Defence Science Journal, Vol. 61, No. 1, January 2011, pp. 19-24, DOI: 10.14429/dsj.61.30

Detonating Cord for Flux Compression Generation using Electrical Detonator No. 33

P.B. Wagh*, S.V. Ingale*, A.S. Rav*, T.C. Kaushik*, Satish C. Gupta*,
S.N. Asthana#, R.D. Wasnik#, R.B. Sohoni# and M.N. Adya#

*Bhabha Atomic Research Centre, Mumbai–400 085
#High Energy Materials Research Laboratory, Pune–400 021
E-mail: pbwagh@barc.gov.in

ABSTRACT

The paper highlights the use of electrical detonators for magnetic flux compression generator applications which requires synchronisation of two events with precise time delay of tens of µs and jitter within a few µs. These requirements are generally achieved by exploding bridge wire type detonators which are difficult to develop and are not commercially available. A technique has been developed using commercially available electrical detonator no. 33 to synchronise between peak of seed current in stator coil and detonation of explosive charge in armature. In present experiments, electrical signal generated by self-shorting pin due to bursting of electrical detonator has been used to trigger the capacitor discharge and the detonating cord of known length has been used to incorporate predetermined delay to synchronise the events. It has been demonstrated that using electrical detonator and known length of detonating cord, the two events can be synchronised with predetermined delay between 31 and 251 µs with variation of ± 0.5µs. The technique developed is suitable for defence applications like generation of high power microwaves using explosive driven magnetic flux compression generators.

Keywords: Electric detonators, jitter, exploding bridge wire detonators, detonating cord, synchronisation, magnetic flux compression

1. INTRODUCTION

Explosives are used for defence applications like magnetic flux compression generators (FCG) to generate high power microwaves[1,2]. A helical FCG[3] consisting a conducting cylindrical coil (stator) and a conducting cylindrical tube (armature) filled with high explosives. A capacitor bank is discharged through stator coil which introduces magnetic flux. The stator and armature are connected via an inductive load into which the magnetic flux is concentrated. When initiated, explosives in the armature rapidly expand the armature in a conical fashion that will short out the coil[4]. As detonation wave moves forward the stator coil is shorted out turn by turn by the armature, reducing the inductance of the circuit. As flux is conserved, the current in the circuit amplifies rapidly[5]. Using pulse transformer, this high current pulse can be converted into high voltage pulse to drive device like virtual cathode oscillator (VIRCATOR) which is used to generate high-power microwave[6].

The crucial condition required for FCG experiment is synchronisation of the peak current at quarter cycle (rise time) of the discharge of capacitor bank passing through the stator coil and initiation of explosive in the armature. It is reported that only exploding bridge wire (EBW) type detonators are suitable candidates for achieving such synchronisation required in FCG applications[1,7] since their bursting time is of a few µs and jitter is around tens of ns[8]. The synchronisation is achieved by simultaneous triggering of capacitor bank and EBW detonator through suitable electronic delay. EBW type detonators are initiated by shock waves which are generated by vaporising a length of thin wire by an electrical discharge[9]. The extremely short rise time required for EBW is usually achieved by discharging a low-inductance, high-capacity, high-voltage capacitor through suitable switch (e.g. spark gap) into the bridge wire. EBW type detonators require developmental efforts and are in development stage, and hence are not available commercially.

On the other hand, commercially available detonators like electrical detonator[10] have bursting time of around ms and jitter of around 10 to 20 µs and hence are not directly suitable for FCG like applications. To use electrical detonators for FCG like applications, a technique has ben developed using electrical detonator no. 33 for achieving synchronisation between two events, viz., peak of seed current in stator coil and detonation of explosive charge in armature, with jitter of about a µs. In the experiments carried out using this technique, electrical signal generated by self-shorting pin due to bursting of electrical detonator, was used to

Received 1 January 2010, Revised 3 August 2010, Published Online 6 January 2011

trigger the capacitor bank discharge and a detonating cord of known detonation velocity incorporated predetermined delay to achieve synchronisation condition. Experiments were carried out by varying length of detonating cord and the delay time were recorded on storage oscilloscope in terms of signals received from self-shorting pins. The detonating cord is routinely used for incorporating the delay in detonation but this feature of the cord in conjunction with the commercially available electric detonator in a very novel way was utilised to achieve the synchronisation that could be used for defence applications like high power microwave generation using flux compression generator with aid of explosives.

