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Applying the investment methodology for materials (IMM) to aluminium foams

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Abstract

A methodology for assessing the commercial potential and thus, the business case, for a materials innovation was presented in a companion paper (Maine and Ashby, 'An investment methodology for materials' Mater Design, 2002). The investment methodology for materials (IMM) is here applied to a recent innovation — that of metal foams. Several processes for making foamed aluminium are now in the process of scale-up for large scale production, although none, at this point in time, have found a viable commercial application. Here one class of application — that of energy absorption in automotive design — is explored in depth, examining technical viability, market structure and the probability of value capture, illustrating IMM in operation. The method helps direct R&D programs, informs business decision-making and guides investment policy-making. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Materials; Investment methodology; Metal foam; Innovation; Value capture

1. Introduction

1.1. The investment methodology for materials (IMM)

Innovations in material development are high risk investments [2], characterised both by long gestation periods between invention and widespread market adoption [3] and by uncertainty of ultimate success. For these and other reasons, they have generally been driven by large enterprises [4] and national governments. An investment methodology for new materials (IMM) has been proposed [1] which could both reduce risk and shorten gestation time. IMM provides a structured, informed procedure for assessing the attractiveness of investing in the industrial scale-up of the production of a new material.

It has three linked segments: *viability analysis*, *market forecasting*, and *value capture* (Fig. 1). A material is *viable* in an application if the balance between its technical and economic attributes are favourable. Assessing viability involves technical modelling of the application, cost modelling of manufacturing, input from the market assessment and value analysis. *Market assessment* deploys techniques for identifying promising market applications and for forecasting future production volume. Likelihood of *value capture* is assessed through an analysis of industry structure, organisational structure, IP issues, appropriability and the planned

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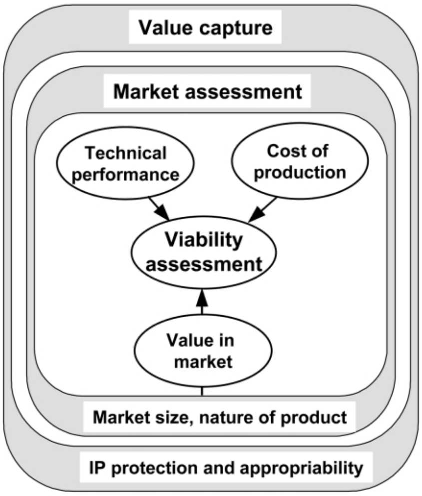

Fig. 1. The Investment methodology for Materials (IMM).

market approach. The most desirable investment opportunities are those with both a large viable market size and a high likelihood of value capture. All these areas are developed in the earlier paper [1].

In this paper we explore the application of the methodology to a materials innovation — that of metal foam.

2. Initial market scan for potential applications

2.1. Potential applications

Aluminium foams have several unusual features, among them, exceptional *energy absorbed per unit volume* and particularly, *energy absorbed per unit weight* [5]. Potential applications are those in which these functions are important, those that also exploit secondary attributes of metal foams (such as flame resistance, heat dissipation, noise reduction, water resistance, blast amelioration), are particularly attractive.

The strongest opportunities for short term take up of aluminium foam lie with substitution into existing markets, since for these the design requirements are well known. Radically new designs taking best advantage of their properties are slowed both by lack of designer awareness and confidence and by current manufacturing difficulties with achieving high tolerances.

There are existing aerospace and automotive applications which require high energy absorption per unit volume. The large scale production of aluminium foams cannot yet meet the tolerances required for aerospace applications (other than the expensive Duocel, which finds a market in defence and space vehicles), thus, automotive applications are prioritised, selecting for study the A-pillar design for occupant safety and the redesigned hood and front bumper regions to meet new pedestrian protection legislation, as test cases.

Table 1
Limiting *g*-factors

Object	Limiting *g*-factor, a^*
Human body, sustained acceleration	5–8
Delicate instruments: gyroscopes	15–25
Optical and X-ray equipment	25–40
Computer displays, printers, hard disk drives	40–60
Human head, 36 ms contact time	55–60
Stereos, T.V. receivers, floppy disk drives	60–85
Household appliances, furniture	85–115
Machine tools, engines, truck and car chassis	115–150

a^*, for a number of objects

2.2. Background-principles of energy absorption

The purpose of energy absorbing systems is to protect a specified object from damaging acceleration or deceleration. The acceleration or deceleration may be accidental (a drop from a fork-lift truck for instance, or a head impact in a car accident) or it may be anticipated (the landing-impact of a parachute drop, the launch of a rocket). The *damage tolerance* of an object is measured by the greatest acceleration or deceleration it can withstand without harm. Acceleration is measured in units of g, the acceleration due to gravity. Table 1 lists typical damage tolerances or 'limiting *g*-factors' for a range of products [5].

Ideal energy absorbers have a long, flat stress-strain (or load-deflection) curve, like that of Fig. 2: the absorber collapses plastically at a constant stress called the *plateau stress*, σ_{pl}. Energy absorbers for packaging and protection are chosen so that the plateau stress is just below that which will cause damage to the packaged object, the most desirable stress–strain curve is then the one that has the longest plateau and therefore, absorbs the most energy. Solid sections do not perform well in this role. Hollow tubes, shells and metal honeycombs (loaded parallel to the axis of the hexagonal cells) have the right sort of stress-strain curves, so, too, do metal foams [6].

To protect fully, the package-material must absorb all the kinetic energy of the object, bringing it to rest

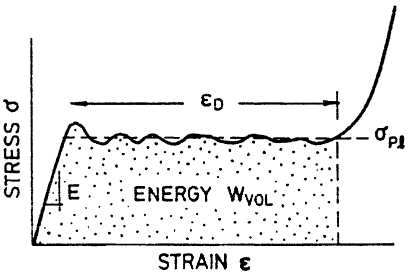

Fig. 2. A stress curve for an energy absorber. The area under the flat part ('plateau') of the curves is the usefull energy W, or energy per unit volume W_v.

without the deceleration exceeding the limiting g-factor. The kinetic energy (KE) depends on the mass m and the velocity v of the object:

$$KE = \frac{1}{2}mv^2 \tag{1}$$

Package design for low-velocity (greatly subsonic) impact differs from that for high velocities (velocities in the sonic range), when elastic and plastic shock waves become important. Here we are concerned with low-velocity impacts.

