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Abstract

The promise of technological developments in advanced materials is attracting increasing attention, but their commercialization raises numerous challenges for incumbents and new entrant firms. These are summarized in a conceptual model of technological innovation as a matching process and in a number of propositions derived from the literature. Further examination and the extension of these propositions in the light of new evidence indicates both that entrepreneurial ventures play an important role in the commercialization of new materials and face shared challenges of matching their technological capabilities to market opportunities and potential alliance partners. These challenges are explored in more detail in a case study exemplar and metrics from 10 advanced materials ventures in the metropolitan Boston area. The paper concludes with policy and managerial recommendations.

Keywords: New Venture Strategy, Opportunity Exploitation, Resource Based Theory, Advanced materials, Technological innovation, Technology entrepreneurship, Alliances, Market strategy

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1. Introduction

National and international science policy organizations have long recommended fostering growth in the areas of information technology and biotechnology. These sectors are viewed as sources of growth for evolving knowledge-based economies. With the maturation of the information technology and biotechnology industries, advanced materials are now viewed as an enabler for further innovations with the potential for major economic impact across a broad range of industries and applications (Massachusetts Technology Collaborative, 2004; OECD, 1998; Oliver, 1999). However, it is unclear whether established firms or new ventures have sufficient incentives for developing and commercialising new advanced materials.

In this paper, we examine the challenge of commercializing advanced materials in the light of a conceptual model of innovation as a technological and market matching process, derived from Christopher Freeman (1982). We define innovations in advanced materials as involving new functional materials as well as product and process innovations that significantly improve the cost-performance frontier of functional materials. Examples of advanced materials innovations include Kevlar fibre for light-weight reinforcement, the use of nanoparticles to alter the mechanical, electrical, and/or thermal properties of a structural product, and organic light emitting diodes used for flat panel displays and other consumer electronic applications.

The structure of this paper is as follows. First, we examine the literature for challenges facing both established and new firms commercializing new advanced materials. We use this secondary evidence to construct propositions about the challenges of innovation in advanced materials. We assess these propositions in the light of new aggregate evidence and from this analysis develop and assess further propositions. Next, we present a case exemplar and disaggregated data from a sample of 10 advanced materials ventures, in order to ground these seven propositions in detailed firm level data. Lastly, we draw recommendations that could be used to guide the strategic product and market priorities of new firms in this sector and examine some policy implications of our findings.

1.1 Prior Work

Extensive literature on technology entrepreneurship has been emerging in recent years (Bhidé, 2000; Gans and Stern, 2003; Garnsey, 1998; Roberts, 1991; Shane, 2001). There is also substantial relevant research on technology industry evolution (Freeman, 1982; Garud & Karnoe, 2003; Pavitt, 1984; Utterback, 1994), technology firm growth (Almus and Nerlinger, 1999; Audretsch, 1995; Hugo and Garnsey, forthcoming; Niosi, 2003), and on technology innovation management (Abernathy and Clark, 1985; Henderson and Clark, 1990; Teece, 1986; Von Hippel, 1988). However, advanced materials firms have unique features on the basis of which they merit specific attention. Such research as has taken place to date on advanced materials innovation has focused at the industry level using such measures as overall R&D alliances in advanced materials (Hagedoorn and Schakenraad, 1991) and production volume growth of new materials (Eager, 1998; Maine, 2000a; Rothman et al., 1987) and at the innovation level using such techniques as patent network analysis (Baba et al., 2004), predictive cost modelling (Maine, 2000b), and multi-attribute utility analysis (Maine, 2002a; Mangin et al., 1995). Firm-level analysis related to advanced materials has mainly been empirical studies of large, established producers of industrial materials (Wield and Roy, 1995) and large, established, chemical producers (Arora et al., 1999; Walsh and Lodorfos, 2002) including two studies with a focus on the development of new plastics (Delorme, 1962; Freeman and Soete, 1997). Among the little evidence available on the early experience of advanced materials ventures is a small empirical study on the motivation for technical alliances among Canadian advanced materials firms (Niosi, 1993) and a case study on the investment attractiveness assessment of a start-up firm commercializing an advanced materials innovation (Maine and Ashby, 2002b). This paper seeks to make a new contribution to the understanding of the commercialization process of advanced materials ventures.

Most of the relevant existing literature focuses exclusively on cross-sectional, aggregate data or on case study sources.[1] Freeman's model of innovation as a resource-market matching process provides a basis for aligning aggregate and individual level evidence and for the integration of a range of relevant issues. Accordingly, the case study in this paper provides an exemplar of the propositions we derive from aggregate evidence.

2. Challenges of Innovation in Advanced Materials

Freeman set out the challenge of matching technical capabilities to market opportunities in the innovation process:

> "Innovation is essentially a two-sided or coupling activity. It has been compared by Schmookler to the blades of a pair of scissors […]. On the one hand, it involves the recognition of a *need* or more precisely, in economic terms, a *potential market* for a new product or process. On the other hand, it involves technical knowledge, which may be generally available, but may also often include new scientific and technological information, the result of original research activity. Experimental development and design, trial production and marketing involve a process of '*matching' the technical possibilities and the market*. (Freeman, 1982)

Although aspects of this matching process are common to emerging technology industries, firms in the advanced materials sector face a unique combination of sustained high technical and high market risk. We illustrate these challenges in **Figure 1**, which shows the complexity of the matching process in this sector. Schmookler's (1966) analogy is particularly apt in that solutions to technical and marketing challenges must be

[1] A notable exception is Freeman and Soete's chapter on innovation in synthetic materials, (Freeman and Soete, 1997, p.106-136),

synchronised if co-evolution is to occur. Value is only created and captured if the scissor blades operate together.

2.1 Technical Challenges

Innovations in new materials involve commercializing new knowledge generated by basic and applied research, generally taking place in universities, government laboratories, and the R&D laboratories of large firms. In addition to basic research and invention, commercialization of a materials innovation requires expensive near-market R&D, prototypes, and pilot plants, which greatly exceed the mandate and budgets of research universities and laboratories. New materials have broad potential applications across multiple markets, including aerospace, automotive, consumer electronics, construction energy and communication infrastructure, sports equipment, marine applications and biomedical devices. R&D is needed for each targeted market application and process innovations are also necessary for economies of scale, generally before a return on investment is achieved. The need for market-specific R&D results from the differing values placed on application attributes in different markets and from diverse regulatory requirements in different sectors. In emerging markets, advanced materials innovators are faced with investing in the most expensive stage of R&D before gaining feedback from their customers. Moreover, advanced materials innovations are not autonomous: they rely on related complementary innovations in order to be brought to market as a product.[2]

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[2] For example, the emergence of the fibre optics market relied on both glass fibre innovation and on innovations in laser technology. The microprocessor was enabled both by advances in silicon chip technology and by simultaneous innovations in smaller circuitry. Similarly, the emergence of a market for proton exchange membranes will depend on innovations throughout the fuel cell

2.2 Market Challenges

The structure of the marketplace creates further uncertainties for the commercialization of advanced materials. First, firms commercialising advanced materials are removed from the end consumer. As they do not deal directly with end consumers in the broad applications to which their innovation may be applied, they have greater difficulty in assessing consumer needs, managing experimentation and market feedback, and convincing their customers (component suppliers and assembled goods OEMS) to design products incorporating their innovation. Even when potential customers are convinced, the new material will not be specified in the current product, and so waits on the product cycle (approximately three years for automotive applications and up to 30 years for aerospace applications). As advanced materials often represent only about one-third of the component cost, which could be less than ten percent of the cost of the fully assembled product, they are not the prime consideration for companies further down the value chain (**Figure 2**).

