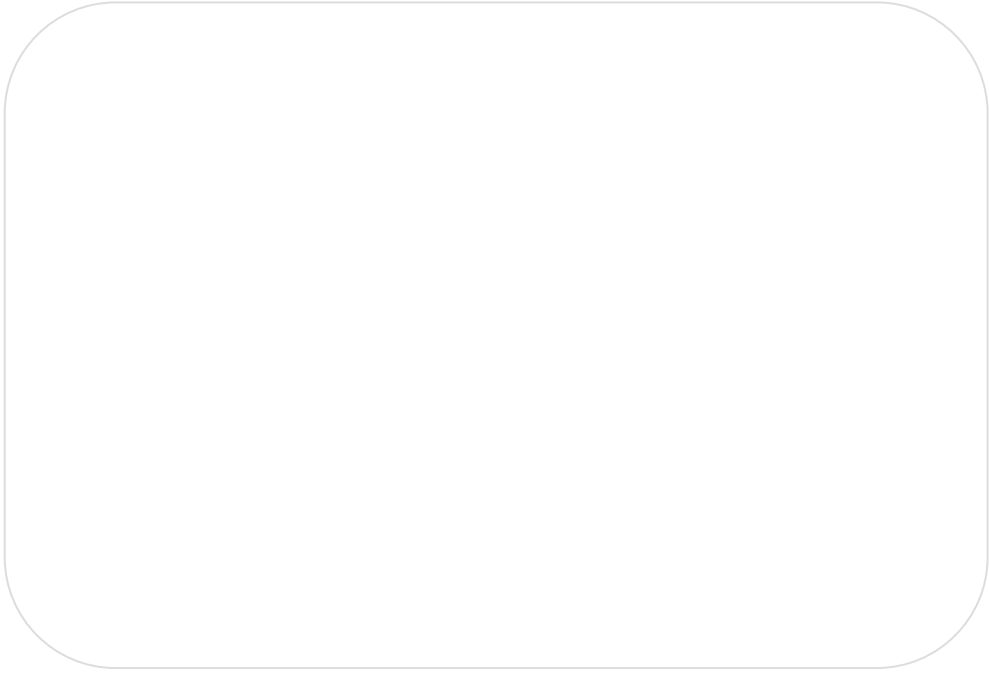




Hitotsubashi University
Institute of Innovation Research



Vectran: Development of High-Functionality Fiber and its Applications at Kuraray Co., Ltd.¹

Keisuke Hori, Fuji University, Department of Economics

Yusuke Hoshino, Musashino University, Graduate School of Political Science and Economics

Hiroshi Shimizu, Hitotsubashi University, Institute of Innovation Research

1. Introduction

Kuraray Co., Ltd. (hereafter ‘Kuraray’) began production of the high-strength polyarylate fiber Vectran™ in February 1990. Vectran is a polyester (polyarylate) fiber made from polymer with a high degree of crystallinity. It is spun and uniformly treated at high temperature based on Kuraray’s proprietary technology, which gives the product greater strength and higher performance.² As a type of ‘super fiber’ possessing high strength and high modulus performance, Vectran was developed over the course of about four years from research and development (R&D) to commercialization,³ and has been used in a wide range of applications,⁴ from fishing nets to a material for airbags used during the landings of NASA’s Mars landing vehicles and surface rovers. Together with Kuralon™ (PVA fibers), it is a symbol of Kuraray’s proprietary technology in the fiber business.

Vectran is a second-generation super fiber that followed Kevlar® and Twaron®, which are referred to as the first generation of super fibers.⁵ One notable point concerning Vectran is that while the market is small compared with those of other super fibers, as shown in Table 1 and Table 2, it nevertheless maintains steady sales. Kuraray is the only fiber supplier that commercialized high-strength polyarylate fiber. In this

¹ The descriptions in this case study were prepared with the purpose of providing material and a point of view for analysis and discussion, and are not intended to illustrate any particular skills in enterprise management. When preparing this case, we received extensive cooperation from Takeshi Fukushima of Kuraray Co., Ltd.’s Fibers and Industrial Materials Division and Junyo Nakagawa, former chief researcher at Kuraray Co., Ltd. We would like to express our sincere appreciation for their support. Any errors concerning the matters detailed in this case are the sole responsibility of the authors. This work was supported by Grant-in-Aid for Scientific Research (A)(No.23243054); Grant-in-Aid for Young Scientists (B)(No.24730308); Kitano Foundation of Lifelong Integrated Education; and Musashino University.