2. EXPERIMENTAL

Before attempting to achieve the synchronisation conditions, jitter for electrical detonator no. 33 and detonation velocity of the detonating cord were measured separately. To measure the bursting time and jitter for electrical detonator no.33, the experiment was carried out using the field set-up as shown in Fig. 1.

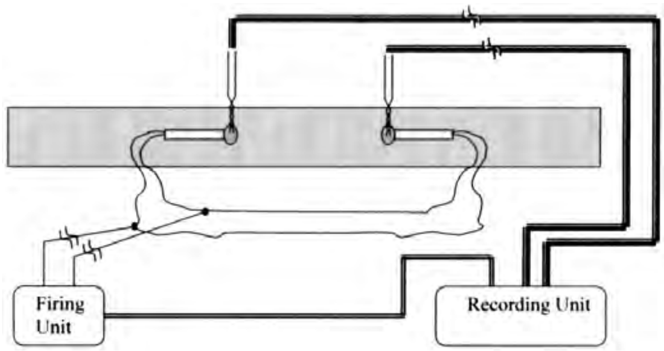

Figure 1. Schematic of the field set-up used for the delay time and jitter measurements of electrical detonator no. 33.

A pair of electrical detonators was placed on a wooden plate and triggered simultaneously by suitable firing device and their bursting time and jitter were measured by recording the detonation output using self-shorting pins on fast storage oscilloscope (Make: Tektronix, Model - DPO 4104, USA). The detonation velocity of detonating cord was arrived at by detonating a known length of detonating cord and measuring the time by putting self shorting pins at two ends. The self-shorting pins were set at the two ends of detonating cord with plastic explosive, Kirkee (PEK). The plastic explosives hold the self-shorting pin at the end of detonating cord and also amplify the detonation signal fed to the self-shorting pin to reliably produce output signal on the oscilloscope. The pulse signals generated due to shorting pins were recorded on fast storage oscilloscope. For 400 mm long detonating cord, the time difference observed between output signals generated by shorting pins at the two ends of the cord was 54.79 μs which leads to the velocity of detonation (VoD) for detonating cord as 7.3 mm/μs.

For assessing the repeatability of achieving synchronisation within ±1 μs using combination of detonating cord and commercially available detonator like electrical detonator no. 33, a series of experiments were carried out and the experimental set-up for such experiments is as shown in Fig. 2. These experiments were carried out in contained firing chamber (CFC).

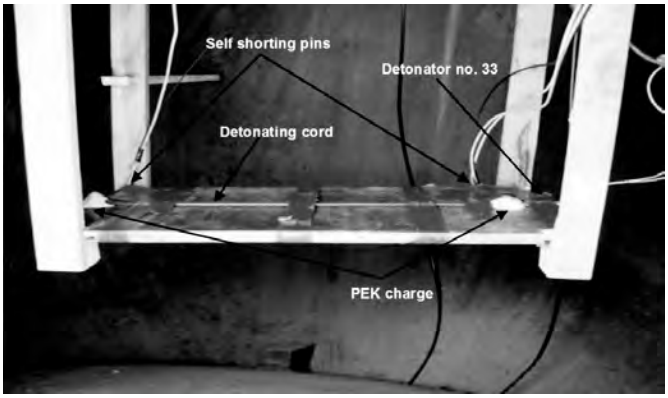

Figure 2. Experimental set-up for the measurements in delay time precision.

