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ACTIVE BLAST MITIGATION SYSTEMS USING LINEAR ROCKET MOTORS

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ABSTRACT

Modern warfighters face a continual threat of injury or death from mine/IED attacks on vehicles, and this, coupled with an increase in operations requiring off-road movement across areas containing substantial blast threats means that an urgent need exists for lightweight blast mitigation technologies which can be easily integrated on new and existing vehicles to protect the occupants from injury. The currently heavy passive protection technology in terms of V-hulls, high ground clearance, and very heavy vehicle weights degrades the off-road capability and performance of the vehicles excessively, so lightweight Active Mine Protection Systems (AMPS™) are viewed as the way forward. This paper describes the development of the ABBS Vehicle Global Acceleration Mitigation (VGAM™) technology designed to keep vehicles on the ground when hit by under-belly mines, and further developments to protect the crew from the other secondary effects of mine blasts such as Floor Shock and Floor Deformation are also briefly introduced.

INTRODUCTION.

Viewing the high speed video of a mine blast test under an ex-Russian BRDM2 armored vehicle in 2008, the author noticed that the vehicle did not begin to move upwards for about ten milliseconds (10ms) after the mine detonated, and it was recognized that this delay provided a time window in which some form of active counter-measure could be initiated to mitigate the effects of the mine blast lifting forces. The simple solution of pushing down on the vehicle was then identified and resulted in the original 2008 Vehicle Global Acceleration Mitigation (VGAM™) patent application by ABBS for pushing a vehicle down during a blast event. The VGAM™ concept has been refined over the past 8 years and is now approaching TRL6 maturity, with a series of evaluation programs now being carried out in the USA and Europe. Further consideration of the full range of threats to the occupants of a vehicle hit by an under-belly mine has led to other developments to deal with both Belly Plate deformation and Floor Shock and Floor Deformation issues by means of an Active Column/Floor system, and a passive belly plate reinforcement concept. Prototypes are being tested in the UK to demonstrate the feasibility of these approaches which are designed to provide a complete suite of protection systems to protect vehicle occupants from all the secondary effects of mine blasts, given that the vehicle is not penetrated by the mine.

Early Development 2008-2010.

The initial VGAM™ concept included the use of rocket motors from the start, because they are the most mass-efficient method of generating the down-force and total impulse required to directly counteract the mine blast lifting forces. Initially a circular, multiple concentric exit cone design was conceived, but initial trials used Martin Baker aircraft ejection seat motors, which it was found took 22ms after initiation to reach full thrust. This meant that the test jigs used had already acquired essentially their full vertical velocity before the motors took effect and slowed the rise of the jigs to a halt and then accelerated them rapidly downwards. This rapid acceleration upwards followed by deceleration to a halt and then being accelerated rapidly downwards would clearly have highly undesirable effects on vehicle occupants, so development switched to using ballistic mass ejection to provide the required recoil/downforce much more rapidly.

Initially, ejecting 1kg masses of water using 42g of propellant in a short steel pot was used, and was found to develop recoil forces in the order of 37,000kgf, but for an indeterminate time which was probably only a fraction of a millisecond. Nevertheless, a 6kg TNT-equivalent test under a 2,000kg Land Rover test jig demonstrated that a significant effect was achieved, a 60% reduction in jump height from 5m to about 2m being observed.

Six of the 1kg water-ejection motors were used on the 2,000kg test jig giving an estimated downforce of about 220 tons, which at first sight might be expected to keep the vehicle on the ground, which it clearly did not, which raised the question of the *duration* of the mine blast force-time curve as well as its magnitude. The baseline test giving a 5m jump height for the 2,000kg test jig demonstrated that the acquired impulse was 20kNs, so the 60% reduction in jump height equates to 12kNs. This implies that the initial velocity of the water mass when ejected from the short barreled steel pots was about 2,000m/s, albeit that the velocity rapidly reduced to about 300m/s 1m from the motor.

Whilst this was a simple, crude test, it was surprisingly successful, given the significant effect that only 242g of explosive and 6kg of water had on the test jig jump height. As a result further funding for development was received from the UK MOD.

Gas expands at a rate of 1.0m/ms under a 4 x 2 = 8sq.m. planform.

Time After Main Charge Initiation.	Gas Pressure.	Impulse Contributed to 8sq.m. Planform per 1ms.	Cumulative Impulse	Percentage of Total Impulse	Cumulative % of Total Impulse
ms	PSI	Ns	Ns	%	%
1	500	2763	2763	21	21
2	127.3	2812	5575	22	43
3	56.6	2046	7621	16	59
4	31.8	1790	9411	14	72
5	20.4	1146	10557	9	81
6	14.1	796	11353	6	87
7	10.4	585	11938	4	92
8	8.0	448	12386	3	95
9	6.3	354	12740	3	98
10	5.1	286	13026	2	100

Figure. 1: Mine-Generated Gas as a Significant Contributor to Impulse Absorbed by the Vehicle.

Mine Blast Force-Time Curve Issues.

