PRECISION BLASTING TECHNIQUES FOR AVALANCHE CONTROL

Kevin M Powell *
Delta K Explosive Engineering Systems Ltd., Dunton Green, Kent , UK

ABSTRACT: Experimental firings sponsored by the Center For Snow Science at Alta, Utah have demonstrated the potential of a unique prototype shaped charge device designed to stimulate snow pack and ice. These studies, conducted against stable snow pack, demonstrated a fourfold increase in crater volume yield and introduced a novel application of "shock tube" technology to facilitate position control, detonation and dud recovery of manually deployed charges. The extraordinary penetration capability of the shaped charge mechanism has been exploited in many non-military applications to meet a wide range of rapid piercing and/or cutting requirements. The broader exploitation of the potential of the shaped charge mechanism has nevertheless remained confined to defence based applications. In the studies reported in this paper, the inimitable ability of the shaped charge mechanism to project shock energy, or a liner material, into a highly focussed energetic stream has been applied uniquely to the stimulation of snow pack. Recent research and development work, conducted within the UK, has resulted in the integration of shaped charge technology into a "common" Avalauncher and hand charge device. The potential of the "common" charge configuration and spooled shock tube fire and control system to improve the safety and cost effectiveness of explosives used in avalanche control operations was successfully demonstrated at Alta in March 2000. Future programmes of study will include focussed shock/blast mechanisms for suspended wire traverse techniques, application of the shaped charge mechanism to helibombing, and a feasibility study into the design and development of non-fragmenting shaped charge ammunition for military artillery gun systems.

KEYWORDS: Avalanche, Explosives, Blasting, Shaped Charges, Artillery.

1. INTRODUCTION

This paper presents the results of a series of experimental studies conducted over the last two years to investigate the potential of the shaped charge mechanism to enhance the shock and blast yield of the basic explosive charge used extensively in avalanche control operations.

The shaped charge effect, in the form of an unlined cavity in an explosive charge, was discovered in the late 1800s through mining activities. Although there are various examples of the introduction of a metallic liner into the hollow cavity throughout the early 1900s, the "lined" shaped charge effect and its extraordinary penetration potential was not reported formally until the 1930s. Military warhead designers soon recognised the potential of the shaped charge in the anti-armour role. The shaped charge has therefore remained the principal warhead mechanism embodied within anti-tank mines and missiles to date.

A shaped charge device can produce controllable and highly directional sources of energy that can be tailored to produce a wide range of output characteristics. These include: purely focussed/directed shock transmission with or without significant penetration effects; shallow plate perforation and/or punching operations; continuous linear effects for more complex cutting/severing applications; ejection of a solid flight stable projectile for accurate long range shock transmission, perforating or disruption and finally deep narrow penetration. Potential applications of the shaped charge mechanism therefore far exceed that of its penetration capability, for which it is more commonly recognised.

2. THE SHAPED CHARGE MECHANISM

The basic components of a typical cylindrical shaped charge device are shown in Figure 1a. The variant shown consists of a thin conical liner (usually a metal), a body containing a small quantity of explosive, a means of initiation and a

* Correspondence author address: Kevin M Powell, Delta K EES Ltd., 170 London Road, Dunton Green, Kent, United Kingdom, TN13 2TA; tel & fax:01732 779018; e-mail: Delta_K@Compuserve.com

system to transfer and control the detonation geometry.