² Kuraray Co., Ltd. website (<http://www.kuraray.co.jp/products/question/fiber/vectran.html>), accessed July 20, 2013.

³ Ide (2011a).

⁴ *The Sen-i News*, January 6, 2004.

⁵ Japan Chemical Fibers Association website, “*Kasen Topics*” <http://www.jcfa.gr.jp/fiber/topics/vol09.html>, accessed December 20, 2013.

case study we will examine the characteristics and applications of Vectran, which was developed using Kuraray's proprietary technology, recount the details of the path from the R&D phase to commercialization, and describe the management issues encountered when developing applications for the product.

Table 1. Production capacity and sales volume of main high-function fibers.

High-function Fiber	Company or Group Name	Product Name	Annual Production Capacity (t)	Annual Sales Volume (t)	Selling Price (Yen/kg)
Para-aramid	DuPont-Toray Co., Ltd.	Kevlar	2,500	1,800	3,000–6,000
	Teijin Group	Twaron	25,000	16,500	3,000–6,000
		Technora	2,000	1,300	
Meta-aramid		Teijinconex	2500	1450	2,000
Ultra High Molecular weight PolyEthylene PE (UHMwPE)	Toyobo Co., Ltd.	Dyneema	3,200	2,500	5,000–7,000
High Molecular weight PolyethylenePE (HMwPE)		Tsunooga	300	300	3,000–4,000
PBO		Zylon	300	220	15,000–25,000
PPS	Toyobo Co., Ltd. / Toray	Procon / Torcon	3,100/3,200	2,900/3,200	1200
Polyarylate	Kuraray Co., Ltd.	Vectran	1,000	700	4,000–5,000

Source: Partial excerpt from Yano Research Institute, Ltd. (2012). Sales volume figures for 2011 are estimates.

Table 2. Size of market for main high-function fibers.

High-function Fiber	Company or Group Name	Product Name	Financial Year2009	Financial Year2010	Financial Year2011
Para-aramid	DuPont-Toray Co., Ltd.	Kevlar	89,825	90,050	89,500
		Twaron			
	Teijin Group	Technora			
Meta-aramid		Teijinconex	3,300	3,300	2,900
Ultra High Molecular weight PolyEthylene (UHMwPE)	Toyobo Co., Ltd.	Dyneema	10,400	15,600	15,000
High Molecular weight PolyEthylene (HMwPE)		Tsunooga	400	800	1,050
PBO		Zylon	3,600	4,000	4,400
PPS	Toyobo Co., Ltd. / Toray	Procon/ Torcon	7,080	7,320	7,320
Polyarylate	Kuraray Co., Ltd.	Vectran	2,925	3,375	3,150

Source: Partial excerpt from Yano Research Institute, Ltd. (2012). Unit: Million yen.

2. Characteristics and Uses of Vectran

(1) Vectran's performance

Although the term 'super fiber' lacks a precise definition, it is generally a fiber possessing high strength and high modulus performance: fibers must have a strength of at least 2GPa(16g/d) and a modulus of 50GPa(400g/d) or greater to be considered super fibers.⁶ In contrast to these, fibers possessing high functionality such as heat resistance or flame resistance are called high-function fibers. The main super fibers produced by fiber manufacturers in Japan are shown in Table 3.

⁶ Based on materials obtained from the Japan Chemical Fibers Association website, <http://www.jcfa.gr.jp/fiber/super/what.html>, accessed July 21, 2013; and materials obtained from Junyo Nakagawa.

Table 3. List of main super fibers produced in Japan.

