研究論文

# Design and performance evaluation of ENERFOIL™ ignition enhancers for passenger side airbag inflators

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A new pyrotechnic material, ENERFOIL™ ignition film, has been used to produce a new class of ignition enhancing system for passenger side airbag inflators. This ignition film is manufactured by physical vapor deposition of magnesium onto a PTFE film substrate. The unique form of this material allows one to design ignition train using standard film handling techniques such as embossing, cutting and rolling. This manufacturing method produces highly efficient and cost effective ignition elements as described in this paper.

Propellant based airbag inflator requires very fast ignition time of a few milliseconds to achieve complete combustion of the propellant grains within about 50 milliseconds. The present paper describes the techniques developed at ICI Explosives to obtain such fast ignition times with the ENERFOIL™ ignition film. Experiments showed that the degree of reaction of the ENERFOIL™ film and the time to reach maximum pressure depended strongly on the separation of the film layers, which was carefully controlled by embossing of the film. The optimum separation between layers was shown to be about 300 micrometers. The confinement of the ENERFOIL™ ignition film element was also shown to be important. This confinement was provided by either a confining tube or by the separation between propellant grains. With optimum interply separation and proper confinement, full reaction of the ENERFOIL™ ignition enhancer could be achieved in less than 4 milliseconds from first current to a typical airbag inflator squib.

The effectiveness of the present ENERFOIL™ ignition enhancing system was demonstrated in tests using this system to ignite ICI's MICROSAF™ propellant grains in a typical passenger side inflator configuration. Ignition of the propellant grains were shown to be well within 4 miliseconds, independent of initial temperatures. Experimental inflator and tank pressures provided positive proof of the excellent performance of the present ignition system at all temperatures of interest.

## Introduction

All automobiles manufactured in North America are now equipped with driver side airbags. By 1998 all passenger cars will also have to be equipped with passenger side airbags. Most of the current gas generators are based on solid propellants, specifically sodium azide based propellants of various formulations. Gas generators require very fast functional times of between 30 to 60 milliseconds, depending on the location of the airbag in the automobile. In order to achieve such fast gas generation time, the propellant must be capable of burning fast. Furthermore the ignition of the propellant surfaces must be prompt and uniform. In order to produce such fast ignition, the ignition system must complete its own reaction within a few milliseconds and distribute its combustion products and heat to all propellant surfaces uniformly

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and simultaneously without significant damages to the propellant grains. This is particularly challenging in the case of a passenger side gas generators which contain more propellant and are usually in a elongated configuration. It has been shown[1,2] to be extremely difficult and expensive to provide an ignition system that would ignite solid gas generant pellets and wafers uniformly throughout the entire length of the generator. The solutions adopted in the past were both expensive and hazardous in manufacturing and handling. One of these[1] utilized a center perforated tube filled with boron potassium nitrate powder and a coaxial fast deflagrating cord. Another design[2] coated the propellant grains with a booster material.

The present paper describes a new ignition system developed at ICI Explosives. This new system is manufactured from a new pyrotechnic material, ENERFOIL™ Ignition film using simple film processing equipment. The simple geometry and straight forward manufacturing technique used substantially overcomes the cost and handling hazard of these systems. The geometric configurations of the film have been found to be important to obtain optimum performance from this type of material. The design criteria and test results are given in this paper.

## Experimental

### Properties of ENERFOIL™ Ignition Film

ENERFOIL™ Ignition Film is a variant of magnesium - polytetrafluoroethylene, PTFE. It is manufactured by the novel process of physical vacuum vapour deposition invented by Allford and others[3,4]. In this process, a sheet of PTFE is coated with magnesium on both sides giving a sandwich structure of well controlled dimensions. The ENERFOIL™ film thus produced possesses excellent safety properties[5], significantly better than identical chemical composition produced in powder form. Thermal stability is better than 450°C by DSC and time to ignition at 550°C is 30 seconds. Impact and friction sensitivities by the BAM testing methods exceeded 16 joules and 360 N respectively. Static electricity ignition threshold is 20 joules.

Ballistic properties have been computed by thermochemical calculations. The isochoric and isobaric flame temperatures are 5010K and 3800K respectively. The computed heat of reaction is 9.1 MJ/kg. Unconfined flame spread rate was found to be approximately 1 m/s at atmospheric pressures and with confinement the flame propagation rate is close to 300 m/s. More details on the properties of ENERFOIL™ Ignition Film can be found in Refs. 4 and 5.

