A Simple Comparison of the Characteristics of Energy-Absorbing Foams for Use in Safety Cushions in Glider Cockpit Environments

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Abstract

A simple comparison was made between different energy-absorbing foam combinations for use as safety cushions in cramped, glider cockpits. The most comfortable combination of Confor C47 and C45 was found to be better than the viscoelastic Sunmate X-Firm product, marketed as Dynafoam in the UK, and which has hitherto been the well-accepted, safety-cushion product.

Introduction

Starting in the mid 1980s, a concerted effort was made in the UK, in particular, to get glider pilots to use energy-absorbing foam for crash-related, safety reasons. However, following this initiative, evidence also accumulated to indicate that the energy-absorbing foam recommended was, itself, uncomfortable. A result of the latter was that many pilots forsook its use and resorted to cushions that were inherently unsafe in the case of accidents generating high-impact decelerations. Solutions included inflatable cushions, soft furniture foam and even builders' foam in order to make themselves comfortable. The use of energy-absorbing foam, however, is very important in gliders. In a comparison of different cockpit seating positions by van der Merwe Meintjes[1], the glider pilot's supine posture was noted as having the following specific disadvantages: "Minor accidents can result in back injury caused by spinal compression due to body position, *very little energy-absorbing distance between seat and fuselage floor*, ….."

Although the value of a softer, energy-absorbing foam placed on top of a firmer one was originally recognised in 1986[2], there were no authoritative attempts in the UK until circa 2006/2007 to promote this concept in gliding[3] in order to render such cushions more comfortable as well as safe. Even independent, sustained, commercial initiatives in the UK appeared to have limited success in increasing the adoption of such cushions. It was suspected that this was because even this type of cushion, formed from two foam layers, was still uncomfortable, in particular on long flights. A significant, additional, contributory factor to the low take-up was the lack of space in many glider cockpits that precluded any substantial thickness of foam being introduced.

As a result, work was undertaken by Jackson, Emck, Hunston and Jarvis[4] to measure objectively the comfort of different, safety-cushion options, made up of combinations of viscoelastic, energy-absorbing foams, for use in a glider cockpit environment. The measurements involved were made by reference to critical, tissue pressure. This study found that a combination of Confor C47 and C45 energy-absorbing foams provided a comfortable solution for 95% of pilots tested and appeared likely to provide this for more than 80% of all UK glider pilots. The study also found that the use of Sunmate X-Firm (Dynafoam Extra-Firm) produced the opposite effect and appeared likely to be uncomfortable for more than 80% of all UK glider pilots.

Since Sunmate X-Firm under its Dynafoam brand name was considered to be a well researched and recommended safety foam in gliding in the U.K., in particular, it became necessary to perform a basic comparison to verify that the energy-absorbing properties of the C47/C45 cushion option were not inferior to those of Sunmate X-Firm. This report describes the work undertaken to perform that comparison.

In the original work by Jackson, et al[4], the following foam options were selected for test:

1. Sunmate X-Firm (manufactured by Dynamic Systems Inc. and sold by a third party in the U.K. under the name Dynafoam Extra-Firm),
2. a layer of Sunmate Soft (Dynafoam Soft) on top of Sunmate X-Firm,
3. a layer of Tempur Firm (T85-18, manufactured by Tempur World Inc.) on top of Sunmate X-Firm,

4. Confor C47 (manufactured by E-A-R Specialty Composites),
5. a layer of Confor C45 on top of C47.

The underlying layers of Sunmate X-Firm and Confor C47 were nominally 1 inch thick (actually 25 mm). The overlaying Sunmate Soft, Tempur Firm (T85-18) and C45 were nominally 0.5 inches thick (actually 11 mm, 10 mm and 13.5mm, respectively). These thicknesses are those supplied commercially. Given the restrictions of glider-cockpit space, UK pilots typically purchase 1 inch of primary, energy-absorbing foam and then, in some cases, attempt to make it more comfortable by placing a 0.5 inch layer of softer, energy-absorbing foam on top of it.