Second, the commercialization of advanced materials often requires changes in consumer behaviour and/or investment in new public infrastructure, as depicted by the horizontal axis of **Figure 2**. This constitutes a major barrier to commercialization and increases both the uncertainty and time of market adoption. Fuel cells targeted at replacing the internal combustion engine in automobiles, with their reliance on new materials, are a classic example. In this instance, a fuelling infrastructure is required before automotive OEMS will produce and consumers will purchase fuel cell powered vehicles. Additionally, fuel cell vehicles may require changes in consumer behaviour such as a tolerance for lower performance attributes. This may

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system, and the emergence of a market for light emitting polymers will depend on innovations in flat panel display design and manufacturing processes.

lead to a time to market of 15 years. The advanced materials firms which are focused on the development of proton exchange membranes or carbon nanotube hydrogen storage for primary automotive fuel cell applications are unlikely to see substantial revenue in the next decade.

2.3 Matching Process

It is a paradox of generic technologies that there is massive potential for value creation in many applications, but this very multiplicity of possibilities creates targeting problems. This results in a complex innovation environment where multiple customer and distribution alliances must be formed, research and development specific to various industry applications must be performed, diverse regulatory hurdles must be surmounted, user reluctance to change specifications for an established product must be overcome, and process innovation plays a major role (Maine, 2000a; Wield and Roy, 1995). Firms can recognize a new market use for an existing advanced materials technology (through substitution) when the management team has varied industry experience or when advice is sought from a technology brokering firm such as IDEO (Hargadon, 2002). However, when advanced materials inventions both overturn current technological knowledge and enable entirely new markets, trial and error must be employed to guide new product development.

For co-evolving technologies and markets, Leonard (1995) and others recommend a strategy of market experimentation rather than an early exclusive focus on any one particular market or product design. To find an initial market application in which potential product attributes are highly valued by users who have the ability to pay requires a trial and error approach that can be lengthy and expensive. Further, if the application is to be viable, gestation times, regulatory barriers, and production cost must not be prohibitive (Maine and Ashby, 2002a)[3] and complementary innovations may need to be developed. These factors contribute to severe investment constraints despite potential for value creation.

Investment costs and time to market can be reduced when advanced materials are moved from the application for which they were originally developed to new uses in different markets.[4] The example of Teflon (PTFE), transferred from NASA's space application to domestic use is often cited. Some established companies can enter new markets by finding new customers in this way, but in general entrepreneurial entrants are more adept at identifying opportunities of this kind. Historical example demonstrates entrepreneurial alertness to opportunities overlooked by established companies, particularly in emerging markets with new potential customers (Christensen, 1997; Miller and Garnsey, 2000; Shane and Khurana, 2003).

3. Advanced Materials Innovations: Some Generalizations

Having identified unique features of innovation in the advanced materials sector, we now formulate a number of propositions (Ps) relating to the opportunity and challenges of commercializing new materials and the role of new ventures as innovators in this sector. New evidence presented in this paper supports these literature-based propositions. Analysis of this

[3] In particular, substitutions into existing applications present challenging, albeit known, production cost targets. Small volume applications, which are of less interest to VCs and to large companies, will more often support price differentiation and allow for lower upfront capital investment due to a higher ratio of variable to fixed costs. Large volume applications require a greater initial capital investment to contest the incumbent material which has had the opportunity to exploit production learning curves and economies of scale.

[4] Abernathy and Clark (1985) refer to this as a "niche market" innovation.

new evidence allows us to put forward three further related propositions on issues which have not yet been explored in the literature. A case study and disaggregated metrics from ten advanced materials firms provide more detailed evidence on both the potential of and the challenges facing new companies in this sector.

P1: New material innovations have the potential for substantial value creation.

Those firms that succeed in matching their technologies to evolving market needs will deliver substantial value. The potential of advanced materials (in particular, when created or manipulated at the nanoscale)[5] to improve products throughout broad sectors of the economy and to enable entirely new markets is articulated by statements from the OECD, by technology forecasters, by national and regional science policy statements, and supported by investments by national governments in related research:

> "Materials Technology is the hidden revolution. Historically, we have been dependent upon the inherent limitations of materials in whatever we build… Fundamental new knowledge now allows us to realistically consider designing new materials from scratch with any set of characteristics we choose." (OECD, 1998, p. 40)

> "While it is quite clear that information technologies increasingly became the major economic engine of the past five decades, a whole new set of technologies – biology and advanced materials – are poised to become the new engine driving the economy. Their scope, scale, and importance in our business and political lives supersede those of the electronic era with every passing day." (Oliver, 1999)

> "And materials with superior characteristics – many times stronger than steel but a fraction of its weight, for example – could be used to build better cars, planes, spacecraft, buildings, and creations we have yet to imagine. Clearly, nanotechnology has the potential to profoundly change our economy, to improve our standard of living, and to bring about the next industrial revolution." (National Science and Technology Council, 2003)

> "The utopian view of nanotechnology is that it will provide a platform of technological advancements that positively impact economy, workforce, existing industries and society in general. The U. S. federal government clearly believes in these possibilities, and demonstrated its belief in December 2003 when Congress and the President approved a

[5] The nanoscale refers to dimensions of up to approximately 100 nanometres, or 10^{-7} metres.

> four-year authorization of nearly $4 billion for the National Nanotechnology Initiative, thus making nanoscale research one of the few new spending priorities in an otherwise tight fiscal climate." (Massachusetts Technology Collaborative and the Nano Science and Technology Institute, 2004, p.2)

However, reaching the market involves major challenges.

P2: Commercialization of new advanced materials that alter the cost-performance frontier involve high capital cost.

This follows from the elaborate and costly process of basic R&D and commercialization for specific market applications that are needed for advanced materials innovations, as discussed earlier. Case study evidence reveals that DuPont spent $5.7 million on lab research, $32 million on pilot plant development, over $300 million on commercial plant construction and approximately another $150 million on marketing, sales and distribution, and that it took 15 years to break even on their Kevlar investment (Christensen, 1998; Hounshell and Smith, 1988, pp. 431-432). Cambridge Display Technology (CDT), the subject of the case study in this paper, has found it necessary to raise over $130 million in venture capital in addition to establishing extensive partnerships and pursuing a licensing business model.

P3: The time lag from invention to significant market adoption is high for advanced materials innovations relative to other emerging technology sectors.

