Author:

Dr J Nedwell
SUBACOUSTECH Ltd
Chase Mill
Winchester Road
Bishop's Waltham
Hampshire SO32 1AH
Tel:+44 (0) 1489 891850
Fax:+44 (0) 1489 891851
email: subacoustech@subacoustech.com
website: www.subacoustech.com

Underwater Spark Sources:

Some experimental information.

Report Reference: 440R0102

by

J. R. Nedwell

21 December 1994

Approved for release: ....

Mr K Needham, Principal Consultant

Contents

1. Introduction.

The purpose of this report is to provide information on a substantial development programme on underwater spark sources undertaken by the author.

It is not generally realised that water can be ionised in a similar way to air, leading to a high voltage discharge. Bjorno[1] indicates that the pressure waves resulting from underwater sparks have much in common with those arising from high explosive discharges. A high voltage is generated between a pair of electrodes in the water, typically rising to its peak value within a microsecond. Streamers of electric current are emitted from the electrodes and a weak current will flow. Dependent upon the voltage gradient the breakdown of the water between the electrodes will occur within 5 – 100 μs. A considerable rise in the current occurs, causing a rapid temperature rise and explosive expansion, leading to a pressure wave. The duration of the pulse is typically 3 μs.

Typical source peak pressures generated by underwater sparks are from 10 kPa upwards. While Bjorno indicates that a voltage gradient between the electrodes of 1 kV/mm is sufficient to cause a discharge, it has been found by the author that a gradient of 3-10 kV/mm is more suitable.

There are two main problems with underwater sparks as a source of transient waves:

1. They are inherently dangerous due to the high voltages and electrical charges necessary to reliably generate discharges.

2. The discharges emit powerful radio-frequency interference which disrupts or damages nearby equipment if not carefully screened.

Despite these faults, underwater sparks provide a high powered, reliable and reproducible source, and for this reason several investigatory spark sources have been produced by the author. For reliable and safe operation careful design is essential, for which reason full details of the circuitry, design and problems associated with the construction of a spark source are given in section 4.

[1] Bjorno, L. "A comparison between measured pressure waves in water arising from electrical discharges and detonation of small amounts of chemical explosives". J. Eng.Ind., Trans. A.S.M.E, 1970.

2. Spark Sources and Some Problems Associated with their Use

Initial work by the author concentrated on a "single-ended" spark source, that is, a source wherein the spark was formed between a central charged electrode and an outer concentric earthed electrode. Figure 1 illustrates the major components of the system. These comprise

1. the electrode assembly or "spark head",

2. the capacitor storage and discharge assembly, and

3. the high voltage charging circuitry.

2.1 Measurements Taken using a "Single-Ended" Spark

2.1.1 The influence of gap size on source characteristics

Figure 2 shows two typical measurements of a pressure wave generated by a single-ended spark source. The geometry of the test is shown in Figure 3. The measurements were made by means of a B & K Type 8103 hydrophone connected to a B & K Type 2635 charge amplifier. Figure 4 shows a self contained spark source.

Twenty-four measurements of peak pressure were taken at a radius of 0.25 mm from the source to the hydrophone, using a gap of 1.0 mm and a discharge voltage of 8 kV. The mean recorded peak pressure was 0.4×10^5 Pa indicating a source strength of 0.1×10^5 Pa.m. The normalised standard deviation was 0.24. It was noted that discharges were occurring along the surfaces of insulators in the high voltage connectors connecting the spark head to the discharge equipment, although these were rated at 16 kV breakdown voltage. This was thought to be due to E.H.T. transients causing ringing in the supply cable to the spark head of substantially greater than the E.H.T. working voltage. The supply line and connectors were thus upgraded to 40 kV breakdown voltage.

A series of firings were recorded at distances from 0.971 m to 0.35 m to determine whether the attenuation of peak pressure was inversely proportional to radius of measurement, as expected for a weak monopole. The results of these firings are shown in Figure 5. The peak pressure was averaged over ten recordings at each distance. This was performed under two test conditions, with and without the supply cable earthed at the support tube. It may be seen that, within the limits of experimental accuracy, variation of peak pressure is inversely proportional to radius of propagation. The increased source strength with the cable earthed at both ends may be due to reduced inductance in the discharge circuit.

Figure 6 shows the measured source strength of an 8 kV spark as a function of the electrode gap, averaged over 12 recordings. The peak pressure is approximately given by:

$P_m = k\,(l^{0.84}/r)$

where $k = 2.5 \times 10^5$ and l is the gap in mm.

The measurements using a gap of 1.3 mm were excluded in calculating this curve, as irregular firing occurred.

Figure 7 shows the standard error of the peak pressure as a function of gap size. It may be seen that there is a high degree of scatter in the results, but in general the variation in amplitude between successive firings decreases as the gap decreases. A suitable compromise between amplitude variations and excessive precision of construction and regulation of the spark gap is achieved by using a gap of about 0.25 mm. A standard error of about 0.065 is achievable with this setting.

2.2 The scaling of spark generated waves for linear response

Where a repeatable signal is required and the structure under test is linear in its response, scaling of results may be performed relative to the output of a reference hydrophone at a fixed distance from the source. Figure 8 shows a typical example of the repeatability of the scaled impulses from two successive sparks. The geometry of the test is shown in Figure 9. Two successive recordings were made, and the time histories scaled by the peak voltage recorded by the reference hydrophone, after low pass filtering at 48 dB per octave with a 100 kHz cut-off point. It may be seen that the time histories agree closely with one another. The phases of the FFT's of the time histories show excellent agreement. The moduli also show good agreement; much of the variation that does exist is thought to be due to quantisation noise caused by A/D conversion.

3. The Balanced Spark Gap

3.1 The reasons for balancing the spark

When a spark is generated underwater, the voltage on the electrode coupled to the capacitor rapidly rises to the working voltage.   The rapid change in voltage causes a very strong electromagnetic field to be generated.   In addition, a strong potential gradient is generated in the water as the electrical screening of the spark gap cannot be complete if it is to be acoustically transparent.