The absorber collapses plastically at σ_{pl} up to a limiting 'compaction' strain ε_D, beyond which the stress rises steeply. The area under the flat part of the curve $\sigma_{pl}\varepsilon_D$, measures the energy absorbed per unit volume up to the end of the plateau. Real absorbers approximate the ideal, but are generally a little less good. The efficiency of an absorber (the ratio of actual energy absorbed to ε_D divided by the ideal case) is given the symbol B_j where $B_j = 1$ describes ideal behaviour. Real energy absorbers have sufficiently large values of $B(0.9 < B < 1)$ that we can — at the level we need here — set $B = 1$ and thereafter, ignore it.

Consider a package made from an absorber with a plateau stress σ_{pl} and a compaction strain ε_D. The packaged object, of mass m, can survive deceleration up to critical value a^*. From Newton's law the maximum allowable force is $F = m\,a^*$. If the area of contact between the absorber and packaged object is A, the foam absorber will crush when $F = \sigma_{pl}A$. Assembling these, we find the absorber that will just protect the packaged object from a deceleration a^* is that with a plateau stress

$$\sigma_{pl} \le \frac{ma^*}{A} \tag{2}$$

It remains to decide how thick the package must be. The thickness is set by the condition that all the kinetic energy of the object is absorbed if the absorber crushes to the end of its plateau. Equating the kinetic energy of Eq. (1) to the energy absorbed by thickness x of absorber when crushed to its densification strain ε_D gives

$$\sigma_{pl}\varepsilon_D Ax = \frac{1}{2}mv^2 \tag{3}$$

from which

$$x = \frac{1}{2}\frac{mv^2}{\sigma_{pl}\varepsilon_D A} \tag{4}$$

Eqs. (2) and (4) are the key to the initial selection of an energy absorber.

The volume V of absorber required to fully protect the packaged object is xA, thus:

$$V = \left(\frac{1}{2}mv^2\right)\left(\frac{1}{\sigma_{pl}\varepsilon_D}\right) \tag{5}$$

or, if, expressed as a volume per unit energy absorbed, $\tilde{V}$; it is

$$\tilde{V} = \frac{V}{\left(\frac{1}{2}mv^2\right)} = \left(\frac{1}{\sigma_{pl}\varepsilon_D}\right) \tag{6}$$

Thus, to minimise the volume, we seek absorbers with the lowest values of $\tilde{V}$, which at the same time meet the limit of Eq. (2) for σ_{pl}.

2.3. Automobile occupant and pedestrian head protection

Currently, passenger head protection is regulated in the US market by the Federal Motor Vehicle Safety Standard (FMVSS) 201u. This regulation limits the allowable deceleration for an automobile occupant's head on impact with all upper interior components of the passenger vehicle, to do this they must meet the Head Impact Criteria (HIC):

$$\mathrm{HIC} = \left\{\frac{1}{t_2 - t_1}\int_{t_1}^{t_2} a\,dt\right\}^{2.5}(t_2 - t_1) \le 1000 \tag{7}$$

Here a is the resultant deceleration of the headform in g units and t_1 and t_2 are any two points in time during the impact event separated by not more than a 36-ms time [7]. Proposed legislation to increase passenger head protection to safe levels for higher velocity impacts (HIC d) is currently under consideration:

$$\mathrm{HIC}(d) = 0.75446\ (\mathrm{HIC}) + 166.4 \le 1000 \tag{8}$$

Here we consider the design of an A-pillar to meet these requirements (A-pillars are the near-vertical structural columns on either side of the windshield). For the legislated tests, a dummy head form with mass 4.8 kg is crashed against the A-pillar at a speed of 24.1 km/h. The impact zone on the dummy forehead is of dimension 125 × 100 mm, as shown in Fig. 3. Generally, actual contact occurs over an area of 20 × 40 mm within this zone. Currently the requirement is met by attaching crush elements (typically, hollow hexagonal extruded metal profiles) to the inside face of the A-pillar.

Due to design constraints, it is particularly difficult to meet the new criteria for the A-pillar. A second major change in head-impact legislation [8] is proposed by the European Commission stipulating four tests that cars should meet by 2005 in order to protect pedestri-

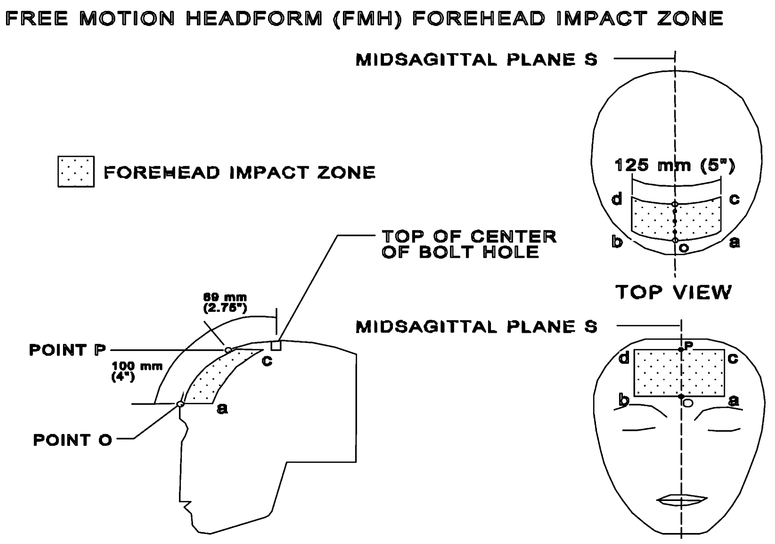

Fig. 3. FMVSS201u head impact legislation.

ans from serious injury on impact at speeds up to 40 km/h. Two of the four are head impact tests, using an adult headform (4.8 kg and impacting at 25° from vertical) and a child headform (2.5 kg and impacting at 40° from vertical), as shown in Fig. 4 and should achieve HIC(d) performance. They apply to the upper portion of the hood for the adult headform and the lower (frontal) portion of the hood for the child headform [9].

Metal foams are potential candidates for all these applications. Here we apply the IMM to explore their potential, starting with technically viability.