As shown in **Figure 3**, advanced materials innovations have long adoption time lags due to the bottlenecks that impede penetration into broad market applications. Some of these bottlenecks include designer unfamiliarity, incumbent product life cycle, firm technology capabilities, market-specific regulations, and distance from the end customer. Of the four examples depicted in **Figure 3**, Polypropylene took 37 years, Teflon (PTFE) took 31 years, Kevlar took 17 years, and carbon fibre took 34 years to reach 50 percent of their eventual (or current) sales volume.

These adoption times are long relative to those experienced by firms in other emerging technology industries. For example, a typical game developed by a gaming software development company takes one to two years of development and reaches 50 percent of its eventual market volume in one to two years, for a total time of between two and four years (Van der Mescht and Weber, 2002). Drugs developed by biotech firms have a typical development time of seven-and-a-half years (DiMasi et al, 2003), and their 50 percent adoption time is not directly comparable as drugs are consumables rather than durable goods. Consequently, advanced materials ventures which are focusing on radical innovations represent a less attractive investment than ventures in other sectors of the emerging technology economy.

P4: Complementary innovations are required before significant adoption of materials innovation occurs.

New materials are not a source of autonomous innovations. They call for congruent developments in related areas of production and consumption. As an example of the need for complementary innovations in advanced materials, DuPont struggled to achieve adoption of its Kevlar fibre until changes in body armour design (in recognition of new functional possibilities) and the new requirements of fibre optic infrastructure eventually resulted in viable market niches for the new material. Similarly, the significant adoption of carbon fibre was dependent on process innovations in polymer composite manufacturing and required significant design changes in eventual aerospace, marine, sporting goods, and race car applications. Today, proton exchange membrane (PEM) fuel cells, targeted at replacing the internal combustion engine in automobiles, are waiting on process innovations to reduce the cost of or need for polymer membranes and fuel cell stacks, on infrastructure standards to be established, and on legislation reflecting the costs to society of pollution. Likewise, the light-emitting polymers (LEPs) developed by our case study, CDT, are waiting on further product and process innovations for flat panel display applications, as well as design innovations that take advantage of the flexibility of LEPs for flexible panel displays.

3.1 Implications for Innovators

Propositions *P1* to *P4* relate to conditions that shape the incentives and constraints affecting those who takes up the challenge to match advanced materials technologies to market needs. We now consider how these incentives and constraints differentially impact established firms and new ventures. From this analysis, we develop three further propositions relating to the agents of innovation in this sector and ways in which resource-constrained entrepreneurial ventures can overcome their liabilities.

There are established corporations which have the technological capabilities and resources to develop and commercialize advanced materials. Such companies have already achieved significant innovations and often have major R&D programs. Over the 1980s and 1990s, the number of the world's largest firms with competencies in advanced materials has increased substantially (Patel and Pavitt, 1997). However, since the early 1990s, many established firms with competencies in advanced materials have focused their new product development resources on incremental innovations and on existing markets rather than radical or revolutionary innovations or emerging markets.[6]

Although there are opportunities to create substantial value from advanced materials innovations (*P1*), there are also considerable disincentives facing established firms. For

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[6] In Canada, established corporations are even less likely to focus on significant advanced materials innovations due to a lack of domestic demand from aerospace, automotive, or traditional energy customers (Niosi, 1993).

publicly-held companies, short-term shareholder pressures are in conflict with the required high capital costs (*P2*) and long lead times (*P3*). This pressure has led to established advanced materials firms allocating R&D resources in a risk-averse fashion and avoiding innovations that overturn their technology or production capabilities.[7] Additionally, established firms do not use their resources to exploit opportunities for radical innovation for path dependent reasons. Specifically, established companies are at least partially defined by their existing products and technological capabilities (Penrose, 1959), and are reluctant to cannibalize or jeopardise these existing profit streams, for example, through reputational damage due to a failed new product release. Established firms are resource constrained in that they can only focus on a limited number of divergent opportunities at any one time (Leonard, 1995; Penrose, 1959; Rothwell, 1984; Shane, 2005). To determine the opportunities they will attempt to exploit, and, subsequently, their R&D focus, established companies generally listen closely to their customers (Christensen, 1997; Von Hippel, 1988), yet this strategy can blind them to emerging opportunities in markets outside their existing customer base (Christensen, 1997; Shane, 2005).

From *P1* to *P4* and the ensuing implications for entrepreneurs, *P5* follows.

P5: It is not exclusively established firms that introduce new advanced materials.

New ventures may seem an unlikely source of innovations in this challenging and capital-intensive sector which could be classified within Pavitt's taxonomy as "scale-intensive" (Pavitt,

[7] For example, Alcan did conduct R&D on a range of higher risk innovations in the 80s and early 90s, when the peak of new alliances in the advanced materials industry were being created. Pressure from shareholders and advice from consulting firms convinced Alcan and others to focus on their "core capabilities," in their case, cheap hydro-electric power which bestowed a cost advantage on the smelting of aluminum ore.

1984; Tidd et al., 2001, p.114). Indeed, nearly all new polymeric materials developed after World War I were developed by large chemical companies (Soete and Freeman,1997, p.109). However, information technology innovations have enabled "a proliferation of advanced materials with greatly enhanced properties" (Soete and Freeman, 1997, p. 130) and a reduction in the advantages of large firms over small firms in commercialising advanced materials innovations (Maine, 2000). Additionally, unlike the established materials firms, new ventures have no sunk investment in the past, and are free to explore promising opportunities to exploit their technologies.[8] They are better able to see opportunities where they have scientific founders who understand the potential of new technologies and no existing customers to limit their view. New ventures are more flexible, better able to adapt quickly to changing market opportunities, and more willing to exploit highly uncertain opportunities than established firms (Bhidé, 2000, p. 120). And new technology-based firms generally enjoy strong linkages to the science network, often through PhD founders, informal access to university facilities and/or personnel, and/or access to government research laboratories.[9]

New ventures have lower fixed and semi-fixed costs than more established firms, and thus a smaller sized market can attract their attention. Penrose referred to these neglected areas of opportunity to exploit a firm's resources as interstices, and recognized that some of these may be early stage growth markets (Penrose, 1959, p. 224). Christensen points out that such

[8] For example, Nucor exploited the far cheaper electric arc furnace ignored by the established and integrated steel manufacturers to reduce the production cost of steel.

[9] Primary research conducted by authors.

beachhead markets will make no immediate impact on the revenues of an established firm,[10] and are thus not deemed to be worthwhile by larger firms. Yet that same market opportunity could provide a valuable profit stream and learning ground for a new venture. To illustrate larger companies' reliance on larger markets, the Apple II was considered a great success when it was released on the basis of sales of 43,000 units. When the same company released the Newton I PDA and achieved sales of 120,000 units, the product release was deemed a dismal failure (Christensen, 1997). A new venture with a radical innovation experiences advantages in the pursuit of emerging market opportunities that could disrupt incumbent firm's markets.