The effect of the electromagnetic field may be seen in Figure 2 by the large spurious interference signal at the start of the recording, which considerably exceeds the amplitude of the true signal from the recording hydrophone. This is caused by the electromagnetic field from the spark inducing currents in components and conductors in the associated test and measurement equipment.

In use, it was found that the source caused malfunctioning of computers within a 20 metre radius. In particular, word processors in an adjacent building crashed every time that the spark source was used. While considerable efforts were made to screen the interference from the spark, including a Faraday cage around the test tank, it was not found possible to completely avoid these effects.

An alternative approach is to generate the spark between two electrodes charged to an equal, but opposite, voltage. Any electromagnetic field radiated from the circuit carrying the negative voltage will be nearly cancelled by the field from the circuit carrying the positive voltage.   Additionally, the potential gradient generated in the water surrounding the spark will be similarly reduced, with consequent improvement in safety. In practice, the electrodes are fed by a twisted pair of wires with about 1 turn per 5 cm.

The discharge equipment is essentially equivalent to two single-ended high voltage discharge circuits, working at identical but opposite voltages and discharging into each other via the water spark gap.   The two primary discharge gaps are fired by the same coil to ensure that the two electrodes change voltage simultaneously. Were this not the case, then a discharge could occur between one electrode and the surrounding Faraday cage. Further details of the double ended discharge equipment are given in Section 4.

The balanced spark gap was found to behave in a similar way to the single-ended spark in respect of repeatability of waveform. The radiated field was reduced substantially, to the point where no special precautions to prevent interference with adjacent equipment were necessary.

3.2 Measurements of Spherical Asymmetry of the acoustical field from the Balanced Spark Source

The volume occupied by the spark during discharge is acoustically very small. The wave radiated from it would thus be expected to be very nearly spherically symmetric.

Figure 10 shows repeatability of the scaled impulses from two successive sparks. The geometry of the test is shown in Figure 11. It may be seen from the arrival time of the pressure wave that the positioning of the hydrophones is accurate. The moduli of the FFT's show a considerable difference at 10 kHz, 25 kHz, and 100-130 kHz. The source is seen to be non-symmetrical at these frequencies, as the receiving hydrophone has an omnidirectional sensitivity. This is probably caused by acoustic scattering by the structure supporting the electrodes. This needs to be relatively massive to ensure that the electrodes are not forced apart under the influence of the spark generated between them. More refined design of the electrode supports would be likely to reduce the degree of assymmetry.

4. Technical information: The High Voltage Spark Discharge Assembly

4.1 The spark head

The spark head comprised a 1 metre length of 6.5 mm bore brass tubing support, soldered to the outer braiding of a 4-metre length of coaxial high voltage cable (rated at 40 kV). The central core of the cable passed through the tube and protruded by 15 mm, being clamped into the tube by a plastic screw. A spark gap was formed between the- cut end of the core and an adjustable screw, attached to the tube rather in the fashion of an automobile spark plug. The gap was surrounded by a 15 mm radius sphere of fine wires as a Faraday Cage to reduce radiated electrical fields. At its other end, the cable was terminated by a high voltage connector for attachment to the capacitor discharge equipment.

It was found to be essential that the support tube was earthed independently via a heavy duty earth cable attached to a remote earth point, despite being earthed via the braiding of the cable to the capacitor discharge equipment. This was due to the coaxial cable acting as a transformer when pulses of current passed down its core and inducing high voltages on the unearthed end of the braiding: voltages in excess of 10 kV were measured before the extra earth was added.

4.2 The capacitor discharge equipment

This is shown diagramatically in Figure 12. It comprised a high-voltage capacitor connected to a high voltage switch formed by a pre-ionizable air spark gap. This switch essentially relied upon the semiconducting properties of air. It was established in initial tests that while silicon semiconductor switching devices were available which could work at the voltages required, pro-gressive damage to them was caused by the high transient discharge currents, eventually resulting in their destruction.

Initial tests indicated that a discharge energy of about lOJ was necessary for the reliable formation of a spark underwater. It was intended to use the lowest possible discharge energy for maximum safety. It should be clearly noted, that lOJ of electrical energy discharged into the human body is capable of causing death, and 2J capable of causing a severe shock.

The design of the pre-ionizable spark gap is shown in Figures 13. Two heavy primary electrodes form, with the air gap between them, the current carrying route through the switch. A fine trigger electrode is interposed centrally in the gap between the two primary electrodes. This gap is adjustable and the electrodes are supported by an insulating P.T.F.E. block.

The operation of the spark gap is as follows. Under operating conditions, when the capacitor is charged, the electrode connected to the capacitor will be at operating voltage. The electrode connected to the load will initially be at ground potential due to the finite resistance of the water gap. The gap between the primary electrodes is set such that the voltage gradient in the air gap is rather lower than that required for a spontaneous discharge. A voltage gradient of 750 V/mm is generally suitable. The proportion of the gap occupied by the trigger electrode is ignored in this calculation, as no voltage gradient will exist over it. It may be assumed that the voltage gradient will be equal in both halves of the gap as capacitor C3 shown in the figure allows the trigger electrode to float at a potential between that of the two electrodes. Electrode to electrode capacitance and minor airborne discharges will tend to retain it at a suitable level.

To initiate a discharge, a trigger pulse is applied to the trigger circuit at point A, turning on thyristor TH1. Capacitor C2 is normally held charged to 300V via resistor R1. It dis-charges via thyristor TH1 to ground, causing a rapid flow of current through the primary of coil L1. This in turn causes a flow of current in the secondary and through capacitor C3, causing a high voltage to appear on the trigger electrode. Whatever the polarity of the voltage, the voltage gradient in one or other half of the spark gap will as a result exceed that necessary to cause ionization of the air. Ionization occurs, leading to a low-resistance path being formed between one primary electrode and the trigger electrode- Current flows to the trigger electrode, which rapidly changes in potential as the capacitor C3 charges, until the voltage gradient in the other half of the spark gap is such that it, too ionizes. The discharge current rapidly increases as the main storage capacitor C4 discharges. The underwater spark gap now represents the largest discharge circuit resistance and consequently the entire voltage of capacitor C3 appears across it, leading to an underwater discharge as previously described.