Name of Fiber	Japanese Company, Trademark, etc.	Characteristics	Uses
Para-aramid fiber	Teijin Techno Products Ltd. (Technora) (Twaron) DuPont-Toray Co., Ltd. (Kevlar)	High strength, high modulus, heat resistance, chemical resistance, abrasion resistance	Tire cords, belts, body armor, protective clothing, aircraft materials, concrete reinforcement, asbestos substitute
Ultra High Molecular weight PolyEthylene fiber	Toyobo Co., Ltd. (Dyneema)	High strength , high modulus, low specific gravity, abrasion resistance, chemical resistance, abrasion resistance, impact resistance, weather resistance	Ropes, protective clothing, sports and leisure goods, fishing lines, fishing nets
Polyarylate fiber	Kuraray Co., Ltd. (Vectran)	High strength, high modulus, heat resistance, abrasion resistance, acid resistance, low ductility, high creep resistance, low moisture absorption, high vibration damping	Ropes, fishing nets, sports and leisure goods, electrical materials, protective clothing, molded products
PBO fiber	Toyobo Co., Ltd. (Zylon)	High strength, high modulus, high heat resistance, high flame retardancy, abrasion resistance, impact resistance, high creep resistance, low moisture absorption	Protective materials, belts, ropes, sailcloth, various reinforcement materials, heat resistant cushion material
Carbon fiber	Toray Industries, Inc. (Torayca) Toho Tenax Co., Ltd. (Tenax) Mitsubishi Rayon Co., Ltd. (Pyrofil)	High strength, high modulus, heat resistance, flame retardancy, impact resistance	Sports and leisure goods, aeronautic and space materials, automobile materials, wind generator blades

Source: Prepared based on material from the Japan Chemical Fibers Association website, <http://www.jcfa.gr.jp/fiber/super/summary.html>, accessed July 20, 2013. The table shows only the super fibers manufactured by member companies of the Japan Chemical Fibers Association: Technora® is a registered trademark of Teijin Techno Products Ltd; Twaron® is a registered trademark of Teijin Twaron BV; Tenax® is a

registered trademark of Toho Tenax Co., Ltd.; Torayca® is a registered trademark of Toray Industries, Inc.; Kevlar® is a registered trademark of E. I. du Pont de Nemours and Company in the United States; Vectran™ is a registered trademark of Kuraray Co., Ltd.; Dyneema® and Zylon® are registered trademarks of Toyobo Co., Ltd.

Vectran has a broad range of characteristics, including: high strength and high modulus (tensile properties); low moisture absorbency; high dimensional stability (creep properties); excellent thermal properties; fiber-to-fiber abrasion resistance; excellent flex fatigue and bending resistance; impact resistance; high vibration damping; cut resistance; chemical resistance; and ultraviolet light resistance.⁷

Table 4. Vectran's general properties.

Characteristic	Unit	Polyarylate fiber		Para-aramid fiber		
		Vectran		PPTA		
		High strength HT	High modulus UM	High strength (regular)	High modulus	
Density	(g/cc)	1.41	1.40	1.44	1.44	
Decomposition temperature	(°C)	>400 (Decomposition)	>400 (Decomposition)	>400 (Decomposition)	>400 (Decomposition)	
Moisture regain	(%)	<0.1	<0.1	7.0	3.5	
Flame retardancy (LOI)	(%)	28	30	30	30	
Yarn	Fiber structure	(dtex/f)	1670/300	1580/200	1670/1000	1670/1000
	Tenacity (standard state)	(cN/dtex)	24.2	21.5	20.3	20.8
	Elongation at break	(%)	4.0	2.8	3.6	2.4
	Young's modulus	(cN/dtex)	530	740	490	781
	Shrinkage					
	WSr (boiling water 100°C × 30 minutes)	(%)	0.15	0.04	0.1	0.04
	DSr (180°C × 30 minutes)	(%)	0.15	0.01	0.15	0.04
	Tenacity in wet	(cN/dtex)	24.0	21.4	18.3	18.7
Dry/wet strength ratio	(%)	99	100	90	90	

Source: Ide (2011a).