Thus, among the routes to commercialization for the extensive opportunities presented by radical inventions in the materials, physics, and chemistry laboratories of university and government research facilities, evidence and theory suggests that the route taken by technology entrepreneurs is of particular interest. There is good reason to look to entrepreneurial ventures as innovators in new advanced materials based on observations of other emerging technology industries. They have played an important historical role of matching emerging technologies to market opportunities with examples including the development of the telegraph, telephone, electric lighting, integrated circuits, personal computers, internet service providers, routers, browsers, and many drugs and software programs. Historically, the strengths of entrepreneurial ventures have been their alertness to new opportunities, their low overheads which make initially small markets viable, their flexibility in choosing a new opportunity, and their adaptability to

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[9] Christensen's use of the term beachhead markets refers to niche markets that value the current combinations of attributes that can be provided by the technology, can serve as learning sites, and may be emergent growth markets.

changes in their opportunity space. Advanced materials ventures have additional advantages – when they spin out of a research laboratory, their knowledge and technological capabilities constitute barriers to entry especially when embedded in intellectual property and where they have access to a scarce and skilled labour pool in the university.

There is also good reason to expect that advanced materials ventures are more likely to be the harbingers of change today than they were in the past. **Figure 4** demonstrates that there has been substantially more growth in the number of very small firms in advanced materials sectors in the United States than any other size category of firm.[11] There were 32 percent more very small firms (those with between zero and 19 employees) in advanced materials industries in 2000 than there were in 1990. This entry of entrepreneurial ventures implies that very small firms are able to commercialise products which employ advanced materials innovations.

P6: Small firms are important innovators in the advanced materials sector.

The industry-level evidence of **Figure 4** implies that advanced materials ventures are being formed and surviving and thus commercialising products.[12] Patents are more relevant than industrial classification data to *emerging* knowledge-based industries.[13] **Figure 5** also demonstrates for the emerging technology of elemental carbon synthesis that large firms do not play a dominant role in number of patents obtained. Small firms, along with individuals,

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[11] This analysis was based on US SIC codes and NAICS codes for the industry classifications which were judged to contain advanced materials manufacturing and research.

[12] More evidence is needed to suggest that the ventures are commercializing new materials rather than merely providing products and services to support incumbent materials and processes.

[13] Patents have their own limitations as they are not proof of commercialization, but merely an indicator.

universities and government laboratories, have played a very significant role in this aspect of commercialization.[14] The importance of small firms, individuals, universities and government laboratories is expected to vary among technological areas of advanced materials depending on the maturity of markets utilizing related technologies. Delorme (1962) showed that small firms played a similarly important role in the early stages of plastics innovations, before the maturation of the plastics industry and the development of sophisticated technological capabilities of large chemical firms. With advanced materials developments overturning the existing competencies of established firms and the decreasing transaction costs associated with alliances, small firms are likely to become increasingly important in the commercialization of advanced materials innovations.

P7: Alliances alleviate some of the constraints faced by small firms with strong IP innovating in advanced materials.

A means of overcoming barriers to entry in the form of capital requirements is strategic alliance with established companies. The important role of alliances has been established by many studies in other sectors, in particular biotech (Niosi, 2003; Tyebjee and Hardin, 2004). Over the past two decades, the number of overall R&D alliances between small and large firms have increased dramatically (Hagedoorn, 2002; Hagedoorn and Schakenraad, 1991), implying that entrepreneurial firms have better access to the complementary assets needed to commercialize innovations. The IT developments that have lowered the transaction costs of these alliances have also enabled small firms to connect with the outside world for a fraction of the previous cost. For example, small firms can import knowledge instead of funding costly internal R&D,

[14] Patents assigned to university laboratories and to individuals can lead to the formation of an advanced materials venture.

previously a barrier to entry. They can also establish an international presence more easily through websites and email communications which reduces the need for international sales and marketing divisions. Several founders perceived that the impact of these changes was important to entrepreneurs in the advanced materials sector (Maine, 2000). Thus, some of the disadvantages facing small firms engaged in commercialising innovations have been eroded.

Having based *P1* to *P7* on the literature and on aggregate data, we seek to show that these propositions are supported by evidence from individual firms. Given the paucity of research on firms commercializing advanced materials, we seek to ensure that our literature-based propositions are consistent both with aggregate evidence and evidence collected at the individual firm level.

As evidence of this consistency, we present a detailed case study below of an advanced materials venture. The experience of this venture, Cambridge Display Technology (CDT), is consistent with each of our literature-based propositions (P1 – P7), including those we support with new aggregate evidence (P3, P5, P6). That this case exemplifies the challenges facing ventures in this sector is further supported with disaggregated firm-level evidence from the population of advanced materials ventures in the Boston area. These findings from specific cases enable a more holistic understanding of the commercialization challenges faced by advanced materials ventures and suggest a product and market strategy that could reduce the risks they encounter.

4. Firm Level Evidence – Cambridge Display Technology (CDT) and Boston Sample

Cambridge Display Technology (CDT) is a privately-held spinout company from Cambridge University, UK. It was founded in 1992 following ten years of basic science on the behaviour of interacting electrons during which transistors created from polymers were developed as research tools. It became clear that light emitting polymers had the potential to replace the aging cathode ray technologies still standard in electronic display applications. Intellectual property was created in technology platforms and production processes for flat panel Organic Light Emitting Diode (OLED) displays using Light Emitting Polymer (LEP) technologies.

The initial strategic objective was to manufacture products for such applications as flat panel displays and back lighting for LCDs. The potential of this technology in major markets attracted funding from the university and a seed capital fund, Cambridge Research and Innovation Ltd., together with high-profile private investors including the rock group Genesis. After four years it became clear that the cost of developing applications of this kind and penetrating markets dominated by powerful companies made it essential to undertake manufacturing partnerships. An experienced CEO was appointed and a licensing arrangement with Philips Components was finalised in 1996. The strategy was now to license the core technology to key customers to enable them to use their expertise and resources to develop marketable LEP displays. Confidence in CDT was boosted when Intel Corporation's VC fund bought an equity stake in CDT. By 1998, CDT was able to announce a joint venture with the Seiko-Epson Corporation. This resulted in the first video display on LEP through a creative combination of CDT's technology and SEC's active matrix and ink-jet printing technologies (*Reuters News,* 16 Feb 1998). A cross-licensing deal with Hewlett Packard further enhanced CDT's reputation.

By this time the company had surrounded their fundamental OLED patent with other patents on materials and device structure, but the costs of development were still very high. In 1996, a UK venture capital fund specializing in light emitting polymers was formed that took out a 33 percent stake in CDT. Lord Young, former Secretary of State for Trade and Industry, became Chairman of CDT in 1997. These promising developments did not suffice to keep CDT independent. In 2000, an offer to buy CDT by two New York private equity funds, Kelso and Hillman, was accepted and generated $133 million. A new US parent company was established, CDT Acquisition Corporation, as a privately-held company. Another $16 million was made available by Kelso and Hillman for R&D at CDT.