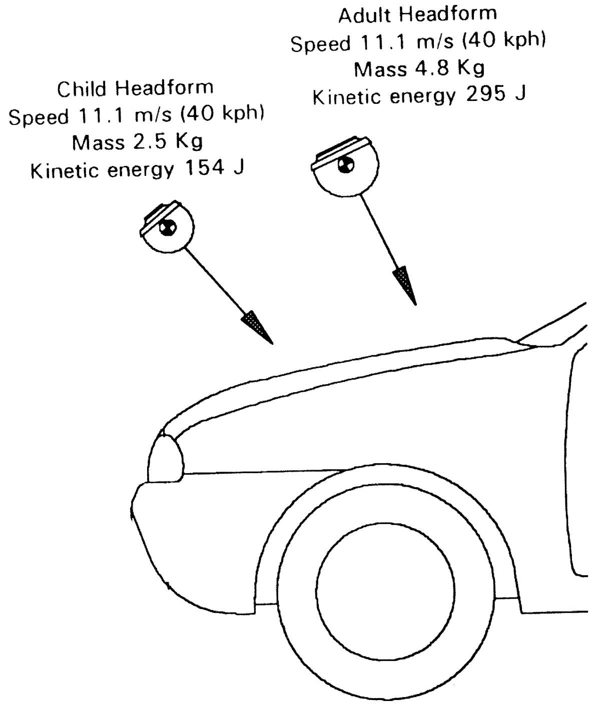

Fig. 4. Proposed pedestrian protection head impact legislation [7,8].

3. Technical assessment

3.1. Selecting foams for packaging

The stress–strain curve of aluminium foams (Fig. 5) approximate the idealised stress–strain curve for energy absorption, shown in Fig. 2, suggesting their use in energy absorbing applications. How can we establish their technical viability? Fig. 6 illustrates the method[2] [10]. The vertical axis plots $\tilde{V}$ (Eq. (6)), the horizontal one plots the plateau stress σ_{pl}. Each bubble describes the performance of a foam, a sub-set of these have been labelled. Polymer foams are labelled with their composition followed, in brackets, by their density in mg/m^3. Metal foams, almost exclusively made of aluminium (alloyed with a foaming agent), are labelled with their trade name followed, in brackets, by their density.

The first step is to mark the maximum acceptable value of σ_{pl} onto Fig. 6 where this has been taken to be 2 Mpa, only foams with a plateau stress less than this are acceptable. The second step is to read off the foam with the smallest value of $\tilde{V}$ since this is the one that safely protects at minimum volume; here the best choice is an Alporas foam with a density of 0.21 mg/m^3 and those near it. This, of course, is not the end, it simply provides a set of markets that meet the primary design requirement. There remains questions of cost, durability and availability.

To explore these applications more deeply, we look at available measures of the value of performance (or

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[2] The chart of Fig. 6 was constructed using the "Foams" data base of the Cambridge Engineering Selector (CES, 1999)[10]

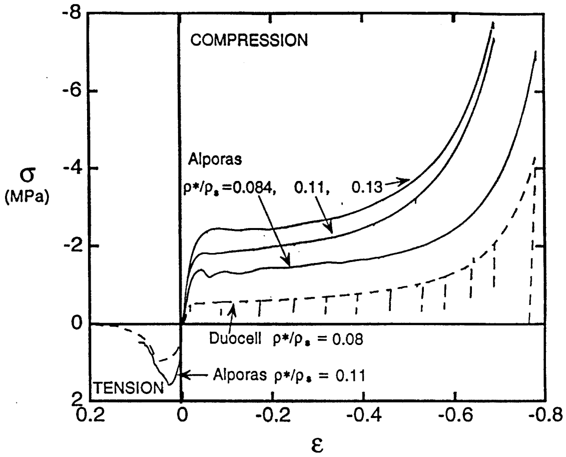

Fig. 5. Stress–strain curves of closed-cell Alporas and open-cell ERG metal.

'exchange constants') in automotive applications. In many engineering applications the exchange constants can be derived approximately from technical models. Thus, the value of weight-saving in transport systems is derived from the fuel saving or the increased payload which this allows (see Table 2).

3.2. Selection of foams for automotive A-pillar head protection

Reducing head injury in an impact to an acceptable level requires that the deceleration, a, in units of g, must not exceed the value a^* defined by Eq. (7).

The quantity in curly brackets is the average deceleration, $\bar{a}$. For an initial exploration of the choice of materials for head protection, we will work with this quantity. Eq. (6) then becomes

$$\bar{a}^* = \left(\frac{1000}{\Delta t}\right)^{0.4} \tag{9}$$

where $\bar{a}$ is the critical value of $\bar{a}$, which must not be exceeded and $\Delta t = t_2 - t_1$ is the contact time. If the contact time is 35 ms, the value of $\bar{a}^*$ is 60 g for the current HIC legislation. In order to meet the more stringent HIC(d) legislation, the value of $\bar{a}^*$ would be 42.5 g.

An adult human head weighs approximately 4.5 kg. A typical value for the contact area between head and A-pillar is typically $A \approx 40 \times 20\ \text{mm} = 0.0008\ \text{m}^2$. Inserting this value of A, together with $\bar{a}^* = 60\ g^*$ and $m = 4.5$ kg into Eq. (2) it gives:

$$\sigma_{pl} \leq 3.5\ \text{MPa} \tag{10}$$

Foam-based energy absorbing structures exploit the plateau of their stress–strain curve, which allows energy to be absorbed at a near-constant deceleration. In selecting a foam for passenger protection, the plateau stress is chosen to be equal to the value calculated above. The thickness of foam is then chosen to absorb the kinetic energy of the packaged object (in this case the head) moving at an initial velocity of v. It is given by Eq. (4). Using the data given above and with $v = 24.1$ km/h and $\varepsilon_D = 0.8$ gives

$$x \geq 45\ \text{mm}$$

Up until this point, we have been assuming that 100% of the energy absorbed in this test legislation must be dissipated by the crushing of the energy absorbing element (here an aluminium foam part). However, in realistic automotive applications, a substantial portion of the energy is absorbed by the deflection of the vehicle structure. For very stiff structures with the A-pillar rigidly attached, approximately 25% of the energy is absorbed by the structure. For less stiff structures with some elasticity in the A-pillar, the fraction rises to 75% [11]. Thus, the required thickness of the A-pillar energy absorption element is dependent on the stiffness of the structure, varying, in this example, from 11 to 34 mm.