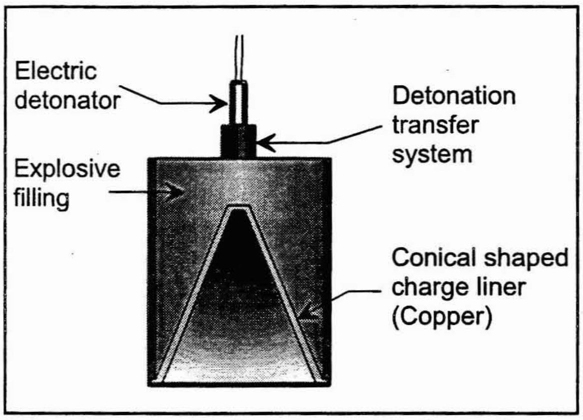

Figure 1a: Principal components of a conical shaped charge

Figure 1b shows the progression of the liner collapse process resulting from a simple axial initiation of the explosive filling. As the detonation front passes over the liner at a velocity of about 7,800m/s, the applied pressure, in excess of 250kilobars, causes the liner material to flow as a fluid towards the charge axis. As the liner material is steadily fed into the axis, upon collision, a stagnation zone is formed about which approximately 1/3 of the liner material turns to form a high velocity "jet" flowing along the axis, away from the point of initiation and the remainder gathers in the opposite direction to form a solid "slug". The slug is in effect the waste product of the liner collapse process. It travels at less than 1/10th of the jet tip velocity, at about 800m/s, typically that of a rifle bullet.

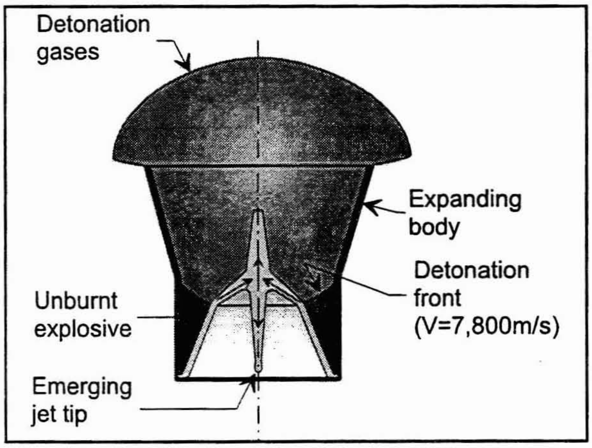

Figure 1b: Early stage of the liner collapse process 5 microseconds after initiation.

Figure 1c shows a sequence of the jet development at 30, 33 and 40μs after initiation, the explosive having fully detonated after 7μs. Figure 1c also shows that, for the type of shaped charge shown in Figure 1a, a velocity gradient of about 6000m/s would exist between the tip of the jet and its tail. This gradient causes the jet to stretch whilst in forward motion until it eventually breaks up into a number of individual elements, each being capable of a specific amount of penetration into a given target medium. The slower "Slug" separates from the tail of the jet after approximately 60μs.

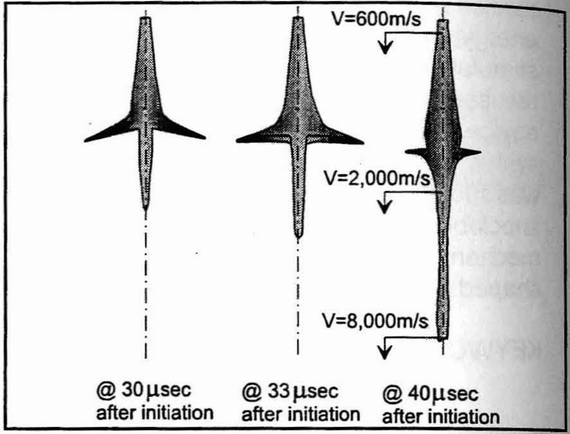

Figure 1c: Final collapse of the shaped charge liner and subsequent extension of the jet following complete detonation of the explosive.

At an impact velocity of 7,800m/s the local loads arising from the pressure created at the point of impact between the jet and target material greatly exceed the mechanical properties of all known materials. The response of materials under such loading conditions is to behave hydrodynamically i.e. as a fluid - *Cook (1958)*. Consequently, if one considers the simplified case of a jet of uniform length l, with uniform velocity v, penetrating a target at uniform velocity u, given continuity of pressure across the junction between the jet and target, Bernoulli's theorem gives:

$$\rho_j (v - u)^2 = \rho_t u^2 \tag{1}$$

where ρ_j is the density of the jet and ρ_t is the density of the target. Now the penetration p is given by ut_f where t_f is the time required to consume the jet, which is simply $l/(v - u)$. The total penetration is therefore:

$$p = l \sqrt{\frac{\rho_j}{\rho_t}} \qquad (2)$$

For practical purposes the length of the penetrating jet is normally determined from flash radiographic diagnostic techniques.