Provided that the current supplied to thyristor TH1 by resistor R1 is below its holding current, the circuit will reset and be ready for discharge after a time determined by the time constant of R1 and C2, or the charging time of the main storage capacitor. Discharge rates of 10 discharges per second are quite feasible using the equipment described-

4.3 High voltage charging circuit

Commercial high voltage supplies are expensive and not particularly suitable for charging capacitor discharge circuits for generating underwater sparks, due to the need to run cables carrying the full voltage into close proximity with water. A more desirable approach would be to use a circuit capable of generating the required voltage, able to fit inside the box containing the discharge equipment, yet powered by a low voltage. The risk of accidental contact with a high voltage would thus be greatly reduced.

A suitable circuit, using an automobile ignition coil as a high voltage transformer, is shown in Figure 14. It is capable of generating 15 kV at about 1 mA. The circuit utilises the voltage resonance of the coil at about 60 kHz. A stable oscillator generates a sinusoidal signal at this frequency. It is fed to a power amplifier capable of generating 70V r.m.s. at about 150W. This is fed to the low voltage terminals on the coil. The resultant E.H.T. at about 10 kV r.m.s. is rectified by an E.H.T. diode and fed to a small capacitor for some smoothing of the waveform. The smoothed voltage may be measured by means of a high-voltage probe connected to a D.V.M. Tuning of the frequency to suit the individual coil is performed to enable the maximum rectified voltage to be generated with the minimum amplifier output voltage. This reduces losses in the coil which may otherwise cause rapid heating.

The practical upper limit of working voltage is set by the ionization and breakdown of the insulating surface of the ignition coil to about 18 kV. Prior to this, ionization may be seen in the vicinity of the E.H.T carrying surfaces as a blue corona. It is important to avoid sharply radiused points on the E.H.T conductors, as these carry high charge concentrations and are thus liable to cause discharges. A high-value resistor is included in parallel with the smoothing capacitor so that no charge is held when the circuit is deactivated.

Figure 1. The main components of a spark source

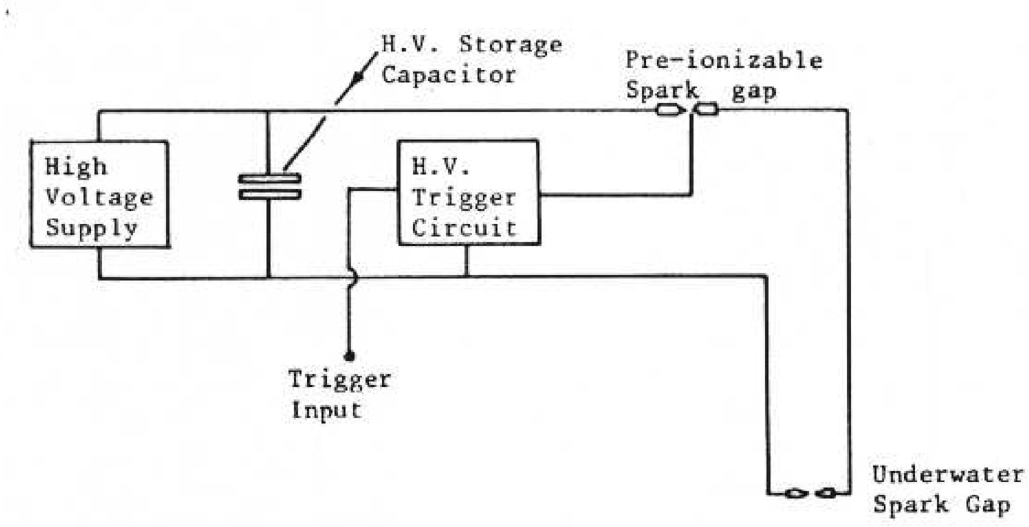


Figure 2. Two typical measurements of a pressure wave generated by a single-ended spark source