In the present application, the thickness of the PTFE film was of the order of 25 microns and that of the magnesium was about 8 microns per side. The magnesium coating thickness was selected to bring the overall composition of the finished film to stoichiometric. The material used in the present study was manufactured in an experimental coater at the UK Defence Research Agency, Fort Halstead, Sevenoaks, U.K. The pyrotechnic film produced in this machine had a width of 152 ㎜, limited by the size of the coater, and lengths of about 10 m.

### Ignition Enhancer Preparation

All test samples were cut to the required dimensions from the 10 m length sheets. The cut sheets were pre-treated by embossing[6] with rows of dimples. It was done by passing the precut sheet between a steel roller with the surface machined with the desired pattern and a rubber roller. Most of the samples tested in the present study used a pattern consisting of regularly spaced dimples at 3 ㎜ centres in each direction and each dimple was approximately 3 ㎜ square at the base, 0.79 ㎜ square at the top, and 0.79 ㎜ high. The resultant embossed pattern on the ENERFOIL™ sheet had dimples approximately 3 ㎜ square at the bottom, 0.2 ㎜ square at the top and 0.4 ㎜ high. The upper layer of the magnesium was ruptured around the periphery of the top of the dimples to expose the PTFE film at the magnesium/PTFE interface. The embossing thus has the effect of increasing the ignition sensitivity of the material and providing controlled separation between stacked layers.

In most tests, the sample sheets were cut into quadrilateral shape with at least two opposite sides parallel. One of the parallel side was attached to and wound around a 3 ㎜ diameter former with controlled tension to obtain a finished coil with the desired interply separation distances. The former was then withdrawn from the coil leaving a hollow core in the coil (Fig. 1). The top and bottom edges of the sheet thus formed helices, one internal and the other external, co-axial with the former and extending at each end along the coil. During tests, the end with the internal helices was inserted to face the igniting

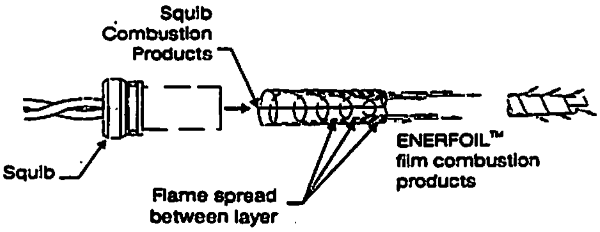

Fig.1 ENERFOIL™ ignition enhancer design considerations

squib as shown in Fig. 1. The present hollow center core design confines the squib combustion products and guides them to flow over the exposed helical edge of the coil. Thus the internal helical edge is ignited almost simultaneously. Once ignited, the combustion of the ENERFOIL™ sheet proceeds rapidly downstream through the interply spaces. The propagation speed of the combustion is also significantly increased by the self confinement of the coil layers. The bottom end helical edge faces outward and it provides quick release of the combustion products to adjacent propellant grains. This spiral wrap design, particularly that with parallel top and bottom edges, also facilitates production allowing one to use relatively simple continuous paper wrapping technologies.

### Ballistic Test Setup

The hollow-core, coiled ignition enhancer was inserted into a 12.7 ㎜ diameter perforated stainless steel tube 260 ㎜ long, 0.9 ㎜ wall thickness. The perforations of the confining tube consist of a number of 2.7 ㎜ holes. The assembled ENERFOIL™ ignition enhancer was placed in the center of a cylindrical combustion test vessel (ballistic bomb) which simulates the physical dimensions of a typical passenger side airbag inflator (Fig. 2). The propellant grains and filter normally used in an inflator were replaced with cores of nylon and stainless steel, respectively, with holes drilled into them to simulate the porosity of the real grains and filter elements. The resulting ballistic bomb had an effective free volume of 200 cc. This simulates the propellant combustion chamber of a typical passenger side gas generator. The top and bottom edges of the confining tube were inserted into the top and bottom covers of the vessel leaving an unsupported length of 235 ㎜. In some tests, where confinement effects of the propellant grains were investigated, the confining tube was not used and the nylon core was replaced with inert propellant grains. In most tests, squibs (ICI IGN-193) containing 155 mg of $Ti/KClO_4$ were used to ignite the ENERFOIL™ ignition enhancers. The end of the enhancer was positioned within 5 ㎜ of the squib end surface. This strength of squib was found to be sufficient to ignite promptly all configurations of ENERFOIL™ ignition enhancers investigated. Squibs loaded with the same composition of other weights were also studied and reported in the following.