The strategy for CDT was now to establish development partnerships and licensing agreements with major display manufacturers. "This way we get licensing income on the original IP [licenses with material suppliers] and from end products we have been involved in developing," announced Danny Chapchal, appointed CEO in 1996.[15] CDT's alliance strategy had to include materials suppliers,[16] auxiliary component manufacturers,[17] display manufacturers,[18] and fully-assembled product OEMs.[19]

Relations with the new parent company did not prove straightforward, however. Chapchal departed and in 2000 the founder of CDT, Richard Friend, formed a new company, Plastic Logic, to which he switched his research efforts. In order to increase the attractions of licensing agreements with CDT, it became clear that it was necessary to demonstrate the viability of the pioneering technology. To this end, another $28 million was raised from shareholders and

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[15] *Electronic Times*, 1999.

[16] Bayer, Covion, Dow Chemical and Sumitomo.

[17] STMicroelectronics, Plastic Logic, Dai Nippon Printing.

[18] Delta Optoelectronics, DuPont Displays, Eastgate (Singapore), MicroEmissive Displays, Osram Opto Semiconductors, Phillips, Seiko Epson, and CDT's subsidiary, Litrex.

[19] Philips, Seiko-Epson, Samsung.

used to finance a $25 million facility near Cambridge for developing commercial scale production techniques and know-how and to help licensees develop their own manufacturing methods in LEP. The 2001 acquisition of a Californian company with advanced ink jet tools, and the 2003 acquisition of an Oxford company with another OLED technology further extended CDT's ownership of complementary technologies.

In 2002, products using CDT's LEP display had been made available to end customers in mobile and cellular phone applications through a partnership with the German company Osram Opto Semiconductors. Partnerships with Dupont Displays and a Hong Kong chip firm, GDesign, and a licensing agreement with Trident Display followed with the aim of extending CDT's displays in mobile phones globally. However, development costs remained very high and, in July 2003, a loss-making production line in their nearby production facility was closed and the decision made to restrict production to prototypes. The CEO, Dr Fyfe, announced, "Things are slower than we would have experienced two years ago and we don't expect a business upsurge until 2005/6 when technology will find its way into large screens and licensees like Philips will have their big plans up and running. That's when the royalties will be coming in."(CDT website July 2003). Meanwhile a 50 percent equity interest in their subsidiary Litrex was sold to Ulvac Inc., a Japanese company that had marketing capability in the Far East.

CDT's growth history and early financial indicators are depicted in **Figure 6** and **Table 1**. **Figure 6** emphasizes the extent of resources required to commercialize a major advanced materials innovation. In the case of CDT, the capital was required for R&D, growth of business development, marketing, finance and legal functions, prototype development, a pilot scale manufacturing line, and acquisition of complementary manufacturing process technology. The negative gross profit figures are an indicator of the high level of investment required for R&D and scaling up CDT's activities (**Figure 6**).

CDT's R&D achievements are signalled by the growth in the company's patent portfolio (**Table 1**). A notable feature of companies with costly R&D to undertake before products are market ready is the expansion of employment prior to reliable revenues. Thus, while employee numbers at CDT rose steadily to 150 in 2002, it was five years before revenues were achieved and these were highly unstable through to 2000. It is not unusual amongst advanced materials innovations that, after a decade, only $13.5 million of revenues was being generated.

The LEP market has been predicted to total over $4 billion by 2005. The flat panel market has been valued at over $30 billion. CDT's objectives are to be at the centre of a network of companies developing technologies for these markets and to grow by providing the technology and intellectual property to this development network. By focusing on installing its technologies in products such as mobile devices in the short term, and developing technologies and IP for future products in massive growth markets, CDT has retained the confidence of investors despite difficulties encountered. In 2004, CDT was preparing to float on NASDAQ.

CDT's current business model focuses on two areas: licensing the IP and contracting the transfer of production knowledge to manufacturers in the display industry, and establishing licensing to the supply chain for the supply of materials and electronic equipment that goes with the displays. CDT considered manufacturing displays twice thus far. In the early days of the firm, a manufacturing model was seen as the way to prove feasibility. However, the investment was beyond CDT's resources. In 2001 and 2002, CDT acquired three small firms with manufacturing capabilities. However, CDT moved away from that strategy with the sale of some of their new manufacturing assets and the formation of further licensing deals. This return to a licensing model is influenced by the scale of investment and time required for large-scale manufacture of displays and materials.

CDT's LEP technology undoubtedly has the potential for substantial value creation (*P1*), given the $30 billion dollar projected size of the emerging flat panel market. Efforts to commercialise their LEP technology has already required in excess of $130 million (*P2*), and successful commercialization will involve far greater investment. Light-emitting polymers were first patented in 1989, following several years of basic scientific research, and CDT has been attempting to commercialise this technology since 1992 (*P3*). As of 2003, CDT has generated only 13.5 million pounds in revenue. CDT has been awaiting complementary innovations in manufacturing and in design of flat panel displays (*P4*). CDT is a new venture, which spun out of the University of Cambridge, has grown to 120 employees, has generated 120 patents which tightly protect their LEP intellectual property, and is leading the commercialization efforts for LEPs in flat panel displays (*P5* and *P6*). Creative negotiations with a network of alliances partners who are co-developing consumer electronic products have been crucial to the growth of CDT (*P7*). Thus CDT serves as an exemplar for the propositions developed in this paper.

CDT has a unique technology trajectory, but is not unique as an advanced materials venture in facing particular challenges matching its technology to market requirements. A study of the 10 advanced materials ventures in the Boston area is used to provide disaggregated evidence bearing on this issue, and is summarised in **Table 2**. These firms were interviewed in 2002 and were still in existence in 2004. Six of the ten firms were less than five years old, although half of those new ventures were previously incubated within another, larger firm. The experiences of these firms provide further evidence about the formation and growth of advanced materials ventures, their financial challenges and methods employed to address these challenges.

All 10 of the firms had the opportunity to create substantial value (*P1*), with large target markets often spanning multiple industries. Those which attempted to alter the cost-performance frontier, will incur high capital costs as they commercialise the products they are currently developing (*P2*), and seven of the 10 firms identified lack of finance as the primary barrier to growth for their firm (**Table 2**). Six of the ten firms indicated that SBIR grants (competitive US government agency grants which fund prototype development) were critical to their survival and growth as a firm in this sector. Of the four firms which did not receive SBIR grants, two had been incubated within a larger firm and one had other government funding. The older firms depicted in **Table 2** show the slow rate of revenue growth typical of advanced materials ventures without venture capital investment, with one firm taking 17 years to reach $5 million in revenue. This lends further support to *P3*. Six of the 10 firms were waiting on complementary innovations in order to commercialise one or more of their products (*P4*). The existence of these ventures attempting to commercialise advanced materials innovations with substantial potential value supports *P5* and *P6*. And 9 of the 10 firms had created strategic alliances in order to commercialise their innovations, with 7 of these firms having created alliances which effectively lowered their barriers to entry into their target market. Thus, the experience of the advanced materials ventures in this sample is consistent with all of the propositions developed earlier in this paper.