The issue of the force-time curve of the mine blast, and the total duration of impulse being absorbed by the vehicle had already arisen previously when the initial 10ms delay before Global Acceleration of the vehicle begins was observed in 2008. A simple analysis of the role of the gas generated by the mine suggested that for the first 5 or 6 ms of the event the elevated quasi-static pressure of this gas under the vehicle compared to the ambient pressure above the vehicle could have a significant effect, which was calculated at generating about 13kNs impulse on its own.

Add to this a dynamic gas effect amounting to about 5kNs from half of the mine-generated gas rising as a column above the mine at about 2000m/s, plus a few kg of soil over-burden at a similar velocity and a further 10kNs impulse can be estimated, giving 23kNs total, without any contribution from the main ejecta impact. Conveniently, the LS-DYNA simulation done by Jankel Armoring UK in 2009 and presented below in Fig. 2 and 3 predicted exactly the same 10kNs impulse being generated in the first 1ms of the blast event, so sophisticated simulation and some simple basic physics appear to agree in this instance.

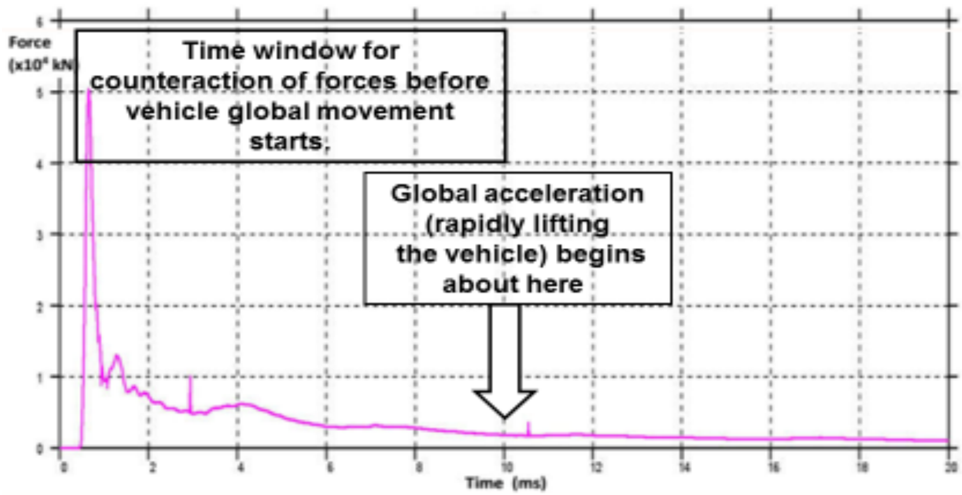

Figure. 2: Understanding the mine blast event – LS-DYNA force/time curve with 6Kg mine.

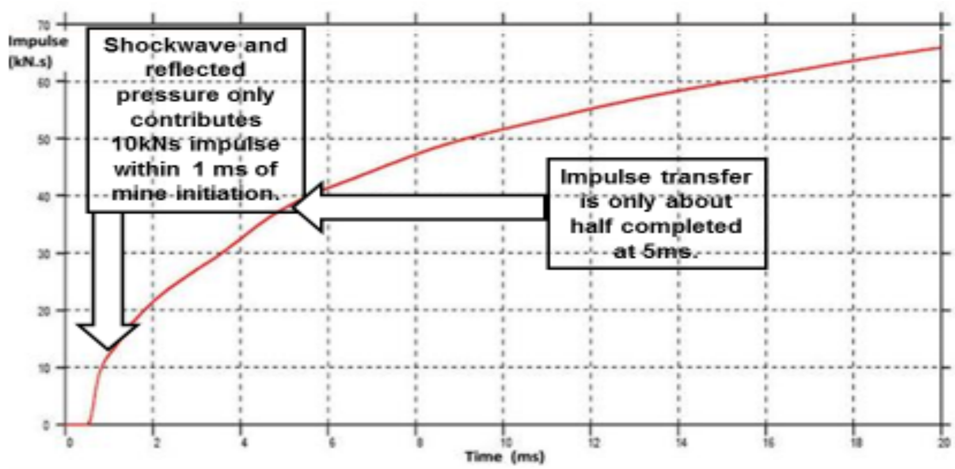

Figure. 3: Understanding the mine blast event – LS-DYNA Impulse transfer prediction with 6Kg mine.

The effects of the gas generated by the mine and the longer duration (10 to 250+ms) ejecta propulsion from the developing crater represent other interesting elements of the total impulse equation which usually seem to be ignored in the multitude of scientifically orientated 'blast-effect-on-vehicles' papers, but which is crucial if you are trying to directly counteract the total lifting impulse acting on the vehicle with countermeasures producing downforce.
Clarke et al [1] illustrates this well. Figure 4 extracted below shows a typical pressure-time history for a mine blast acting on a plate, with the biggest area under the curve all delivered in less than 0.5ms. But a long flat tail just above the zero pressure line is also shown, extending to 100ms. When this is simplified for numerical simulations as shown in Figure 5 the time is cut off at 10ms, neglecting the subsequent 90ms as if it is irrelevant.