Since Option 3 above, was found to be not significantly different from Option 2 in terms of comfort and, furthermore, was not commonly used, the energy-absorption properties of Option 3 were not pursued. However, although the objective was to measure those properties for Options 1 and 5, it was decided to include 2 and 4 as these were more widely available for use in aircraft. In fact, the use of Confor was suggested by an ejection seat manufacturer, Martin-Baker Aircraft Company. They had tested many energy-absorbing foams for their particular purposes and suggested that the Confor foam series be included in the tests. The properties of Confor have been investigated by Davies and Mills[5]. Tests undertaken by Hooper, et al[6] in 1994 demonstrated Confor C47's compliance with FAR 23.562. This placed a manikin on the foam, pre-compressed to 1g, and used a horizontal sled arrangement to create the correct 19g deceleration pulse required for the test.

It has been suggested that foams used for ejection seat cushions are unsuitable because they are only "impact tested" for the relatively low, controlled acceleration rates of 16-18g and that they are not tested for crash-impact g levels. This is not so. Ejection seat manufacturers are also given individual specifications for which crash impacts have to be tolerated in the case that ejection is not initiated. These are normally confidential. It appears that the typical vertical deceleration to which a cushion has to be tested (Gz) is 35g. The maximum appears to be about 40g.

Finally, it should be noted that the objective was to compare the energy-absorbing properties of the foam cushion options used and not to compare equal thicknesses of the same material (although the Sunmate X-Firm and C47 were of nearly identical thickness as were the Sunmate X-Firm/Soft and C47/C45 options). The focus, however, was on comparing the C47/C45 and Sunmate X-Firm cushion options.

Methods

The comparison of the energy-absorbing properties was undertaken by dropping a spherical impactor onto the foam-cushion options from preset drop heights. The weight used was almost identical to that used in Segal's original tests[2]. A spherical impactor was selected as being a representative arrangement that would more realistically reproduce the penetration that would occur with the ischial tuberosities as opposed to using a flat plate. A still more representative penetrative arrangement could have used two partial and linked hemispheres in a compression-rebound test such as described by van der Merwe Meintjes[1].

The details of the simple equipment designed to compare the impact response of the different foam options are as follows and are illustrated in Fig. 1.

A spherical indenter of 132 mm diameter, made up from a mixture of polyester resin, silica and phosphor-bronze powder, was used to create a weight suitable for the impact experiments. This was connected to a cylinder of 106 mm diameter providing the shape shown in Fig. 1. The weight of this complete assembly was 5.19 Kg. This impactor was rigidly connected to a long, lightweight arm (0.4 Kg) of length 1.94 m, pivoted at the opposite end from the weight. The arm was made from an aluminum channel section infilled with birch timber and resin bonded to increase its torsional stiffness. This pendulum was mounted so that the arm was horizontal when the mass was just touching the pad to be impacted. Hence, by lifting the mass and releasing it from a known height, an almost vertical drop could be achieved with a given impact velocity. The radius of the pendulum being large compared to the mass dimensions meant that the fall was close to vertical. However, since the impactor had a spherical form, this meant that at whatever the angle, the impact footprint was consistently the same. The foam to be impacted rested on a solid concrete slab cemented to a concrete floor. This slab, forming the concrete base, was planed to have a smooth, horizontal surface. The drop heights were measured on a vertical scale erected behind the pendulum mass.

The impactor and arm were lifted into position to predetermined test heights (accurate to plus/minus 1 mm) with a rope and retaining wire attachment. Height accuracy was achieved by lifting the arm to a predetermined marker on a calibrated board, which also served as an arm guide to prevent the weight toppling over after stroke completion.

An accelerometer attached to the top of the weight provided a response transient during the various drop tests conducted. The accelerometer was a Bruel and Kjaer 4384. Its output was analyzed by a Picoscope 2000 oscilloscope connected to a PC.