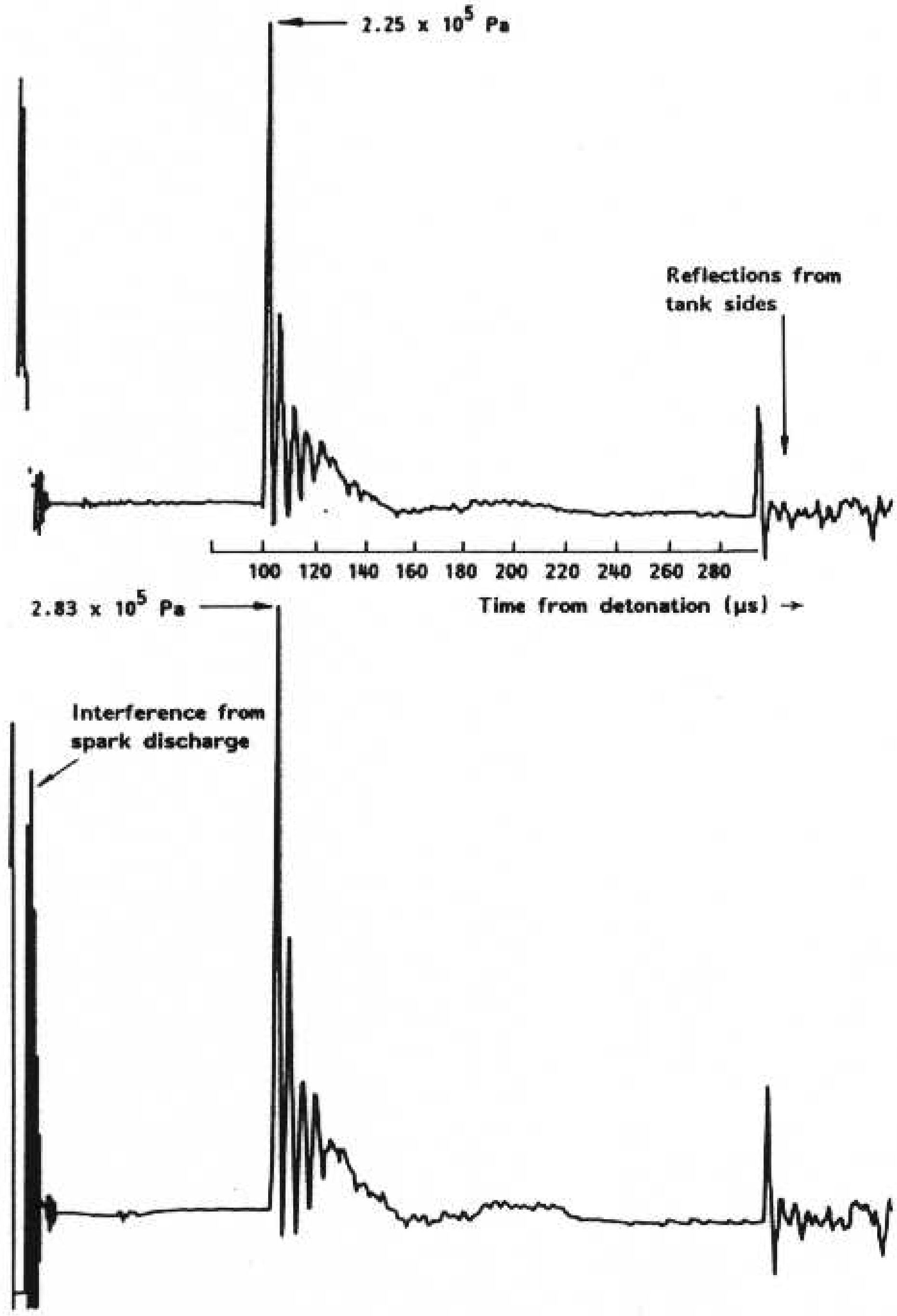


Figure 3. The geometry of the spark measurements

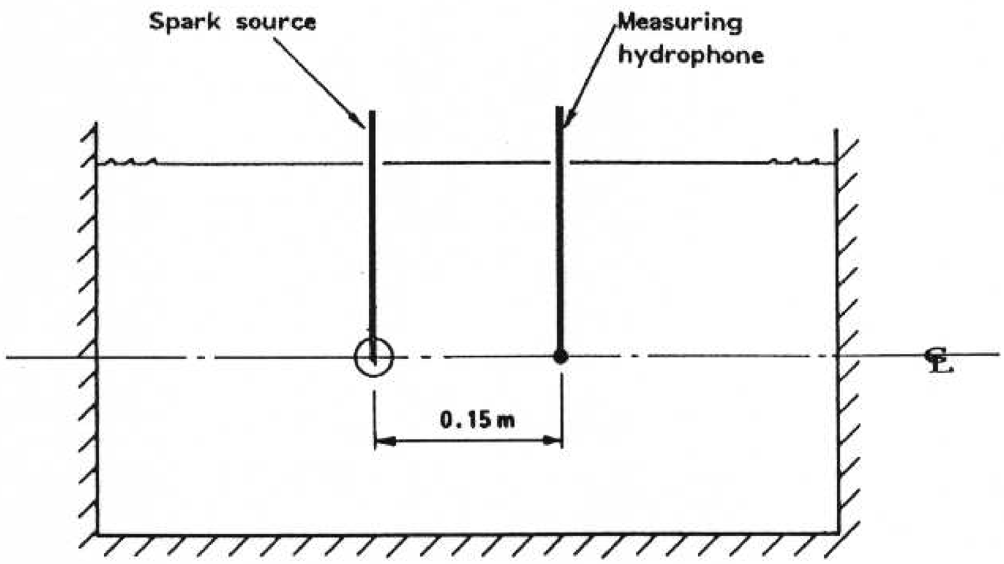


Figure 4. A self contained spark source

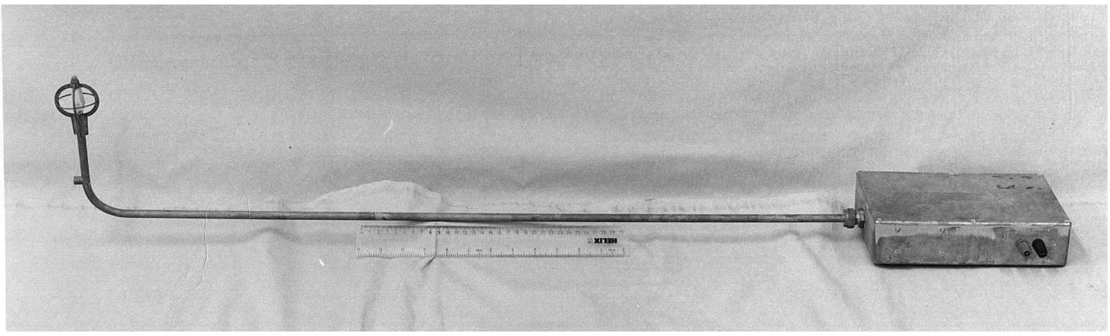