However, the authors then state that "For the highest magnitude tail pressure (of 5MPa), the impulse associated with the tail is 74% of the total impulse", and this is for a test charge buried at 10cm under the soil surface, not a deeply buried mine where the elements of high pressure gas retention and ejecta projection are more significant.

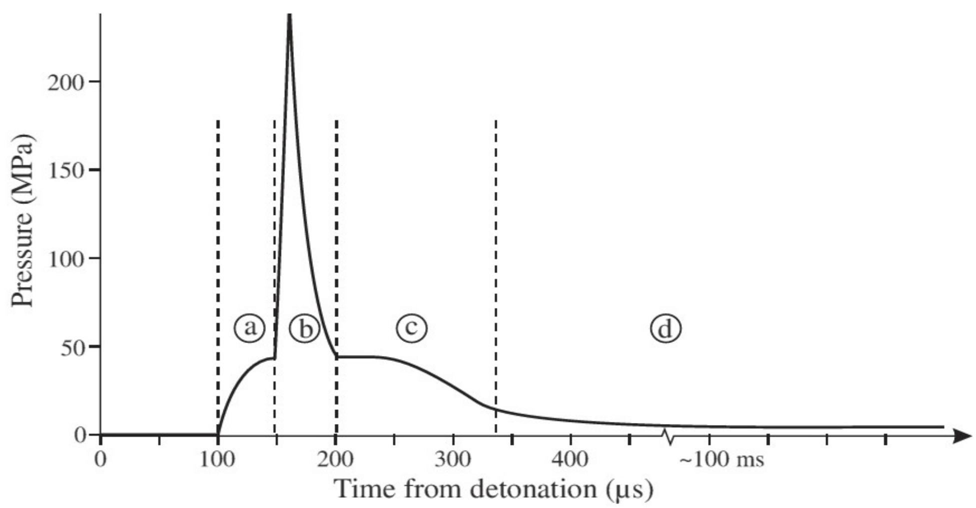

Figure. 4: Indicative pressure-time history for instrumented regime [1]

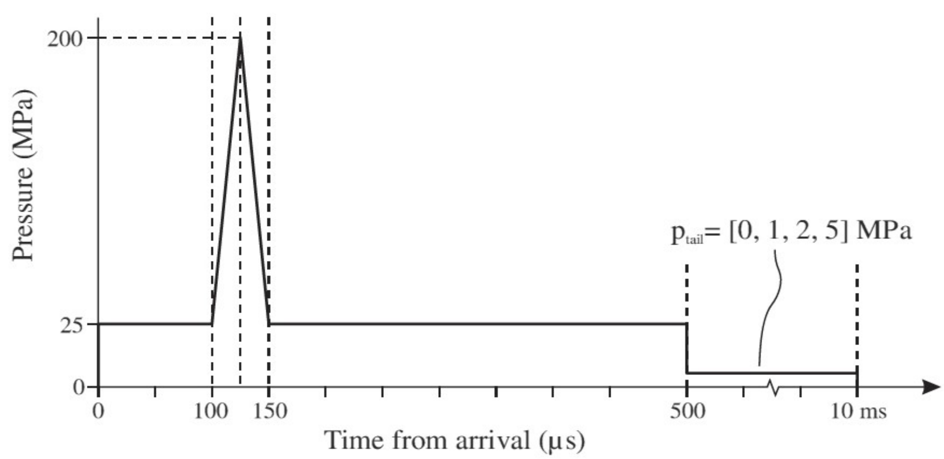

Figure. 5: Simplified pressure-time history for numerical simulations [1]

Another paper by Southwest Research Institute [2] which looked at mine blast loadings on plates above charges buried in soil includes numerous graphs showing the velocity or momentum of the plates reaching a maximum after about 2ms and then almost plateauing out, suggesting that there is little or no further impulse absorbed after this time, although the 'plateau' areas were always very gently rising slopes, similar to the 'tail' mention in paper [1], as shown in Figure 6 below.

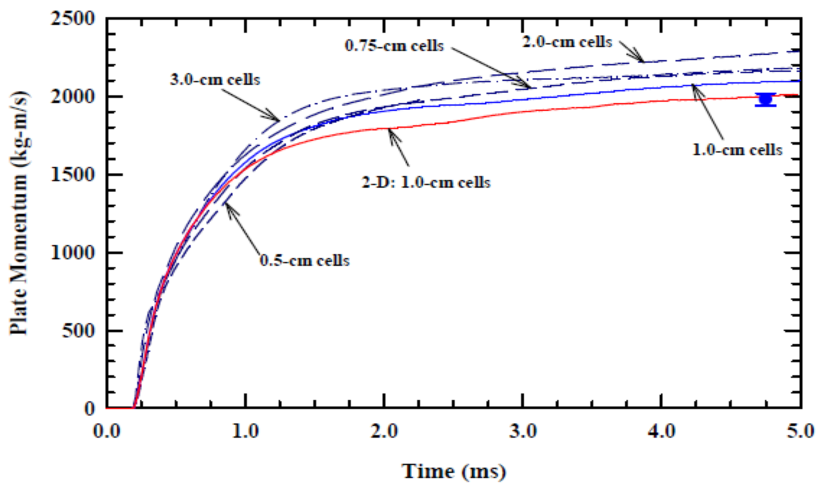

Figure. 6: Plate momentum for various grid resolutions: 3-D simulations – 20 cm standoff. [2]

Hence in these very scientific and professional papers [1,2] there almost always appears to be a strong focus on the early part of the mine blast force-time curve where the damage is being done to the vehicle, but the whole impulse curve up to 250 to 500ms, which is certainly relevant to deeply buried or culvert mines, is not generally dealt with.