The ballistic bomb was instrumented with two pressure transducers (Kistler 211B2). One of these transducers was mounted in the end flange opposite

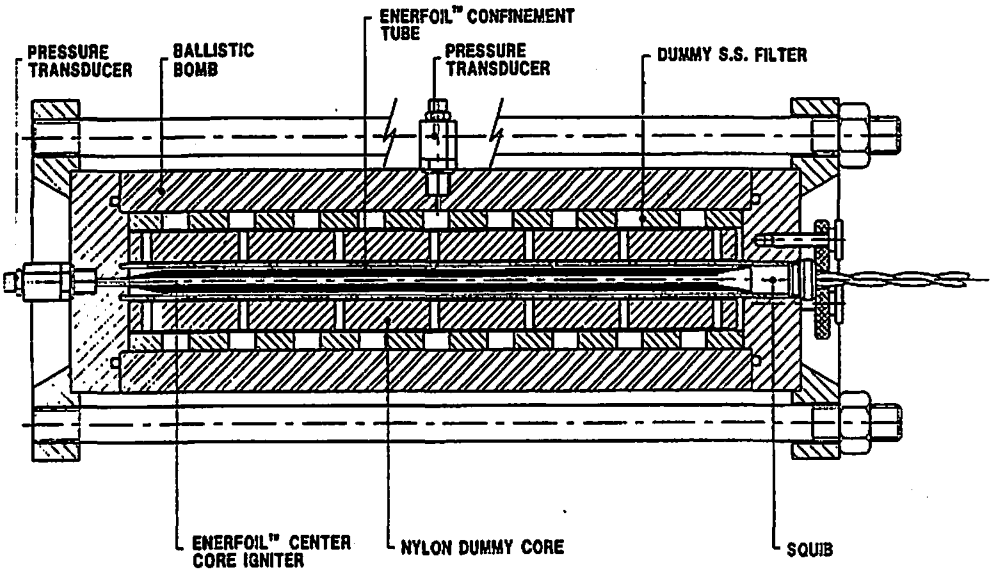

Fig. 2 Schematics of ballistic test bomb

Table 1 Dimensions of ENERFOIL™ Enhancers for Interply Separation Experiment

| Sample | Side 1 ㎜ | Side 2 ㎜ | Included angle degree | OD㎜ | Weight gm | Separation microns |
|---|---|---|---|---|---|---|
| 1 | 132 | 369 | 75 | 8 | 4.0 | 76 |
| 2 | 132 | 369 | 75 | 9 | 3.78 | 117 |
| 3 | 132 | 369 | 75 | 10 | 3.80 | 159 |
| 4 | 132 | 369 | 75 | 11 | 3.83 | 204 |
| 5 | 133 | 319 | 73 | 11 | 3.34 | 247 |
| 6 | 135 | 270 | 70 | 11 | 2.78 | 303 |
| 7 | 139 | 222 | 66 | 11 | 2.29 | 347 |
| 8 | 145 | 171 | 62 | 11 | 1.74 | 476 |
| 9 | 156 | 125 | 54 | 11 | 1.27 | 508 |

to the squib, with communicating hole through the flange to measure the pressure inside the confining tube. Another pressure transducer was mounted in the cylindrical wall of the ballistic bomb. It measures the pressure from the confining tube into the free volume of the ballistic bomb.

The start of the current pulse to the squib was used to trigger the digital recorder (Tektronix Testlab) which was used to record the signals from the two pressure transducers. The time at the start of the firing current pulse was taken as the reference time for all pressure signals referred to in the following.

## Results and Discussion

### Effect of Interply Separation

To investigate the effects of the interply separation on the performance of a coil of ENERFOIL™ ignition enhancer, a series of experiments was carried out. In these experiments, the ENERFOIL™ sheets were cut in parallelogram shape from 126 ㎜ wide material with an average areal density of 82.5 gm/m$^2$. The overall lengths of the finished coil were kept to a constant value of 229 ㎜. The dimensions of the sheets are shown in Table 1. Side 1 in Table 1 refers to the sides parallel to the former and Side 2 refers to the top and bottom sides. The cut sheets were embossed and wound with controlled tension to obtain coils to the desired outside diameters. The interply separation distances were estimated by theoretical calculation assuming that the coil was formed by a continuous spiral with constant separation distance. In practice, the outside diameter was limited to 11 ㎜. Therefore, in order to increase the interply separation, the dimensions of the cut sheets for Samples 5-9 had to be altered. The samples were inserted into perforated tubes. These tubes had 32 venting holes, 2.7 ㎜ diameter, (total area of 183 ㎜$^2$) distributed evenly along the free length of the tube.

The pressure inside the confining tube at the end opposite to the squib and that in the ballistic bomb for Sample number 6 is shown in Fig. 3. The tube pressure reached peak value at about 1.2 milliseconds and decayed from then on as the combustion products continued to vent into the ballistic bomb chamber. While the squib reaction time is about 1 ms, therefore it took only about 0.2 ms for the combustion/shock front to travel through the 299 ㎜ length of the ENERFOIL™ ignition enhancer. External to the confining tube, the pressure started to increase at the same time as the pressure inside the tube. The slight differences in the two starting times in Fig. 3 was due to the locations of the two pressure transducers relative to the squib position. The external pressure increased continuously and reached its peak value at 3.47 ms. It then decayed slowly with time due to the cooling of the products and gases.