One current design of an A-pillar energy absorber is based on the crushing of a hexagonal aluminium extrusion (Fig. 7, lower element). This element is effective in energy-absorbing efficiency, but, because of its curved shape, it is expensive to manufacture. A foamed aluminium replacement (Fig. 7, upper element) can be moulded to a complex shape. Its adoption now hinges on its cost.

Candidate foams for the A-pillar application must meet the constraints of Eqs. (2) and (6). Rearranging these gives

$$a^* = \left[\frac{A}{m}\right]\sigma_{pl} = \alpha_1\,\sigma_{pl} \tag{11}$$

and

$$x = \left[\frac{1}{2}\,\frac{mv^2}{A}\right]\frac{1}{\sigma_{pl}\varepsilon_D} = \alpha_2\,\frac{1}{\sigma_{pl}\varepsilon_D} \tag{12}$$

Values for α_1 and α_2 are given below in Table 3, for a number of scenarios. Using these and data for σ_{pl} and ε_D, allows plots to be constructed showing the combinations of a^* and x that foams can provide. Figs. 9 and 10 are examples. Using these, the foam that limits the deceleration to a^* and minimises volume, can be read off. Fig. 8 describes the standard test conditions (24.1 km/h) for the A-pillar in the case of a very flexible BIW structure: the required A-pillar deformation element thickness is 10 mm and can be made of either aluminium foam or a polymer foam (poly-

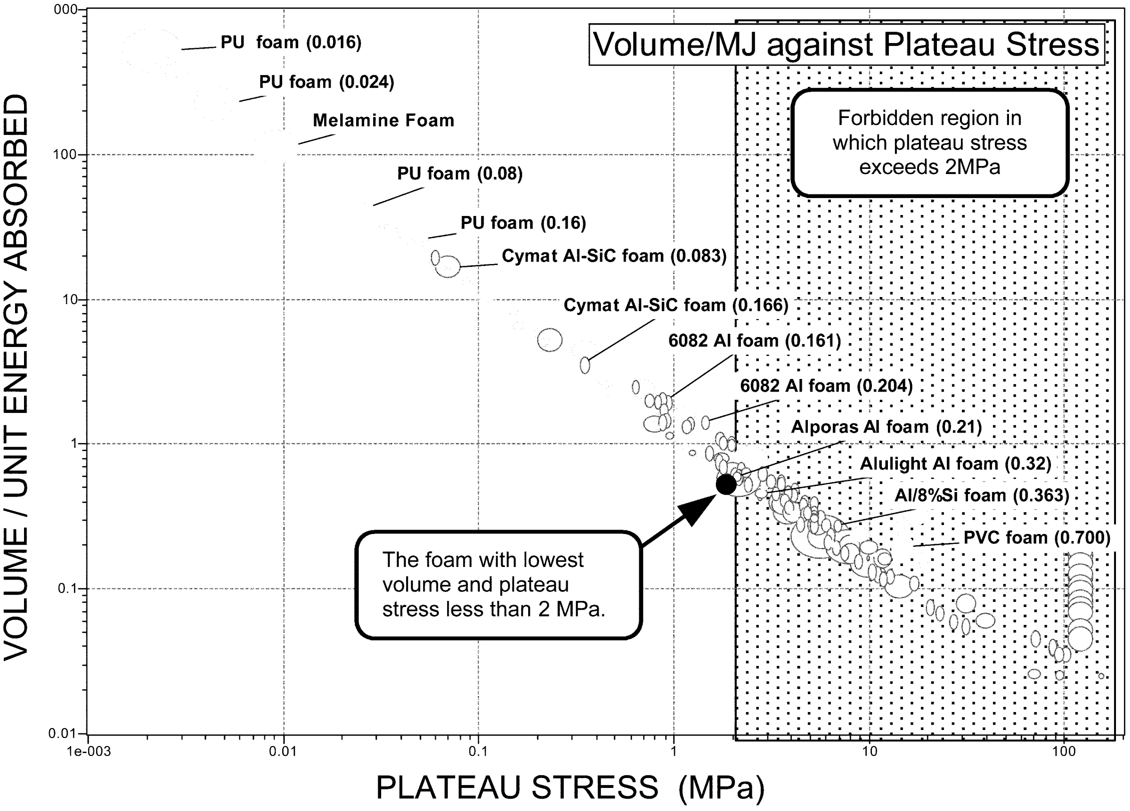

Fig. 6. Selecting a material for energy absorbtion at minimum volume [10].

Table 2
Utility of weight saving in transport systems

Transport system	*U* (US $/kg)	High end utility requirement
Family car (based on fuel saving)	0.5–1.5	CAFE limit or secondary weight savings
Truck (based on payload)	5–10	Value of payload
Civil aircraft (based on payload)	100–500	Power/weight ratio guarantee limit
Military aircraft (performance, payload)	500–2000	Power/weight ratio guarantee limit
Space vehicle (based on payload)	1000–10 000	Value of payload
Bicycle (based on percieved performance)	1–1000	Tour de France standard

ethersulfone with a density of 0.20 mg/m^3 or Alulight with 0.37 mg/m^3). Fig. 9 shows the other extreme — a stiff structure and a higher impact velocity (40 km/h). A foam thickness of 85 mm is required; metal foams are the best candidates. For pedestrian protection, a thickness of 210 mm is required which is impractical regardless of which material chosen.

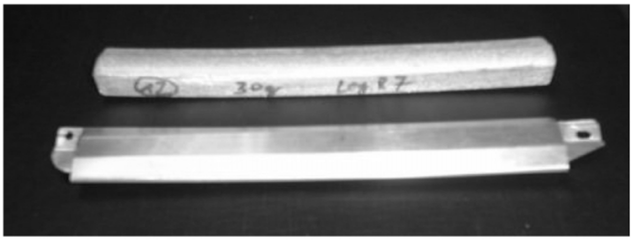

Fig. 7. Hexagonal tube and aluminium foam deformation elements.