Practical Observations on the Mine Blast Force-Time Curve and Implications for the 'Ideal' VGAM™ Countermeasure Design.

This focus on the early, damage-producing effects of mine blasts by many papers appears to have generated considerable confusion on the issue of the total force-time curve that is relevant for under-belly mine blasts on vehicles, and the total duration of the impulse transfer to the target vehicle, which is what matters for the design of the ABBS VGAM™ system.

The early Land Rover tests in 2009 suggested that delivery of the total counter-impulse within 1ms was not fully effective in counteracting the mine blast lifting forces, and the simple observations noted earlier lead to a commonsense conclusion that a countermeasure duration well beyond 1ms and designed to roughly match a major percentage of a 'normal' mine blast force-time curve is what is required.

So what is a 'normal' mine blast force-time curve, and hence the ideal duration of thrust application for the countermeasures?

The initial jig tests with 6kg of water apparently being ejected at about 2,000m/s apparently very briefly made the test jig weigh 220 tons, but it still jumped 2m in the air, and this immediately led to the conclusion that the mine blast lifting forces were acting for longer than 1ms, which is the duration indicated in many technical papers, and by some mine blast experts.

Viewing the expansion of the gas and ejecta cloud under the test jig, as shown in the sequence of pictures below, clearly shows that the residence time of the high pressure gas under the vehicle, and the period of the ejecta impacting the vehicle both last at least 5 or 6ms under a small vehicle so the duration of the force-time curve is clearly at least that long.

However, consideration must also be given to the 2.5kg 2,000m/s gas column from the mine that drives down into the ground, and carries the main mass of ejecta out with it as it escapes from the crater. Clearly, this will take longer than 6ms, so it is not surprising that the LS-DYNA prediction of the force-time curve, and the resulting impulse curve obtained by integrating the area under the curve shows that impulse is still being absorbed by the vehicle at 20+ms, and probably significantly longer.

Figure. 7: UK MOD funded baseline vehicle VGAM test. Time zero – detonator igniting.

Figure. 8: 1ms – Det cord lighting

Figure. 9: Time 2ms – Gas ejecta cloud 1m diameter

Figure. 10: Time 3ms – Gas ejecta cloud 2m diameter.

Figure. 11: Time 4ms – Gas ejecta cloud 3m diameter

Figure. 12: Time 5ms – Gas ejecta cloud 4m diameter

Figure. 13: Time 6ms – Gas ejecta cloud 5m diameter

Further visual evidence is available from the initial ejection seat motor trials in 2009, shown below in Figure 14, in which ejecta is still flying out of the mine crater at high velocity even after the motor has burnt out at 250ms after initiation, and this was with a burial depth of only 10cm.

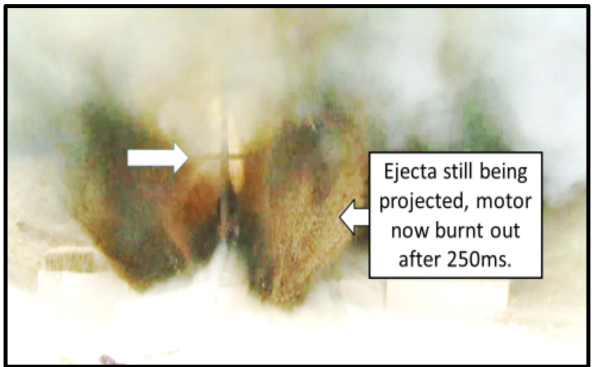

Figure. 14: Duration of Mine Blast Ejecta Projection.

Even more dramatic is what happens with deeply buried or culvert mines, where essentially all the impulse is transferred to the vehicle by the ejecta, which is clearly acting for an extended period, probably in the region of at least 250 to 500ms. The sequence below illustrates this well.

Such events transfer very large amounts of impulse as a large volume and mass of ejecta, probably between 15 and 30 tons of ejecta travelling at 5 to 10m/s impacts the vehicle, easily delivering impulse levels in the range of 100 to 300kNs or higher.

Figure. 15: Time Zero.

Figure. 16: Approx. 80ms?

Figure. 17: Approx. 160ms.

Figure. 18: Approx. 240ms?

Figure. 19: Approx. 320ms?