To initiate an impact, the retaining wire was severed, allowing the impactor to free fall under gravity until it struck the foam. The recording of the oscilloscope output, in turn driven by the output from the accelerometer, was initiated at the same time that the wire was cut. In this way, the deceleration experienced by the impactor was recorded as well as the acceleration leading, in some cases, to bouncing and further impacts. An example of the unfiltered output from one such drop is given in Fig. 2.

For each foam option, several drops were made using the accelerometer. Drops were made from the following heights: 50 cm, 75 cm and 100 cm.

To further understand the behavior of the foam options under impact, a series of drop tests were made with a Tekscan 9500 Hi-Speed pressure pad inserted under each foam option between it and the concrete-base surface. A similar series of drops were made for each foam option and the pressure pad output was recorded and analyzed using BPMS Research version 5.84 software.

To obtain direct measurements of the penetration achieved by the impactor on striking the different foam combinations, the following further series of experiments were carried out. A thin membrane of Lycra was placed on top of each foam option and held firmly in its unstretched condition in a square frame. The Lycra was placed on top of the foam surface. The impactor was then painted in a thin coating of black, emulsion paint. The former was, then, allowed to drop from the predetermined heights applied in the previous experiments. Each drop resulted in a circular outline being produced on the Lycra. The diameter of this was, then, measured. Knowing the diameter of the spherical impactor, simple geometry then enabled the depth of penetration to be calculated. For each combination of foam option and drop height, this process was repeated three times.

All of the experiments were initially carried out with the temperature of the foam at approximately 12˚ C. Two further series of drop tests – but not the other experiments – were undertaken with the foams at approximately 16˚ C and 26˚ C. The work was carried out in November and December 2007 and in June 2008.

Results

For each foam-option tested, amongst the results obtained, the following are particularly pertinent:

– peak deceleration measured in g,
– rate of rise of g (jolt),
– percentage energy absorbed (unabsorbed energy results in a bounce).

Peak deceleration and jolt

The output of each drop test was taken and the peak deceleration noted in terms of g. An approximation for the rate of rise of g was obtained by dividing the peak g by the time taken to rise to that level from the beginning of impact. Where the rate of rise of g was relatively slow, this was a good proxy for the relatively steady, ambient rise of g delivered. This typically occurred where the foam was not approaching a "bottoming out" situation (see Fig. 3). Where "bottoming out" occurred, this could underestimate the highest level of ambient rise of g produced (see Fig. 4). Only a few test drops were made at the highest temperature. Apart from the difficulty of maintaining the temperature, it was found, for example, that a 100 cm drop onto Sunmate X-Firm was likely to have broken the apparatus because of the material's degraded elastic properties generating exceptionally high levels of deceleration for the particular thickness of foam used. For each foam option and drop distance combination, the average of the set of results for decelerative g and rate of rise of g was calculated. These are shown in Table 1. The standard deviations for the results, expressed as a percentage error, lie in the following ranges for the temperatures measured: Peak deceleration for Sunmate X-Firm is 0.8-9.4%, C45/C47 is 0.1-2.9%, Sunmate Soft/X-Firm is 1.8-2.6% and C47 is 2.1-12.9%. Rate of rise of g for Sunmate X-Firm is 2.8-12.1%, C45/C47 is 0.5-3.1%, Sunmate Soft/X-Firm is 2.9-4.0% and C47 is 3.8-14.3%. The Table shows that the C47/C45 foam option generates less peak g than the Sunmate X-Firm (Dynafoam Extra-Firm) option. C47/C45 also generates a lower rate of rise of g (jolt) than Sunmate X-Firm. In addition, the C47/C45 results improved with the increase in temperatures tested whereas the Sunmate X-Firm deteriorated.

The output of the pressure pad showed that the impact force was not transmitted to the structure under the foam in a straightforward way. Fig. 5 shows a short sequence of pressure pad output from a 100 cm drop onto C47, Option 4. It shows that, prior to the pressure being transmitted from the centre of the impactor face, an initial ring of higher pressure is generated first at some distance from but concentric to the centre of impact. The main, central impact is, then, subsequently generated in the centre of this ring.

