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Commercializing generic technology: The case of advanced materials ventures

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Abstract

Generic, radical technology is of interest because of its potential for value creation across a broad range of industries and applications. Advanced materials ventures are attracted by this opportunity yet face distinctive challenges in commercializing such technology. We explore an anomaly in common assumptions about the commercialization of generic technology. We build on Freeman's concept of technological innovation as a technological and market matching process, on existing literature and on prior experience to build, inductively, a model of the variables influencing value creation by advanced materials ventures. We then test the model on the basis of detailed observation and analysis of two case studies, which have successfully created value through commercialization of advanced materials technology. Extending this theory, we offer managerial and policy recommendations to support value creation by advanced materials ventures.

Keywords: Generic technology; Radical innovation; Value chain; Opportunity exploitation; Advanced materials; Technology innovation; Technology entrepreneurship

1. Introduction

Generic, radical technology is of interest because of its potential for value creation across a broad range of industries and applications. By 'generic technology' we refer to "a technology the exploitation of which will yield benefits for a wide range of sectors of the economy and/or society" (Keenan, 2003). We define "radical technology" as having "the potential for delivering dramatically better product performance or lower production costs, or both" (Utterback, 1994, p. 158). Thus defined, the commercialization of generic, radical technology is highly desirable both to national governments and to firms seeking profit. Nevertheless, generic, radical technology may face very high barriers to commercialization despite its potential for value creation.

Information technology is a well studied example of a generic technology that has created new value for a broad range of industries throughout the economy. Radical developments in advanced materials technology 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; Oliver, 1999; OECD, 1998). Advanced materials are attracting both government interest and new entrants. Existing literature investigates the benefits of generic technologies, and predicts that new ventures will enjoy substantial advantages when they commercialize generic technologies (Shane,

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2004). However, the upstream position in the value chain accessible to most entrants, along with the costs, time and uncertainty associated with commercializing radical advanced materials technology have implications that have not been widely recognized in policy discussions. This paper sets out to explain the challenges to commercialization faced by advanced materials ventures and the ways in which these challenges can be addressed.

We build on Freeman's (1982) concept of technological innovation as a technology and market matching process, existing literature, and prior experience to inductively develop a model of the variables influencing value creation by advanced materials ventures. We show how the generic and radical nature of the technologies of advanced materials ventures, combined with their upstream position in one or several industry value chains and the need for industry specific and application specific complementary innovations, lead to high sustained levels of technology and market uncertainty impacting their ability to create value.

Radical advanced materials technologies are here defined as product and process improvements that significantly enhance the cost-performance frontier of functional materials. This type of technology has the potential to lead to radical innovations downstream in several industry value chains (Klevorick et al., 1995). Examples of radical advanced materials innovations include the use of nanomaterials to alter the mechanical, electrical, and/or thermal properties of components of products in a broad range of industries, organic light emitting polymers used to create diodes for flat panel displays and other consumer electronic applications, and Kevlar fibre used as a light-weight reinforcement in aerospace, sports equipment, automotive, military, and marine applications.

The structure of this paper is as follows. We first review the technology innovation literature. We interpret this literature in the light of other research relevant to advanced materials innovation, with the prior experience of one of the authors, and with discussions with the senior managers of advanced materials ventures,[1] to develop a model of the variables influencing value creation by advanced materials ventures. We provide preliminary testing of the model through observation and analysis of two in-depth case studies. After building and testing this exploratory theory, we outline future research and provide managerial and policy recommendations to assist advanced materials ventures in creating and capturing value.

1.1. Literature review

There is an extensive management literature on technological innovation, but no known studies that explicitly address the issue with which we are concerned: the commercialization of generic technology that is radical in nature and initiated from an upstream position in several industry value chains. In this section, we review relevant management literature on technological innovation, distinguishing between generic technology, radical technology, revolutionary innovation, disruptive innovation, product versus process innovation, and upstream versus downstream innovation, as shown in Table 1.

A generic technology[2] has a wide breadth of applications across industry sectors (Keenan, 2003; Martin, 1993; Hagedoorn and Schakenraad, 1991). Examples of generic technologies include steam power, telecommunications and Information Technology (Rosenberg and Trajtenberg, 2004; Bresnahan and Trajtenberg, 1995). Shane (2004) proposes five benefits to new ventures who exploit such technologies: first, they allow the flexibility to pursue alternative market applications should the first attempt prove unviable; second, they allow ventures to diversify risks and amortize R&D costs across separate applications; third, the markets with potential are at various stages of maturity, and thus provide short-term, medium-term and long-term revenue opportunities; fourth, target market applications in different sectors can be compared; fifth, the breadth and scope of opportunity attracts investment. Shane argues further that new ventures benefit from the very features of generic technologies, which hinder commercialization efforts by established firms (Shane, 2004, pp. 123–124). In Section 2, we show how, for advanced materials ventures, these benefits are counterbalanced by difficulties created by the generic, radical and upstream nature of advanced materials technology.

Where the term generic technology signifies breadth, radical technology signifies depth. That is to say, a radical technology has significant value potential in an individual application. Foster (1986) depicted a radical innovation as achieving a higher performance level than the incumbent technology along S-curves of performance attributes over time. Thus, equivalent efforts

[1] The authors interviewed the founders and/or senior managers of all identifiable advanced materials ventures in the Boston, USA, and Cambridge, UK regions from 2000 to 2003.

[2] A closely related term, general purpose technology, also refers to technology that impacts a broad range of industries.

Table 1
Literature review of technological innovation types

Innovation type	Emphasis	Authors
Generic technology/general purpose technology	Breadth of impact across industries	Hagedoorn and Schakenraad (1991); Martin (1993); Bresnahan and Trajtenberg (1995); Rosenberg and Trajtenberg (2004); Keenan (2003); Shane (2004)
Radical technology/radical innovation	Depth of impact on industries substantial cost/performance improvements	Foster (1986); Utterback (1994)
Revolutionary innovation/competence altering innovation	Requires change in firm capabilities	Abernathy and Clark (1985); Tushman and Anderson (1986); Utterback (1994)
Discontinuous innovation/disruptive technology	New competencies enable new entrants to take market share from incumbent firms	Utterback (1994); Christensen (1997)
Product innovation versus process innovation	Emergence of a dominant design	Abernathy and Utterback (1978); Utterback (1994)
Upstream innovation versus downstream innovation	Position of introduction in value chain	Pavitt (1984); Porter (1985); Klevorick et al. (1995); Arora et al. (2001)

on improving the incumbent technology and the radical technology result in relative advantage for the firm utilizing the radical technology. (Foster, 1986, pp. 101–102, 123–125). When radical technology enables new performance attributes that may lead to entirely new applications, it generally cannot be commercialized through a standard "market pull" strategy: customers may have latent requirements they cannot articulate or even know before an invention occurs (Freeman, 1982, pp. 109–110). Thus radical technologies are either commercialized through "technology push" (e.g. the laser and the personal computer) or through a technology-market coupling process (Freeman, 1982, pp. 109–110; Rothwell, 1992). Additionally, several authors argue that small firms are better at commercializing radical innovations than large firms (Rothwell, 1984; Utterback, 1994; Freeman and Soete, 1997; Shane, 2005).