Equations (1) and (2) represent an idealised model of the penetration process where the "root density" relationship of equation (2) dominates the penetration process. The peculiar consequences of this relationship are that for a given length of jet and jet material, the penetration into two materials of similar density but otherwise dissimilar mechanical properties (typically a structural aluminium alloy and concrete) will be similar.

However, the response of the above two target materials to penetration by a shaped charge jet will be very different. Since the tensile strength and ductility of concrete is significantly lower than that of the aluminium alloy, unless the concrete target is relatively massive or heavily confined, there will be a tendency for the high internal pressures and associated compressive shockwave to cause a catastrophic and explosive disassociation of the target. This is particularly true of an ice target. Consequently, with an appropriate layout of shaped charges it is possible to spal or scab a free surface. The mechanism and effect is therefore similar to that of bench blasting used by the quarrying industry - but without the need to drill and pack explosives!

In general, the majority of shaped charge applications tend to exploit the extraordinary penetration potential of long narrow jets. However, the high kinetic energy packaged in the shaped charge jet also offers the potential to stimulate a range of secondary reactions which do not necessarily have to be accompanied by significant levels of penetration. This potential to generate a highly energetic environment, purely from the kinetics of particle interaction, is the root of applications presented in this paper. It is, furthermore, a simple step to consider bringing a wide range of potentially reactive materials together, which in normal circumstances would remain relatively inert.

3. EXPERIMENTAL ICE AND SNOW PACK TARGETS

In order to obtain detailed, non-volatile, data from snow pack targets, research studies were confined to stable snow pack located at the foot of a basin area in Alta. The charges were fired horizontally at a depth of 1.2m below the surface as shown in Figure 2.

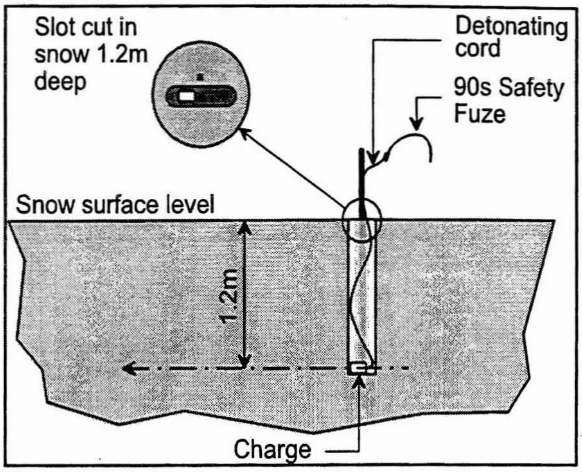

Figure 2: Charge set-up for experimental firings in stable snow pack.

Early work studied and characterised the response of snow pack to jets produced by classical high precision metallic shaped charge liners. A typical result of a borehole produced by a copper lined variant is shown in Figure 3. Note the relatively deep penetration of some 5m in length, vertically above which is a significant level of heave generated by the passage of the jet.

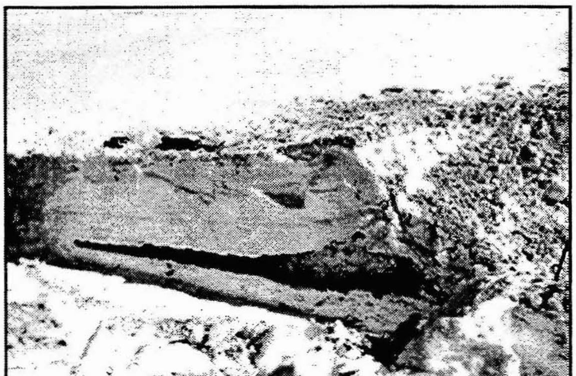

Figure 3: Vertical section through a typical borehole produced by a copper lined shaped charge in stable snow pack.

To fully characterise the response of the full spectrum of snow pack states, ranging from fresh snow to near solid ice, typical of cornice build-ups, it was necessary to conduct tests against ice targets.