The effect on an armored vehicle is also well illustrated in the sequence below, where the IED is located beside the road, not under the vehicle. Hence while the vehicle will have experienced some side force due to the direct blast effects, the main impulse is delivered by the road lifting up underneath the vehicle, which is thrown about 10m high and 25m sideways before it hits the ground.

Figure. 20: Deep Buried IED Explodes.

Figure. 21: Little Direct Damage to Vehicle.

Figure. 22: Road Surface Lifts Vehicle.

Figure. 23: Vehicle Accelerated Upwards.

Figure. 24: Vehicle Approx. 10m in Air.

Figure. 25: Vehicle Thrown 25m Sideways.

So to prevent Global Acceleration in these cases it is clear that ballistic mass ejection, which delivers all its impulse in only a few ms at most, cannot provide the extended duration that can be achieved with a rocket motor system, other than by staging the firing of the BME countermeasures.

However, the problem then becomes the weight and space claim of BME system required to generate the total impulse required. Generating even 100kNs, the lower end of the deep buried, large IED spectrum, would require 20 5kNs BME pods weighing about 2000kg, and locating them on the sides of a vehicle would occupy practically all the side area, so using BME at this level is clearly impractical.

Rocket Motors vs Ballistic Mass Ejection (BME) to Generate Downforce - Efficiency of Counterforce Generation and LRM™ Performance

Compared to rocket motors, the BME principle is very inefficient at generating impulse because of the basic physics involved, where:-

Impulse = mass X change in velocity

It is not practical to use BME in Global Acceleration Mitigation applications at maximum mortar velocities of about 300m/s due to the barrel mass that would be required to contain the internal pressure, and the very short residence time of the ejected mass in, for example a 1m long barrel, which would only give about a 3ms duration impulse. Hence it is anyway more efficient to eject a heavy mass at a lower velocity of about 100m/s to keep it in the barrel for longer and extend the duration and total impulse. In addition, the large surface area of a 5kNs BME unit weighing over 100kg (including a 50+kg ejection mass) needs to armored to protect it from ballistic impact. This compares with the current steel-cased Linear Rocket Motor (LRM™) system weighing 45kg and ejecting about 4kg propellant mass at about 2,000m/s, which generates over 6.0kNs (allowing for propellant losses through the exit slots) so that it is already three times more efficient at generating impulse than BME. Crucially, the impulse is also delivered over a longer period, about 10ms in the case of the current LRM™ design which is a 125mm square section steel tube just over 1m long, with the exit slots cut transversely across the full length of one side of the tube. Using a composite wound motor casing instead of steel will reduce the casing plus ancillary weight to about 15kg for a 6.0kNs motor, increasing the efficiency differential compared to the BME alternative to a factor of nearly seven.

i.e. BME mass efficiency is about 20kg/kNs

LRM™ mass efficiency is about 3kg/kNs

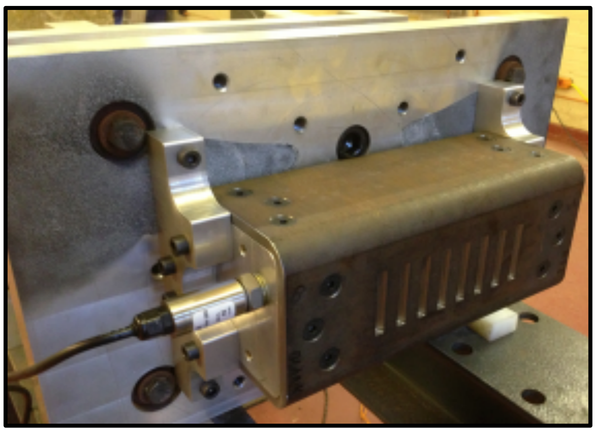

Figure. 26: Prototype Linear Rocket Motor

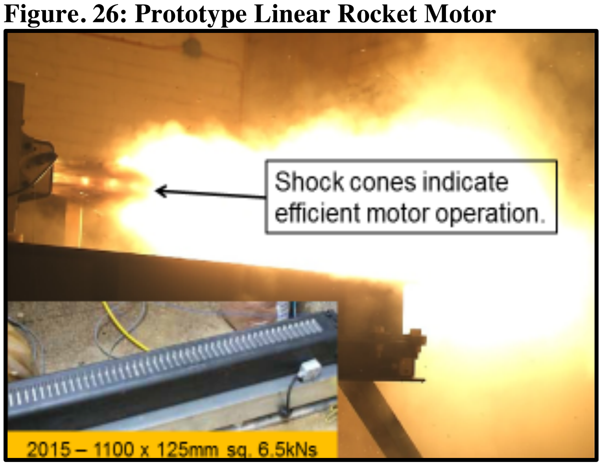

Figure. 27: Second firing of novel, patented, low cost Linear Rocket Motor design concept - 2013

Clearly, the rocket motor option is by far the most efficient, but the crucial issue as illustrated by the early aircraft ejection seat motor tests is the speed of initiation.