The maximum values of the external pressures for the different samples of Table 1 are normalized by the weight of the samples and plotted in Fig. 4 as a function of the interply separation. The dashed line was a fit to the data and shows the trend of the pressure variation with separation. The time to reach peak pressure is also shown in Fig. 4. The data in Fig. 4

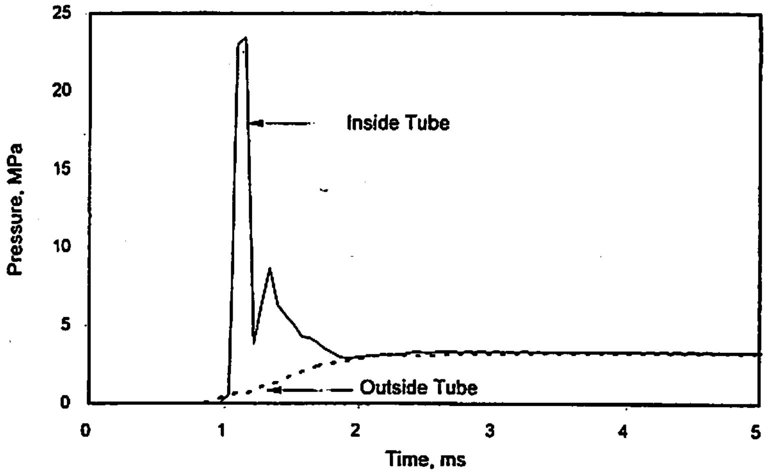

Fig. 3 Ballistic performance of ENERFOIL™ ignition enhancer in confined tube

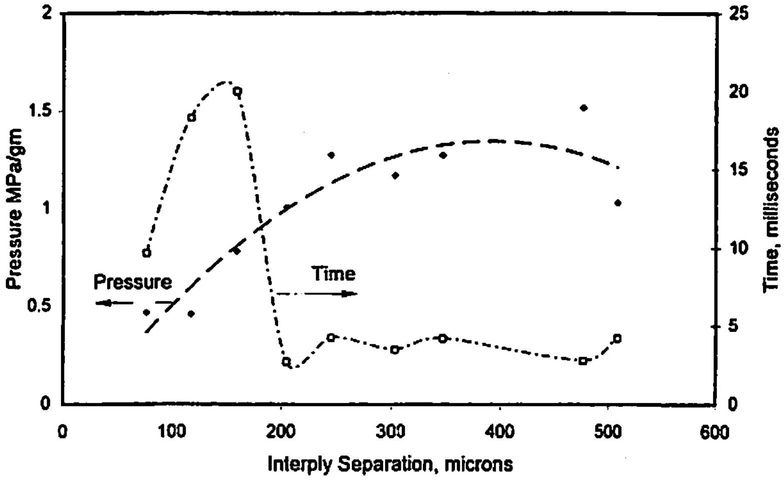

Fig. 4 Effects of interply separation on combustion efficiency of ENERFOIL™ ignition enhancers

shows that the pressure increases with separation up to about 250 microns and remains fairly constant after that. The times to peak pressure remain fairly constant at between 2.8 and 4.2 ms above about 200 microns separation. However, its value increases sharply at separation below 200 microns. Similar trend is also observed in the maximum tube pressure as shown in Fig. 5. Here, above 200 microns separation, the peak pressure increases sharply while the time to reach such pressure decreases to a constant value. Below 200 microns, the peak time increases with a reduction in the separation distance. Both sets of data suggest a change in the combustion mechanisms of the coiled enhancer. Above 200 microns separation, propagation of combustion through the interply spaces was extremely fast as indicated by the very short elapsed time (0.2 ms estimated) from squib functioning to the arrival of the peak pressure at the end of the confining tube. These results in the ignition and combustion of the individual ply almost simultaneously along its entire length to generate high pressures outside the tube in very short times of between 2.8 to 4.2 ms. Discounting the squib reaction and flame propagation time of about 1.2 ms, these times correspond to a total burn time of 1.6 to 3 ms or a linear burn rate of 12.5 to 6.6 mm/s for a 40 microns thick pyrotechnic sheet. Similar burn rates were reported by Kubota and Serizawa[8] for Mg/PTFE in the pressure range of between 2 to 0.8 MPa. However, the burn times below 200 microns are longer by a factor of 4-9.