Unconfined ice was expected to have a violent response to shaped charge attack and, although inducing such an "explosive" response was one of the main objectives of these studies, once again, a non-volatile target was required to enable penetration data to be recovered. Many difficulties were experienced finding massive ice targets suitable for this work, which resulted in the design of a fabricated configuration. This consisted of a stack of water ice blocks, surrounded by a stack of steel confinement cylinders as shown in Figure 4.

During construction the ice blocks were packed out with sand and after firing the steel cylinders were progressively removed from the top of the target to allow the ice blocks to be sectioned to reveal the borehole profile.

Figure 4: Experimental ice target being sectioned to reveal the borehole produced by a copper shaped charger liner.

4. THE DESIGN OF SHAPED CHARGES FOR AVALANCHE CONTROL APPLICATIONS

The most effective way of coupling and transferring energy into a target medium via a supersonic impact is to improve the impedance match between the target and impacting medium. In practice this comes down to attempting to match densities. For simple shaped charge designs with metallic liners, magnesium and aluminium offer the most practicable solution against ice and snow.

However, a jet produced by solid metallic liners tends to have a narrow cross sectional area and consequently a small area of intimate contact with the target medium. This tends to produce high penetration with low diametric effects and this is substantiated by the results of early studies, results from which have been shown in Figures 3 and 4. The design objectives to defeat ice and snow pack were to induce two principal effects: firstly, a significant increase in the effective surface area of the jet material exposed to the environment within the target during the penetration process, and secondly, attack of a larger cross sectional area of the target medium.

To meet these requirements, two basic shaped charge configurations were tested, one with a conical liner geometry and one with a more complex cylindrical liner geometry. These were filled with C4 explosive and designated Type 1 and Type 3 respectively. The performance of these charges was compared directly to a control set of 4 lightly cased blast charges each containing an explosive content of 1kg.

Charge Types 2 and 4 consisted of smaller pairs of charges with geometries identical to those of Types 1 & 3 respectively. In each case the total explosive content for the paired charges was 1kg of C4 and the charges were arranged such that the jets produced by each pair would collide on the charge axis after detonation. The general arrangement for this paired configuration is shown in Figure 5.

The explosive compositions used in the four control blast charges consisted of: Pentolite, in the form of a standard Avalauncher round (without tail fin); Trigran, a prilled aluminised TNT based Canadian military explosive; C4, an RDX based military plastic explosive and ANFO, a common commercial blasting composition.

These compositions were chosen to introduce an array of detonation output characteristics ranging between high shock pressure with short duration to low detonation pressure with long duration. Typically, the short duration, high shock

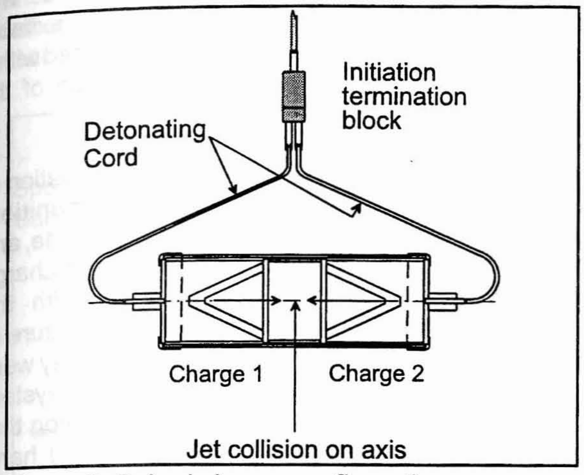

Figure 5: Paired charge configuration comprising 2 scaled down charges (Type 1 shown) co-axially arranged such that the jets collide upon simultaneous charge detonation.

compositions are used for fracturing i.e. fragmentation effects, and the compositions, producing longer duration lower shock pressures, are used for pushing and heaving i.e. trenching.

5. RESULTS FROM EXPERIMENTAL FIRINGS

The cross section of the crater profiles produced by the 4 control blast charges and 4 experimental shaped charge configurations are shown combined in Figure 6.

It is important to recognise that these were far from an exhaustive series of tests in terms of absolute performance of each composition or device. Indeed only one shot of each type was fired. The objective of the study was to determine the cratering characteristics of a group of simple "bare" charges with differing detonation pressures and power. These could then act as a broad baseline against which the benefits of various shaped charge configurations could be demonstrated.