As shown in Table 4, the strength and elastic modulus of Vectran equal or exceed

⁷ The following descriptions are taken from Nakagawa (2003) and Ide (2011a).

those of para-aramid fibers. One important characteristic in particular is that Vectran suffers no decline in physical properties under low-temperature atmospheres because of its molecular structure. While its strength under a 20°C atmosphere is about 24cN/dtex, Vectran significantly demonstrates its performance as the temperature is lowered, having strength of about 29cN/dtex in a -70°C atmosphere. In addition, because its decomposition temperature is above 400°C, Vectran possesses high heat resistance and does not easily burn. Although para-aramid fibers have equally high flame retardancy, the toxic gases are generated when these fibers are burned. On the contrary, Vectran does not produce toxic gas when it burns. One further characteristic of Vectran is low moisture absorption: Vectran's mechanical properties under wet conditions are nearly identical to those under dry conditions. As a result, because Vectran does not retain moisture under a high moisture atmosphere, it maintains stable physical properties when used as a reinforcement material, and this low moisture absorption can be said to be Vectran's strongest point when compared with aramid fibers.

(2) Vectran grades and development of uses

There are two types of Vectran fibers: regular (high-strength) HT type and high-modulus UM type. Like polyester and nylon, Vectran is spun by the melt spinning method. One advantage of this spinning method is the comparative ease of producing yarns with various thicknesses, from very fine to coarse. Consequently, among high-strength fibers Vectran has the biggest grade variety of 27, making it possible to meet the requirements of various products, especially to enhance grades of 560dtex or less. An additional advantage is that small production runs can be handled easily.⁸ Sales volume and market size are shown in Table 5.

Table 5. Vectran sales volume and market size.

	2006	2007	2008	2009	2010	2011
Volume	600	800	650	600	750	700
Sales	3,550	4,800	3,700	3,300	3,375	3,150

Source: Prepared based on data from Fuji-Keizai Group (2008, 2010), for 2006 - 2009; and Yano Research Institute, Ltd. (2012) for 2010 - 2011. Unit: Tons; Amount: Million yen.

The following can be enumerated as the main uses of Vectran⁹: (1) marine uses

⁸ Yano Research Institute, Ltd. (2012).

⁹ Nakagawa (2003).

(fishing lines, long line ropes, fishing nets, marine ropes); (2) non-marine ropes and slings (lead rope for restringing power lines and railway wiring); (3) cords and tension members (window blind cords, wire replacement cords, optical fiber cables, earphone cords, gut cords, screen door cords, etc.); (4) civil engineering and construction materials (used together with other materials such as Kuralon); (5) safety and protective materials (protective clothing such as work gloves and boots, protective materials, fire-resistant cable cloth, etc.); (6) sheet and membrane materials (floating roofs for building sites, sails for competitive yacht racing, airbags for the Mars explorer vehicles, etc.); (7) molded products and fiber reinforced plastics, or FRPs ¹⁰(speaker cones, skis, golf clubs, table tennis paddles, etc.); (8) papers and nonwoven clothes (motor insulation papers, base cloth for printed circuit boards).

Sales volume and total sales by use for Vectran products are shown in Table 6.

Table 6. Vectran demand by use (global market).

	2006		2007		2008	
	Volume	Sales	Volume	Sales	Volume	Sales
Marinen ropes and cables	220	1,310	250	1,500	200	1,100
Fishing nets	150	850	200	1,150	150	800
Nets and cords	50	280	50	290	50	300
Others	180	1,110	300	1,860	200	1,100
Total	600	3,550	800	4,800	600	3,300

Source: Prepared based on data from Fuji-Keizai Group (2008, 2010). Unit: Tons; Amount: Million yen.

When Vectran was initially developed, its main uses (demand) were marine applications, but recently changes in the product's applications have been notable. Viewed on a monetary basis, a breakdown of the global market in 2006 by use showed marine applications were the core business, with marine ropes and cables and fishing nets accounting for 36.9% and 23.9% of sales respectively, followed by net cords for sporting goods at 7.9% and other uses at 31.3%. By 2011, a change in demand could be seen, with electrical and electronic applications newly accounting for 35% of total demand, followed by ropes and cable at 25%, fishing and other nets at 15% and other

¹⁰ Abbreviation for Fiber Reinforced Plastics.

uses at 25%.¹¹ Due to Vectran's unique characteristics, such as electrical insulation properties, low moisture absorbency and dimensional stability, the fiber is being used as a reinforcement material for products such as earphone cords and tension members (optical fiber cables), and sales for electrical and electronic uses have become the main application supporting total Vectran sales. According to Yano Research Institute, Ltd. (2012), in the electrical and electronics sector where demand has been increasing recently, finer fibers are constantly required, making it necessary to maintain earnings with such fibers.