The pressure outside the confined tube can be interpreted as an indication of the efficiency of energy transferred into the free space in the ballistic bomb. Since ignition of solid propellants depends strongly on the rate of heat transferred to the surface of the propellant[7], an efficient ignition system must be able

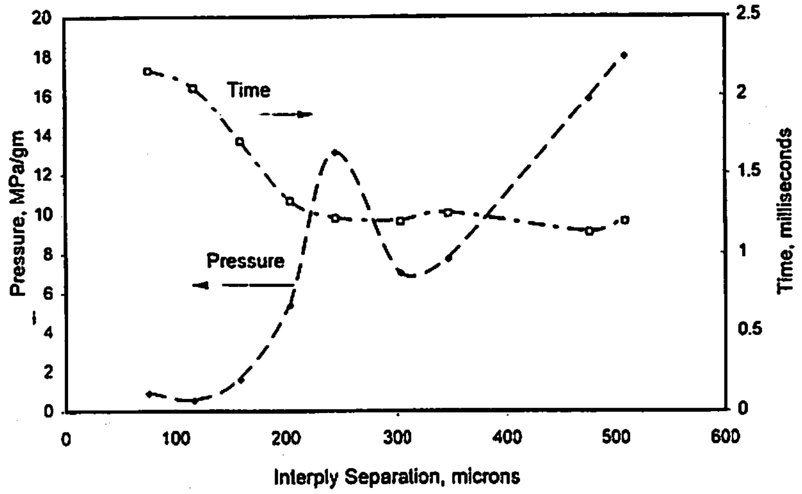

Fig. 5 Effects of interply separation on maximum center core pressure and time to reach maximum pressure

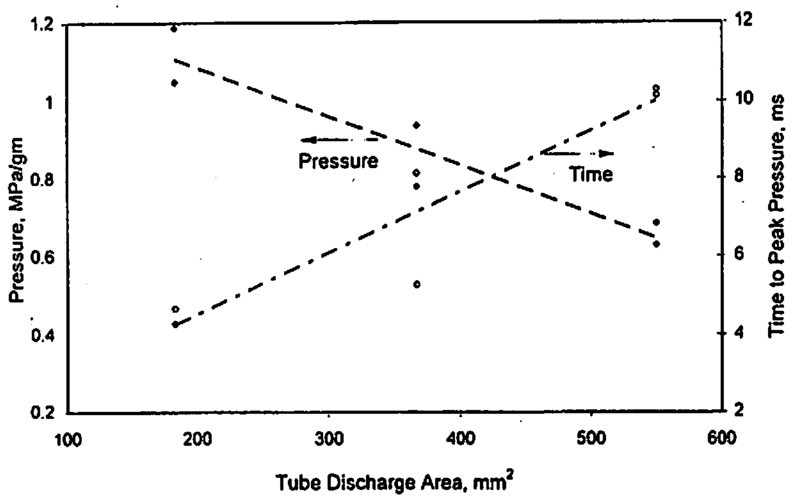

Fig. 6 Effect of confining tube (229 ㎜ long) discharge area on ENERFOIL™ enhancer performance

to deliver high energy in a short time, i.e. high rate of energy output. The data of Fig. 4 suggests that, in order to assure consistent fast combustion and most efficient use of coiled ENERFOIL™ ignition enhancers, the interply separation should be controlled to above 200 microns, preferably at 300 microns to assure reproducibility.

**Effects of Confinement**

The combustion rate of Mg/PTFE, like most solid propellants, depends on pressure[8]. In order to achieve high combustion rate, it is necessary to control the venting rate to achieve a sufficiently high combustion chamber pressure. To verify this hypothesis, a series of experiments was carried out in which the number of venting holes in the confining tube was varied. The resulting ballistic bomb peak pressure and the corresponding times are shown in Fig. 6. As expected, the pressure decreases while the time increases with an increase in the venting area. However, it was not practical to reduce venting area much below the 183㎜$^2$, or about 1% of the surface tube area. Nevertheless, the performance of the ENERFOIL™ ignition, even with this venting area, was sufficiently energetic to produce fast ignition of airbag propellant grains.

The confinement can be provided by either the confining tube or by the inter-grain spaces between propellant grains. Tests with dummy propellant grains with controlled separation showed no reduction in performance of the ENERFOIL™ enhancer, provided that the venting area through the grains is the same as that used in the confining tube.