4. Economic analysis

4.1. Technical cost modelling

Economic analysis aims to establish the manufactur-

Table 3
Calculating Factors α_1 and α_2

Area A m^2	Mass m Kg	Velocity v m/s (km/h)	Knock-down factor[a]	Factor α_1 (a^* in g σ_{pl} in MPa)	Factor α_2 (σ_{pl} ε_D in MJ/m^3)
0.0008	4.5 (adult head)	11.2 (40)	1	18	0.35
			0.75		0.26
			0.25		0.088
		6.7 (24.1)	1		0.13
			0.75		0.095
			0.25		0.032
0.0008	2.5 (child head)	11.2 (40)	1	33	0.19
			0.75		0.14
			0.25		0.049
		6.7 (24.1)	1		0.072
			0.75		0.053
			0.25		0.018

[a] The factor of the fraction is the fraction of the impact energy actually absorbed by the foam.

ing cost differential between a component made with a novel process or material and the incumbent processes and materials. To this purpose, technical cost models were constructed for three processes for manufacturing aluminium foam:

- Liquid-state foaming of aluminium;
- TiH_2 expansion via powder metallurgical processing as a batch processes; and
- TiH_2 expansion via powder metallurgical processing as a continuous processes

The cost models themselves include sub-models to capture the effect of component size on production rate, the die and equipment costs, allowance for scrap, die-life, and capital write-off. Details can be found in Maine [3]. The outputs of the model (Figs. 10 and 11) show the way in which the cost of the manufactured component depends on production volume and also identify cost drivers. In this instance the batch powder metallurgical process is the most economical option for annual production volumes of up to 20 000 parts. Fig. 11, which shows a snapshot of the line item costs for each process at 20 000 and 300 000 parts per year, reveals that it is fixed costs, in particular equipment costs, that drive the low volume cost of both continuous PM processing and liquid state processing higher than that of batch PM processing. In this way, the cost model can be used to aid the decision about the suitability of converting to a continuous process.

By comparing the cheapest aluminium foam component (at the required production volume) with an in-

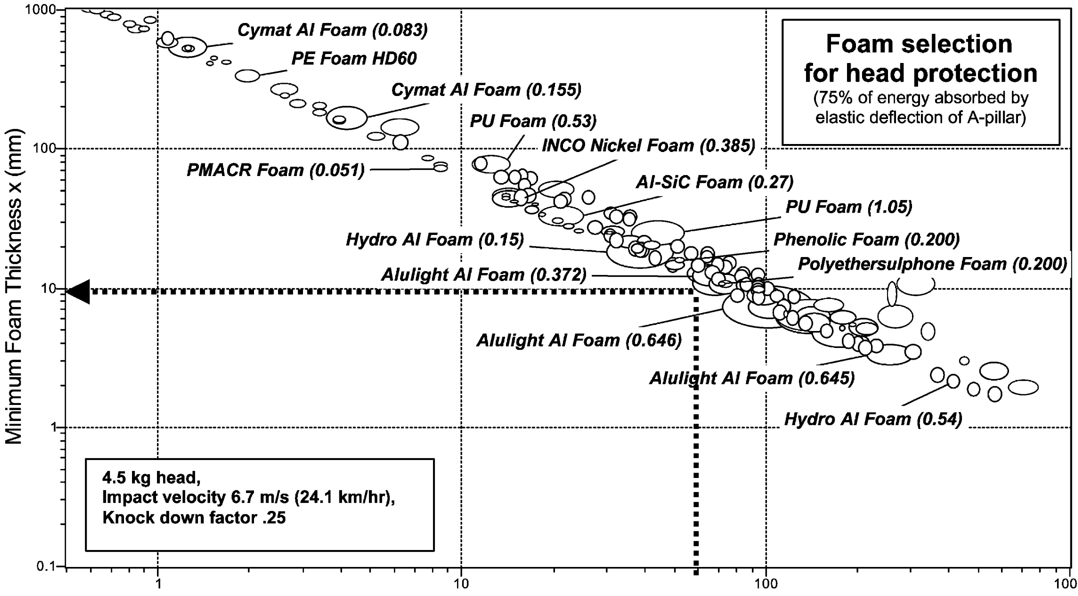

Fig. 8. Foam selection for automotive A-pillar application.

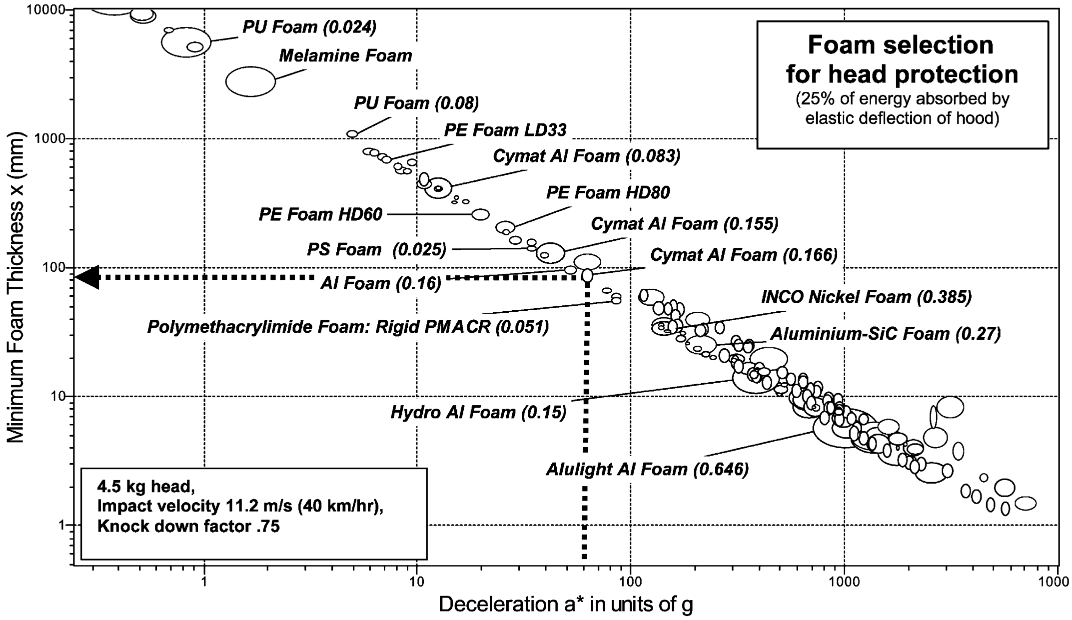

Fig. 9. Foam selection for automotive pedestrian protection applications.

cumbent material for any given application, the cost differential between a new and an incumbent material solution can be established. This provides input into the value assessment.