Figure 5. Measurement of Source Level

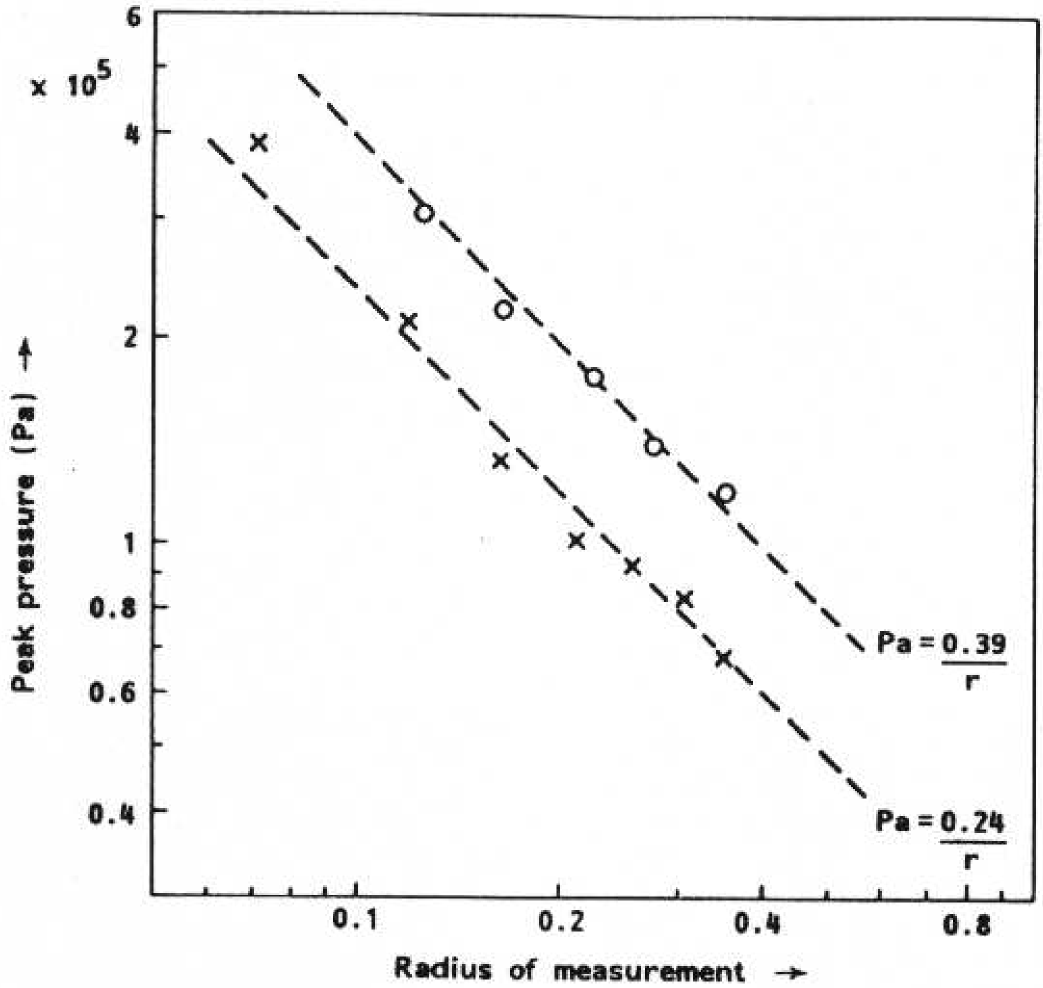


Figure 6. The measured source strength of an 8 kV spark as a function of the electrode gap, averaged over 12 recordings

