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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 intensified challenges in commercializing technology of this kind as upstream entrants into distinct established value chains. In this paper, we build on Freeman's concept of technological innovation as a technological and market matching process to develop a new model of the variables influencing value creation by advanced materials ventures. We then demonstrate the model using evidence from a sample of 10 US advanced materials ventures, including an in-depth case study exemplar. From the literature, our model, and our case study observation, we construct four propositions concerning the success of advanced materials ventures in commercializing radical technology.

Keywords: Generic Technology, Radical Innovation, Value Chain, Technology Market Matching, Opportunity Exploitation, Advanced materials, Technology innovation, Technology entrepreneurship, Adoption of Innovation, New Ventures

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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 further define "radical technology" as having "the potential for delivering dramatically better product performance or lower production costs, or both" (Utterback, 1996, p. 158). Thus defined, the commercialization of generic, radical technology is highly desirable both to national governments and to firms seeking profit. Nevertheless, there are instances where generic, radical technology faces 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. However, the upstream position in the value chain accessible to most entrants, and 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 to 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, leads to high sustained levels of technology and market uncertainty. We further show how these high levels of uncertainty impact 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 (Klevorik 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. First, we provide a review of the technology innovation literature. Next we draw on this literature, along with other literatures relevant to advanced materials innovation, in developing a model of the variables influencing value creation by advanced materials ventures. We then provide an exposition of the model with evidence from a sample of ten US advanced materials ventures, and, in particular, from an in-depth case study of the most established venture in our sample. From the literature, our model and our case study observations, we construct four propositions predicting venture success in commercializing radical advanced materials technology. Lastly, we put forward managerial and policy recommendations meant 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**. In section 2, we review the existing literature on innovation in the advanced materials sector, and integrate it with the literatures on technology-market coupling, adoption of innovation and dynamic capabilities.

A generic technology[1] 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, 2001; Bresnahan and Trajtenberg, 1995). Scott 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

[1] A closely related term, General Purpose Technology, also refers to technology that impacts a broad range of industries

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, Foster argued, equivalent efforts on improving the incumbent technology and the radical technology would 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 matching or 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, 1996; 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 (1996) 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 1996 p.125)."

An industry value chain is a depiction of the primary and supporting activities performed by a firm or by a group of firms to convert raw materials and information into products and services of value (Porter, 1985). 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. Thus upstream innovation refers to innovation initiated at the furthest extreme of an industry value chain from the consumer. Firms are more likely to initiate innovation from an upstream position as the applicability of the technology to various industries increases (Arora et al, 2001, pp. 146-149). In other words, generic technologies are more likely to be introduced by upstream specialized technology firms, supplying downstream customers in several industries. 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, in theory, easier for new upstream entrants to commercialize than established incumbents; but, in practice, this may be very difficult to achieve in some sectors. In sections 2.1 and 2.2, we discuss the impact 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 orginators 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 as technology, market, or technology and market matching factors, 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 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.

2. Technological and Market Challenges of Innovation in Advanced Materials

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 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)

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 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 generic radical technology. We illustrate these cicumstances in **Figure 1**, where the challenges of innovation in the advanced materials sector are represented by 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 systematically discuss each of 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, in which a positive influence by one factor on another is marked by a 'plus' arrow, the negative influence of one factor on another by a 'minus' arrow. The interactive nature of the causal 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 (**Figure 2**). We choose to 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. This technological 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 **Figure 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., 2005; 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, 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 vast potential markets do not perceive utility ex ante.

The need for process innovation results from by 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., 1994). This upstream position means that the creation of a prototype product, for any industry, requires more than just the venture's intermediate product.[2] It will depend on downstream design and process innovations, and may depend on

[2] 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

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 applications 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 there are established substitute products, the valuation of attributes is generally linked to that of the incumbent product, which may be produced in large volumes. To displace the substitute product, process innovations are required to make a new material viable (Maine and Ashby, 2002) 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 4x 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, 1988, p. 432). The need for market-specific R&D results from the differing values placed on application attributes in different markets

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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.

(Maine & Ashby, 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. Certainly to commercialize their technology, external financing is required for advanced materials ventures following an in-house manufacturing strategy.