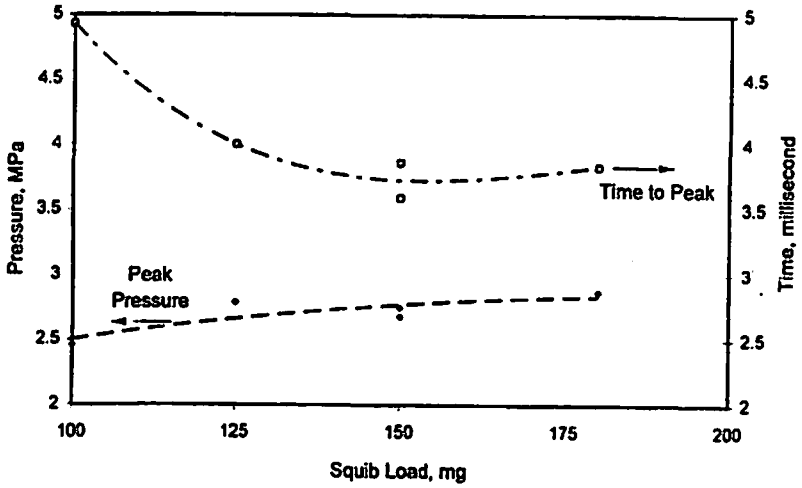

Fig. 7 Effect of squib load on ENERFOIL™ ignition enhancer

### Effect of Squib Loading on Ignition of ENERFOIL™ Enhancer

The ENERFOIL™ material is very insensitive to thermal ignition. Therefore, it is expected to require a strong squib to effectively ignite the enhancer made from this material. A series of experiment was carried out to determine the minimum loading required. Special squibs were made with different amount of pyrotechnic powder (Ti/$KClO_4$). These were tested with ENERFOIL™ enhancers with dimensions similar to that of Sample 7 in Table 1. The peak pressures and the time to reach these pressures outside the confining tube are shown in Fig. 7. The results show that maximum enhancer performance was achieved with squib loading above 125 mg. In fact, the performance was acceptable even at the lowest tested squib load of 100 mg. Therefore, the standard ICI squib load of 155 mg is definitely sufficient.

### Performance of ENERFOIL™ Ignition Enhancer in Passenger Side Inflators

The performance of optimized ENERFOIL™ ignition enhancers[9] was verified by full scale tests in experimental passenger side gas generators[10] designed by ICI using ICI',“ MICROSAF™ propellant grains[11-13]. The MICROSAF™ propellant formulation was $NaN_3/Fe_2O_3/SiO_2$ (63/29/8) with a linear burn rate of 39 ㎜/s. The propellant grains were pressed wafers having dimensions of 35 ㎜ OD, 14 ㎜ ID and 4 ㎜ thickness. One surface of the grains had 8 radial ridges (0.25 ㎜ height) extending 6.5 ㎜ from the circumference of the inner hole and 8 radial ridges extending the same distance from the outer circumference of the grain. Details of the experimental setup and instrumentation are described in Ref. 10. This grain geometry provides very efficient energy transfer to the grain surfaces for prompt ignition from the ENERFOIL™ ignition enhancers. The averaged amount of propellant used in these shots was 370 gm, containing between 52 - 55 individual wafers..

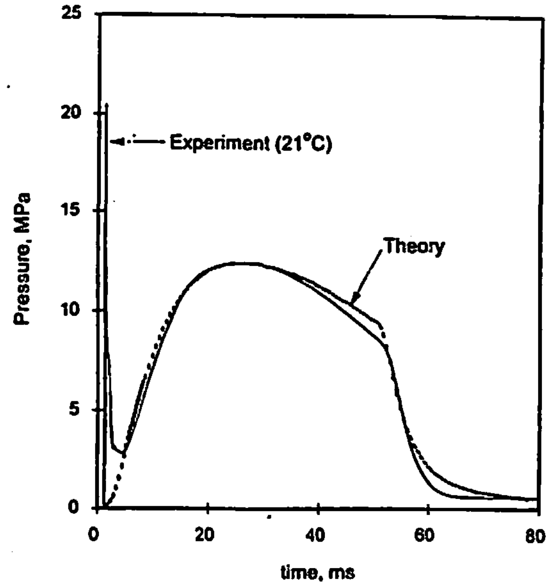

Fig. 8 Comparison of theoretical (1.5 ms delay, 3.5 ms flame spread) and experimental generator pressures

The experimental inflator pressure from the transducer connected to the end of the confining tube is shown in Figure 8. The first pressure spike was from the reaction of the ENERFOIL™ enhancer. This spike is followed by a rise in pressure after 4.2 ms as a result of the combustion of the propellant grains.