Abernathy and Clark (1985) defined revolutionary innovation as a product or process change that overturns a firm's technical and/or production competencies. Their concept of revolutionary innovation is relative to a firm's resource base and history, rather than describing a technology in absolute terms. Tushman and Anderson (1986) broadened this concept of revolutionary innovation to include a firm's knowledge, skills, routines and relationships. They describe the impact of a discontinuous technology on incumbent firms as either competence-enhancing or competence destroying. Competence-enhancing discontinuities are normally initiated by incumbent firms, which use their existing competences to master the new technologies, maintaining their competitive advantage over potential new entrants. The structure of the industry remains stable as few new firms, if any, enter. Leadership consolidates and barriers to entry, such as minimum scale requirements, are introduced during a relatively short era of experiment. Competence-destroying discontinuities, on the contrary, are normally initiated by new firms, lowering barriers to entry. The pioneers with discontinuous technologies are often new start-ups that do not suffer from the inertia preventing incumbent firms from seeing the need for and developing the required competences. 'Incumbent inertia' describes the resistance of an organisation to change, and results from organisational culture (values, beliefs, attitudes), structure, defensive response from leadership, traditions, sunk costs, and current customer's satisfaction (Lieberman and Montgomery, 1988, pp.41–58). Christensen's (1997) concept of 'disruptive technology' describes such competence-destroying discontinuities, and the inertia that prevents incumbents from recognizing the potential of an emerging market and/or product feature.

Another distinction made in the field of technology innovation is that between innovation in *products* and innovation in *production processes*. Utterback (1994) has shown that, as an industry matures, experimentation in production processes result in what is known as an enabling technology. For a process innovation the enabling technology (e.g. float glass production) is equivalent to a dominant design in a product (e.g. internal combustion engine) in that both a dominant product design and an enabling process innovation become the industry standard. The enabling technology "incorporates many of the elements needed in a continuous production process and allows the focus of technological effort to shift to process improvements from product innovation and design (Utterback, 1994, p.125)."

To understand how the market position of different innovation types can affect the commercialization process, we use Porter's (1985) industry value chain model. The model depicts the primary and supporting activities performed by a firm or by a group of firms to convert

Table 2
Technology and market factors impacting value creation and capture in the commercialization of radical, generic technology

	Radical, generic technology	Upstream input into value chain	Presence of market incumbents
Technology	Value created by new cost/functional frontier (+++)	Complementary innovations and downstream process innovations required (−)	Process developments required for production economies of scale (−)
Technology and market matching	Iterative market prioritization and subsequent refinement of attributes for specific applications through customised R&D (−)	Uncertainty about consumer utility for attributes and achievable production economics requires pilot plant investment and development before market viability is confirmed (−−)	Potential for alliances with vertically integrated firms and/or OEMs with complementary assets (+)
Market	Broad potential market applications (++)	Upstream input into value chain requires either vertical integration in each market or alliance creation in each market to mobilize complementary assets (−)	Incumbents unwilling to cannibalize existing products (−)
	Widely varying attribute utility between these markets (−−)	Downstream barriers to adoption (product, organizational, designer, regulatory) (−−)	Price competition (−)

+: Positive impact on value creation and/or capture; −: negative impact on value creation and/or capture.

raw materials and information into products and services of value. When firms are described as occupying an upstream or downstream position on an industry value chain, this refers to the distance from the activity performed to the consumer, with downstream being closer to the consumer. Generic technologies are more likely to be introduced by upstream specialized technology firms, supplying downstream customers in several industries (Arora et al., 2001, pp. 146–149). However, the ease of entrance of new ventures is technology sector specific (Pavitt, 1984), with initial economies of scale being more important in sectors such as advanced materials. Thus, generic technologies may be expected to be easier for new upstream entrants to commercialize than for established incumbents; but in practice, this does not hold in some sectors. Advanced materials is an example of just such a sector. In Sections 2.1 and 2.2, we discuss the sector specific impacts of upstream innovation on the ability of advanced materials ventures to commercialize radical, generic technology.

An innovation creates value for consumers when the products it enables outperform existing substitutes, match substitute performance at lower cost, or meet consumer needs for which there is no existing substitute. Value capture measures the extent to which the originators of an innovation are able to appropriate this newly created value (Teece, 1986). In Table 2, we summarize the influence of the radical and generic nature of a new technology, an upstream value chain position, and the presence of market incumbents on a new entrant's ability to create and capture value. These influences are categorized in accordance with Freeman's (1982) concept of innovation as a process of technology and market matching. In the next section, we develop a model (Fig. 2) that depicts the influence of these factors on the likelihood of value creation by ventures commercializing a specific set of generic, radical technologies, that of advanced materials. We begin by reviewing the sparse literature on the commercialization of advanced materials technology, integrating it with the literatures on technology–market coupling, adoption of innovation and dynamic capabilities.

2. Technological and market challenges of innovation in advanced materials

Advanced materials represent a sector, which does not follow conventional wisdom as to the attractiveness and commercialization advantages of radical generic technologies. Firms in the advanced materials sector face a unique combination of sustained high technological and high market risk because of their upstream position in the value chains of their target markets and because of the difficulty of appropriating much of the value generated by their generic radical technology. In this section, we categorize the challenges facing advanced materials ventures, and predict how they will influence value creation.

Freeman set out the challenge of matching technological 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

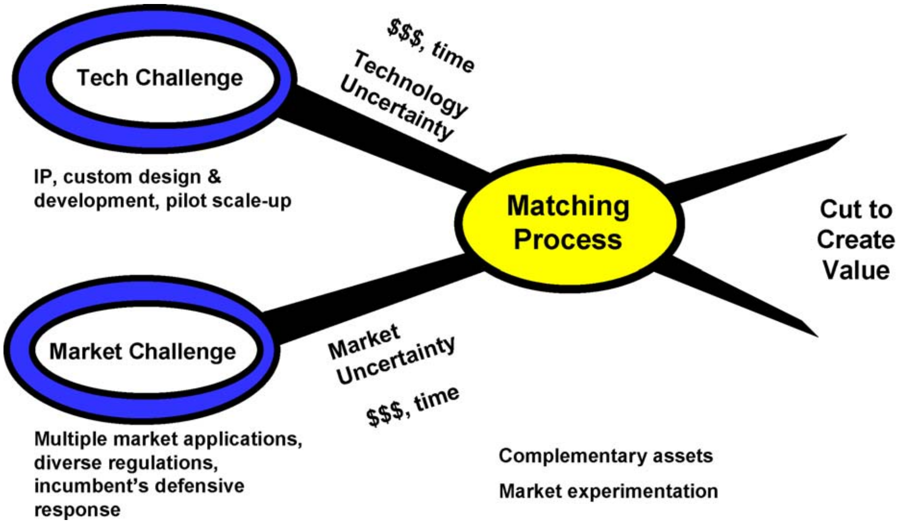

Fig. 1. The matching process required for the commercialization of advanced materials technology.

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, p.109)

Fig. 1 depicts these challenges of innovation for the advanced materials sector. The sector specific challenges of innovation are categorized along the technology and market scissor blades, respectively, "matching" is represented by the axis where the blades are attached and aligned, and value creation is represented by the cutting edge. Schmookler's (1966) analogy is particularly apt in that solutions to technological and marketing challenges must be synchronised if successful co-evolution is to occur. This synchronisation or matching process is particularly complex for new entrants in the advanced materials sector as it involves high cost product and process development, complementary innovation, vertical integration or alliance formation, long time horizons, financial investment, and tolerance of sustained technology and market uncertainty. In the remainder of this section, we examine the technology and market challenges facing advanced materials ventures in terms of the distinctive features of the advanced materials sector.