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. The high level of market uncertainty inherent in the commercialization of advanced materials technology 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 **Figure 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 their 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 three 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 didn't 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 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, 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.

Lack of continuity leads to greater market uncertainty and delays in adoption of an innovation (Rogers, 1995). 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),[3] 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 (O'Riorden and Hoddeson, 1997, p. 102,172-174, 178-180, 198-199, 207-209, 230). In this case of new functionality, OEM customers are facing 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.

[3] 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.

Thus, radical innovation such as that enabled by advanced materials technology makes significant demands on customers and sometimes 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 1995; Moore 1991). 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 utility for performance attributes for 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 percent of their peak annual sales volume (**Figure 3**). 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 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 **Figure 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 firms commercializing radical advanced materials technology.

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). New ventures generally access these complementary assets through alliance partners in each target market (Niosi, 1993). Ventures can prioritize market applications through modelling the viability and attractiveness of each application for substitution applications (Maine et al, 2005). However, when advanced materials inventions overturn current technological knowledge and also enable entirely new markets, both modelling and less formal 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).[4] 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 be in a good position to create and capture value. To successfully match a new ventures technology with a market application, and thus to demonstrate value in specific applications, an advanced materials venture needs both financing and access to complementary assets (**Figure 2**).

3. Firm Level Evidence

3.1 Sample of Advanced Materials Ventures

[4] 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.

The challenges of commercializing generic, radical technology from an upstream position in several industry value chains are evident when such ventures are examined at the firm level. We studied the identifiable advanced materials ventures in the region of Boston, MA, USA, and summarize our observations in **Table 3**. We chose the greater Boston area because it has a substantial concentration of advanced materials ventures by world standards. These ventures were interviewed from 2002 to 2003 and were all still in existence in 2005. Six of the ten ventures were less than five years old at the time of the interviews: half of those new ventures had previously been incubated within another, larger firm. The experiences of this sample of advanced materials ventures highlight the challenges of commercialization of generic radical upstream technology and the methods employed to alleviate financial constraints.

All ten of the firms had prospects for creating substantial value, with large target markets often spanning multiple industries. **Table 3** outlines the current and future target markets of the sample firms: seven of these firms identified four or more distinct target market verticals. Eight of these firms are currently following a manufacturing business model, albeit often also incorporating licensing, contract research, and manufacturing with outsourcing. This demonstrates both their potential for value creation and the importance of their technology market matching process.

However, commercialising advanced materials technology which alters the cost-performance frontier of downstream products involves high capital costs over significant timeframes. Only three of the 10 firms did not identify lack of finance as the primary barrier to growth for their firm (**Table 3**). Of those three firms, one employed a licensing model only, one had already achieved substantial VC financing, and the last was spun out of a larger firm after establishing an ongoing revenue stream from product sales. Six of the ten firms indicated that SBIR grants were critical to their survival and growth. These are substantial

US government agency grants, awarded through competition, which fund prototype development. Of the four firms which did not receive SBIR grants, two were among those which were spun out of a larger firm, one had other government funding, and the last had ongoing strong ties with a prestigious research university. Lastly, seven of the ten sample firms had created effective strategic alliances which reduced their barriers to entry by providing them access to complementary assets for product commercialization. Thus SBIR grants and strategic alliances were used by these sample firms to alleviate financial constraints when developing prototypes for their generic, radical, upstream technology.

We turn now to the oldest and most successful of the ten companies in our sample, and give a more detailed case study examination of their technological development and technology market matching experiences. We chose Hyperion as our case study exemplar because they have been through their initial development of their advanced materials technology, and have successfully commercialized over 40 products in three distinct industry value chains. They have also experienced several of the difficulties we have outlined thus far. We demonstrate those challenges in section 3.3, where we apply the analysis set out in **Figure 2** to Hyperion.

3.2 Case History of Hyperion Catalysis[5]

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 pick 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

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[5] This case study was compiled from primary and secondary sources, including interviews with Hyperion Marketing Director Pat Collins on Oct. 31, 2003, and Aug. 19, 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 uspto.gov.

