and stresses present in the glass particles remaining in the chamber towards the end of the process may be such as to reduce the probability of the glass breaking under the influence of the shock waves. Secondly, attrition may be taking place between the glass particles in the chamber as a result of agitation caused by the HPU pulses. As the quantity of the material in the chamber decreases, the probability of collisions occurring between glass particles also will decrease, leading to a reduction in the attrition occurring in the system. It is not clear at this point how significant collisions between glass particles are to the processing rate for the material.

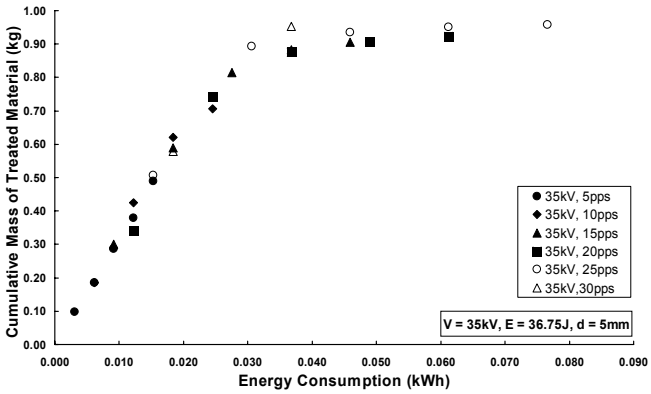


Figure 6: Relationship between mass of glass treated and electrical energy input into the system.

It is informative to plot the relationship between the mass of material treated and the total electrical energy input into the system. This has been done in figure 6. The data for this graph comes from the same set of experiments that were used to produce figure 5.

From the graph it can be seen that independent of the pulse repetition rate used, the results all lie along a common curve. Again the curve saturates when the majority of the material in the chamber has been processed. The linear section of the curve, when less than 80% of the material has been treated, indicates that the mass of glass treated is independent of the pulse repetition rate and depends only on the amount of energy that has been input into the chamber.

It is important to realise however, that although the mass of material processed is independent of the pulse repetition rate, the rate at which this mass is processed *is* affected by the pulse repetition rate.

This can be clearly seen in Figure 5 which shows the rate at which glass is treated in the chamber as a function of the pulse repetition rate. The rate was calculated using the mass of glass that was processed in the first minute of testing. From the results shown in figures 5 and 6, the processing rate would still be expected to be linear at this time with the chamber still containing at least 40% of its original charge of glass. Three plots are shown for varying applied voltages.

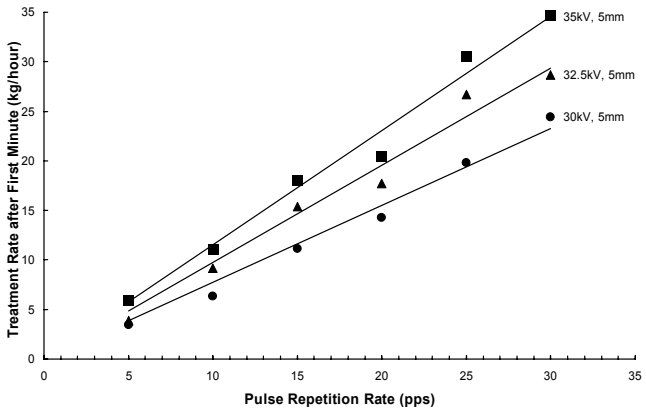


Figure 7: Treatment rate as a function of pulse voltage and repetition rate.

As can be seen from figure 7, as the voltage across the electrodes is increased the rate at which the glass is treated increases. As the pulse voltage increases the energy transferred to the gap increases with the square of the voltage. It is therefore reasonable to conclude that the treatment rate is affected by the energy of the pulses applied. In addition, for each of the voltage levels considered, the rate at which the glass is processed also increases as the pulse repetition rate is increased. Looking at the regression statistics for these lines, we can be confident that there is a linear relationship between the rate at which glass is processed and the pulse repetition rate. If it is assumed that there is no minimum pulse rate required for treatment of the waste to occur it is reasonable to draw the lines of best fit through the origin.

From the gradients of these lines, together with the electrical energy of the pulses at the various voltages, it is possible to calculate the energy cost to treat one metric tonne of glass using the HPU system. These calculations indicate that the cost would be 32kWh per metric tonne.

The data presented in figure 7 above can be re-plotted to examine the relationship between the treatment rate and pulse energy. This has been done for some of the data sets and is shown in figure 8. Although there is only data for three voltage levels at present, the relationship over the energy range considered appears to be linear.

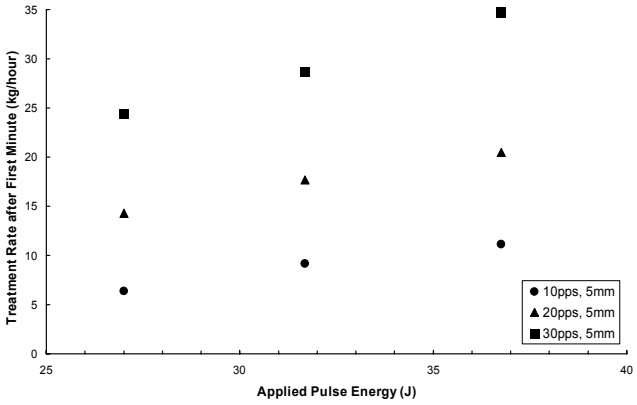


Figure 8: Treatment Rate as a function of applied pulse energy.