This issue is dealt with by the basic LRM™ configuration and propellant design, which enables a very fast initiation and delivery of the total impulse within about 20ms, with thrust delivery currently starting at about 10ms after mine initiation, just in time to prevent any significant global movement of the vehicle. Further developments are expected to reduce this initiation time to about 6ms.

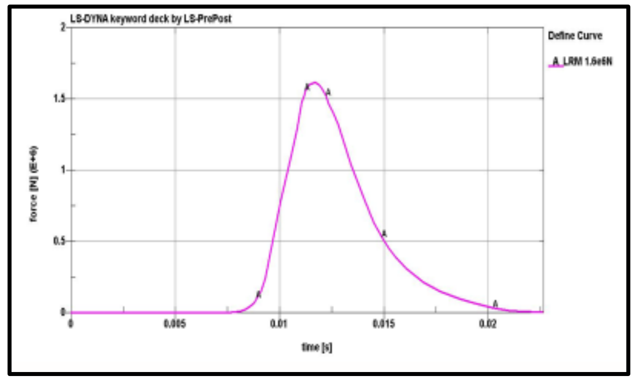

Figure. 28: Force / time curve of VGAM LRM™

Uniquely for a rocket motor, the LRM™ design concept allows rapid initiation and extreme thrust levels, with all the impulse being delivered in a few milliseconds. This has never been possible before the LRM™ configuration was invented, and it can best be described as generating a slow, directionally-controlled explosion, using the propellant energy efficiently to provide the huge peak loads and rapid total impulse delivery necessary to counteract the mine blast forces.

Other LRM™ Applications

Prior to the development of the ABBS VGAM™ technology it was generally thought to be impossible to detect the mine blast, measure its strength, and react quickly enough with sufficiently powerful countermeasures to deal with the mine blast forces involved and prevent the vehicle being thrown in the air. However, it is now clear that this approach is possible, and the technology has several other potential applications which require the same very rapid delivery of a lot of impulse. Some of these are:-

a) Helicopter Crash Prevention
b) Air Drop Cargo Pallet Retardation.
c) Fully Recoil-Less Munition Launch Systems.

Safe & Arm Technology and the AMPS™ Sensor, Control and Initiation System (SCIS)

Safe & Arm mechanisms are required in all energetic military systems to ensure that they do not activate inappropriately, and the ABBS systems use Exploding Foil Initiator (EFI) technology within a high-reliability in-line electronic safety and arming system. In the case of mine blast under an armored vehicle, it also important that the AMPS™ systems do not activate if there is an explosion under, or nearby the vehicle that poses no significant threat to the vehicle or its occupants.

Hence the strength of the mine blast must be measured to avoid the systems activating for an anti-personnel mine or hand grenade. This discrimination is achieved by a combination of sensor types which detect the shockwave from the mine, and the deformation of the belly plate.

Both stimuli need to be above set thresholds within a specific timeframe for the system to respond, and the AMPS™ system will do this as appropriate to the mine blast location and size, with no-fire, part-fire, or full-fire responses to only use the motors required to counteract the mine blast forces.

Importantly, this discrimination of the mine blast location and size is achieved completely autonomously, without the use of any safety-critical software within the control system. The sensor system design allows this to be done, and the control system response is pre-set for each blast scenario and size during design qualification of the AMPS™ ystem on the vehicle.