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 – 1989, Hyperion focused on developing the first viable multiwalled carbon nanotube product & 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[6] and became key to Hyperion's patent portfolio (US Pat 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 with high purity. Next they began focusing on commercialization. Although they were certain of their intention to follow an in-house manufacturing business model, they 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

[6] 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.

marketplaces. Hence, they publicized their technical achievements widely, in the hopes of attracting potential customers and/or alliance partners. This strategy proved successful, as Hyperion was approached by their first alliance partner as a result of these efforts.

This first alliance 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 product into the automotive market, as 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 three years of development, and achieved their first product sales in 1992.

After this first successful product development, Hyperion moved to a larger facilities to have room for commercial scale production equipment and further growth. Hyperion then concentrated on developing prototypes and specifying their product into 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.

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 on as Director of Business Development, and he had a large influence on Hyperion's subsequent 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. In fact, 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 SBIR grants from the 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;[7] yet, to achieve that success, Hyperion needed patient capital, alliance partners, and an early focus on substitution rather than emerging markets.

3.3 Analysis of Exemplar Evidence and of Boston Sample

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[7] revenue estimate obtained from ReferenceUSA

The evidence from our case exemplar and our sample of advanced materials ventures provide further validation of our model (**Figure 2**) and allow us to generate propositions for future empirical testing. Hyperion Catalysis demonstrates the potential for substantial value creation of an advanced materials venture. To date they are still a relatively small firm, but there is substantial utility for their product in automotive and consumer electronics static dissipation applications, and they are developing applications in the aerospace and power generation industries. In the longer term, they could enable entirely new applications, such as the new consumer electronics products enabled by field emission displays and economically viable automotive fuel cells. The other advanced materials firms in our sample are developing generic upstream technology which could also enable substitutes for a broad range of products in several existing markets and enable both new applications and entirely new markets. To generalize, advanced materials innovations are generic technologies with the potential for significant value creation.

However, our case exemplar demonstrates the challenges of matching radical advanced materials technology to market applications. Hyperion considered many markets for their MW carbon nanotube technology in 1989, most notably structural thermoplastic composites in the automotive industry, structural thermoset composites for aerospace, and energy storage applications for the power generation industry.[8] Hyperion had difficulty prioritising these markets, largely because of the factors influencing technological and market uncertainty, depicted in **Figure 2**. They resolved much of this uncertainty over time with the assistance of long-term financing and effective alliance partners.

The technological uncertainty facing Hyperion in 1989 stemmed from their radical technology, the need for process innovations to scale up production and to reduce cost, and the multiple markets they considered targeting, all with different attribute valuations. The

[8] see, for example, the abstract of US PAT No. 4,663,230

radical nature of their technology is evidenced by the substantial new functionality provided by their composite resins and by their extensive patent portfolio. 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 success.

Hyperion's process innovations, from 1985-1997, included scaling up production of nanotubes, dispersion of these nanotubes in various resins, and application specific production process innovations. Their need for process innovations was increased by the existence of established substitute products. As an example, in fuel lines, Hyperion needed to match existing mechanical attributes and compete on component price with steel fuel lines.

In Hyperion's case, their most promising market applications emerged when other material suppliers approached them with an application idea. However, in these different markets, Hyperion's customers have differing utility for the performance attributes that can be achieved with Hyperion's composite products, such as static dissipation, processability, cleanliness, strength, stiffness, fire retardance, processability, and weightsavings. As the relative importance of performance attributes is understood for specific market applications, process innovations can optimize production of the customized material. Until these are understood, technological uncertainty remains.

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/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. The left hand side of **Figure 4** depicts the layers of the automotive value chain with which Hyperion needed to work in order to commercialize their materials innovation in a single industry. This information gathering and communication challenge is exacerbated when the consumer is not aware of their own preferences for the intermediate product attributes.

Figure 4 also demonstrates the breadth of the challenge facing advanced materials ventures, as complementary innovations are 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 remainder of our sample of advanced materials ventures also demonstrates the need for complementary innovations, as six of the ten firms specified that they were waiting on complementary innovations in order to commercialise one or more of their products.