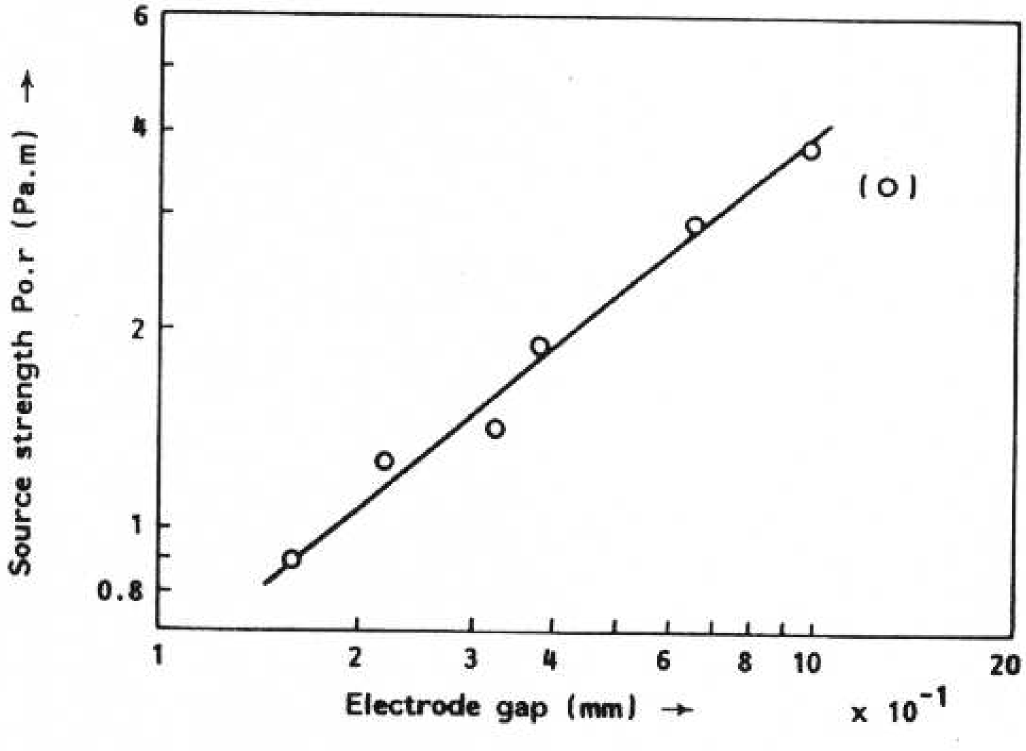


Figure 7. The standard error of the peak pressure as a function of gap size

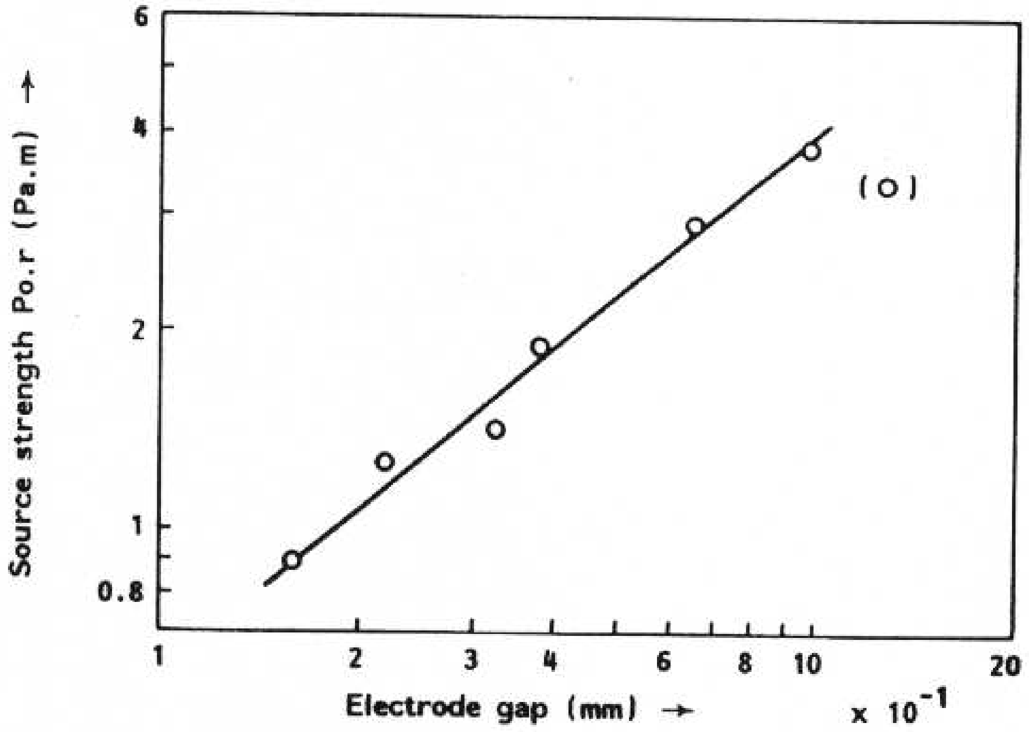


Figure 8. A typical example of the repeatability of the scaled impulses from two successive sparks

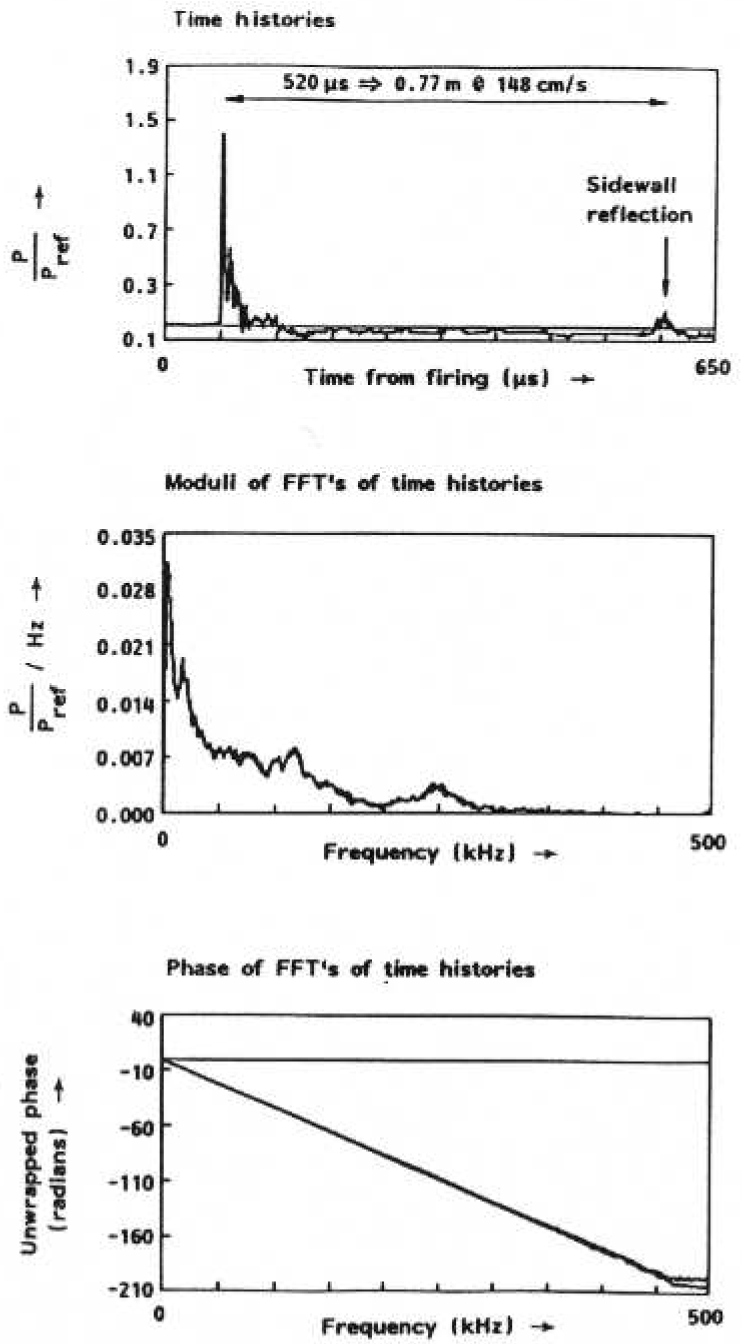


Figure 9. The geometry of the test of repeatability of successive sparks.