In the light of evidence presented in this paper, it is clear that new materials ventures need to consider not only customer utility and the total size of the revenue opportunity, but also their ability to attract and develop alliance partners, the availability of subsidies and grants, and the attractiveness of an opportunity to potential angel and VC investors. The senior management of these firms must balance the desire to pursue large opportunities (which are necessary to attract venture capital investment) with the need to generate revenues in the near- to medium-term future. Hence, they must match the current productive base of their firm with one or two near market opportunities,[20] while simultaneously staking a claim on future large volume opportunities. This makes it appropriate to target specific market sectors in sequence and to adapt their business model in the light of emerging opportunities.

5. Discussion and Conclusions

We have shown that advanced materials ventures have an important role to play in advanced materials innovations, but that they require large investments over extended periods of time, strategic alliance creation, and a focused market prioritization strategy to have a reasonable chance of success. The complicated matching process of technology to market opportunities is mediated by alliances in this sector. The benefits of alliance partners include access to complementary technologies, access to manufacturing, regulatory, legal, reputational, marketing, and distribution resources, financial investment, and risk-sharing.

From the analysis undertaken in this paper, it follows that advanced materials ventures can reduce risk if they are alert to different time-to-market requirements of various applications of their technology and the need to balance resource allocation. Their technology and market strategies can be based on the recognition that applications closest to end users (e.g., incremental automotive innovations) that offer early substitutability and which do not require new infrastructure or new consumer behaviour, provide an early source of revenue (around 3 years).

[20] The Penrosean concept of productive base here encompasses the capability inherent in networks of entrepreneurs and senior management, technological capabilities and IP, market reputation, alliance capability, and availability of additional knowledge.

However, in the longer term, such innovations are too specific and too low margin to have sufficient market potential to be of interest to venture capitalists. It is generic advanced materials with many applications in major markets and the potential to enable entirely new markets and capture future returns on a substantial scale that can attract venture capital and large corporate investment. When the Intel Corporation's VC fund bought equity in CDT, they explained, "We make investments with strategic intent in companies where we think they have a technology that will help drive the marketplace." (Liberman, 1997). Thus, advanced materials ventures need to develop an IP claim on a long-term market application with major potential. However, they need to limit the time and resources spent on these long-term initiatives and avoid neglecting short-term revenue generation.

Advanced materials ventures can reduce risk by prioritizing early revenue product partnerships while also developing the technology for applications with major future market potential. Unlike the soft-start strategy sometimes adopted in other technology sectors, advanced materials ventures cannot readily achieve revenues from service activities prior to launching their products.[21] Even near-market innovations have relatively lengthy development requirements.

Thus, resource-constrained advanced materials ventures would be well advised to focus the majority of their resources initially on technology development for specific near-term applications (top left of **Figure 7**) and focus their alliance building and sustaining efforts on either component or OEM product manufacturers involved in these near-term applications. In short, they should aim at substitution initially with a view to new market creation in the longer

[21] Unlike pharmaceutical companies, large materials firms are either commodity producers (i.e., aluminum, steel) or have large R&D facilities and seldom purchase research or consultancy services from new firms.

term. Prioritizing market applications in this way could be guided by viability analysis (Maine and Ashby, 2002a) and by ranking of interested potential alliance partners.

At the same time, advanced materials ventures ignore the generic nature and new market creation potential of an advanced materials innovation at their peril. The valuation of their firm will be greatly enhanced by gaining a stake in IP (top right corner of **Figure 7**).[22] A convincing presence in this area can generate positive PR and attract top technical employees. Resource allocation recognizing this long-term potential could involve filing a patent that gives the firm future rights to appropriate value in this space. Since alliance creation with firms intent on developing the technology towards future applications (top right corner of **Figure 7**) can be a major drain on the resources of an advanced materials venture, this should be undertaken with caution or not until profitability is achieved. As a guideline, it is recommended that only a small amount of the resources (around ten percent) of an advanced materials venture be spent on promising but long-term opportunities. Thus advanced materials ventures are advised to allocate the bulk of their resources on one or two near-market applications, and to simultaneously pursue a targeted R&D effort towards securing IP in a high-value, long-term opportunity.

If cash pressures can be reduced by successfully competing for government grants, this opens up strategic options for the advanced materials venture. In the Boston population of advanced materials ventures, the majority of the ventures reported that federal SBIR funding was critical to achieving their strategic aims. Sufficient near-market R&D support has not been available elsewhere, for example in the UK (Garnsey and Moore 1993) and in Canada

[22] Examples of efforts in this categorization would include PEM fuel cells for automotive applications, carbon nanotubes for next generation microprocessors and memory storage, and LEPs for flexible TVs and signage.

(Conference Board of Canada, 2004). Market-oriented government granting programs are particularly important to advanced materials ventures, given the scarcity of VC funds available to firms commercialising advanced materials.

Policy solutions should be aimed at supporting innovators' exploratory processes, for instance, by subsidising marketing information for the entire sector, providing product regulatory testing at government laboratories (serving also to endorse emerging technologies) and providing incentives for partnerships between large and small companies developing product prototypes for specific market applications. While realism dictates that new ventures aim at near-market applications, resource constraints and narrow investor expectations can block the exploration of future possibilities, the main strength of new ventures. Our evidence shows that experiments with the matching process often make it appropriate for advanced materials ventures to shift target products and markets and to mutate their business models. Investors and policy makers should recognize that flexibility in this regard represents responsiveness to unfolding opportunities.

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Figure 1: The Matching Process Required for the Commercialisation of Advanced Materials