Percentage energy absorbed

The recorded accelerometer output from each drop test showed where bounces occurred. An example of this has already been given in Fig. 5. By taking the time of flight of each bounce, elementary physics can be used to calculate the velocity which the foam on the rigid concrete base must have imparted to the impactor to project it upwards. Knowing the height of the initial drop, a similar application of elementary physics provides the impactor's velocity prior to striking the foam. By this means, the energy before and after each bounce can be compared. This enables the percentage of energy absorbed at each bounce to be calculated. The average results for each combination of foam and drop height are also shown in Table 1. The standard deviations for the results, once again expressed as a percentage error, lie in the following ranges: Sunmate X-Firm is 0.4-1.3%, C45/C47 is 0.1-0.3%, Sunmate Soft/X-Firm is 0.4-0.7% and C47 is 0.1-2.0%. The Table shows that the C47/C45 foam option absorbs more energy than that of Sunmate X-Firm (Dynafoam Extra-Firm). At the higher energies tested, the latter generated significant bounces that could be easily observed.

Penetration

The radius, r_1, of the circular imprint made by the painted impactor on the Lycra membrane is related to the depth of penetration, h, by the formula $r = (h^2+r_1^2)/(2h)$, where r is the radius of the spherical impactor. Using this method, the depth of penetration was calculated and the average computed. The results (for 12˚ C only) are shown in Table 2. The objective of this was to find out just how far the foam was being compressed into a bottomed-out state by the impacts. The Table shows that, at this temperature, both the Sunmate X-Firm and C47 foams appeared to reach a "bottoming out" by the 50 cm drops and compressed no further when subjected to 100 cm drop tests. This did not happen with the C47/C45 foam option. In this bottomed-out state, Sunmate X-Firm did not compress as much as C47.

Discussion

The results obtained provide a salutary illustration of the high Gz that can be created in an aircraft cockpit where the vertical impact occurs with the fuselage in a horizontal attitude (this type of accident typically occurs as a result of badly-misjudged, final glides in competitions). Elementary physics shows that the lowest, peak g that can be generated is produced in the case of a constant deceleration and this can be calculated as the result of dividing the free-fall height by the distance in which deceleration takes place.

As a result, in the absence of an undercarriage, a pilot sitting on 2.5 cm of perfect, uniformly-decelerating, energy-absorbing foam would experience a constant deceleration of 40g from a fall of 1 m, assuming that the foam was placed on the seat pan, which, in turn, was placed next to the glider fuselage material. By contrast, if the undercarriage was deployed, assuming it to be some 25 cm in length and designed to absorb energy perfectly, as above, a similar calculation would reduce the "ideal", uniform deceleration to around 4g. This illustration shows that pilots should not have unrealistic expectations from the use of energy-absorbing foam alone.

In reality, energy-absorbing foams do not decelerate constantly. Peak decelerations can be around 4 times the "ideal" value. Nevertheless, decelerating over a distance of 2.5 cm is better than achieving this within a few millimeters, providing that bouncing does not take place. The latter is particularly dangerous as, in a bounce, it is possible for the buttocks and lower spine to be descending after a bounce at the same time as the underlying aircraft structure is traveling back upwards as a result of impact with the ground. Bounces are minimized if the energy-absorbing foam absorbs almost all of the energy. By this standard, the C47/C45 option performs better than Sunmate X-Firm (Dynafoam Extra-Firm) as revealed in Table 1.

The energy-absorbing properties of all the viscoelastic foams tested can be seen to be temperature dependent. This is a well known property of these materials. It does appear that the usefulness of safety cushions made out of these materials can be significantly compromised at temperatures well over 20˚ C.