A detonating cord with PETN core material (prima cord) of varying lengths was used so as to derive different delay times. Due care was taken to prevent spillage of the explosive powder from detonating cord while cutting and handling the cord. A sharpened copper (non-sparking) hacksaw blade was used to cut the prima cord. To prevent spillage of filled explosive powder from cut end of the cord, PEK (about 5 mg) was used for closing terminating ends of the prima cord. The detonating cord of desired length was cut and fixed on the wooden board using adhesive tape. Electric detonator no. 33 was put at one end of the detonating cord and PEK (around 5 g) was used for proper contact between electric detonator no. 33 and the detonating cord. PEK was also put at the other end of the detonating cord. Self-shorting pins were inserted in PEK at both the ends of the detonating cord. The trigger to oscilloscope was fed from the shorting pin placed at the detonator end of the detonating cord. The detonator initiated detonation in detonating cord and at the same time-shorted the pin that generated signal pulse to trigger the oscilloscope. The shorting pin placed at the other end of detonating cord generated the pulse signal on oscilloscope when the detonation reached at the end of the cord. These signals were used to measure the delay time incorporated by the predefined length of the detonating cord. The persons handling the explosives were in proper uniform consisting of cotton clothes and conducting type shoes. The detonator was transported separately from the other explosive store. The explosive firing was carried out from the control room located at around 100 m from the experimental chamber.

3. RESULTS AND DISCUSSION

The data signals recorded for the two detonators in the experiment carried out for measuring the bursting time and jitter of electrical detonator no. 33 are shown in Fig. 3. The bursting times of two electrical detonators were observed

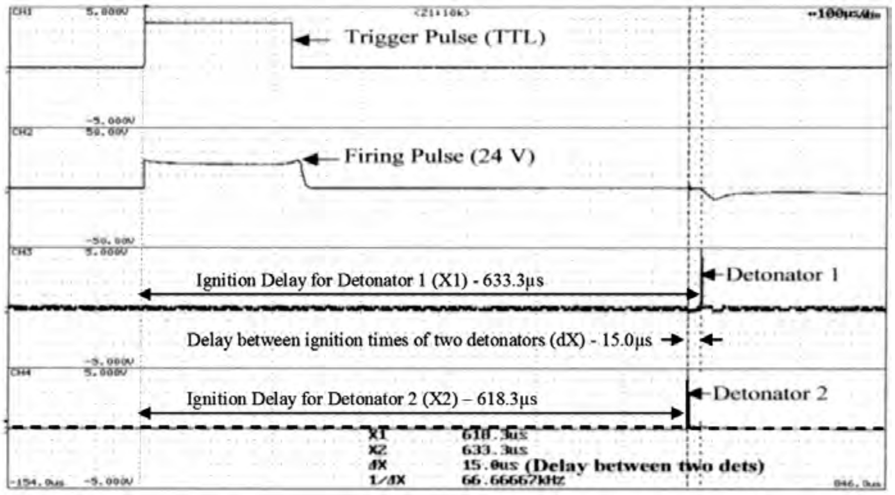

Figure 3. Recorded data signal for delay in ignition time and jitter for electrical detonator no. 33.

to be 633.3 µs and 618.3 µs which ultimately resulted in a jitter of 15 µs.

As the fillings of compositions in metallic cylinders were done by means of scoop at commercial scale, the quantity of explosive composition cannot be exactly equal for any two electrical detonators, which might results in such high jitter. Therefore, electrical detonators as such are not useful for FCG applications which require synchronisation of two events within ±1µs.

The capacitor bank used in FCG experiments had inductance of 44 µH and capacitance of 7.1 µF, that resulted in switching time of capacitor bank discharges as 1 µs and quarter cycle time where peak current appeared at 44 µs. Therefore, the total delay time between the triggering of capacitor bank discharge and peak current in the stator coil was 45 µs. For achieving the synchronisation condition in FCG system, the explosives in an armature needed to be initiated at around 45 µs after triggering the capacitor discharge.