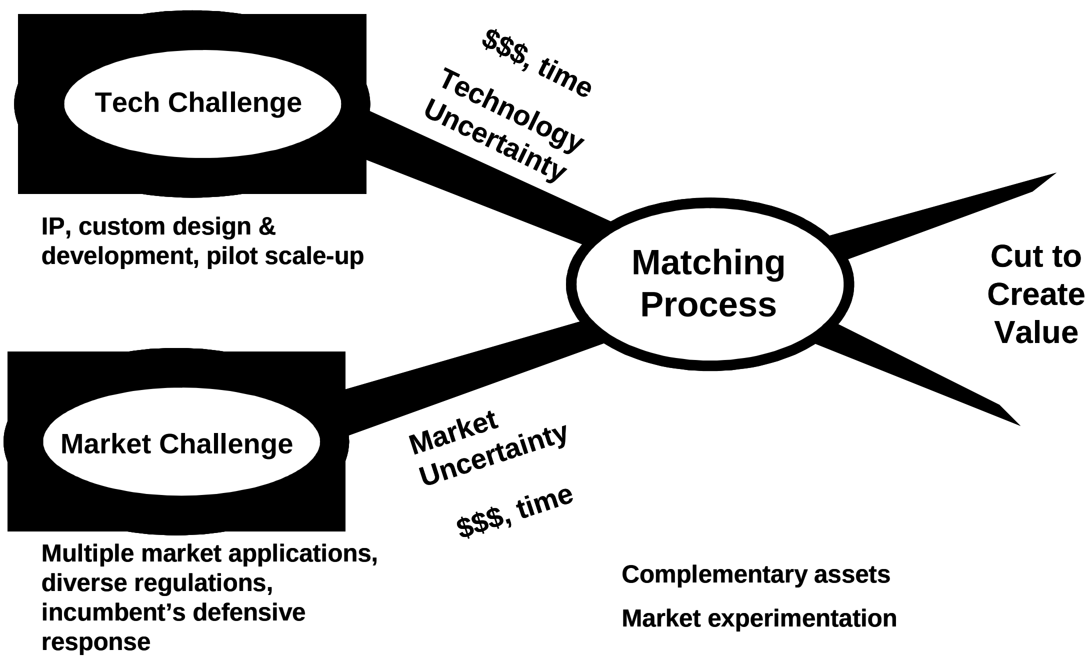
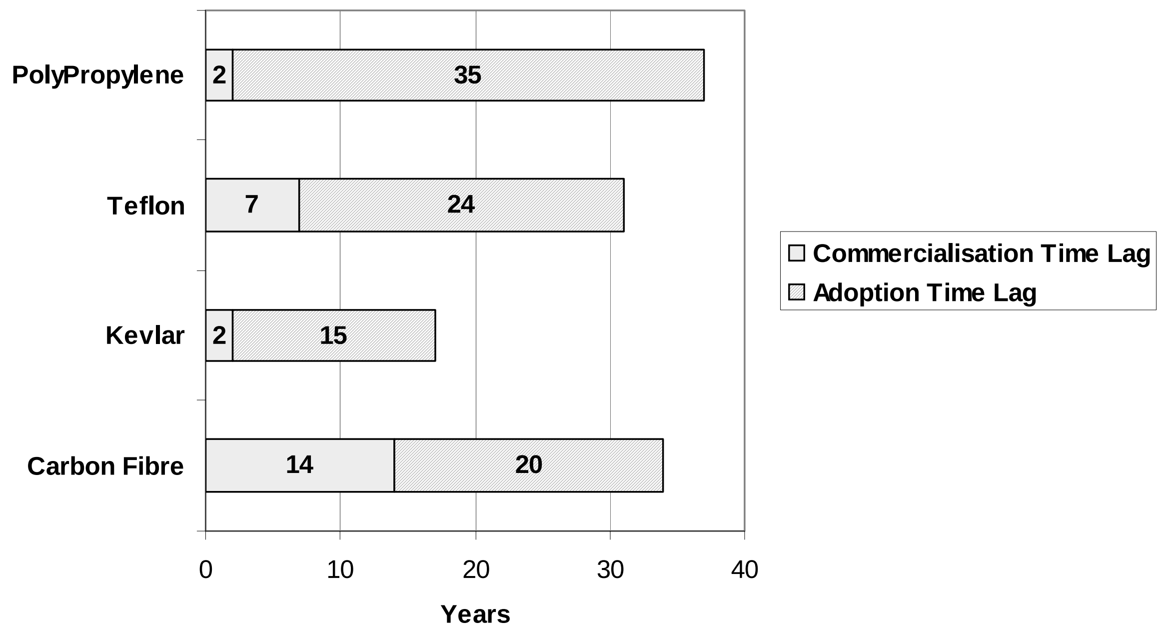


Figure 2: Market Factors Impacting the Commercialisation of Advanced Materials

Separation from Final Customer	Low	High
High (Input to Components)	PEM for fuel cells for auxiliary power Carbon nanotubes polymer composite	PEM for Auto Fuel Cells Carbon Nanotubes for logic circuits and hydrogen storage
Medium (components)	Carbon nanotubes polymer composite fuel lines for auto	PEM fuel stacks for auto
Low (fully assembled product)		PEM fuel cell powered automobiles

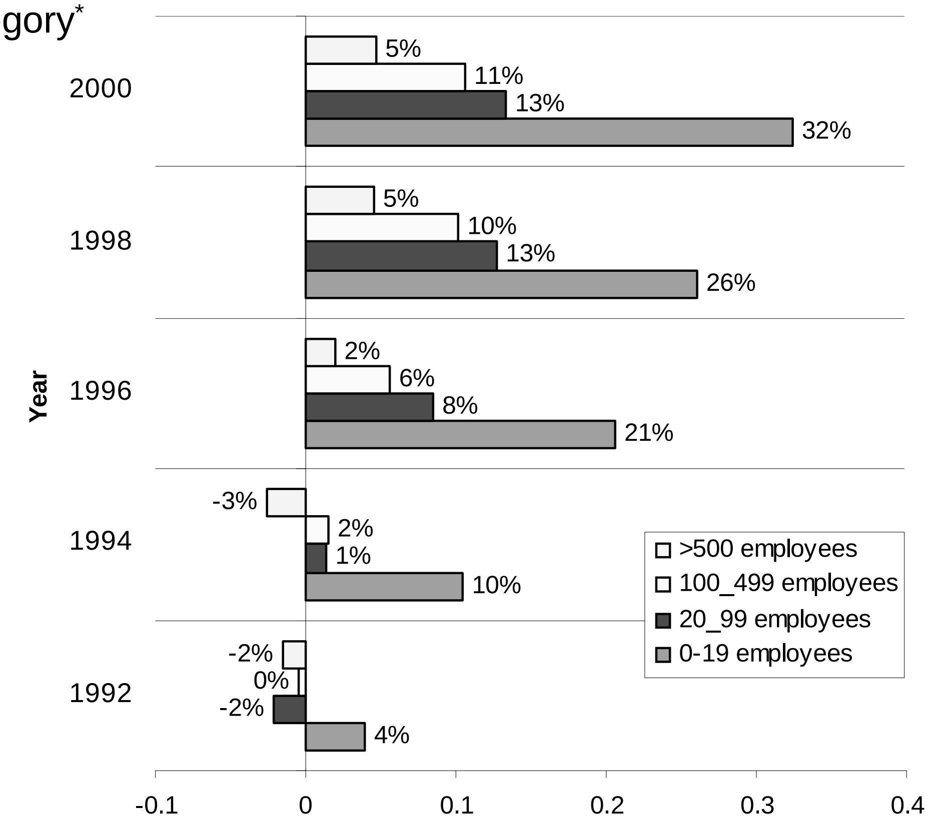
Need for New Public Infrastructure and/or New Consumer Behaviour

Figure 3: Commercialisation and Adoption Times for Advanced Materials Innovations*