4.2. Co-minimising volume and cost in energy-absorbing applications

In most applications cost is a strong consideration and this raises the issue of co-minimising two objectives — volume and cost (or mass and cost). Used as an energy absorber in the form of a simple panel or slab application, the cost C of the finished block of foam is essential that of the foam itself, $C_m M$, where C_m is the cost per kg of the foam[3] and $M = V\sigma$ is the mass of the panel, where σ is the foam density and V is the panel volume, given by Eq. (5). Thus

$$C = C_m M = \left(\frac{1}{2}mv^2\right)\left(\frac{C_m\,\rho}{\sigma_{pl}\,\varepsilon_D}\right)$$

or, expressed as a cost per unit energy absorbed, $\tilde{C}$,

$$\tilde{C} = \frac{C}{\left(\frac{1}{2}mv^2\right)} = \left(\frac{C_m\,\rho}{\sigma_{pl}\,\varepsilon_D}\right) \tag{13}$$

The co-minimisation is best done by constructing trade-off plots. Examples of such plots for co-minimising volume and cost in energy-absorbing applications is shown in Fig. 12. The vertical axis is the normalised

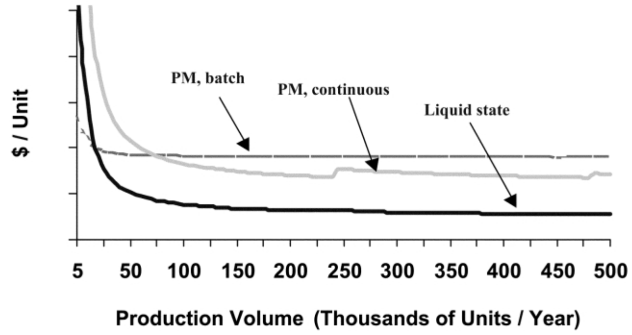

Fig. 10. Production cost for processing of aluminium foam by three methods.

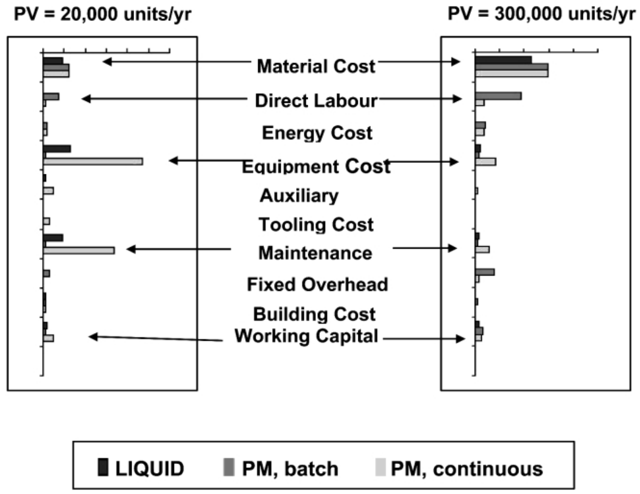

Fig. 11. Life-time cost for crossover annual production volume pf 20 000 and 70 000 units: processing of aluminium foam by three methods.

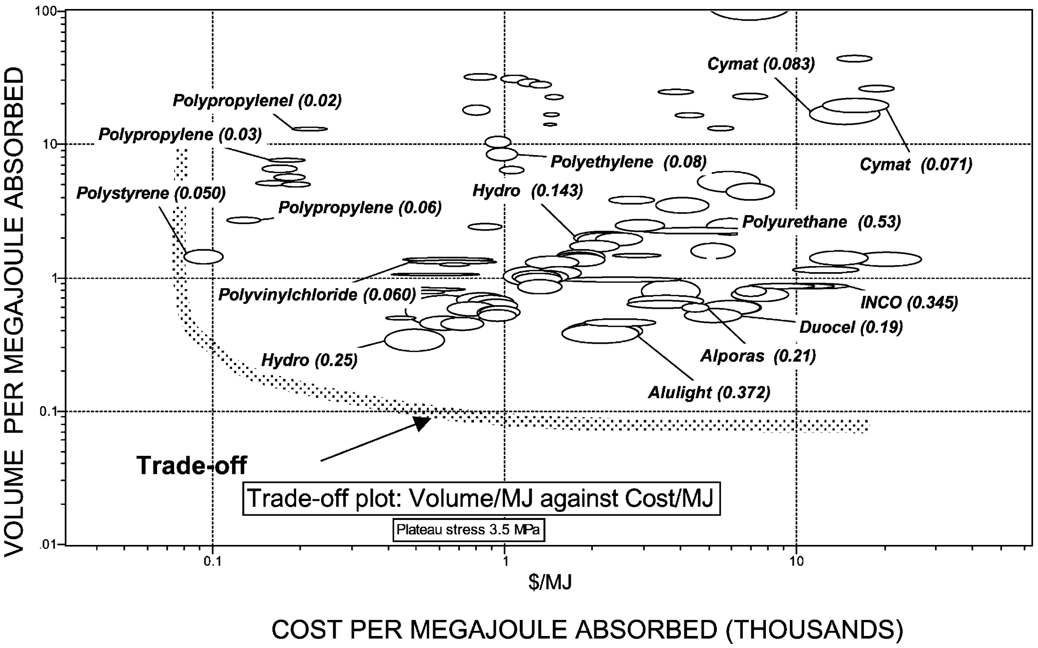

Fig. 12. Selection of metal foams and polymer foams by volume and cost with $\cdot_{pl}\cdot$ 3.5 Mpa.

volume, $\tilde{V}$ (Eq. (6)). The horizontal axis plots the normalised cost, $\tilde{C}$ (Eq. (11)). Each bubble describes a foam, but only foams with a plateau stress below a chosen critical value-in this case, 3.5 MPa, (Eq. (10)) — are shown. The trade-off surface (dotted line) links solutions with the most attractive combination of cost and volume.

The cheapest solution is the polystyrene foam with a density of 0.05 mg/m^3, but the volume (and thus, thickness) required is large. The solutions with the lowest volume are offered by the Hydro (liquid-state) or the Alulight (PM) aluminium foams, both with densities of approximately 0.25 mg/m^3.

5. Market forecast

The analysis so far indicates that metal foams are technically viable as energy absorption elements within the A-pillar. The next step is to examine the market size and rate of take-up.