Although the tests that were applied are of a simple form, the way that the energy is absorbed is far from straightforward. In particular, the main body of the foam is involved in absorbing energy as well as the volume directly under the impactor. As a result, as part of this project, it was decided to create a dynamic finite element analysis (FEA) model of the Confor viscoelastic foams used. The idea was that, if this succeeded, it would be possible to explore the behavior of this and similar, viscoelastic foams in crash-impact situations in conjunction with other materials. The latter could include parts of neighboring aircraft structures such as the underlying graphite-reinforced-plastic making up a glider fuselage. It could be also used to explore the behavior of items such as spinal shells that are lined and also externally supported by such viscoelastic, energy-absorbing foams. A first attempt at such an FEA approach was to simulate the impact produced by the equipment described above. At the time of writing, this was work in progress. Although an initial simulation was successfully generated, it still required accurate data for Confor's rate-dependent, elastic properties. Hopefully, on-going discussions with academia should eventually produce the necessary properties over the range of rates of compression that are inherent to the impact speeds generated.

The future direction of our research is in the generation of dynamic FEA impact models combining the viscoelastic foams and the other surrounding structural materials.

Conclusions

On the basis of the simple comparison method, in terms of peak impact deceleration, rate of rise of g and energy-absorption, the Confor C47/C45 option is obviously better than Sunmate X-Firm (Dynafoam Extra-Firm).

For reasons that are beyond the scope of this paper to explain, the purpose of safety cushions made up of these materials is to minimize the amplified deceleration and consequent lumbar forces that will be experienced in a vertical crash impact. These will involve cushions pre-compressed by pilots. The reported tests were performed with uncompressed foams. The relative performance characteristics of the different foams' results are unlikely to be significantly changed by this pre-compression.

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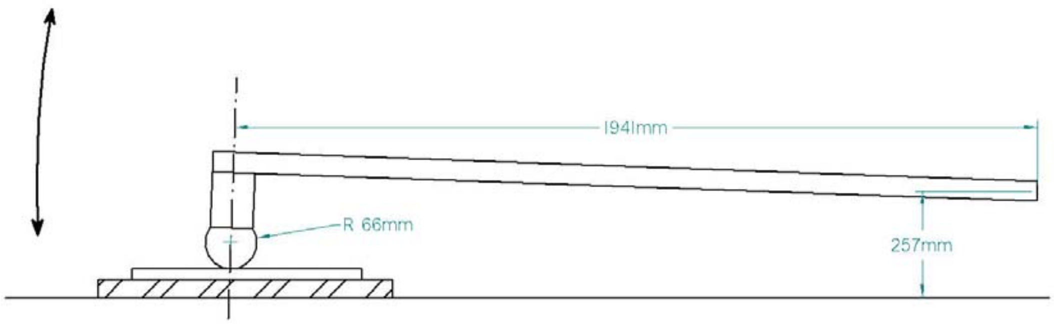

Figure 1 Apparatus used to compare the impact response of the different foam options.

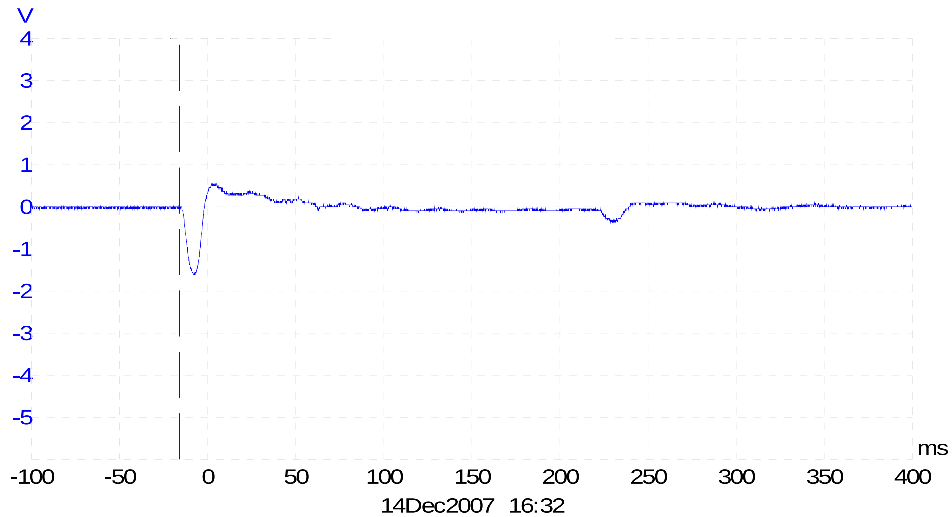

Figure 2 Example of the unfiltered output from one drop test. The accelerometer output, V (volts), is plotted against time (milli-seconds). Accelerometer sensitivity is 27.44 millivolts/g.