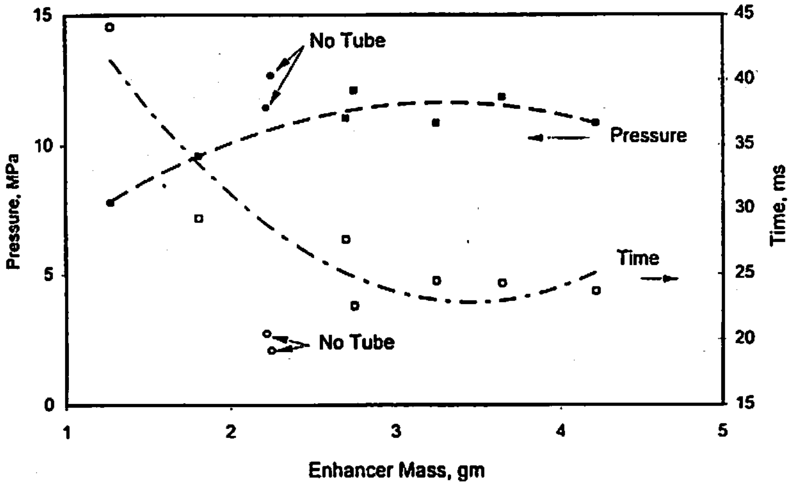

Fig. 9 Effect of ENERFOIL™ ignition enhancer mass on generator (−29°C) maximum pressure and time

Therefore, ignition of the propellant grain surfaces must have been effected well before 4.2 ms.. The pressure in the 60 liter tank, in which the inflator was tested, showed a first gas time of 3.6 ms. The combustion chamber pressure continues to rise, reaching a peak then decreases due to exhaust of gases from the inflator. The pressure shows a change in the rate of decrease at 51.5 ms. This is caused by the completion of combustion of the propellant grains. In this case, the very sharp change in the slope of the curve is a strong indication that the propellant grain surfaces completed combustion simultaneously. The latter was only possible if all exposed propellant surfaces were ignited evenly and simultaneously. This is proven by the excellent fit between the experimental curve and the theoretically predicted pressure from ICI's Lumped Parameter Airbag Gas Generator Model[10]. In the model, ignition of the propellant grains was assumed to commence at 1.5 ms and progressively spread throughout all propellant surfaces in the next 3.5 ms.

To evaluate the minimum mass of ENERFOIL™ ignition enhancer needed to effectively ignite the propellant grains, a series of experiments was carried out with the same gas generator design and propellant load. However, the individual mass of the enhancers was varied by varying the length of the sheet in the direction winding while keeping the overall length of the finished coil constant (229 ㎜). The shots were carried out with the generators conditioned to −29°C. The peak generator pressures and the times to reach such pressures are shown in Fig. 9. The peak pressure increases with an increase of enhancer mass reaching maximum value of about 12 MPa above 2.5 gm. The corresponding time decreases to about 23 milliseconds. Two shots were carried out using 2.2 gm of enhancer without the steel confining tube. The experimental peak pressures and times are also shown in Fig. 9 (circles). The pressures are higher than that for equivalent mass in confining tubes and the times to reach such pressures were lower. This shows that the ENERFOIL™ ignition enhancer functioned more efficiently using confinement provided by the propellant grains only. This was partly due to the elimination of heat losses to the confining tube.

The delay time to detection of first gas in the test tank, in which the gas generator was tested, is an important functional parameter for the gas generator. A summary of these delay times from a large number of generator tests at −29°, 20° and 66°C are shown in Fig. 10. All these tests used optimally wound ENERFOIL™ ignition enhancers. The burst pressure of the generator can be seen to be a controlling factor of the delay time. At low bursting pressures of about 1.4 MPa, it can be seen that the delay times were all between 2 to 6 milliseconds, almost independent of the initial generator pressures. This was due to the temperature independent performance characteristic of the ENERFOIL™ ignition enhancer. Higher bursting pressures required longer pump up time in the gas generator and caused longer delay times before the release of gases from the generator. Nevertheless,

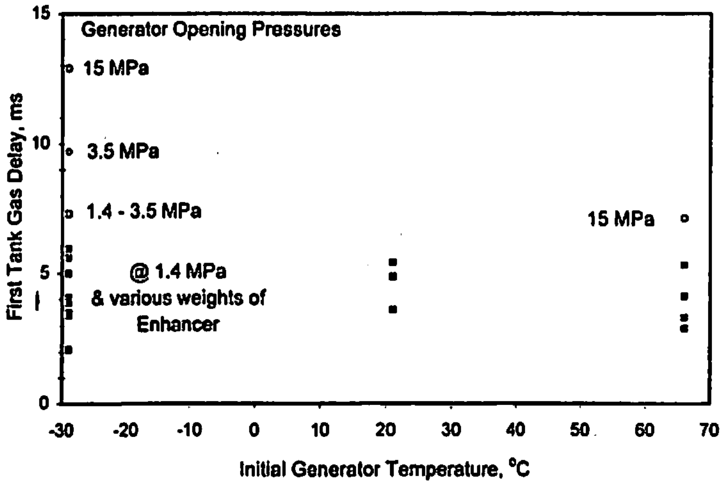

Fig. 10 Delay times to first tank gas of ENERFOIL™ ignition system with MICROSAF™ propellant in ICI and other generators

even with bursting pressures as high as 15 MPa, the delay times were below 13 ms at -29°C.