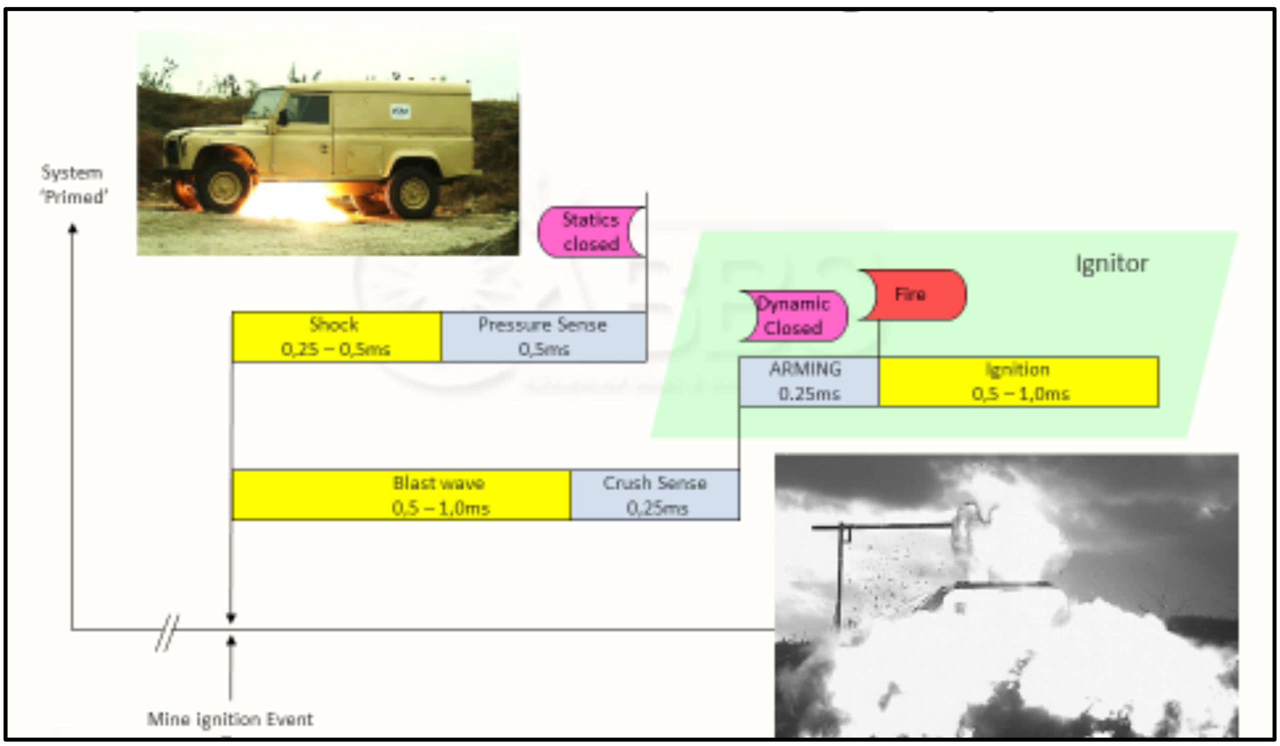

Figure. 29: VGAM™ System Function Timing.

Proof of VGAM™ Concept March 2015 and Application to Vehicles

The objective is to completely eliminate the vehicle global acceleration, and this was demonstrated in March 2015 with a test under an ex-UK Army Snatch Land Rover.

Figure. 30: AMPS™ – Active Mine Protection System Proof of Concept Test.

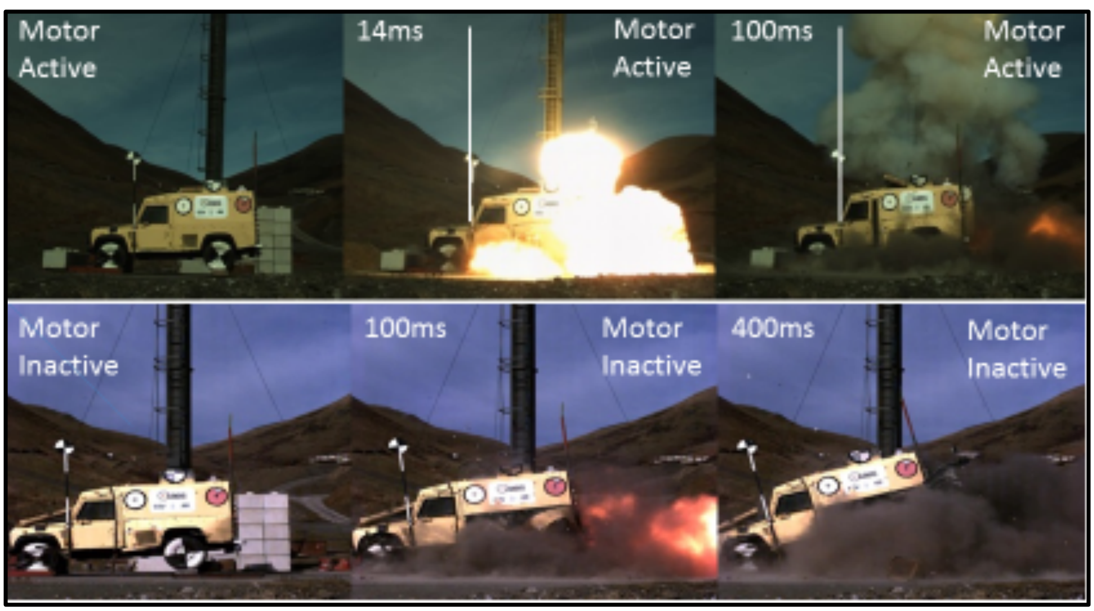

Figure 31: March 2015 Fully autonomous, adjustable response system test, single 6kNs LRM.

Another beneficial attribute of the novel patented LRM™ configuration is that the linear format allows fitting of the motors to various different parts of the vehicle with little difficulty, un-like the situation with the BME 'mortars' which can only realistically be fitted on the sides of the vehicle. If a total impulse in the range of 60 to 100kNs impulse is required to meet the mine blast specification for a vehicle it would require 12 to 20 5kNs BME pods being located on the vehicle sides, with severe space claim and weight implications, making this technology impractical for most applications.

In contrast ABBS is developing 15kNs LRM's so that only 4 motors about 1m long and 0.3m wide are required to produce 60kNs, or 6 motors for 90kNs total impulse. These 15kNs motors would produce a peak force of about 300,000lbf thrust if all their impulse were to be delivered in 10ms, so they are being designed with a 20 to 30ms duration to limit the peak thrust level to about the 135,000lbf obtained with the current 6.0kNs motors.