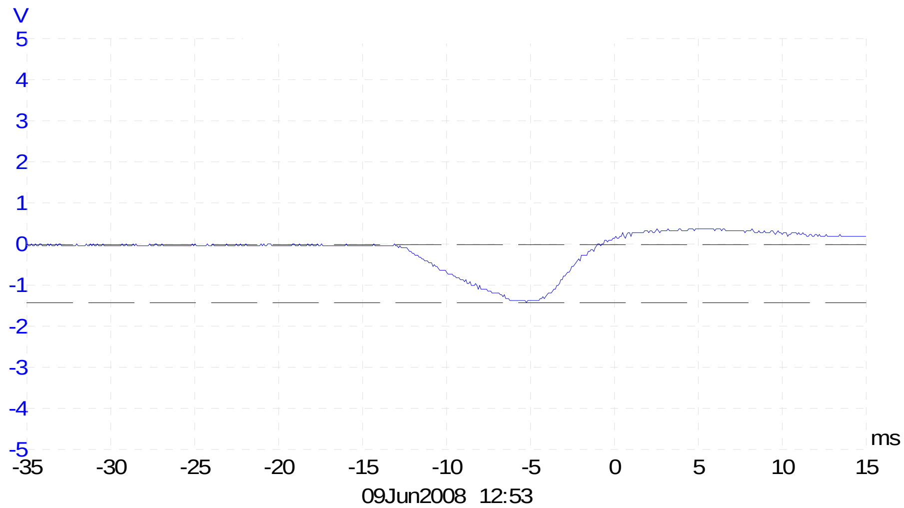

Figure 3 Typical result where the foam under test was not approaching a "bottoming out" situation. The accelerometer output, V (volts) is plotted against time (milliseconds). Accelerometer sensitivity is 27.44 millivolts/g.

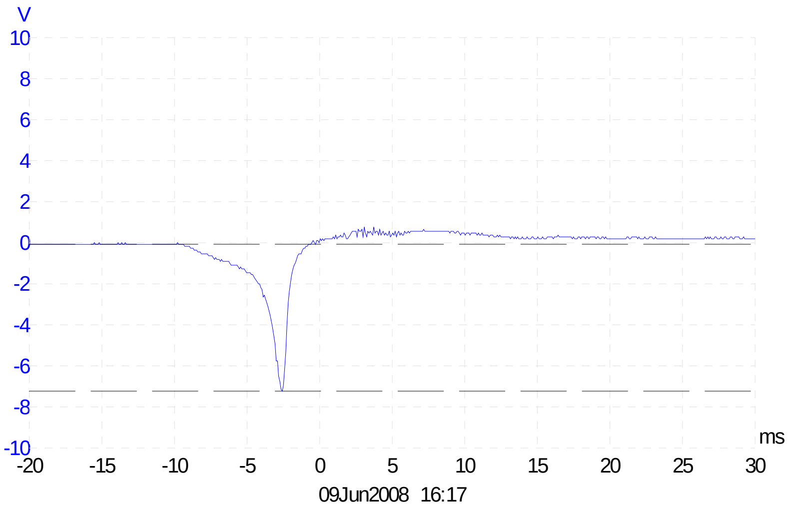

Figure 4 Typical result where "bottoming out" occurred. The accelerometer output, V (volts) is plotted against time (milliseconds). Accelerometer sensitivity is 27.44 millivolts/g.