In the case of advanced materials ventures, the factors identified in Table 2 are revealed to influence one another, and, ultimately, value creation and capture, in a complex, non-linear fashion. Qualitative relationships of a systemic nature that together influence an outcome can be depicted in an influence flow diagram. The interactive nature of the relationships is shown in feedback links which result in a variable operating both as cause and effect (Wolstenholme, 1990). Specifying further from research and observation the factors outlined in Table 2, we identify key variables and their influence on advanced materials ventures' propensity to create value (Fig. 2). We focus on value creation as our dependent variable, as it is a necessary condition for value capture, and gives the model greater testability. Technological uncertainty and market uncertainty are critical intervening variables impacting on value creation, mediated by the venture's capacity to demonstrate the value of its innovation in a specific application, by the availability of finance and by access to complementary assets. The model variables influencing technological uncertainty are described in Section 2.1, those influencing market uncertainty are described in Section 2.2, and the mediating variables influencing value creation are described in Section 2.3.

2.1. Technology challenges

Significant technological challenges, extending over long periods of time, often lead to sustained high levels of technological uncertainty during the attempted commercialization of radical advanced materials technology. Our preliminary interviews with the founders and senior managers of advanced materials ventures indicate that they perceive their technological uncertainty to have been very high at the time of firm founding and to have decreased slowly as the firm matured. This technological

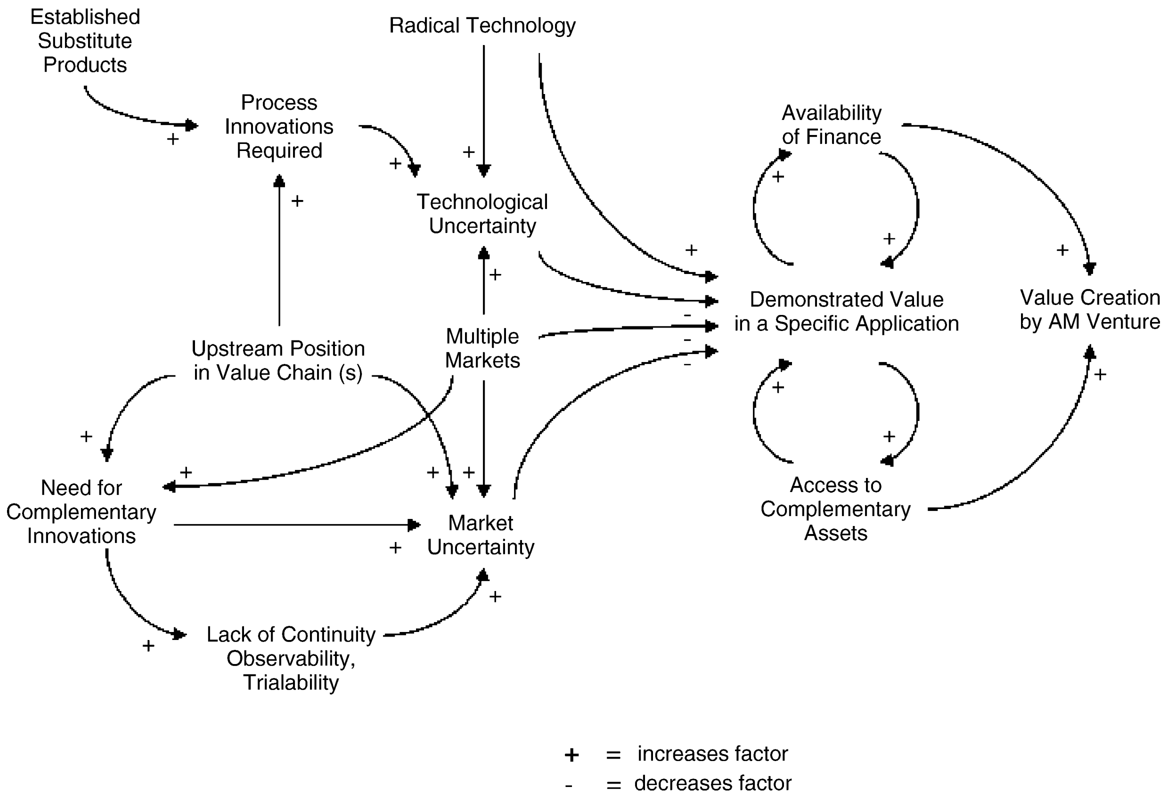

Fig. 2. Influence model of value creation by am ventures commercializing radical generic technology.

uncertainty is directly impacted by the radical nature of the technology under consideration, the need for process innovations, and the multiple markets to which the technology may be applied. These technological challenges are depicted in the top left section of Fig. 2, and discussed below.

Radical advanced materials innovation involves commercializing new knowledge generated by basic and applied research, generally taking place in universities, government laboratories, and the R&D laboratories of large firms (Baba et al., 2004; Eager, 1998; Niosi, 1993; Williams, 1993, p. 23). The novelty of the technology leads to a high level of technological uncertainty regarding the possibility of replicating laboratory attributes in product prototypes and in viable production processes. Thus, in addition to basic research and invention, commercialization of a radical materials innovation requires expensive process innovation, prototype development and pilot plant development (Maine et al., 2005; Hounshell and Smith, 1988, pp. 262–268, 431–432; Williams, 1993, p. 43–44), which greatly exceed the mandate and budgets of research universities and laboratories. Additionally, the radical nature of the technology may initially require a "technology push" commercialization strategy (as undertaken with Kevlar fiber, metal matrix composites, and carbon reinforced polymers) because many consumers in their potential markets do not perceive utility ex ante.

The need for process innovation arises from two factors. The first is the upstream position of advanced materials in the value chains of each of the industries in which it is commercialized (Klevorick et al., 1995). This upstream position means that the creation of a prototype product, for any industry, requires more than just the venture's intermediate product.[3] It will depend on downstream design and process innovations, and may depend on complementary innovations. Customers value product performance attributes at a specific price, in other words, they have a utility for each performance attribute (Maine and Ashby, 2002). Even if a novel performance attribute or package of attributes is agreed to be useful, it will only demonstrate value in a specific applica-

[3] New advanced materials do not fall neatly into either of the standard categories of product or process innovation, discussed in Section 1.1. Rather than representing a breakthrough in a single production process, new materials support and require many layers of product and process innovations right along the value chain. A single advanced material technology can be a product, a production process, an enabling technology, and the enabler of many downstream products.

tions if customers' utility for that attribute or package of attributes is sufficiently high (Maine and Ashby, 2002).

The second factor impacting the need for process innovation is the presence of incumbents with established products. When pursuing a substitution strategy, the valuation of attributes is generally linked to that of the incumbent product, which may be produced in large volumes. To displace the incumbent product, process innovations are required to reduce costs and thus make a new material viable (Maine and Ashby, 2000) by producing in larger volumes and for lower cost. For example, when DuPont was attempting to commercialize Kevlar fibre, they defined their technical process goals as producing fibre with certain mechanical attributes (stiffness, strength, toughness, etc.) at a cost that enabled them to price their material at 4× the price of the steel belts with which they were competing. That converted into a selling price of approximately $2.40/lb (Christensen, 1998). However, DuPont was never able to produce Kevlar fibre for anything close to this cost, highlighting the amount of technological uncertainty involved in their process innovations.

As radical advanced materials technology has broad potential applications across multiple markets (OECD, 1998, p. 40; Williams, 1993, p.7; Hagedoorn and Schakenraad, 1991), R&D is needed for each targeted market application and process innovations in each of these markets are also necessary for economies of scale, generally before a return on investment is achieved (Maine and Garnsey, 2004; Hounshell and Smith, 1988, p. 432). The need for market-specific R&D results from the differing values placed on application attributes in the many different markets in which there is potential demand (Maine et al., 2005; Mangin et al., 1995) 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 the consumer.

Resolving this technological uncertainty typically requires a high level of investment over long periods of time, because of the customized R&D, pilot plants, and process innovation for specific market applications that are required. This also applies to incumbent firms. When developing and commercializing Kevlar fibre, 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. (Christensen, 1998; Hounshell and Smith, 1988, pp. 431–432). Thus, in order to demonstrate value in a specific application, an advanced materials venture needs access to long term financing. Advanced materials ventures following an in-house manufacturing strategy certainly require external financing to commercialize their technology.