5.1. Market size for aluminium foam

A pair of A-pillar energy absorbers weighs approximately 1 lb. Assuming 1 lb of aluminium foam per car for a mass-produced passenger car at a finished cost of \$10/lb allows an estimate of market size at \$5 million annually if installed in a single, large-volume model of passenger car; if it becomes the industry standard, the market size increases to some \$100 million annually. The substitution mode is illustrated by Fig. 13: either lower cost/higher performance, or higher cost/higher performance. The former mode would be followed when the displaced energy absorption element is complex, (as is the case with the hexagonal tube depicted in Fig. 7), where minimising volume is a priority and when flammability is a concern, eliminating most polymer foams. In some other A-pillar designs, the Al foam would be replacing a cheaper existing solution, that is unable to meet new occupant safety legislation.

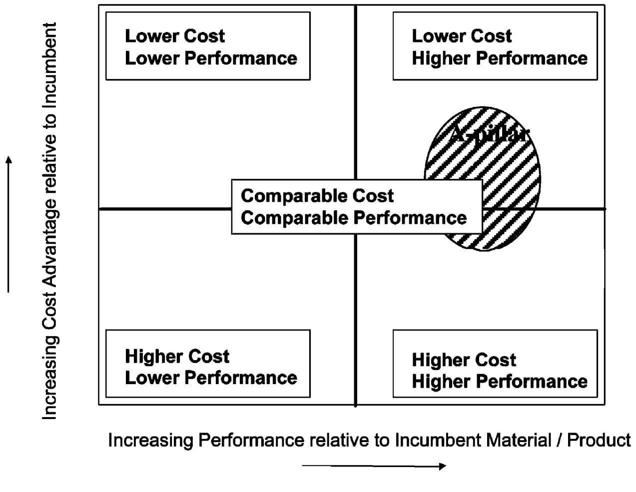

Fig. 13. Performance/cost categorisation for selected aluminium foam applications.

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[3] When, as is in the case study that follows, the foam must be applied, the cost of shaping can be significant and must be induced.

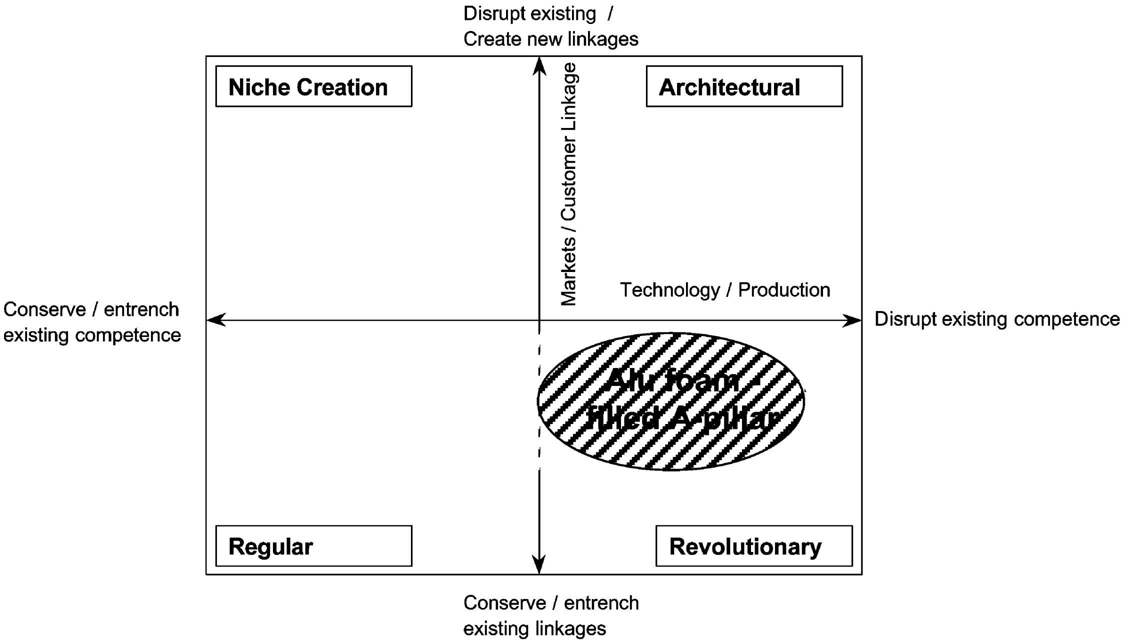


Fig. 14. Aluminium foam location on Abernathy and Clark's transilience map.

5.2. Market timing for aluminium foams

A method of comparison with historical substitutions, such as Abernathy and Clark's transilience map [12], aids a substitution-timing forecast. Aluminium foam for energy absorbing automotive applications is a revolutionary innovation (Fig. 14), in that it overturns established technical and production competencies, but does not overturn customer linkages nor require a company to sell into different markets. Thus, the substitution timing of aluminium foam for A-pillars can be modelled on the historical examples of a revolutionary innovation in the automotive industry that was both lower in cost and higher in performance. Historical examples of these include SMC hoods (bonnets) and polymer composite fenders. SMC hoods are lighter than those made of steel and are cheaper to design and manufacture for low volume platforms, substitution has occurred for these and for vehicles that are close to the legislated CAFE limit, where weight saving is highly valued [13]. Polymer composite fenders are lighter than those made of steel and better able to resist impact without damage. For these, substitution has followed a similar curve to that for SMC hoods [13] (Fig. 15). If aluminium foams in energy absorption automotive applications follow a similar substitution pattern, they could expect to capture 50% of their potential market within 12 years.

Automotive platforms with a flexible BIW structure exact less demanding constraints on the A-pillar energy

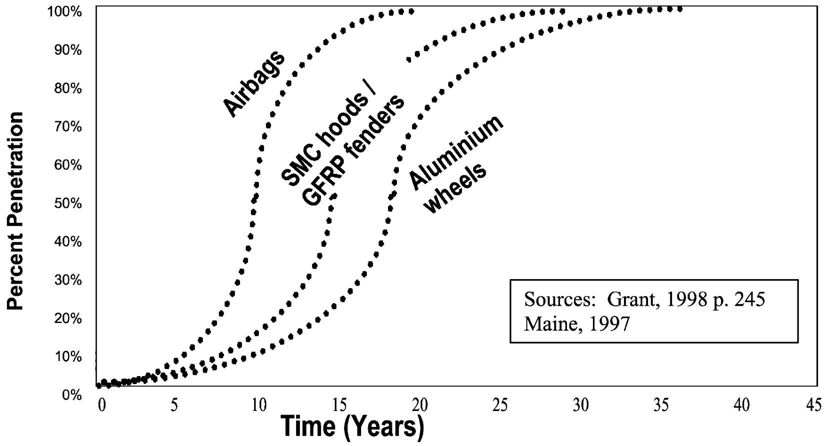
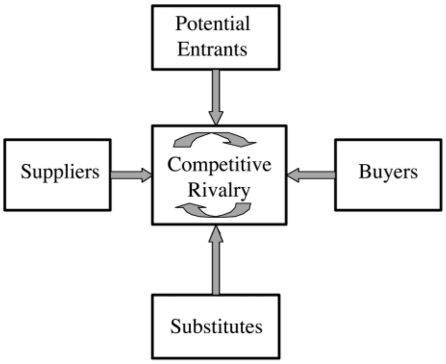


Fig. 15. Senarios for aluminium foam subsitution into A-pillar market.