The schematic of experimental arrangement and the discharge current cycle of the capacitor bank is shown in Fig. 4. Here 'AB' indicates the length of detonating cord. The signal generated from self-shorting pin inserted at 'A' should be used to trigger the capacitor bank discharge. In actual FCG experiments, instead of using PEK charge at the other end 'B' of detonating cord, it should be directly placed in booster pellet embeded in main charge which initiate the detonation of explosive in armature. The length of the detonating cord should be chosen so as to incorporate the suitable delay between triggering of capacitor bank discharge and explosive detonation that matches with the rise time of capacitor discharge cycle.

To achieve the synchronisation between rise time of capacitor discharge cycle and detonation of explosive, it is critical to control the triggering of capacitor bank discharge at a desired time. In experiments carried out using EBW type detonators, the synchronisation can be achieved due to ability of EBW type detonators to produce jitter within range of tens of ns. In using electrical detonator no. 33 in FCG applications, it is difficult to achieve synchronisation within ±1 µs due to its jitter of around 10 to 20 µs in such detonators. To overcome this limitation, the trigger pulse to capacitor bank discharge is to be fed from the pulse generated by shorting pin at the end A which gets shorted on bursting of detonator. Therefore, the variation in bursting time of electrical detonator no. 33 is excluded and the synchronisation can be achieved with desired accuracy if the repetitive delay is produced from the detonating cord. Here, the detonating cord serves two

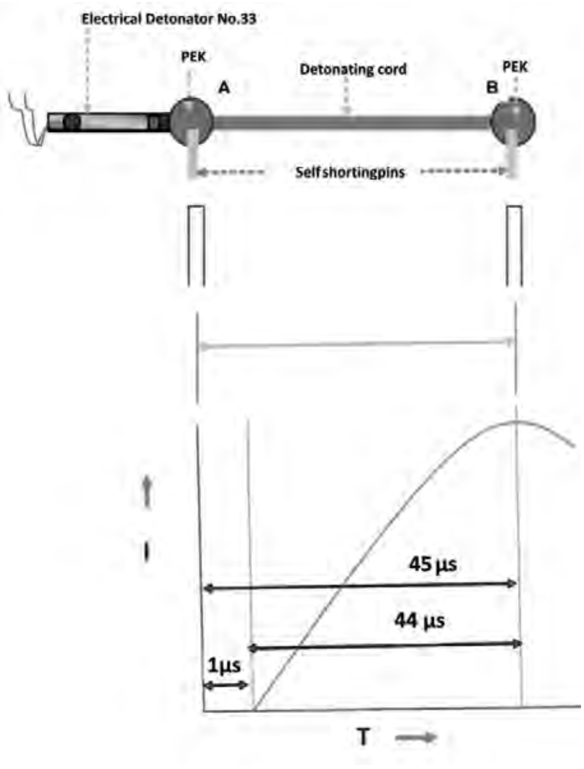

Figure 4. Schematic of charge assembly for optimisation of detonating cord length to synchronise the event of explosion of explosive at peak current in solenoid.

objectives, viz., it incorporates the desired delay time based on it's length and it also transfers shock wavefront to booster pellet which initiates the main charge.

The block diagram for the timing circuit of seed current in stator, high explosive in armature and triggering of the diagnostics to be used in FCG experiments is as shown in Fig. 5.