2.2. Market challenges

The marketing challenges faced by advanced materials ventures are also formidable, leading to sustained market uncertainty and difficulty in demonstrating value in a specific application. Our preliminary interviews with the founders and senior managers of advanced materials ventures indicate that they perceive their market uncertainty to be high at the time of firm founding and to decrease slowly over time. This high level of market uncertainty is directly impacted by the upstream position of advanced materials ventures in the value chains of the industries they target, the need for complementary innovations, the lack of continuity, observability and trialability of the technology, and the multiple markets to which they may be applied. These factors are depicted in the lower half of Fig. 2, and discussed below.

Most firms commercializing advanced materials technology produce an intermediate good (Williams, 1993, pp. 17–18). Thus, they do not deal directly with consumers in the broad applications to which their innovation may be applied, (including aerospace, automotive, consumer electronics, construction, power generation, communication infrastructure, sports equipment, marine applications and biomedical devices). This makes it difficult for them to assess consumer needs and to manage market experimentation and feedback. Their customers are component suppliers and assembled goods original equipment manufacturers (OEMS) who must be convinced to design products incorporating the advanced material innovation. The designers in these manufacturing firms may not be familiar with a new material class and its design possibilities: even if they are aware of the material, they may resist the introduction of a new material because it requires extra learning and effort on their part. When potential customers do agree to adopt the technology, the new material will not be introduced into the current product, and so waits on the product cycle (approximately 3 years for automotive applications and up to 30 years for aerospace applications).

Moreover, advanced materials innovations are not autonomous: they rely on related complementary innovations in order to be brought to market as a product. There are numerous historical examples of the need for complementary innovations in advanced materials. Glass fibre innovations needed to wait on complementary innovations in laser technology before fibre optics applications were enabled. Kevlar fibre did not achieve significant adoption 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 extensive 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, catalysts and fuel cell stacks, on infrastructure standards to be established, and on legislation reflecting the costs to society of pollution. The need for these complementary innovations increase market uncertainty for the advanced materials technology and delay a firm's ability to demonstrate the value of an advanced materials technology in specific applications.

Discontinuity with prior products or processes leads to greater market uncertainty and delays in adoption of an innovation (Rogers, 1983). For example, an advanced materials innovation may enable a new reduced cost substitute to an existing material (aluminium beer cans in place of steel cans). Generally this requires some shift in the design of the product and the manufacturing process (Maine and Ashby, 2002)[4] and thus overturns technology and production competencies of OEM manufacturers. In this case, the OEM customer faces the challenges inherent in revolutionary innovation (Abernathy and Clark, 1985). A new material may also bring completely new functionality: the transistor was made possible by materials process innovations that included developing a process for producing high purity germanium and silicon, and growing first germanium and then silicon as a single crystal (Riorden and Hoddeson, 1997, p. 102, 172–174, 178–180, 198–199, 207–209, 230). In this case of new functionality, OEM customers face both the overturning of production/technology competencies and the overturning of market linkages (Abernathy and Clark (1985) refer to this type of organizational challenge as architectural innovation). Achieving the potential of the new material may also require changes that undermine the dominant product design (Utterback, 1994). As examples, the use of new alloys and composites required changes in the design of aircraft. Likewise, substantial structural use of polymer composites would require the redesign of the automobile.

Thus, radical innovation such as that enabled by advanced materials technology makes significant demands on intermediate customers and sometimes end-consumers. Adoption of radical innovations requires recognition of the relative advantage they offer; however, because they are discontinuous with existing offerings, the change in outlook required for recognition is notoriously difficult to elicit. Research on adopter resistance has shown that innovations that are compatible with existing practices and offer benefits, which can be understood, observed and tried out without incurring switching costs are more likely to diffuse rapidly. Conversely, innovations that lack these attributes face adoption delays (Rogers, 1983; Moore, 1995). Observing or trialing an advanced materials technology generally requires a full working prototype of the downstream product, and even then consumers may have difficulty observing the advanced materials technology itself. Thus, market uncertainty is also increased by the absence of continuity, observability and trialability represented by most advanced materials technologies.

Finally, since advanced materials ventures may target several industries, they must gather information on customer preferences for performance attributes of applications in several industries. Targeting multiple markets also exposes a firm to industry specific changes in regulations, consumer attitudes, designer familiarity, and infrastructure. These factors increase overall market uncertainty and may combine to delay the significant adoption of advanced materials between 15 and 40 years. As examples, Polypropylene took 37 years, Teflon (PTFE) took 31 years, Kevlar took 17 years, and carbon fibre took 34 years to reach 50% of their peak annual sales volume.[5] In each case, annual production volumes increased as more designers became familiar with the new material, as market applications in new industries were recognized or emerged, and as complementary innovations occurred. These long time frames negatively influence investors and the willingness of potential alliance partners to

[4] Substitutions into existing applications present challenging, albeit known, production cost targets. Small volume applications, which are of little 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.

[5] This analysis was compiled by the authors from the following sources: The US Patent and Trade Office, The Chemical Engineering Handbook, DuPont's annual reports and website, and Hounshell and Smith, 1988.

invest time and money in prototype development for their industry.

2.3. Matching process

It is a dilemma of commercializing advanced materials technology that there is massive potential for value creation in many applications, but this very multiplicity of possibilities creates targeting and market experimentation problems. For each target market, research and development specific to various industry applications must be performed, diverse regulatory hurdles must be surmounted, prototypes must be developed, customer reluctance to change specifications for an established product must be overcome, process innovation must occur and complementary innovations may be required (Maine and Garnsey, 2004; Williams, 1993, p.35). As we depict in Fig. 2, external financing and access to complementary assets through alliances significantly increase the likelihood of value creation, conditional on value being demonstrated in a specific application. Recognition and prioritization of such potential applications is a key managerial capability for these ventures.

Firms can recognize opportunities for a new market application 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 (Hargadon, 2002). Firms can achieve superior performance through such a strategy if they have the combination of strong intellectual property generation and protection, strong recognition and exploitation capabilities, and the ability to access and mobilize complementary assets (Teece, 1986; Teece et al., 1997; Eisenhardt and Martin, 2000).[6] New ventures generally access these complementary assets through alliance partners in each target market (Niosi, 1993). Ventures can prioritize market applications by modelling the viability and attractiveness of each potential substitution application (Maine et al., 2005). However, when advanced materials inventions overturn current technological knowledge and also enable entirely new markets, modelling methods and other recognition capabilities are often unreliable.

For co-evolving technologies and markets, a strategy of market experimentation has been recommended by industry experts rather than an early exclusive focus on any one particular market or product design (Leonard, 1995; Eisenhardt and Martin, 2000). This strategy is expensive within any single industry, and more so for advanced materials firms, as emerging applications for advanced materials technology extend over several unrelated industries, each one of which require costly and uncertain efforts at finding and developing a successful initial market application. This cost, uncertainty, and the timeframe involved in the commercialization of a new advanced material often leads to severe investment constraints despite their potential for value creation, undermining the benefits credited to generic technology by Shane (2004). Thus, access to finance is critical for an advanced materials venture, both to demonstrate value in specific applications and to position the venture to create and capture value. The majority of the advanced materials ventures we interviewed in the Boston area identified lack of finance as their primary growth constraint. Thus, to successfully match their technology with a market application, an advanced materials venture needs both financing and access to complementary assets (Fig. 2).