- Few potential entrants but weak IP position
- Substitutes for metal foams: polymeric foams, shaped aluminium sections, fibre reinforced polymer composites, wood
- Strong buyer power in most mass applications (e.g. automotive)
- Overall, medium-low attractiveness

Fig. 16. Porter's 'Five-Forces' as a means of assessing industry attractiveness.

absorber. For these, metal foams, with their ease of shaping, offer aesthetic design improvements (for example, thinner A-pillars with improve lines of sight), but cost more than cheaper alternatives — a higher cost/higher performance mode of substitution. Historical examples of these include aluminium alloy wheels and air bags.

With aluminium wheels, a combination of aesthetic qualities and lighter weight drove substitution in sporty platforms along the path depicted in Fig. 15 with a 50% take-up after 18 years. In the case of airbags, consumer safety concerns, the viability of the innovation and automotive regulation drove substitution much more quickly (Fig. 15) — an unlikely scenario in the case of metal foams in the A-pillar. We conclude that, if all other conditions are favourable, the time to 50% take-up would be in the range of 12–18 years.

6. Value capture

In this investment assessment, we consider the position of a small firm, producing medium quality, medium priced, three-dimensional, aluminium foam parts by a powder metallurgical process. The viability assessment and market assessment indicate a potential future market for aluminium foams in the automotive market starting at \$5 million per annum and going to \$100 million per annum. It remains to be seen, however, whether the small companies who are at present in the process of commercialising the material are in a strong position to capture the value created by the innovation. In this section, tools to assess industry attractiveness, appropriability, and organisational structures are utilised to predict the likelihood of capturing value.

6.1. Industry structure

Porter's methodology for assessing *industry attractiveness* [14] is described in the accompanying paper [1]. It directs attention to the competitive threats and to buyer/supplier pressures that might reduce value-capture by the innovating firm. In the present context we find that several companies are able to make metal foams and that no one of them has tight control of the IP rights to the process, which is not difficult to reproduce. Their position is made less attractive because they must fight both against competitors who are commercialising alternative processes for making metal foams (the lower end liquid aluminium foam process, for instance) and against substitutes for energy absorption in automotive applications, such as, polymeric foams, shaped aluminium sections and fibre reinforced polymer composite sections. Additionally, the automotive companies exert very strong buyer power that will be difficult for the small producer to counter. Fig. 16 summarises these points.

6.2. Appropriability of profits

Teece's concept of appropriability [15] is useful in establishing the potential for value capture. Table 4

Table 4
Assessment of appropriability — moderate

IP/Trade Secret Protection	High	Medium	Low	None
Specialised Assets	High	Medium	Low	None
Co-Specialised Assets	High	Medium	Low	None
Innovation Type	Architectural	Niche Product	Revolutionary	Regular
New Product Cycle Time	Slow	Medium	Fast	Continuous
Protectable Industry?	Yes	Medium	Low	No

Table 5
Assessment of organisational strengths — medium

Strategic tasks[a]	Small firms	Aluminium foam producer
Integrating technology with production and marketing	Responsibilities of senior managers	medium
Monitoring and assimilating new technical knowledge	Trade and technical journals Training and advisory services Consultants Suppliers and customers	good
Judging the learning benefits of investments in technology	Judgements based on qualifications and experience of senior managers and staff	medium
Matching strategic style with technological opportunities	Qualifications of managers and staff	medium

[a] This table was adapted from the Tidd, Bessant and Pavitt, Managing Innovation: Integrating Technological, Market and Organisational Change, Whiley, Chichester, UK, 1997

summarises the appropriability position of a small company seeking to sell metal foam automotive components (shaded boxes). Tight appropriability lies to the left hand side of the table.

As already stated, the IP position appears to be a poor one. Specialised assets exist with the process, but most could be assembled by a die casting competitor without excessive difficulty. There is a possibility for co-specialised assets, if certain methods of automotive design propagate. Aluminium foam for energy absorbing automotive applications is a revolutionary innovation (Fig. 14), in that it overturns established technical and production competencies, but does not overturn customer linkages nor require a company to sell into different markets. New product cycle time is slow, giving a longer period over which to appropriate value and the structure of the automotive industry allows for protection of IP. The conclusion is that the appropriability position is not strong, but might be classified as medium.

6.3. Organisational structure

The companies at present developing metal foams have little entrepreneurial experience and may lack visionary deal-makers. On the positive side, they appear relatively flexible, with effective knowledge acquisition and good operational efficiency (Table 5).

7. Conclusions: applying IMM to aluminium foams

This paper has illustrated the methodology for analysing a material innovation by applying it to the case of metal foams. The conclusions of the key steps are listed below:

- *Target market*: energy absorption in automotive applications: the A-pillar, and front-end pedestrian protection.
- *Viability*: yes in energy absorption applications in the automotive industry. No in pedestrian protection applications currently.
- *Market assessment*: market size of up to \$100 million annually, with 50% take-up in 12–18 years.
- *Competitive position*: poor: uncertain IP protection, vulnerable to extreme buyer power.
- *Value capture*: medium to low chance.

As the chances of value capture are relatively low and the payback period is relatively long, a small firm would be disadvantaged in commercialising this innovation unless as a joint venture with a metal supplier or automotive producer. A larger company might be interested in pursuing this opportunity if it was in a good position to capture the value created. Alternatively, a government sponsored initiative for pedestrian or occupant safety might subsidise the commercialisation of such an innovation.

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