For the baseline "bare" charges, two compositions with high detonation pressure (C4 and Pentolite) were chosen for broad comparison with two compositions of a lower detonation pressure (Trigran and ANFO). The crater profiles produced for these 4 control charges are shown on the left side of Figure 6. It is immediately apparent that Trigran produced the highest crater volume of 5.2m^3, followed by C4 at 4.6m^3, ANFO at 3.2m^3 and Pentolite at 2.7m^3.

Trigran is a powerful Canadian blast composition, specifically formulated for battlefield engineering applications. Trigran therefore represents the upper limits of what could be achieved with modern military explosive compositions, should it become commercially available. Note that the open mouth of the crater suggests early venting and that it may have performed better if placed a little deeper.

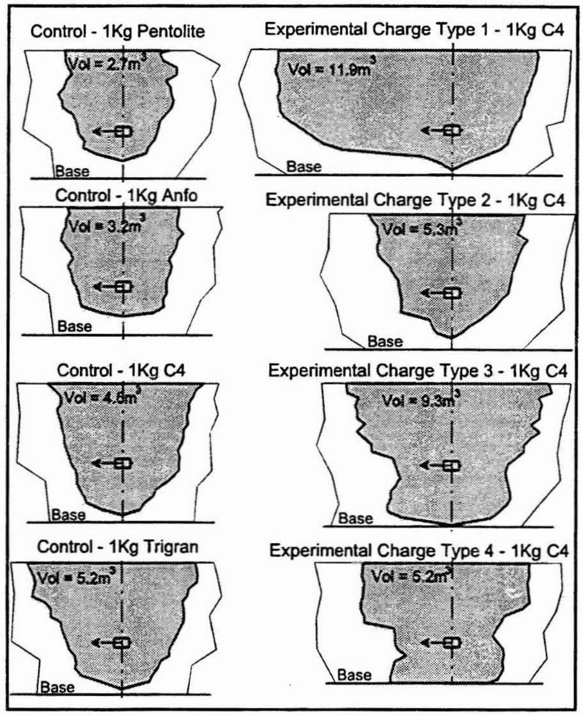

Figure 6: Comparison of crater profiles for blast charge and experimental shaped charges configurations.

C4 was probably the most energetic of the four compositions tested. With a high detonation pressure, it would not necessarily produce the best cratering effects since snow pack is an effective shock attenuator. However, the parallel sides of the C4 crater indicate that the 1.2m emplacement depth was optimum for 1kg.

ANFO is not a particularly powerful composition and is particularly difficult to detonate effectively in small quantities. The smaller crater volume is therefore consistent with expectation.

The behaviour of the Pentolite charge (in the form of a standard Avalauncher round) was anomalous. It is assumed that the composition was 50/50 PETN/TNT which should have produced a relatively high detonation pressure and power factor, just a little lower than that of C4.

The crater profiles for the four experimental shaped charge configurations tested are shown on the right hand side of Figure 6. Charge Type 1 shows a remarkable increase in the crater volume, rising from $4.6m^3$ for the C4 control shot to $11.9m^3$ for the Type 1 charge. This result confirms the approach taken towards optimising the liner design and clearly demonstrates the contribution made by the shaped charge to the bare C4 explosive equivalent of 1kg.

The results of the Type 3 charge also indicate that a significant increase in crater volume from $4.6m^3$ for the C4 control shot to $9.3m^3$ was produced by the cylindrical liner configuration. The most significant additional effect noted for this charge was the unusually high ground shock accompanying the firing which was commented on by a number of spectators.

The Type 2 and Type 4 shots both produced volumes that were marginally higher than the C4 control shot but did not produce a yield greater than their single counterparts (Types 1 & 3 respectively). Similar work conducted by the author for other applications has demonstrated that there are considerable benefits to be gained from the effects of colliding jets, so background research work will continue in this area.

In summary, the results from the 1999 firings clearly demonstrated the potential of the shaped charge mechanism and established the foundations of a database to support future studies. The unexpected performance of the Type 1 shaped charge has also provided a firm foundation for early product development.