3. Firm level evidence

To verify our model, we examine two in-depth case studies of the formation and growth of advanced materials ventures. As the commercialization process of advanced materials ventures is an unexplored and unique research area, case study analysis is well suited to address our research question. We observe and analyze these case studies to confirm that the factors identified in our model (Fig. 2) exist, that they influence each other in a manner consistent to our model, and to examine variation in the presence and impact of these factors. As such, we have chosen two successful advanced materials ventures which have demonstrated value in specific applications, have commercialized products, and have created value through differing business models and strategic focus. Our first case study, Hyperion catalysis (Hyperion), has created value through an in-house manufacturing model and has successfully commercialized over 40 products in three distinct industry value chains. Our second case study, Cambridge Display Technology (CDT), has created value using a licensing model and has been involved in the commercialization of five products in a single industry value chain. After providing rich case histories in Sections 3.1 and 3.2, we compare and contrast the commercialization experiences of these ventures in Section 3.3, and Table 3.

[6] Though there is debate as to whether dynamic capabilities are firm specific (Teece et al., 1997) or replicable (Eisenhardt and Martin, 2000), the importance of these capabilities for a firm's competitive advantage are not in question.

Table 3
Comparison of commercialization strategies and variables of Hyperion and CDT[α]

	Metric	Hyperion catalysis	Cambridge display technology (CDT)
1	Founding year	1982	1992
2	Technology	Fullerenes/fullerenes dispersed in resin	Light Emitting Polymers
3	Size (employees)[a]	35	150
4	Size (revenues)[b]	$20–50 million USD	7 million pounds sterling (approx. $15 million USD)
5	Business models	In-house manufacturing	Licensing (with previous attempts at in-house manufacturing)
6	Value created	Significant	Significant
7	Current and future target markets	Automotive, Consumer electronics, power generation, aerospace, transportation	Consumer Electronics
8	Technological uncertainty at founding	High (radical technology; established substitute products; need for process innovations; multiple markets)	High (radical technology; established substitute products; need for process innovations)
9	Market uncertainty at founding	High (upstream position in value chain; need for complementary innovations; lack of continuity, observability, trialability; multiple markets)	High (upstream position in value chain; need for complementary innovations; lack of continuity, observability, trialability)
10	Number of patents[c]	100	140
11	Importance of IP	High. Key to alliance formation, customer negotiation, and prevention of being squeezed out of value chain	High. Critical to alliance formation, licensing business model and to developing an emerging market
12	Access to complementary assets	Through alliance partners	Through alliance and licensing partners
13	Availability of finance	Patient angel investor, SBIR, retained earnings	University of Cambridge, local seed capital, angel investors, US venture capital funding
14	Time to first product commercialization	Ten years (1992 fuel lines)	Ten years (2002 electronic shaver displays)
15	National/regional support for experimentation	SBIR grant, knowledge workers from Boston region. key employee(s) from MIT	Key employees and knowledge transfer from the University of Cambridge. Funding and knowledge workers from the University and Cambridge Science Park. Required VC funding from US firm

[a] As of 2002.
[b] As of 2002.
[c] Hyperion has filed over 100 patents as of 2005. CDT had 140 patents issued as of 2003.

3.1. Case history of Hyperion catalysis[7]

Hyperion catalysis was formed in 1981 with funding from a Silicon Valley venture capitalist who judged that the advanced materials sector offered outstanding long term value potential. He brought together a scientific advisory board to help him select an appropriate focus within the advanced materials sector. This board, consisting mainly of scientists from MIT and Harvard, advised on carbon microfilaments, subject to resolving technical uncertainty about synthesis. One employee, a retiring industrial chemist, was hired to start conducting research on this area. With some encouraging results, Hyperion incorporated in 1982, locating in Cambridge, MA because of the existing location of their key employee and most of the scientific board. Their goal was to develop a radical innovation in advanced materials technology; if successful, the potential for long term value creation was enormous, as such an innovation could improve products across most industrial sectors.

From 1982 to 1989, Hyperion focused on developing the first viable multiwalled carbon nanotube product and process, with patient capital provided by their founder and owner. Their key breakthrough was their 1983 synthesis of multiwalled carbon nanotubes, which Hyperion protected by filing for a patent in 1984. This patent, which issued in 1987, is the first US carbon nanotube patent[8] and became key to Hyperion's patent portfolio (US Patent No. 4,663,230). From 1984 to 1989, Hyperion's scientific team developed their technology from a laboratory process to a production process with numerous patents filed on improvements in the reactor design and the development of a continuous manufacturing process. The output of this vapour deposition process is their key intermediate product, multiwalled (MW) carbon nanotubes, later trademarked FIBRIL™.

By 1989, Hyperion had achieved their technical objectives, which included learning how to make these MW carbon nanotubes in large scale production volumes and to a high level of purity. When they began focusing on commercialization, they wanted to follow an in-house manufacturing business model, but struggled to choose between the many potential uses for their advanced materials product and process inventions, including potential uses in the automotive, aerospace, and power generation industries. Hyperion did not yet have prototypes suitable to demonstrate feasibility to these markets. Hence, they publicized their technical achievements widely, in the hopes of attracting potential customers and/or alliance partners. This strategy proved successful, as it resulted in the approach of their first alliance partner.

This partner, a European-owned resin supplier, thought that Hyperion's technology would solve their own problem with an automotive application. The resin supplier had been attempting to displace steel fuel lines, and had established a solid production cost advantage, but needed to make their polymeric fuel lines conductive for safety reasons. The resin supplier had already identified the resin, Nylon 12, and was confident that Hyperion's MW carbon nanotubes could be compounded with that resin to make conductive composite automotive fuel lines. The resin supplier's compounding and manufacturing equipment, along with their contacts into the automotive industry were key to Hyperion successfully selling into the automotive market, since automotive OEMs and Tier 1 suppliers rarely pay for any prototype development. In successfully developing a prototype, Hyperion developed a process to disperse their interim product of billions of intertwined MW carbon nanotubes into individual nanotubes throughout a polymeric resin. In order to have their composite fuel line specified in the development stages of an automotive model, Hyperion also needed to scale up their process to make tonnes of the product. Hyperion filed several patents over 3 years of development, and achieved their first product sales in 1992.

After this first successful product development, Hyperion moved to larger facilities to have room for commercial scale production equipment and further growth. Hyperion then concentrated on developing prototypes and specifying their product for other automotive applications. In the mid 90s, Hyperion partnered with GE Plastics to develop further automotive product applications. First they developed conductive polymer composite automotive mirror casings for Ford and other automotive OEMs, which could be electrostatically painted (along with the rest of the metallic portions of the car). Next they jointly developed conductive polymer composite fenders, which met or surpassed metallic alternatives, giving advantages of weight-savings and styling options. Most of their materials sales for polymer composite fenders have been for European car models, as weight savings have been more highly valued in the European market.

[7] This case study was compiled from primary and secondary sources, including interviews with Hyperion Marketing Director Pat Collins on 31 October 2003, and 19 August 2005, articles by Small Times, The Economist, New Scientist, Automotive News, Chemical Market Reporter, and European Venture Capital Journal, and the US Patent database at http://www.uspto.gov/.

[8] Carbon nanotubes have generated considerable interest as they enable radical improvement in the performance attributes of composite materials as well as enabling entirely new products.

During this time, Hyperion also continued to scale up their process and developed a high tonnage nanotube reactor. In 1998, an MIT graduate with technology product development experience was hired as Director of Business Development. He went on to have a major influence on Hyperion's product expansion and commercialization strategy. Some of his initiatives included expanding their sales presence globally and moving slightly further down the value chain, by compounding resins in-house in order to have control over the dispersion of their MW carbon nanotube product. Hyperion's growth was rapid, but could have been even more so with additional external financing. And, although their product development efforts were largely successful, they did not meet with universal success. For example, Hyperion's R&D team had been working on developing their product for structural composite aerospace parts. This involved dispersing their nanotube product into the thermoset resins most suitable for aerospace structural parts. Their efforts at demonstrating enhanced value in these applications have been largely unsuccessful to date.