Plotting trend-lines through these sets of points in figure 8 allows an estimate to be made for the minimum pulse energy required to cause glass fragmentation in the HPU treatment chamber. Although variation is seen between the results at 10pps compared to the results obtained for 20 and 30pps, the minimum pulse energy lies in the range of 5 to 15J.

From the results obtained in these tests of the HPU treatment system on glass, the following general conclusions can be drawn. The energy required to treat a given amount of waste seems independent of the pulse energy and the pulse repetition rate. However the speed at which glass can be treated seems to have a linear dependence on both pulse energy and pulse repetition rate.

One area of concern in the use of HPU to treat waste material is that as the spherical shock wave propagates through the liquid its peak intensity will diminish, therefore it is expected that there will be a finite volume of material that can be treated with a single HPU source. A larger test chamber (24.5cm diameter) was therefore constructed to determine the effective treatment volume. Preliminary tests in this chamber have shown that the shock waves produced from electrical pulse energy of 36.75J can treat glass out to a distance of 122mm (from the electrodes situated at the centre of the chamber).

### 3.2 Tests on Stainless Steel Slag

Millions of tonnes of waste are generated as a direct consequence of new metal production. In the stainless steel making process for example, by-products take the form of a dense slag – in which is contained a percentage of stainless steel metal. Currently, there is no efficient processing method to extract the metal and hence the waste is stockpiled in landfill sites. For example, a site in Scandinavia currently holds 3 million tonnes of slag waste, of which approximately 60,000 tonnes is made up of entrapped stainless steel nuggets. Current separation processes, such as ball milling, are uneconomic and hence the stocks lie untouched, awaiting a successful processing technology. The use of HPU in conjunction with separation and sorting technologies may provide an economic approach to dealing with this waste, allowing the recovery of stainless steel and the recycling of the silicate slag as a building material.

When dealing with stainless steel slag, the system consists of two phases, stainless steel inclusions and surrounding silicate material. When treated with HPU, the shock waves initially cause the stainless steel to become separated from the silicate matrix. The silicate is then affected by further shock waves, causing it to fragment into smaller particles.

A sample of stainless steel slag was placed in a treatment chamber. The appearance of the slag before treatment is shown in figure 9. The sample mass was 400g.

Figure 9: Appearance of stainless steel slag before treatment.

The system was pulsed at a voltage level of 35kV and a pulse repetition rate of 30pps for one minute. The silicate material that had been reduced in size sufficiently to fall through the grid into the collection chamber was removed, dried and weighed. The system was then pulsed for a further minute. At the end of this period a relatively small quantity of silicate material was found in the collection chamber. The treatment chamber was therefore opened to examine its contents. It was observed that the slag material had almost completely separated from the stainless steel.

The material remaining in the upper chamber was separated into two phases: stainless steel and silicate, and weighed. The results from this test are shown in table 2.

| **Recovered Components** | **Mass (g)** |
|---|---|
| Stainless steel | 170 |
| Silicate remaining in upper chamber after 2 minutes | 61 |
| Silicate collected in lower chamber after first minute | 131 |
| Silicate collected in lower chamber after second minute | 30 |
| **Total** | **392** |

Table 2**:** Breakdown of recovered components of stainless steel slag, starting sample = 400g.

The stainless steel recovered is shown in figure 10 and the silicate material collected in the first minute of treatment is shown in figure 11. As with the tests on glass, a rounding effect had taken place on the comminuted silicate material.

Figure 10: Appearance of recovered stainless steel.

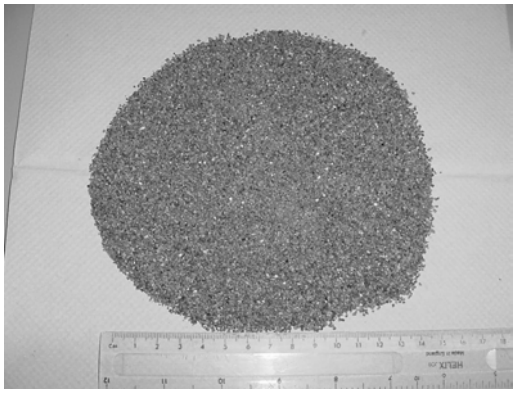

Figure 11: Appearance of comminuted silicate slag.

The results of this test indicate that low pulse energies can effectively separate the silicate material from the stainless steel and can also reduce the size of the silicate material. The input energy required to process the 400g sample was 132.3kJ. Assuming that the process scales in a linear manner

this would suggest an energy input of approximately 92kWh to process 1 metric tonne of stainless steel slag.

## 4 Conclusions

The application of HPU generated by the electrical breakdown of a water gap has been shown to be an efficient method of reducing glass to a powder. This may be of significant interest to people involved in the glass industry, particularly in the area of recycling laminated glass from vehicles.

HPU has also been shown to be capable of separating stainless steel from a silicate matrix as found in stainless steel slag. The electrical energy of the pulses required to generate the HPU can be relatively small, of the order of 35J. The process has the additional advantage of reducing the silicate to a granular form which would be easy to handle and transport, and may provide a useful material for the construction industry. The preliminary results indicate that the energy cost is low.

At present, research is ongoing into characterising the behaviour of the treatment system with stainless steel slag to determine the optimum parameters for the electrical discharges. It is intended to develop a technology demonstration system within the next 12 months.

## Acknowledgements

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