6. A SHAPED CHARGE DEVICE FOR AVALAUNCHER AND HAND CHARGE OPERATIONS

During the summer of 1999 an intensive period of experimental studies, conducted in the UK, concentrated on the feasibility of integrating the shaped charge effect into an Avalauncher projectile. However, the many idiosyncrasies of the existing Avalauncher gun system, particularly with respect to the ammunition, necessitated a comprehensive review of the existing system in order to enable the programme to proceed. This also provided an insight into the maximum performance limits that could be introduced within the current cost effectiveness envelope of the system.

Following extensive dynamic characterisation of the Avalauncher gun and ammunition, appropriate interim modifications were made, and a series of inert filled prototype shaped charge projectiles was successfully tested, with the existing basic fin design. A significant feature of the new Avalauncher charges was that they were designed as part of an integrated system providing a "common" charge configuration that could be used for both Avalauncher and hand charge operations.

As part of this integrated system, a novel technique for controlling, retaining and firing hand charges was also introduced. This consisted of a thin fibreglass tube containing a coil of non-electric initiating line (generically referred to as shock tube). The coil of shock tube can either be fitted to the charge or attached to the operator so that when the charge is either thrown, launched or released, the spool pays out in an orderly fashion.

Figure 7 shows an example of the use of a shock tube spool with a standard D90 booster charge. The high strength of the shock tube (40kg dead load) allows the charge to be either re-positioned or suspended, typically over either a cable-line or cornice. The operator then has absolute control over "*instant* fire" or "veto", using a hand held fire unit and, if necessary, subsequent recovery of the charge.

Pyrotechnic Safety Fuze is used extensively in the US and Canada for detonating hand charges, although the use of this particular method remains under review. Electronic time delays are probably the most convenient replacement for Safety Fuze but even the military demands for similar reliable miniature time fuzes have met with a number of fundamental safety and reliability problems. In the meantime the spooled shock tube option offers a practicable interim solution that ensures a high degree of safety, comprehensive control over positioning and orientation of the charge. With delay detonators, the benefits of accurate ripple delay firing of a pre-prepared charge sequence can also be exploited. Figure 8 shows the above D90 charge in mid-flight after being launched by hand. The shock tube tether can be seen paying out from the spool cannister, in this case, attached to the charge.

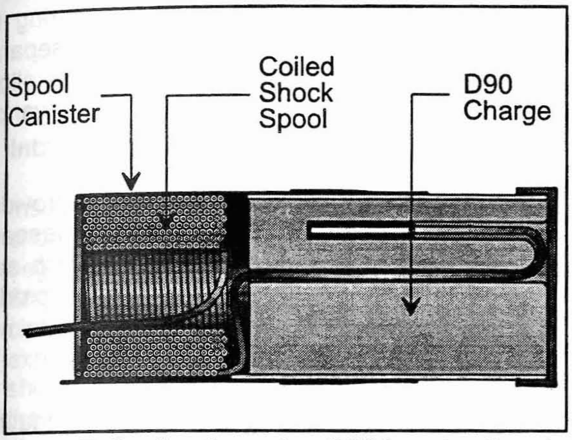

Figure 7: Section through a D90 booster (hand charge) fitted with a spool canister carrying 23m of shock tube.

Following the inert dynamic tests conducted in the UK, twenty of the new charges were tested with live explosive fillings in Alta in March 2000. Ten of the new charges were assigned to hand charge operations and the remainder were fired from an Avalauncher gas gun. Funding constraints precluded re-design of the fin component, so these firings were conducted using the existing fin design. This combination was not suited aerodynamically, consequently accuracy and flight stability remained poor. An optical instrumentation technique was employed to determine muzzle velocity and this was correlated with an electronically monitored chamber pressure. All of the new charges behaved and performed as expected although particularly stable conditions did not result in any releases that day.