Hyperion's first successful product development outside of the automotive market was in consumer electronics. In this instance, Hyperion was approached by a consumer electronics OEM who valued their material's attributes. Hyperion found consumer electronics OEMS to be far more open to collaboration on product development than automotive OEMs. Hyperion was able to create strategic alliances with consumer electronic OEMS and co-developed several components which took advantage of their static dissipation properties and the integrity and cleanliness of their composite materials. These products, including internal disc drive components, handling trays and devices for manufacturing disk drive components, and test sockets for integrated circuits, have become a major product revenue stream for Hyperion.

In the late 90s and into the early 2000s, Hyperion's R&D team also developed products, which used their material in advanced batteries for the power generation industry. Hyperion received competitive Small Business Innovation Research (SBIR) grants from the US Department of Defence (DoD) from 1996 to 1999 to develop MW carbon nanotube electrodes for electrochemical capacitors, and issued several patents from this work. Concurrently, they were developing composites with non-polymeric matrix materials. From 2000 to 2004, Hyperion developed their MW carbon nanotube product as a catalyst support, which has power generation and emerging alternative automotive applications. They also filed a patent on the use of their product for the emerging application of field emission displays. Hyperion has found IP protection to be critical to their ability to capture value, both in negotiating with large strategic alliance partners and in discouraging new entrants. Hence, they have filed over 100 patents, and actively expand and extend their patent portfolio.

Currently, Hyperion's product line consists predominantly of composites of their MW carbon nanotube product, dispersed into thermoplastic resins. They are continuing to grow their products and revenues into the automotive, electronics, power generation and communication segments, and are looking to expand their sales into other market verticals, as well as 'staking out' IP in emerging markets. They are the oldest and, arguably, the most successful dedicated nanomaterials venture in the world to date, achieving between $20 and $50 million in annual revenues;[9] yet, to achieve that success, Hyperion needed patient capital, alliance partners, and an early focus on substitution rather than emerging markets.

3.2. Case history of Cambridge display technology (CDT)[10]

Cambridge display technology (CDT) was founded in 1992 following 10 years of basic science at the University of Cambridge's Cavendish Lab, which led to the invention of polymer transistors. CDT's founder, Prof. Richard Friend, saw that light emitting polymers had the potential to replace the aging cathode ray technologies still standard in electronic display applications. On advice from a local seed capital firm, Cambridge Research and Innovation Ltd. (CRIL), Friend and his co-inventors had already filed their fundamental patent[11] on the electroluminescence of polymers in 1989. CDT created further intellectual property in light emitting polymer (LEP) technology platforms and production processes for flat panel organic light emitting diode (OLED)[12] displays.

The initial strategic objective was to manufacture products for such applications as flat panel displays and back lighting for liquid crystalline displays (LCDs). The potential of this technology in major markets attracted funding from the university and CRIL, together with high-profile private investors including the rock group Genesis. Within a couple of years it was clear that the

[9] revenue estimate obtained from Reference USA.

[10] This case study was compiled from primary and secondary sources, including interviews with the founder, CEO, and IP lawyer conducted from June 2000 to November 2003, and from CDT annual reports, the ICC database, and press articles cited throughout.

[11] This patent, WO9013148, was also the basis for CDT's key US Patent US5,247,190.

[12] Also referred to more recently as polymer light emitting diodes (PLEDs).

cost of developing applications of this kind and penetrating markets dominated by powerful companies made it essential to undertake manufacturing partnerships. An experienced CEO, Danny Chapchal, was appointed in 1996 and licensing arrangements with Philips Components, Hoechst, and Uniax were finalised by 1997. 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, Chapchal had negotiated a favourable joint venture with the Seiko-Epson Corporation, in which CDT was able to retain 50% of rights to any co-developed IP. This partnership 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 February 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, even without a manufacturing strategy, CDT's R&D costs were still very high. In 1996, a UK venture capital fund specializing in light emitting polymers was formed that took out a 33% 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 from 1996 onwards was to establish development partnerships and licensing agreements with both materials suppliers and 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 Chapchal.[13] CDT's alliance strategy included materials suppliers,[14] auxiliary component manufacturers,[15] display manufacturers,[16] and fully-assembled product OEMs.[17] CDT was able to leverage their key patents to negotiate favourable royalty terms.[18] 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, on which he focussed his research efforts. In order to increase the attractions of their licensing agreements, the CDT management team decided to re-enter small-scale manufacturing to demonstrate the viability of their pioneering technology. To this end, another $28 million was raised from shareholders and 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 an OLED technology, further extended CDT's ownership of complementary technologies.

CDT's first commercial product, an OLED electronic shaver display, was released in 2002. Later in 2002, products using CDT's LEP display were distributed 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, both small-scale manufacturing costs and overall development costs remained very high. In 2003, a loss-making production line in CDT's production facility was closed, CDT sold most of their manufacturing capabilities, and the decision was made to restrict production to prototypes. The CEO, Dr. Fyfe, announced, "Things are slower than we would have experienced 2 years ago and we do not 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). Thus, CDT returned to an IP licensing model.

CDT's R&D achievements are signalled by the growth in the company's patent portfolio from 13 in 1993 to 140 in 2003. A notable feature of companies which have to undertake costly R&D 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 5 years before

13 Electronic Times, 1999.
14 Bayer, Covion, Dow Chemical and Sumitomo.
15 STMicroelectronics, Plastic Logic, Dai Nippon Printing.
16 Delta Optoelectronics, DuPont Displays, Eastgate (Singapore), MicroEmissive Displays, Osram Opto Semiconductors, Phillips, Seiko Epson, and CDT's subsidiary, Litrex.
17 Philips, Seiko-Epson, Samsung.
18 Interview with Daniel Chapchal, 1999.

any revenues were achieved and these were highly unstable (and under $2 million annually) through to 2000. The first products from CDT's technology were commercialized in 2002. By 2003, over a decade since the formation of the company, a modest $13.5 million of revenues were generated.[19]

However, the longer term potential is still evident. LEP displays have been established as thinner, lighter and more efficient than LCD displays. Their joint developments in ink-jet printing are likely to lead to lower manufacturing costs than for LCD displays. The LEP market has been predicted to total over $4 billion and 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 getting its technologies into 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 and went public on the NASDAQ in December of 2004.

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. Hyperion Catalysis faced many similar challenges and a similar timeline to first product commercialisation. We believe that the challenges faced by these two case studies are representative of those faced by advanced materials ventures, as we have interviewed the founders or senior management all of the advanced materials ventures in the Boston, USA and Cambridge, UK regions[20] and have found that the experience of this broader sample also supports our model.

3.3. Analysis of case study evidence

The cases of Hyperion and CDT demonstrate the factors influencing value creation by advanced materials ventures (Fig. 2). Both exemplars have successfully created value through the commercialization of advanced materials technologies and have done so in two different countries, with different business models and strategic focus (Table 3). Hyperion deliberately chose an in-house manufacturing model, and attempted to appropriate additional value from their upstream innovation by targeting five distinct industry value chains. CDT deliberately chose to focus exclusively on the consumer electronics value chain. CDT iterated between a manufacturing and licensing business model before settling on licensing. Both cases demonstrate the technical and market uncertainty inherent in the early stages of the commercialization of radical advanced materials technology and the contributing role of the other variables shown in our model (Fig. 2).