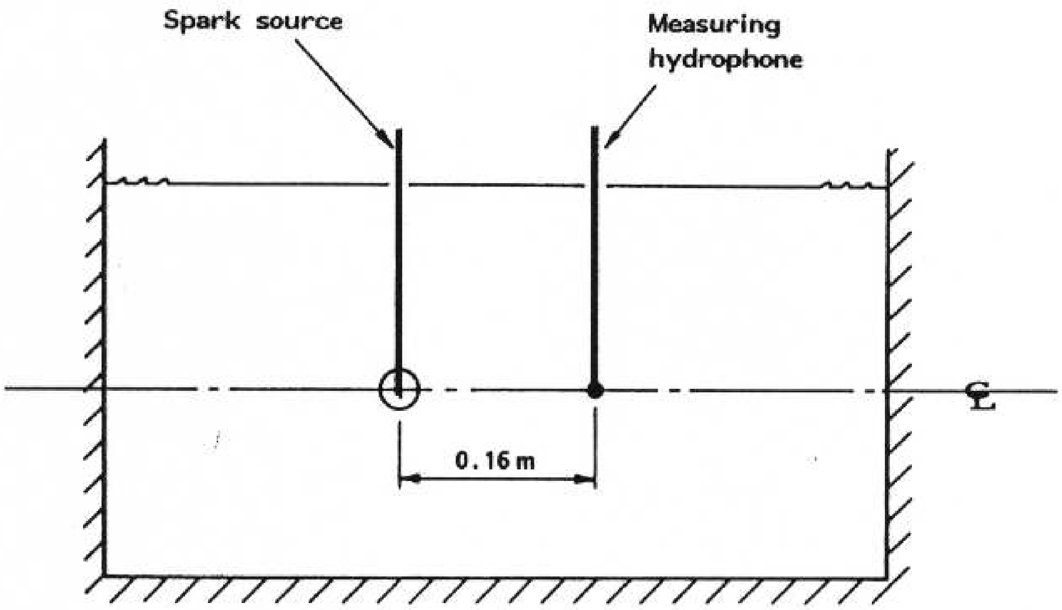


Figure 10 The symmetry of spark impulses.

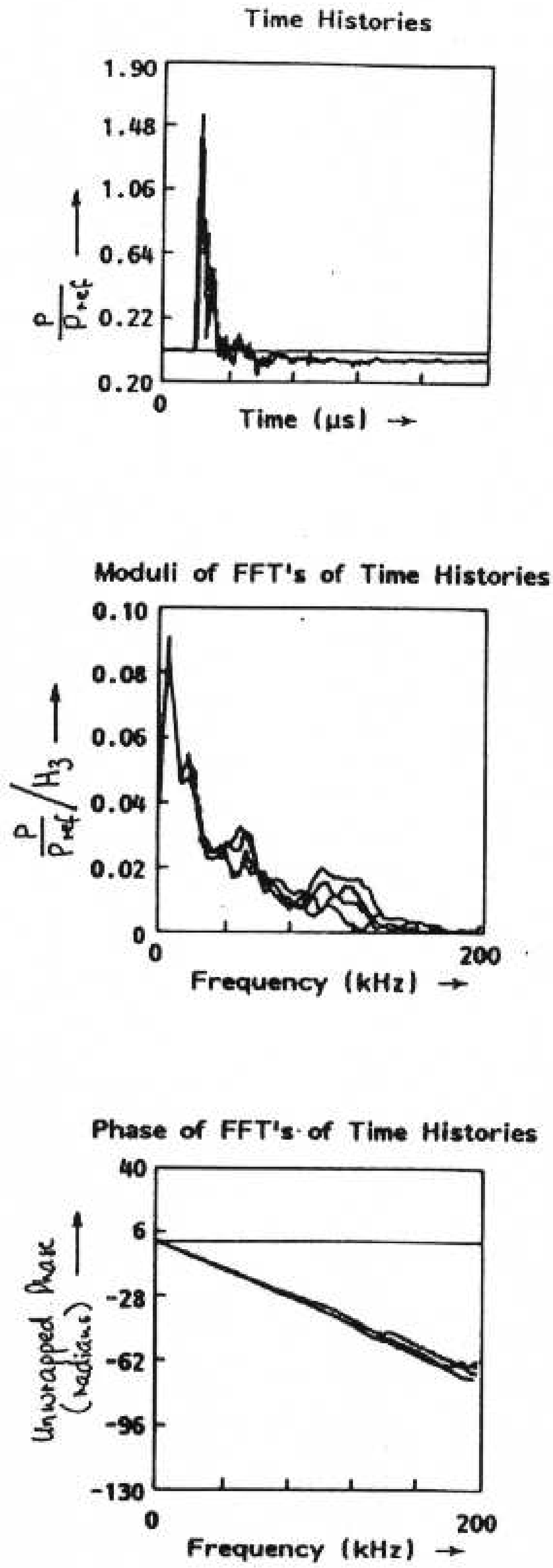


Figure 11 The geometry of the test for symmetry of spark impulses.

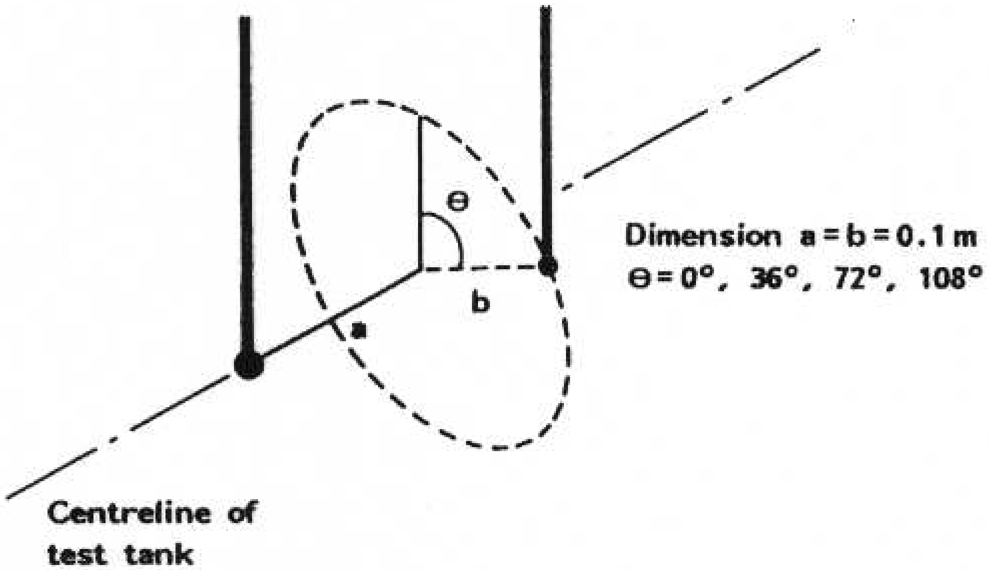
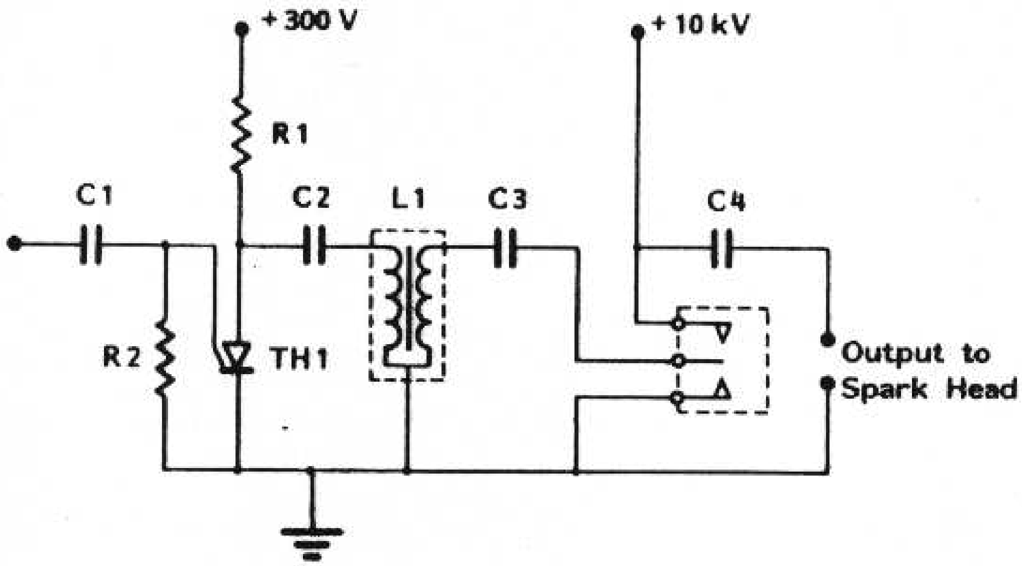