Of the ten hand charges, six were deployed in various surface, sub-surface and air burst positions and compared directly with standard 2lb Pentolite boosters. The effects of the shaped charge were visually spectacular and produced significantly greater sonic report. "Bamboo shots" arranged to fire at 90 degrees to the fall line with about 1m separation produced both a significant increase in sonic reports, accompanied by a clearly visible surface "heave" and drop, effective over many metres about the penetration axis of the jet.

The most spectacular effects obtained from the new charges were the 4 fired against established cornice build-ups. In one area many Pentolite boosters had been fired to try to dislodge the cornice without success. However, a single shaped charge brought the full length of the cornice down. Since it was not clear if the cornice had been weakened by previous work, the same tests were repeated at other sites with equally spectacular results.

Figure 8: Deployment of hand charge showing shock tube paying out from a spool housing attached to the charge.

7. CURRENT PROGRAMME

The twenty prototype charges fired at Alta resulted in a spectacular and convincing display of the versatility of the shaped charge mechanism. The success of the technology demonstrated to date has prompted a joint funding initiative from a number of West Coast DOTs to provide a sustained period of funding for further work.

Between one and two thousand pre-production rounds will be prepared for evaluation over the 2000/2001 season to be fired under controlled conditions at a number of sites. Approximately half will be assigned to Avalauncher operations and these will embody the fin improvements arising from the latest (October 2000) UK firing programme to include: a redesigned "one piece" all plastic baseplate and draw pin assembly; a more robust fin/initiator design more compatible aerodynamically with the new forebody; an improved safety pin arrangement that links the baseplate to a fin vane. These features will improve performance within the current Avalauncher gun system and will primarily introduce the robustness necessary to support planned enhancements to future Avalauncher gun systems.

Principal design features of the new charge designed for dual Avalauncher and Hand Charge operations are shown in Figure 9.

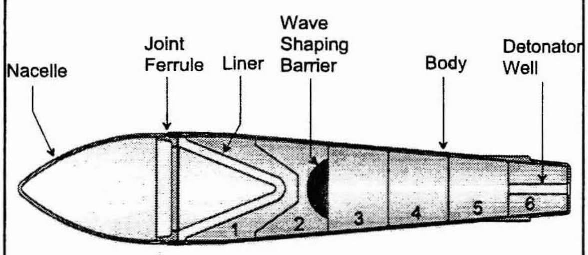

Figure 9: Section through the Mk I Avalanche Control Charge.

The main body consists of an injection moulded polypropylene body and nacelle which firmly clip together via the joint ferrule, without the use of screws or rivets. The Joint Ferrule also retains the Liner and HE pellets within the Body component.

The hollow Nacelle provides aerodynamic streamlining and stand off between the mouth of the shaped charge liner and target material and allows alternative Nacelle configurations to be introduced to control the detonation delay time in soft snow pack.

The Liner is pressed from aluminium powder bound with wax. This facilitates cost effective production and allows alternative liner compositions to be introduced to cater for special conditions. Different liner geometries can readily be introduced into the "Pellet 1 zone".

The explosive charge consists of six pre-pressed pellets. These allow alternative explosive compositions to be introduced to meet specific requirements. Typically, aluminised (addition of up to 20 % of Al. powder) would significantly enhance blast yield from pellets 3, 4, 5 & 6, but pellets 1 & 2 would be a high density HMX and/or RDX/wax composition, better suited to the shaped charge mechanism.

The barrier shapes the geometry of the detonation front and influences the way in which the shaped charge liner collapses. Different effects can be both introduced and controlled by altering the barrier geometry. The introduction of a separate pellet (Pellet 2) containing this feature allows considerable latitude to accommodate various barrier geometries.

This configuration has been selected to provide a robust research vehicle to support future research studies and a build standard upon which early development of a commercially available product can be based with the flexibility necessary to meet worldwide requirements.

In addition to the planned pre-production assessment in Alta March 2001, a broad range of variants of the Mk I configuration will also be tested against stable snow pack. When appropriate levels of funding are secured, R&D work will also commence on shaped charge systems for helibombing and a review of the feasibility of introducing polymeric based shaped charge replacement round for military artillery gun systems.

8. REFERENCES

Cook, M. A., 1958. The Science of High Explosives. - Reinhold 1958.