The relatively 'soft' force application (compared to ballistic mass ejection) and longer 20 to 30ms duration may enable fitment of the LRM's directly to un-reinforced parts of the vehicle ballistic shell, if that is the preferred method. If any local reinforcement is found to be required it is expected to be very minor.

There are many different positions on the outside of the vehicle hull which can be used to locate the LRM's, and whilst the approx. 1m long x 125mm or 300mm width motors are currently the standard designs, the LRM™ concept can also be produced either in long thin versions, or as square or rectangular packs of any size containing multiple LRM's in whatever dimensions are convenient for fitting on the vehicle.

However, consideration of the potential interaction of the LRM™ efflux with other vehicle systems, and the safety of any personnel partially out of the top of the vehicle may make the top of the vehicle a non-preferred location for the main LRM's. Hence using motor mounting points supported by the front and rear tow hitch structures, and over the front suspension points on a wheeled vehicle are obvious potential location points, and there could also be significant advantages to a position between the belly plate and the main vehicle cabin. This latter location would have the advantages of moving the LRM™ efflux effects as far as possible from the top gunner/commander positions, but it also places them in a position where the ejecta from the mine blast will have a substantial mitigation effect on the shockwave, noise, and heat efflux. It will also probably make the functioning of the VGAM™ system very difficult to observe, so will potentially prolong the time it takes for enemy observers to ascertain why vehicles fitted with the systems are not reacting as they expect when they are hit by under-belly mines or IED's.

Current Status in USA.

ABBS is now discussing a Cooperative Research & Development Agreement (CRADA) with TARDEC to further test and characterize the AMPS™ technology and there are various other evaluation projects being defined.

With the VGAM™ system now proven, new ABBS developments in the UK include the investigation of both passive and active systems to deal with Floor Shock and Belly Plate/Floor Deformation issues, which will shortly be available to be added to the suite of systems designed to fully protect vehicle occupants from all the secondary effects of mine /IED blast under their vehicles.

Active Columns, Seats and Floor.

Active columns in the vehicles can provide multiple functions to help protect the vehicle occupants from injury:-

a) An active function is incorporated to push the floor down away from the occupants' feet within a fraction of a ms of the mine exploding to prevent lower limb injuries. In addition, any loose items on the floor are prevented from being projected upwards at high velocity with the resultant threat of serious impact injuries.

b) Current blast mitigating seats use a stroke of between 3 and 8 inches to achieve the required results, so if the VGAM™ system is used to eliminate any Global Acceleration this stroke requirement can also either be eliminated, or reduced substantially. This can help vehicle designers obtain a significant reduction in vehicle height and weight.

c) Mounting the seats on the columns enables the provision of Active Seats. The Active function within the mounting system can be used to maximize the benefit of the shortened seat stroke by optimizing the response of the seat to any residual vertical acceleration inputs.

Passive Belly Plate Reinforcement.

Lastly, a passive structural reinforcement system is being used to support the belly plate and hence mitigate the gross deformation that occurs directly over the mine location. This system will reduce the space that needs to be left open between the belly plate and the vehicle floor, and hence reduces the space claim of this blast-mitigating feature of the vehicle design, again potentially reducing vehicle height and weight.

Modular Active Protection System.

An open-architecture controller is being developed for TARDEC's Modular Active Protection System (MAPS) program, which will process information from multiple sensor and self-defense systems that can be used to protect the vehicle, enabling autonomous or semi-autonomous detection and defeat of a variety of inbound threats, including RPG's, antitank guided missiles. The system is also intended to control all the elements of the Active Blast Mitigation Systems being pursued by TARDEC.

The ABBS AMPS™ technology combines multiple sensor types designed to detect and measure all the secondary threats to vehicle occupants from under-belly mine blasts, and initiate active countermeasures to either eliminate or mitigate them, including Global Acceleration countermeasures, and potentially both Active Floor and Active Seat elements. The MAPS system will obviously require discrete elements to deal with specific threat types, and it is proposed that the ABBS system controller could comprise the part of the MAPS system dealing with mine blast.

Summary and Conclusions.

The extraordinary physics and timelines of the mine blast event might appear to be very difficult to deal with and use to control an Active Mine Blast Mitigation system, but this is achieved by the ABBS system.

- The sensor systems detect the mine blast, locate its position, and measure its impulse within 2 to 3ms of the mine exploding.

- The control system takes the sensor inputs and activates a preset response within microseconds without the use of any safety-critical software.

- The Active Column, Seat, and Floor systems activate in less than 1ms to prevent lower limb, and any Floor Shock or acceleration-induced injuries.

- The LRM™ countermeasures ignite within 6 to 10ms to counteract the mine blast lifting forces. Using a rocket motor-based countermeasure is the lightest, most efficient way of providing the required rapid initiation, extreme downforce level, total impulse, and the force-time curve duration to deal with the majority of the mine blast force-time curve.

- Installing the LRM™ systems on vehicles is much easier than the only alternative of using Ballistic Mass Ejection, and is a fraction of the weight and space claim.

The LRM™ technology was invented and developed specifically for the mine blast countermeasure application, and it is now demonstrated to be effective in this role.

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