The need for process innovations and component design changes by Hyperion's customers creates a lack of continuity for the customer. This lack of continuity slowed down the adoption of Hyperion's products and continues to slow down the broadening of their product line into further applications. Additionally, lack of observability and trialability of

Hyperion's MW carbon nanotube materials by first customers and then consumers acted to slow down the adoption of Hyperion's products. Until Hyperion was able to create a prototype fuel line, they weren't able to demonstrate the value of their innovation to their automotive OEM customers. The automotive consumers do not observe Hyperion's innovation in the fuel line application whatsoever 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 needed to divide their R&D and business development focus between two streams of automotive industry applications, 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 engaging 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.

Hyperion would have been unable 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 difference 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 will further require 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. However, financing remained a constraint for them, as they indicated that they could have grown more quickly in the 1990s with additional financing. Pat Collins, marketing manager of Hyperion, believes that 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.

The rest of our sample of advanced materials ventures also face financial constraints in their attempts to demonstrate value in specific applications and, ultimately, to create and capture value. AM5 and AM7 in **Table 3** demonstrate this anticipated slow rate of revenue growth. AM4, AM8, and AM9 also demonstrate this slow growth rate, as they all were incubated for over a decade within larger firms. These long timeframes, high technological and market uncertainty, the need to demonstrate value in specific downstream applications, and the time necessary to develop and maintain effective strategic alliances, all make intensive demands on these small (average size of 26 employees) advanced materials ventures.

In addition to the need for financing, the creation of effective alliance partnerships is essential to creating and capturing value for an advanced materials venture. 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. Pat Collins of Hyperion 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." He also believes 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 attempt to realise and capture the value potential from radical advanced materials technology requires a large investment of capital over a long period of time, and the resolution of high levels of technological and market uncertainty. A strategy of experimentation is required, which may involve R&D and business development across several industries. 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.

4. Creating and Capturing Value from Advanced Materials Innovations

Although there are opportunities to create substantial value from advanced materials innovations, there are also considerable disincentives facing both established firms and new entrants. For publicly-held companies, short-term shareholder pressures are in conflict with the required high capital costs, long lead times, and uncertainty surrounding complementary innovations. Additionally, established firms have many other reasons to avoid the adoption of new technology (Abernathy and Clark, 1985; Leonard, 1996; Utterback, 1996; Christensen, 1997). For new ventures, their upstream position in the value chains of their target markets and the cost, time, and uncertainty of market experimentation make successful commercialization of generic radical technology extremely challenging. When they can access patient capital and mobilize complementary assets, they may be able to create and capture maximum value through a manufacturing strategy. Alternatively, where new entrants can create and protect radical advanced materials technology, they may be able to create and capture value through a licensing strategy. As 80% of the firms in our sample are currently employing an in-house manufacturing business model, they clearly believe it is the best route to creating and capturing value. However, as discussed in sections 2 and 3, an in-house manufacturing model also exposes an advanced materials venture to prolonged technical and marketing uncertainty and the need for external financing. We propose that, over time, the population of advanced materials ventures which follow in-house manufacturing models will have the largest variance in their success metrics – either creating and capturing substantial value or failing outright. Thus,

P1: AM ventures which employ in-house manufacturing models have a bimodal success profile, experiencing either high growth or failure

The prolonged, high level of uncertainty and the commercialization costs faced by advanced materials ventures can be reduced by access to complementary assets through alliance partners (Niosi, 1993), who themselves are taking advantage of the specialized R&D capabilities of the venture. These resource and risk-sharing features of alliances between new technology ventures and industry incumbents have been well established in other emerging technology sectors (Tyebjee and Hardin, 2004; King et al, 2003; Niosi, 2003). Eisenhardt and Schoonhoven (1996) found that those semiconductor firms with more innovative strategies and targeting emerging markets had higher rates of alliance formation, suggesting that both the venture and alliance partner have growth and risk-sharing motivations. The benefits of alliance formation for advanced materials ventures include access to complementary technologies, access to manufacturing, regulatory, legal, reputational, marketing, and distribution resources, financial investment, and risk-sharing (Niosi, 1993). An alliance partner must provide access to one or more of these resources in order to reduce the barriers to entry to a particular industry for an advanced materials venture. Such 'effective' alliances are expected to increase the likelihood of success for an advanced materials venture. Thus,

P2 AM ventures which build 'effective' alliances will be more likely to survive and achieve high growth