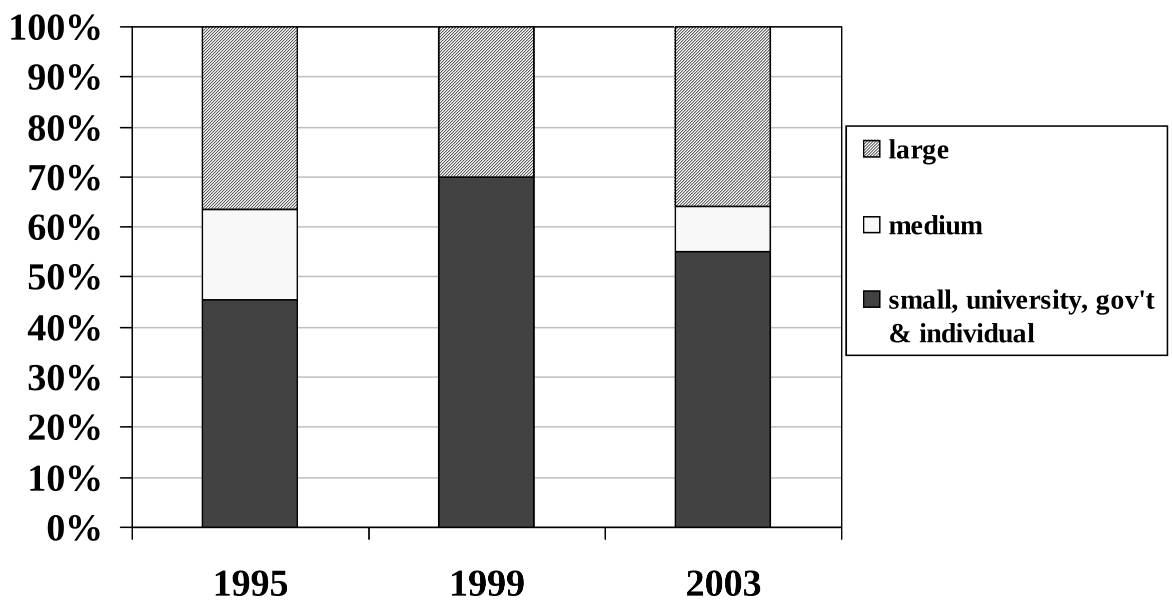
***** Commercialization time lag refers to the time between the initial patent application and the first commercialization of the technology. Adoption Time Lag refers to the time between the first commercialization of the technology and the time when 50% of the current volume of product sales was reached. Data sources for this analysis include the US Patent and Trade Office, The Chemical Engineering Handbook, DuPont's annual reports and website, and Hounshell and Smith, 1988.

Figure 4: Changes in Number of US Advanced Materials Firms by Size Category*



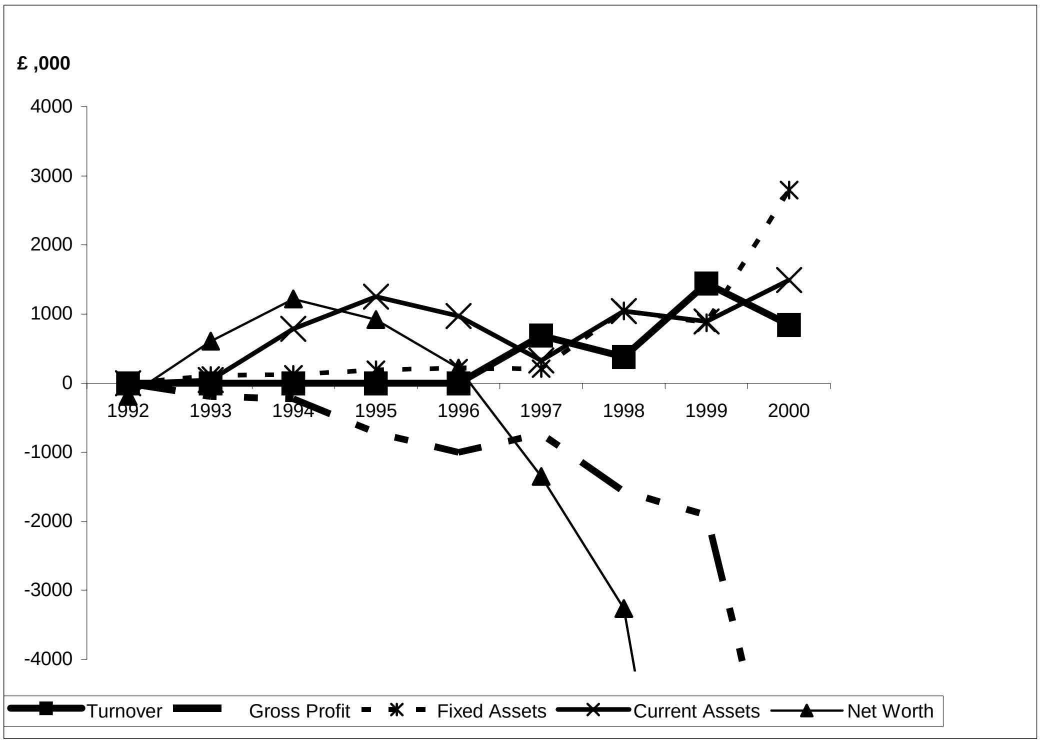
* This figure demonstrates the percentage change in the number of advanced materials companies across size classes from 1990 to 2000, with 1990 as the base year. N = 140,000

Figure 5: Patent Assignees for Patent Class Over Time*



* The patent class analysed is US patent class 423.445B (Elemental Carbon). N=32.

Figure 6: Early Financial Indicators for Cambridge Display Technologies Ltd*



* Source: adapted from ICC database

Figure 7: Product and Partner Prioritisation for Advanced Materials Ventures

Separation from End Customer		**Need for New Public Infrastructure and/or New Consumer Behaviour:** **Low**	**High**
	High (Input to Components)	Specific applications with short term revenue generating potential	Generic technology with major long term market potential
	Medium (components)		
	Low (fully assembled product)		

Table 1: Growth History of Cambridge Display Limited *

	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003
Revenue (millions of pounds)	0	0	0	0	.691	.379	1.44	.841	27.5	7.00	13.5
Employees								80	120	150	120
Patents	13	16	20	32	40	60	80	100	120	140	n/a

* Source: adapted from ICC database, annual reports, and primary interviews by authors

Table 2: Boston advanced materials firms' growth and commercialization metrics$^{\alpha}$

Firm	Founding Year	Size (Rev, $M, 2002)	Size (Empl 2002)	Alliance Formation	Alliances reduce barriers to entry	Primary Constraint (2003)	US SBIR funding (2003)	VC funding (2003)	Spinout from Larger Firm
AM1	2000	0.5	5	Yes	Yes	Financial	Yes	No	No
AM2	1999	.32	7	Yes	Yes	Financial	No	No	No
AM3	1992	18.8	75	Yes	No	None	Yes	No	No
AM4	1999	10*	27	No	No	Financial	No	No	Yes
AM5	1986	5	25	Yes	Yes	Financial	Yes	No	Yes
AM6	2001	13.5#	25	Yes	Yes	Leadership	No	Yes	No
AM7	1982	20-50	35*	Yes	Yes	Financial	Yes	No	No
AM8	2001	7.8	33	Yes	Yes	Competition	No	No	Yes
AM9	1995	2.7	20	Yes	No	Financial	Yes	No	Yes
AM10	2001	0	6	Yes	Yes	Financial	Yes	Yes	Yes

* 2001 data # 2003 data

$^{\alpha}$ Source: Primary interviews conducted by authors, supplemented with publicly available information