Both Hyperion and CDT demonstrate the potential for substantial value creation of advanced materials ventures. To date both are still relatively small firms in terms of employees and revenues (Table 3), but there is substantial utility for their products in current applications, and they could both enable entirely new applications. These could include new consumer electronics products enabled by field emission displays, economically viable automotive fuel cells, and flexible, large screen OLED flat panel displays. Thus, both case study exemplars are commercializing radical generic technologies with the potential for significant value creation.

However, in their path to value creation, our case exemplars demonstrate the challenges of matching radical advanced materials technology to market applications. Our model (Fig. 2) demonstrates the factors influencing the uncertainties facing both ventures. Table 3 indicates which factors increased the uncertainty of each case study. In this section we assess how each of these factors impacted first the technological and then the market uncertainty of each case study.

The technological uncertainty facing Hyperion when they began to commercialize their technology in 1989 stemmed from their radical technology, the presence of established substitute products (making it necessary to have process innovations to scale up production and reduce cost), and the multiple markets they considered targeting, all with different attribute valuations. The radical nature of their technology is evidenced by the substantial new functionality provided by their composite resins and by their extensive patent portfolio. The presence of substitute products, along with the upstream position of Hyperion's radical technology in their target market value chains, led to the need for them to develop process innovations. From 1985 to 1997, Hyperion's process innovations included scaling up production of nanotubes, dispersion of these nanotubes in various resins, and application specific production process innovations. As an example, in developing composite automotive fuel lines, Hyperion needed to match the existing mechanical attributes and component price of steel fuel lines.

Hyperion's technological uncertainty was also increased by their strategy of targeting multiple markets. Hyperion considered many markets for their MW carbon nanotube technology in 1989, most notably

[19] Source(s): ICC database, annual reports, and primary interviews by authors.

[20] Primary interviews conducted by authors in 2002 and 2003.

structural thermoplastic composites in the automotive industry, structural thermoset composites for aerospace, and energy storage applications for the power generation industry.[21] In each of these different markets, Hyperion's potential customers had differing utility for the performance attributes that could be achieved with Hyperion's composite products, such as static dissipation, processability, cleanliness, strength, stiffness, fire retardance, and weightsavings. As Hyperion understood the relative importance of and tradeoffs between performance attributes for each market application within each industry, they were able to optimize production of the customized material for each market, and thus reduce their technological uncertainty.

CDT also experienced high technological uncertainty because of their radical technology, the existence of substitute products, and their need for process innovations to scale up production and to reduce cost. CDT's light emitting polymers (LEPs) were the first of their kind and CDT developed the first organic light emitting diode (OLED). This invention enabled new attributes for display design, such as flexible screens, and offered the potential to improve along some existing attributes, such as efficiency and weight-savings. To achieve these attributes and to convince customers by demonstrating value in a specific market application, CDT required several years of process innovations. Upstream process innovations were needed to manufacture their material in a cost efficient manner to compete with incumbents' rival technologies (cathode ray displays and LCD displays). Downstream process innovations were also required to enable component suppliers and OEM manufacturers to utilize their material in existing product applications. Developing novel applications which utilize the flexibility of OLEDs will require still further downstream design and process innovations.

CDT did not add to their already high technological uncertainty by targeting multiple markets. In contrast, CDT picked a single large industry value chain – that of consumer electronics – but considered many applications within that industry value chain. Despite this focused strategy, CDT's technological uncertainty remained extremely high, so much so that they felt the need to pursue an in-house manufacturing strategy for their first 4 years as a company, and again from 2000 to 2003, to prove that their technology was viable.

As predicted in Fig. 2 and summarized in Table 3, both case study firms also faced extremely high market uncertainty. Hyperion's market uncertainty stemmed from the difficulty of obtaining accurate attribute utility information from a position upstream in a single industry value chain, the need for complementary innovations, the lack of continuity, observability and trialability, and the temptation or need to focus on more than one industry with differing customer utility for product attributes. When commercializing an innovation from an upstream position in targeted industry value chains, it is difficult to establish the consumer needs, which will convince OEM customers to switch to a new product or component. For example, in the automotive value chain, Hyperion had partnered with a resin supplier, but needed to elicit the needs of a Tier 1 automotive supplier and their automotive OEM customer. This information gathering and communication challenge is exacerbated when the consumer is not aware of their own preferences for the intermediate product attributes.

Complementary innovations are also required in different levels of several industry value chains before the innovating firm can realize the value of their innovation. In the automotive industry, for example, Hyperion's alliance partner needed to match a suitable resin to Hyperion's nanotubes to enable good composite properties, adequate dispersion, and good secondary processability. Next, Hyperion's tier one automotive customer needed to develop design and process changes to take advantage of composite material strengths. In the automotive fuel line, this involved altering the powertrain design, with new fasteners and assembly methods, and had the benefit of eliminating the multiple forming steps required to make steel fuel line. Hyperion's other automotive and consumer electronics applications also required design changes, but Hyperion reduced the need for more uncertain complementary innovations by focusing on "mundane" applications which were substituting for existing components. Conversely, for the emerging markets of automotive fuel cells and field emission displays, Hyperion is waiting on many complementary innovations and, in the case of fuel cells, regulatory changes, to enable them to demonstrate value in specific applications.

The need for process innovations and component design changes by Hyperion's customers created a discontinuity for the customer. This lack of continuity slowed down the adoption of both Hyperion's products and continues to impede the broadening of their product line into further applications. Additionally, lack of observability and trialability of Hyperion's MW carbon nanotube materials by customers and then consumers acted to delay the adoption of Hyperion's products. Until Hyperion was able to create a prototype fuel line, they were not able to demonstrate the value of their innovation to their automotive OEM customers. The automotive

[21] See, for example, the abstract of US PAT No. 4,663,230.

consumers do not observe Hyperion's innovation in the fuel line application and may not observe Hyperion's innovation in their exterior structural automotive parts either. Automotive consumers cannot trial the product until it is already specified in a new automotive model. Thus, a lack of continuity, observability, and trailability added to market uncertainty for Hyperion and slowed the adoption of their products.

The applicability of Hyperion's technology to multiple applications across several industries also added to market uncertainty. Hyperion divided their R&D and business development focus between applications in the automotive industry, the aerospace industry, the consumer electronics industry, and the power generation industry. Exploration of each of these industries required the development of relationships with different customers and made it necessary to engage in unique process R&D and additional complementary innovations. The need for industry specific regulatory changes and education of designers also contributed to the market uncertainty involved with a focus on multiple markets.

CDT's market uncertainty stemmed from the difficulty of obtaining accurate attribute utility information from a position upstream in a single industry value chain, the need for complementary innovations, and the lack of continuity, observability and trialability. Like Hyperion, CDT also experienced difficulty establishing the consumer needs, which could convince OEM customers to switch to their OLED technology from the incumbent LCD. CDT has required complementary innovations in the design of electrical shavers and mobile phones to take advantage of the new attributes of their OLED displays. Developing novel applications which utilize the flexibility possible with OLED displays will require further complementary innovations by consumer electronics OEMs. These considerations led CDT to pursue an in-house manufacturing strategy from 1992 to 1996 to produce prototypes and to demonstrate the viability of their technology. After 4 years of building revenues and disseminating their technology through licensing, CDT saw the need to revert to a mixed business model including in-house manufacturing capabilities to demonstrate the economic viability of their manufacturing technology. This was a clear case of the adoption difficulties caused by a lack of production continuity for CDT's customers.

To a lesser extent than Hyperion, CDT also faced some degree of market uncertainty from the need to choose between applications within consumer electronics with differing customer utility for product attributes. For example, OLED back lighting applications have different attribute requirements than those for mobile phone displays and again from those for larger screen displays such as computer and TV screens. However, these attribute differences are generally less than those in separate industry applications. Also, by limiting their technology market matching search to focus on consumer electronics, CDT narrowed their search for potential alliance partners.