As well as demonstrating the impact of effective alliance partners, our case study exemplar demonstrates the technical and market uncertainty reduction and the shortened adoption timeframe of targeting 'substitution' applications in existing product markets. These substitution applications still required process innovations and design changes, but required far less complementary innovations and were less dependent on the regulatory environment or infrastructure changes than emerging market applications. However, most advanced materials ventures require external financing and thus need to attract venture capital: hence, intellectual property in an emerging market is required. As financing is critical to an advanced materials venture's ability to create and capture value, we propose that a blended strategy with an early focus on substitution applications will increase a ventures likelihood of success. Thus,

P3 Firms which focus their resources on substitution markets but create credible IP for emerging markets will be more likely to survive and achieve high growth

Value creation by advanced materials ventures is also dependent on location. It is well documented that some countries provide better environments than others for the formation and growth of firms in specific industries (Nelson, 1993; Porter, 1990). More recent studies have also shown the local environment to be an important determinant of success in many high technology sectors (Stuart and Sorenson, 2003; Porter and Stern, 2001). We propose that, for ventures in the advanced materials sector, both national and regional systems of innovation are determinants of the creation and capture of value, because they impact the effectiveness of ventures' matching process, predominantly through the availability of substantial commercialization grants and through the potential for alliance creation. Thus,

P4 Countries and regions which have innovation systems supporting the market experimentation process will have advanced materials ventures with higher survival and growth rates

5. 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. We have developed a model 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 applied this theoretical model to a case exemplar and a sample of 10 advanced materials ventures and found it helpful in explaining value creation in terms of the existing pieces of literature and evidence. From the relevant literature, our model, our observations, and case study analysis, we offer 4 testable propositions for future empirical studies.

We explain the causes and influences of technological and market uncertainty in the commercialization of advanced materials technology and suggest a method to manage these uncertainties. Advanced materials ventures can manage uncertainties through balancing resource allocation between the pursuit of large opportunities and the pursuit of near-term revenue generation. Technology and market strategies which prioritize substitution markets without the need for substantial complementary innovations are most likely to generate near term revenue. However, in the longer term, such innovations are generally too specific and too low margin to be of interest to venture capitalists. It is generic radical advanced materials technology with many applications in major markets and the potential to enable entirely new markets[9] and capture future returns on a substantial scale that can attract venture capital and large corporate investment. Thus, 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 influence the ability of advanced materials ventures to create and capture value. 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. Interviews with our sample of advanced materials ventures revealed that, for most, US 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 (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. Such national policy solutions can create the most

[9] 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.

value 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.

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Table 1: Literature Review of Technological Innovation Types

Innovation Type	**Emphasis**	**Authors**
Generic Technology / General Purpose Technology	Breadth of impact across industries	Hagedoorn & Schakenraad, 1991; Martin, 1993; Keenan, 2003; Bresnahan & Trajtenberg, 1995; Rosenberg & Trajtenberg, 2001; Shane, 2004
Radical Technology / Radical Innovation	Depth of impact on industries Substantial cost/performance improvements	Foster, 1986; Utterback, 1996
Revolutionary Innovation / Competence Altering Innovation	Requires change in firm capabilities	Abernathy & Clark, 1985; Utterback, 1996; Tushman & Anderson; 1986
Discontinuous Innovation / Disruptive Technology	New competencies enable new entrants to take market share from incumbent firms	Utterback, 1996; Christensen, 1997
Product Innovation vs. Process Innovation	Emergence of a dominant design	Abernathy & Utterback, 1978; Utterback, 1996;
Upstream Innovation vs. Downstream Innovation	Position of introduction in value chain	Porter, 1985 Pavitt, 1984; Klevorick et al 1994; Arora et al, 2001