## Conclusions

Results presented in this paper demonstrated clearly the superior performance capability of the ICI ENERFOIL™ ignition enhancers in solid propellant based air bag gas generators. However, in order to obtain the higher reaction rate and the best performance from this new class of material, there are some limitations one has to observe in designing and using the enhancer. The most important factors controlling the optimum functioning of these enhancers were shown to be the interply separation, which must be kept to 250 microns or higher, and the degree of confinement of the enhancer, which should be kept to about 180mm$^2$ of venting area for typical enhancers of 230 mm long, or 1% of confinement area.

## Acknowledgments

The permission of ICI Explosives to publish this work is acknowledged. Many people have contributed to the ideas and experimental work presented in this paper, particularly those of S. Graham, R. LeBrun and M. Logan. Their contributions are acknowledged here with thanks.

## References

1) Schneiter, F.E. "Wafer Grain Gas enerator", US Patent 4, 890, 860, Jan. 2, 1990.
2) Goetz, G.W. and Vos, T.H. "Gas Generating Material", US Patent 5, 034, 070, July 3, 1991.
3) Allford, F.G. "Pyrotechnic Materials", US Patent 5, 253, 584, Oct. 19, 1993.
4) Allford, F.G. and Place, M.S., Proc. 15th Int. Symp. on Pyrotec hnics, Boulder, Co., U.S.A. 1990, pp. 1-34.
5) Chan, S.K., Graham, S.J. and Leiper, G.A., 26th Int. Ann. Conf. of ICT, "Pyrotechnics", July 4-7, 1995.
6) Chan, S.K., Graham, S.J. Kirby, I.J. and Leiper, G.A. "Pyrotechnic Material", UK Patent Application 2, 282, 136 A, 29 March, 1995.
7) Merzhanov, A.G. and Averson, A.E., Combustion and Flame, 16, pp. 89-124, 1971.
8) Kubota, N. and Serizawa, C., Propellants, Explosives, Pyrotechnics, 12, pp. 145-148, 1987.
9) Chan, S.K., Graham, S.J. and Leiper, G.A. "Pyrotechnic Ignition Device (Enhancer)", UK application No. 9509606, filed 12 May, 1995.
10) Chan, S.K., Proc. 20th Int.Pyro. Seminar, Colorado, July 25-29, 1994.
11) Chan, S.K. "Pyrotechnic Bodies", EP 0 576 161 A1, Publication 29-12-1993.
12) Chan, S.K. and Hsu, N., "Airbag2000", 2nd Int. Symp. on Sophisticated Car Occupant Safety Systems, Karlsruhe, Germany, Nov.29-30, 1994.
13) Chan, S.K., Hsu, N. and Oliver, R. "Process for the Preparation of Gas-generating Compositions", UK Patent Application No. 9505623. 0, Filed March 21, 1995.

# 新規イグニッションエンハンサー「エナフォイル」の設計と性能評価

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新規火工品「エナフォイル」はPTFE上にマグネシウムを物理蒸着したものであり，助手席用エアバッグインフレーターの新しいイグニッションエンハンサーシステムを生産するために使われている。この材料のユニークな形状を利用して様々な形の点火導火線の設計が可能であり，またこの材料は高効率，低コストの点火要素という特徴がある。

この報告ではエナフォイルフィルムを使って高速点火時間を得る技術について述べた。本実験により，エナフォイルの反応のレベルと最高圧に達する時間は層間の分離距離に強く依存することがわかった。それはフィルムをエンボスすることによって制御することができた。最適な層間分離距離は約300ミクロンであった。またフィルムの固定も重要である事がわかった。この固定は固定チューブにするとか，ガス発生剤の中で分離固定することによって行われる。最適分離距離及び適切な固定を選ぶことによって，標準的なインフレータースクイブへの初電流からエナフォイルの十分な反応までの時間を4ミリ秒内にすることができた。

現行のエナフォイルのイグニッションエンハンサーシステムとしての効果は，代表的な助手席インフレーターの仕様であるICIのガス発生剤「マイクロサフ」へ点火するテストを行ったところ，点火時間は実用温度領域で初期温度に無関係に，十分4ミリ秒以下であり，タンク圧も良好であることがわかった。

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