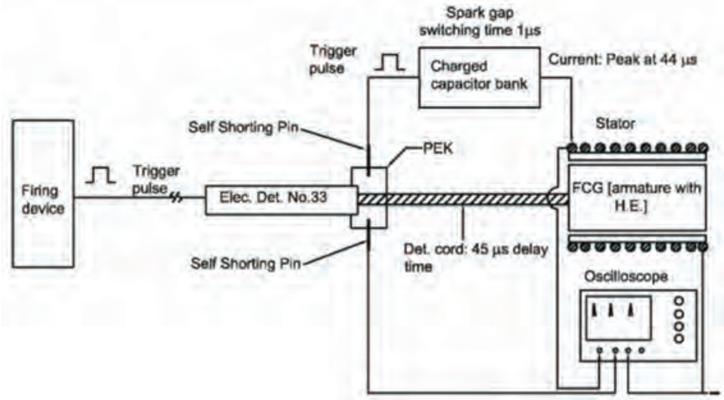

Figure 5. Block diagram for the timing circuit of seed current in stator, high explosive in armature and triggering of the diagnostics.

Figure 6 shows the waveform indicating measurement of delay times as recorded on fast-storage oscilloscope. Depending upon the capacitance and inductance in the circuit, the rise time of the discharge current cycle may vary. To ensure the flexibility of the technique, the experiments were carried out with different lengths of detonating cord to introduce pre-determined delay from 31 µs to 251 µs and the delay time measured experimentally was compared to the estimated delay time arrived at by calculations to ensure that the synchronisation of both occurs within a µs.

As the firing of explosives was constrained to be performed in a spherical volume of about 1 m dia, the detonating cord up to length of 330 mm, corresponding to delay of 45.1µs, was laid straight. For longer lengths of the cord (1840 mm) the detonating cord was wounded in a helical fashion on support 50 mm wide and 6 mm thick wooden plate. To achieve the proper delay within this limited space, it was important to prevent sympathetic detonation. It has been found that 1840 mm long prima cord with a pitch of 50 mm resulted in proportionate delay time of 251.1µs without sympathetic detonation.

The variation in calculated and experimental delay time recorded from 31 µs to 251 µs was around ±0.5 µs. The variation in calculated and experimental delay time versus detonating cord length is shown in Table 1.

It is clear from Table 1 that the experimentally measured delay times are in good agreement with calculated delay times for various lengths of the detonating cord (from 230 mm to 1840 mm). This indicates that with the current developed technique using electrical detonator no.33 and detonating cord of pre-determined length, the precise delay time can be introduced to synchronise the two events in FCG experiments.