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

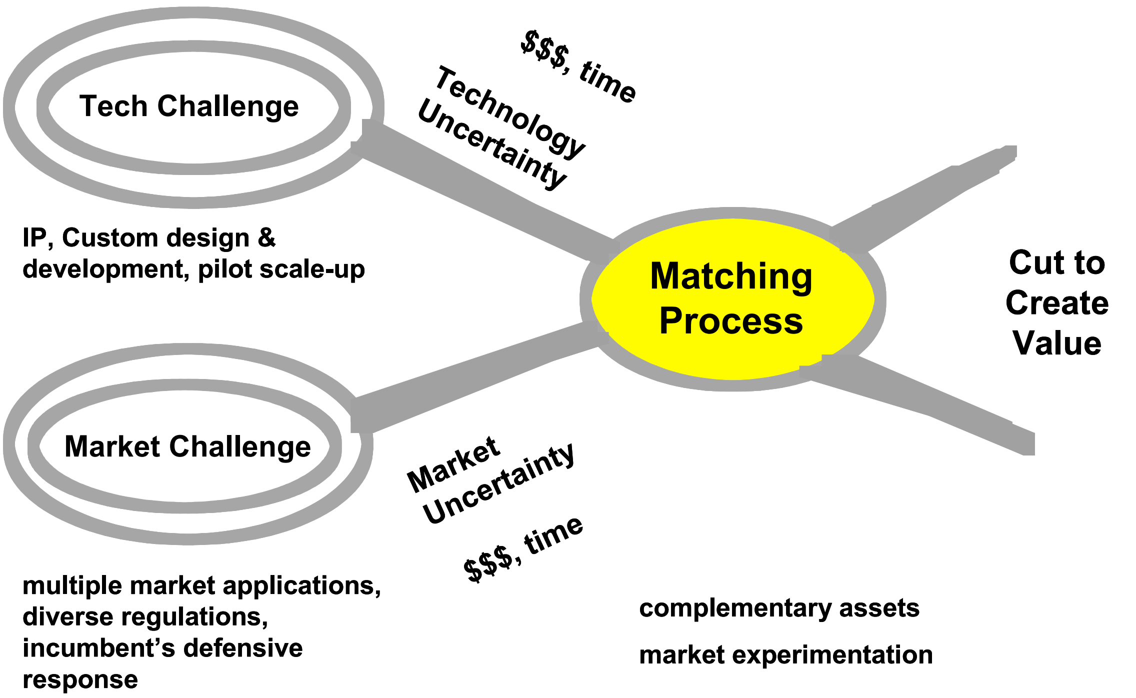


Table 2: Technology and Market Factors Impacting Value Creation and Capture in the Commercialization of Radical, Generic Technology

	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 (++) Widely varying attribute utility between these markets (--)	Upstream input into value chain requires either vertical integration in each market or alliance creation in each market to mobilize complementary assets (-) Downstream barriers to adoption (product, organizational, designer, regulatory) (--)	Incumbents unwilling to cannibalize existing products (-) Price competition (-)

\+ = positive impact on value creation and/or capture
\- = negative impact on value creation and/or capture

Figure 2: Influence Model of Value Creation by AM Ventures Commercializing Radical Generic Technology