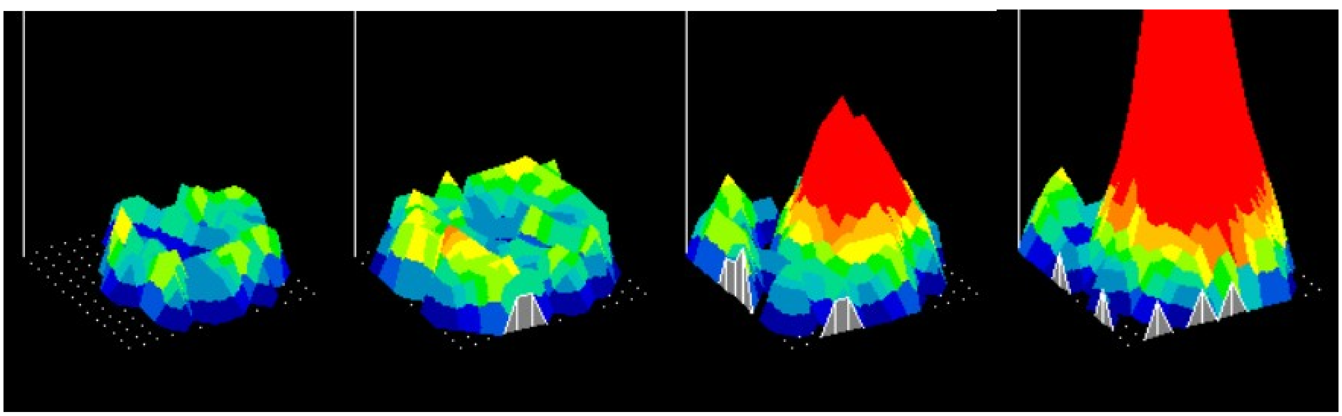

Figure 5 A short sequence of pressure pad output from a 100 cm drop onto C47, Option 4. The horizontal plane represents the surface of the pressure pad used. The vertical axis represents the pressure recorded.

Table 1
Comparison of deceleration and energy-absorbing characteristics of the foam cushion solutions tested for different drop heights and temperatures.

Test Temperature/Foam	Temperature (deg C)	Sunmate X-Firm	Confor C47/C45	Sunmate X-Firm/Soft	C47
	Drop 1000 mm				
Average maximum g	12	112	67	72	92
	16	315	55	97	242
	26	-	78	-	-
Average rate of rise of g (g/sec)	12	17682	9044	9820	14637
	16	52028	6721	11140	35124
	26	-	8102	-	-
Average percentage energy absorbed on 1st impact	12	93	98	94	98
	16	89	94	89	92
	26	-	-	-	-
	Drop 750 mm				
Average maximum g	12	77	55	55	68
	16	106	42	56	111
	26	-	-	-	-
Average rate of rise of g (g/sec)	12	12389	8331	8030	10112
	16	14317	5995	6169	14226
	26	-	-	-	-
Average percentage energy absorbed on 1st impact	12	93	98	94	97
	16	89	94	91	95
	26	-	-	-	-
	Drop 500 mm				
Average maximum g	12	53	46	46	50
	16	49	34	35	53
	26	96	29	-	93
Average rate of rise of g (g/sec)	12	9319	7289	6422	8667
	16	6431	4539	4414	6091
	26	11429	2665	-	10105
Average percentage energy absorbed on 1st impact	12	94	99	94	98
	16	92	96	92	97
	26	85	100	-	-

Table 2
Comparison of indentation and percentage penetration produced by the different foam cushion solutions for different drop heights at 12˚ C.

Cushion	Sunmate X-Firm			Sunmate X-Firm/Soft			C47			C47/C45		
Drop Height (mm)	1000	750	500	1000	750	500	1000	750	500	1000	750	500
Indentation Depth (mm)	21	21	20	30	28	25	25	25	22	36	31	25
Percentage Penetration	85	85	79	84	78	69	99	99	89	95	81	64