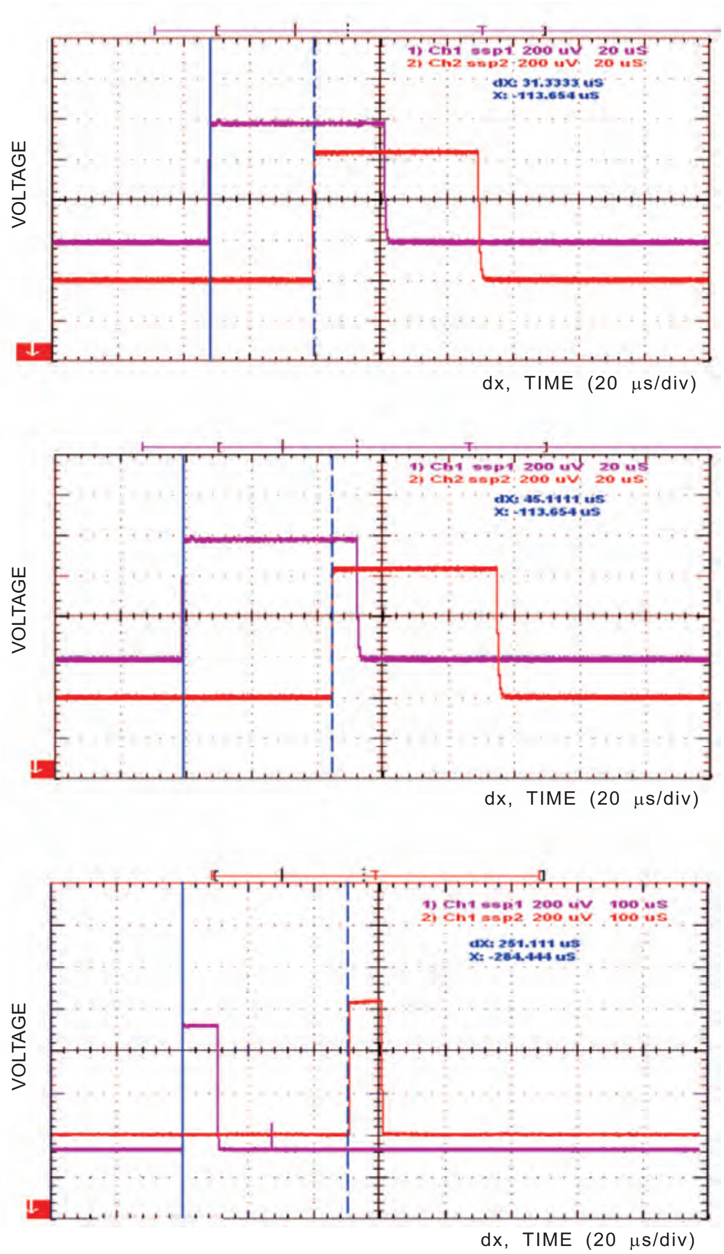

Figure 6. Measured delay time with waveforms for different prima cord lengths (*l*) and observed delay time (*dx*), as recorded on fast storage oscilloscope: (a) *l*=230 mm, *dx*=31.3 µs, (b) *l*=330 mm, *dx*=41.5 µs, and (c) *l*=1840 mm, *dx*=251.1 µs

Table 1. Experimental data on detonating cord length and observed delay time

Length of PETN detonating cord (mm)	Calculated delay time (µs)	Experimentally measured delay time (µs)
230	31.5	31.3
281	38.49	39.3
300	41.09	40.7
320	43.83	43.5
320	43.83	44.1
330	45.20	45.1
400	54.79	55.0
1840	252.05	251.1

4. CONCLUSIONS

The generation of rapidly rising very high currents using explosive-driven flux compression generation involves the discharge of energy storage capacitor through the coil of the FCG and the detonation of the explosive in the armature in FCG when the coil current has reached its peak value. The synchronisation between the discharge of the capacitor and detonation of the explosives needs to be well synchronised (within ±1 μs). The authors have successfully demonstrated that using electrical detonator no. 33 (which generally does have bursting time variation of 10 μs to 20 μs) and detonating cord of pre-determined length, the two events can be synchronised with the pre-determined time delay with the variation within ±0.5 μs. Therefore for applications requiring synchronisation within 0.5 μs, electrical detonator no. 33 with detonating cord can replace the more sophisticated detonators like electric bridge wire detonators. These synchronisation studies are very useful in defence applications like generation of high power microwaves using explosive-driven FCG.

REFERENCES

1. Novac, Bucar M. *et al.* A 10–GW pulsed power supply for HPM sources. *IEEE Trans. Plasma Sci.*, 2006, **34**(5), 1814-1821.
2. Chen,Y. J.; Neuber, A. A.; Mankowski, J. Dickens, J.C.; Kristiansen, M. & Gale, R. Design and optimisation of a compact, repetitive, HPM system, *Rev. Sci. Instrum.* 2005, **76**, 104703-1-8 .
3. Neuber, Andreas A. & Dickens, James C. Magnetic flux compression generators. *In* Proceedings of the IEEE, **92**(7), July 2004.
4. Bola, M.S.; Madan, A.K.; Manjit Singh & Vasudeva, S.K. Expansion of metallic cylinders under explosive loading. *Def. Sci. J.*, 1992, **42**(3) 157-63.
5. Explosively driven pulsed power, *edited by* A.A. Neuber. Springer–Verlag, Berlin, Germany, 2005.
6. Kwan,Thomas J.T. High-power coherent microwave generation from oscillating virtual cathodes. *Physics of Fluids*, 1984, **27**(1), 228-32.
7. Appelgren, Patrik. Small helical magnetic flux compression generators; Experiments and analysis. *IEEE Trans. Plasma Sci.*, 2008, **36**(5), 2673-2683.
8. Varosh, Ron. Electric detonators: EBW and EFI. *Propel. Explos. Pyrotech.*, 1996, **21**, 150-54.
9. Wolfsan, Michael G. A guide to explosives firing, DSTO-GD-0118, DSTO Aeronautical and Maritime Research Laboratory, Melbourne Victoria, November 1996.
10. Austing, J.L.; Tulis, A.J.; Schmitt, H.R.; Urbanski, E.; Mosora, J.A. & Hawley, J. Electrothermal analysis as a tool for designing electric detonator firing circuits, *Propel. Explos. Pyrotech.*, 1984, **9**, 193-200.