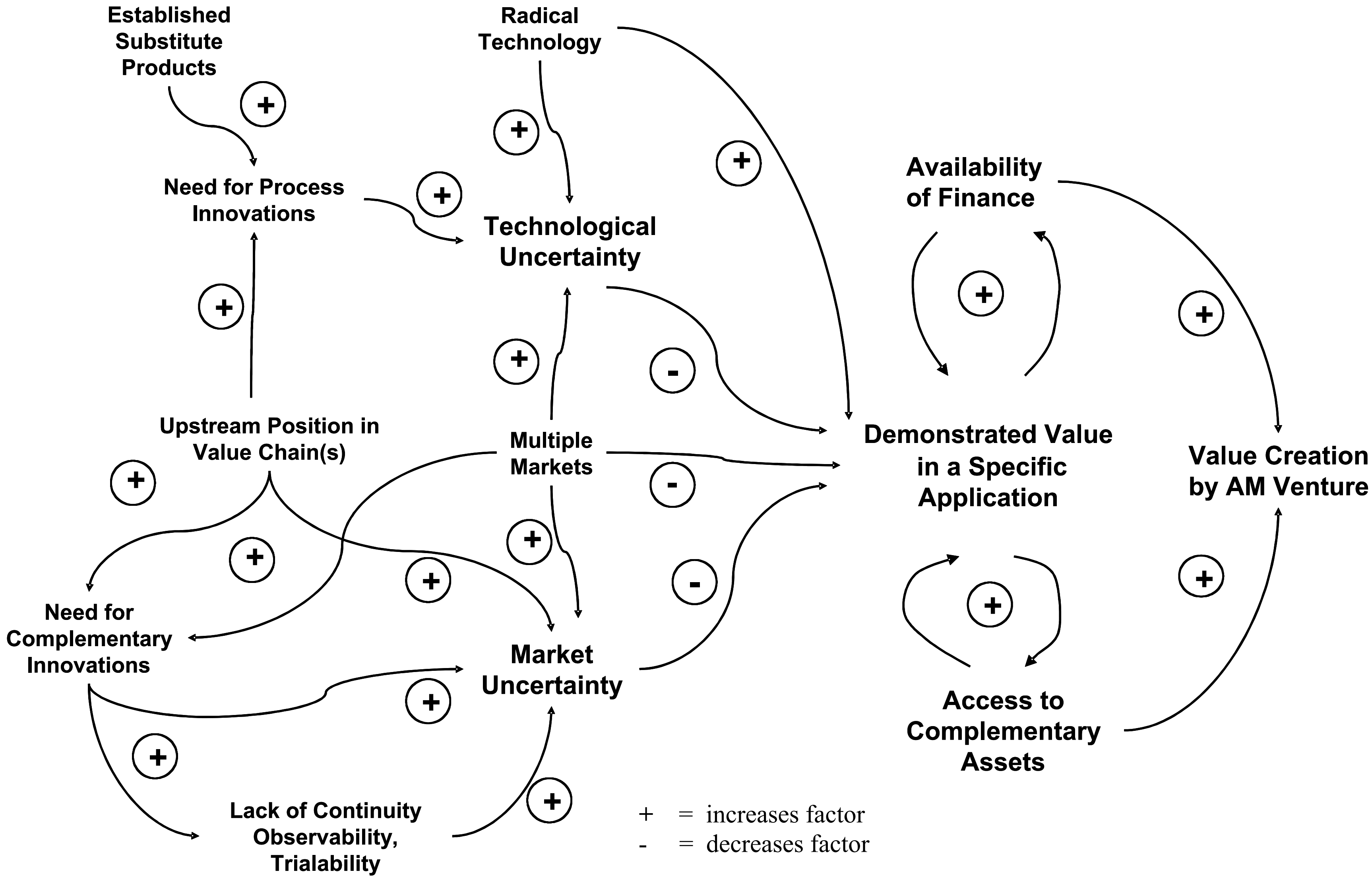
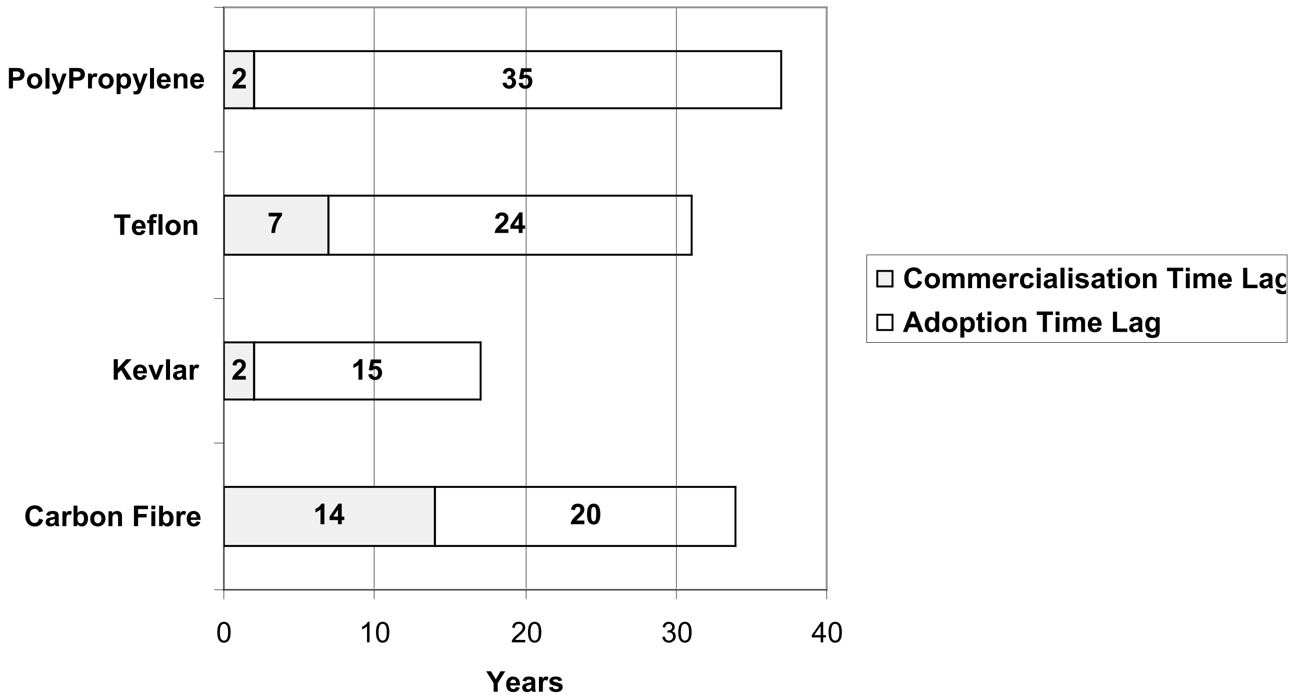