Figure 12. A diagrammatic of the Capacitor Discharge equipment.



Components List :

C1	0.1 µF Polyester
C2	4 µF 400 V
C3	10 µF 20 kV
C4	1 µF 20 kV
R1	1 MΩ
R2	1kΩ
L1	Pulse Transformer 500 : 1

Figure 13 The design of the pre-ionizable spark gap

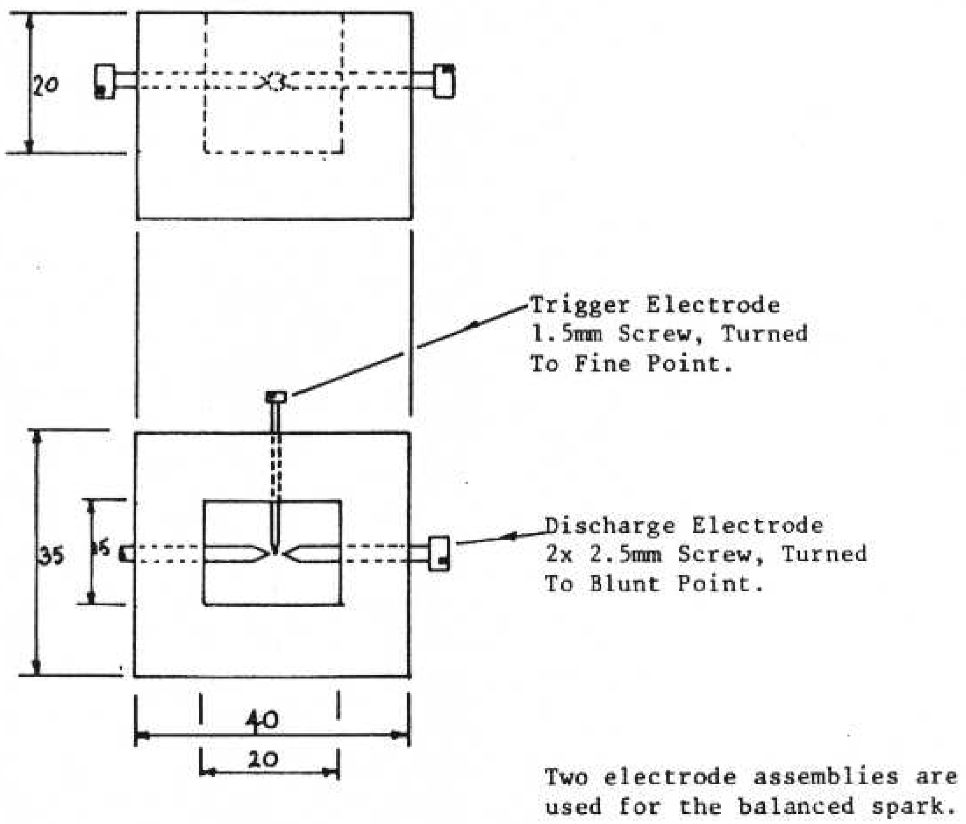
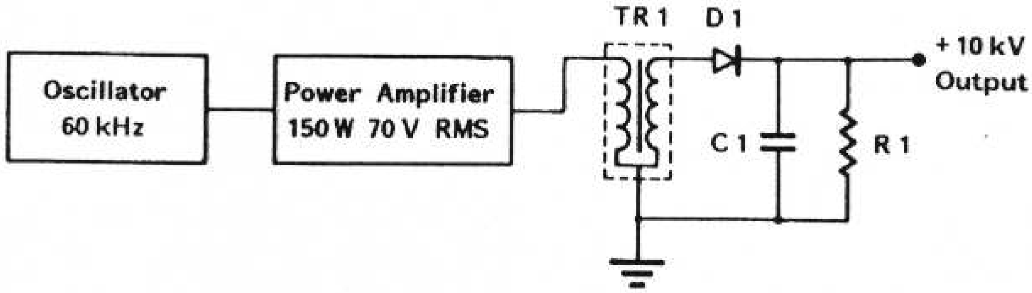


Figure 14 The high voltage charging circuit



Components List :

C 1 0.1 µF 20 kV
R 1 50 MΩ
D 1 BY 713
TR 1 Automobile Ignition Coil