Contributors

Dr P.B. Wagh has received his PhD (Physics) in 1999 from Shivaji University, Kolhapur. Presently he is working as Scientific Officer 'E' in Applied Physics Division, Bhabha Atomic Research Centre(BARC), Mumbai. He has to his credit about 45 research publications in cited international and national journals. Presently, he is involved with synthesis and characterization of nano-size explosive materials by Sol-Gel method. He is life member of High Energy Materials Society of India.

Mr Sanjay V. Ingale has obtained his MSc (Physics) from Shivaji University, Kolhapur. Presently he is working in the Applied Physics Division, BARC, Mumbai. He is involved in the development and processing of nano structured materials and energetic materials.

Mr Amit S. Rav has obtained his BE (Electronics and Communication) from Gujrat University in 1999. Presently he is working in the Applied Physics Division, BARC, Mumbai. He has been working on the development of diagnostic techniques for high energy impact experiments.

Dr T.C. Kaushik has received his PhD from University of Bombay, Mumbai in 1995. Currently, he is the Head, High Energy Density Application Section, Applied Physics Division, BARC, Mumbai. He is recipient of *DAE Special Contribution Award* and has around 80 publications in journal, national and international conferences. Presently he is working on experiments and numerical simulation related to Megagauss magnetic fields, flux compression generators, opening switch, pinches and accelerators (electric gun/rail gun) using pulsed power sources.

Dr Satish C. Gupta working in the Applied Physics Division, BARC, Mumbai. He has to his credit a large number of publications in internationally reputed journals. He is recipient of *DAE Special Contribution Award*. His research interests include: behavior of high energy density matter and response of material to dynamic compression at high strain rate using shock wave.

Dr S.N. Asthana has received his PhD (Chemistry) from University of Pune. Presently, he is Director of Armaments, DRDO HQr, New Delhi. He has been instrumental in the development of technologies of high explosives for warheads of missiles, new class of cast cure polymer-based explosives for futuristic insensitive munitions, and modern high energy materials like CL-20. He has carried out extensive R&D work in the field of solid rocket propellants.

Mr R.D. Wasnik has obtained his BE(Chemical) from Regional Engineering College, Rourkela. Presently, he is working in High Explosives Division, High Energy Material Research Laboratory (HEMRL), Pune. He received *Laboratory Technology Group Award-2005*. He has been instrumental in the development of technologies of high explosives for warheads of missiles.

Mr R.B. Sohoni has obtained his Diploma in Electronics and Communication Engineering. Presently, he is working as Technical Officer C, HEMRL, Pune. His research interest include: Design and development of controllers and instrumentation systems for assessment of high energy materials and software development for the systems. He is expert in development of state-of-the-art instrumentation systems for characterisation of high explosives.

Mr M.N. Adya has obtained his Diploma in Electrical Communication Engineering in 1970, and AMIE (Electronics and Communication Engineering) in 1986. Presently, he is working as Technical Officer C, HEMRL, Pune. His area of expertise include: Development of instrumentation systems for testing and evaluation of high explosives.