Figure 3: Commercialisation and Adoption Times for Advanced Materials Innovations*



* 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.

Table 3: Boston Advanced Materials Firms' Commercialization Metrics

Firm	Founding Year	Current Business Model	Size (Product & Service Revenue, $M, 2002)	Size (Empl 2002)	Current and Future Target Markets	Alliances reduce barriers to entry	Primary Constraint (2003)	US SBIR funding (2003)	VC funding (2003)	Spinout from University (U), Larger Firm (I)
AM1	2000	M, CR	pre-revenue	5	B, EL, MI	Yes	Financial	Yes	No	U
AM2	1999	L, M, CR	pre-revenue	7	B, EL, PC, PG	Yes	Financial	No	No	U
AM3	1992	L	15-20	75	AE, B, EL, MI	No	None	Yes	No	No*
AM4	1999	M	10-15	27	AE, AU, C, EL, PG	No Alliances	Financial	No	dedicated fund	I
AM5	1986	L, CR	5-10	25	C, TR,	Yes	Financial	Yes	No	No*
AM6	2001	M, MOS	pre-revenue	25	C, EL, MI, PG	Yes	Leadership	No	Yes	U
AM7	1982	M	20-50	35	AE, AU, EL, PG, TR	Yes	Financial	Yes	No	No
AM8	2001	M	5-10	33	AE, AU EL, PG, SP	Yes	Competition	No	No	I
AM9	1995	M, CR	1-5	20	AE, AU, C, MI	No	Financial	Yes	No	I
AM10	2001	M	Pre-revenue	6	EL	Yes	Financial	Yes	Yes	I

Sources: Lexis Nexus, SBIR, company websites, author interviews
L= Licensing, M = In-House Manufacturing, MOS = Manufacturing with Outsourcing, CR = Contract Research
AE = Aerospace, AU = Automotive, EL = Consumer Electronics, C = Construction, PG = Power Generation, MI = Military, SP = Sports Equipment, TR = Transportation, PC = Personal Care Consumer Products
* Not a spinout, but strong University ties at time of formation and early growth

Figure 4: Hyperion Catalysis's Upstream Positions in the Value Chains of their Existing and Target Markets

Automotive	Aerospace	Consumer Electronics	Power Generation
R&D and production of MW CN	R&D and production of MW CN	R&D and production of MW CN	R&D and production of MW CN
Composite Material R&D & Production	Composite Material R&D & Production	Composite Material R&D & Production	R&D & Prod. of Batteries / Energy storage
Component Production (i.e. Fuel Lines)	Component Production (i.e. Structural Parts)	Component Production (i.e. EFD Trays)	Component Production (i.e. ICE / Fuel Cells)
Automotive Production	Airplane Production	Computer Production	Generator Production
Sales, Distribution & Maintenance	Sales, Distribution & Maintenance	Sales, Distribution & Maintenance	Sales, Distribution & Maintenance