As shown in Table 3, Both Hyperion and CDT have assiduously protected their radical technology and process innovations with strong patent portfolios. Pat Collins, the Director of Marketing for Hyperion, believes that their strong IP and policy of "patenting everything and patenting broadly" has been very important to their ability to appropriate returns. Part of this importance has been in attracting alliance partners and customers, and the remainder in protecting Hyperion from getting muscled out of their targeted markets by partners or other entrants after demonstrating value in specific applications. CDT's IP was of even greater importance to their ability to appropriate value, in view of their reliance on a licensing model after 1996. Their fundamental patent was virtually impossible to patent around, so that large firms with potentially blocking patents chose to partner with CDT rather than contest their patent. CDT's subsequent development and protection of IP aimed both to make the end products viable and to appropriate further value from their partners and from end consumers.

Neither Hyperion nor CDT would have been able to demonstrate value in specific applications without financing and access to complementary assets. This process of matching technology competencies to market opportunities requires sufficient financing to undertake the initial technological development, subsequent process innovations, experimentation with prototype development for different market applications, alliance partner formation with holders of complementary assets and with potential customers. Commercialization of an advanced materials technology to create and capture value requires obtaining additional external financing. In particular, a manufacturing model requires significant external financing.

Hyperion is unusual as a nanomaterials firm in that they have already achieved substantial product revenues: this success may be attributed in part to their early formation and their conservative focus on substitution applications. However, it still took 11 years from the founding of the firm to achieve any product revenues. Hyperion was fortunate to have 'patient capital' from their founder and access to SBIR grants from US government agencies. Nevertheless, financing remained a constraint for them, as they indicated that they could have grown more quickly in the 1990s with additional financing. According to Collins, Hyperion's success has largely been due to applying new technology to "mundane applications" and thus "shortening their time to market." Thus, instead of waiting 15–20 years to get to market, it took Hyperion only 7 years (1982–1989) to solve their own technological problems and to be ready for commercial applications.

CDT also took a decade from their founding to commercialise their first product, although CDT began to earn licensing royalties after 5 years time. From year 5 to year 8, these licensing revenues totalled less than $2 million annually. CDT was fortunate to be affiliated with the UK's most prestigious scientific university. Financing from the University of Cambridge, a local seed capital firm, and high profile angel investors allowed CDT to develop its first prototype. Additional financing from a UK venture capital firm allowed CDT to survive and switch to their current licensing model. Subsequent investment from Intel and then a US VC firm saw them through to their first product commercialization.

Both Hyperion and CDT overcame their sustained technological and market uncertainty through alliance strategies. Hyperion partnered with a resin supplier for their automotive fuel line application. This partnership provided Hyperion with access to technological assets for compounding, co-extrusion and injection molding, full scale production facilities and fuel line prototype development, and with marketing relationships with an automotive Tier 1 supplier and OEM. In the consumer electronics industry, Hyperion partnered with several consumer electronic OEMS, which helped them access more varied markets. Collins believes that "a small advanced materials firm needs to partner with a larger/established player somewhere along the value chain in each industry vertical they pursue." However, Collins cautions that, although large firms "have all the resources in the world, they are often too focussed on their own customers' current needs to perceive emerging technologies and products." Thus, the onus is on the innovating venture to demonstrate value in substitute products.

CDT's alliance strategy was even more critical to their success, as they pursued a licensing model after 1996 and co-developed much of their application specific IP. After 4 years of attempting to manufacture OLED displays for their first customer, Philips, CDT's investors saw the need to switch to a licensing and co-development model in order to access Philip's manufacturing expertise. This strategy has been maintained as CDT continues to exploit their licensing model by selling and co-developing IP with both materials suppliers and display manufacturers.

Thus, Hyperion and CDT provide an exposition of our explanatory model but also adduce evidence in support of our theoretical contribution (Fig. 2). In particular, they confirm the identity of critical factors underlying the long periods of technological and market uncertainty for firms of this type. They also demonstrate the mediating role of complementary assets and finances in value creation by these ventures.

4. Discussion and conclusions

In this paper, we have demonstrated the challenges inherent in commercializing a radical, generic technology from an upstream position in a variety of industry value chains. Through review and integration of existing literature, prior experience and ongoing observation, we have developed a model (Fig. 2), which demonstrates the influence of the radical, generic, and upstream nature of advanced materials innovation on the ability of a venture to create value. We propose that the attempt to realise and capture the value potential from radical advanced materials technology requires the resolution of high levels of technological and market uncertainty and a substantial investment of capital over a long period of time. Access to financing and the establishment of effective alliance partners are required in order to demonstrate value in specific market applications, a necessary intermediate step for an advanced materials venture to create and capture value. We tested our theoretical model on two in-depth case studies and found it consistent with the evidence there encountered on the challenges and eventual enablers of their process of value creation.

Our contribution to theory building has involved observation, categorization, and association (Carlile and Christensen, 2005). Observation was constituted by prior experience of one of the authors, and the ongoing discussions of both of the authors with the founders of advanced materials ventures. Categorization involved the identification of key factors (Tables 1 and 2) which both link this study to prior work and differentiate its approach. Association was the development of our influence model (Fig. 2) which links the key factors of the commercialization process in the advanced materials sector with value creation by new ventures. Our observation and analysis allows the factors which hinder and enhance value creation by advanced materials ventures to be predicted. More generally, this theory may be extended to all ventures commercializing radical generic technology from an upstream position in the value chains of one or more industries.

In this previously unexplored stream of research, there is opportunity for further theory building and testing, and for more empirical work. Our categorizations of radical, generic, and upstream technology commercialization should be tested for external validity. The factors identified in our model could be operationalized, and their causality and impact on value creation tested further for internal validity through an empirical study of advanced materials ventures. Further research is required to translate this theory into actionable recommendations for managers and policy makers. As a preliminary, we provide some normative recommendations below.

From our analysis, we recommend advanced materials ventures manage uncertainties by balancing resource allocation between the pursuit of large opportunities and the pursuit of near-term revenue generation. Technology and market strategies which prioritize markets for substitute products where there is no substantial need for complementary innovations are most likely to generate near term revenue. However, in the longer term, such innovations are likely to be too specific and too low margin to be of interest to venture capitalists. It is those technologies with many applications in major markets, and with the potential to enable and capture returns from entirely new markets,[22] that can attract venture capital and large corporate investment. Thus, we propose that advanced materials ventures are most likely to achieve success if they develop an IP claim on a long-term, emerging market application with major potential while focusing most of their time and resources on substitution applications. Prioritizing market applications in this way could be guided by viability analysis (Maine and Ashby, 2002) and by assessing the complementary assets of interested potential alliance partners.

National science policy and granting programs also influence the ability of advanced materials ventures to create and capture value through availability of finance. Specifically, the technology-market matching process of an advanced materials venture and their subsequent market experimentation are greatly assisted by early stage financing from government grants. Near-market R&D support has been provided in the USA by their Small Business Innovation Research (SBIR) program but has not been available in sufficient quantities elsewhere, for example in the UK (Garnsey and Moore, 1993) and in Canada (Conference Board of Canada, 2004). Market-oriented government grants are particularly important to advanced materials ventures, given the scarcity of VC funds available to firms commercialising advanced materials. Such national policy solutions can be most beneficial by supporting the exploratory processes of advanced materials ventures, for instance, by subsidising marketing information for the entire sector, providing product regulatory testing at government laboratories and providing incentives for partnerships between large and small companies developing product prototypes for specific market applications.

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

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