From a price and functionality aspect, Vectran competes with para-aramid fibers and Ultra High Molecular weight PolyEthylene fibers (UHMwPE).¹² While most of Vectran's applications are not overlapped with UHMwPE fibers because of the property differences, para-aramid fibers are Vectran's largest competitors since they have already penetrated numerous industrial sectors. Moreover, precisely because para-aramid fibers have already established a position in so many industrial sectors, capturing or regaining these established markets would be difficult. Kuraray therefore is seeking to differentiate from its competitors by fibers of 560dtex or less thickness. It is because Vectran is manufactured using the melt spinning method. Achieving cost-effectiveness will be relatively easy, because compared with para-aramid fibers, the melt spinning method can easily produce fine yarns. Takeshi Fukushima of Kuraray's Fibers and Industrial Materials Division commented on this point as follows:

At least compared with the process for making aramids such as Kevlar, it's easy for us to produce fine yarns. If you look at where Vectran's cost competitiveness lies, it's in fine yarns. With just 1,000 tons of capacity at most, no matter how you measure it, we wouldn't be cost competitive at all, compared to Kevlar or Twaron. Under such circumstances, fine yarns are what enables us to be comparatively cost competitive.¹³

As of 2013, ropes are Vectran's so-called 'plain vanilla' application, but Fibers and Industrial Materials Division has adopted the policy of increasing added value with 'specialty items', such as fine yarns or spun yarns, while continuing to maintain a certain volume of this 'plain vanilla' application.¹⁴ As mentioned above, the size of the market for Vectran is limited, and annual production capacity is about 1,000 tons. Accordingly, it is difficult to use a business model of generating earnings at a low price

¹¹ Yano Research Institute, Ltd. (2012).

¹² Ibid.

¹³ From the authors' interviews with Takeshi Fukushima.

¹⁴ *The Sen-i News*, August 8, 2013.

through mass production and a high volume of sales. In the case of Vectran, Kuraray employs a business model in which it generates earnings from fine yarn applications such as earphone cords and membranes for airship, while covering fixed costs by coarse yarns for applications such as fishing nets and ropes.¹⁵

Table 7. Varieties of Vectran and typical applications.

Product mode	Type (Desitex, type, etc.)		Main Uses
Multifilament yarn	8300dtex(7500Dr)	T-101 T-506	Woven fabrics, FRP, tension members, general industrial materials
HT: High tenacity	5000dtex(4500Dr)		
	3300dtex(3000Dr)		
	1670dtex(1500Dr)		
UM: Ultra-high modulus	1110dtex(1000Dr)	T-117 T-147	Fishing nets, ropes, other
NT: Medium strength, Easy fibrillated	560dtex(500Dr)		
	280dtex(250Dr)		
	220dtex(200Dr)		
Dope-dyed yarner (black, red, blue, green, other)	110dtex(100Dr)		
	56dtex(50Dr)		
	28dtex(25Dr)		
Spun yarn	20 count (cotton count), 30 count, other		Foundation cloth, protective clothing, other
Chopped fiber	1,3,6mm, other		FRP, other
Pulp			High-performance paper, asbestos substitutes, other
Woven fabrics and knitting	Various		General industrial materials
Prepreg	UDPP, cloth PP		FRP, other

Source: Vectran pamphlet. Denier amounts are shown in parentheses.

3. Technology for Making Fiber from Thermotropic Liquid Crystal Polymer¹⁶

The following section explains the characteristics of the Vectran polymer and the manufacturing process.

(1) Thermotropic liquid crystal polymers

¹⁵ In this respect, it is similar to the business model for Dyneema at DSM and Toyobo Co., Ltd. For more on Dyneema, see Hoshino (2012).

¹⁶ The following descriptions concerning polyarylate fibers rely extensively on Nakagawa (1992, 1994, 2000, 2003); Nakagawa and Sanefuji (1993); and materials from the Japan Chemical Fibers Association website, <http://www.jcfa.gr.jp/fiber/word/category.html#origin04>, accessed July 21, 2013.

While the development and commercialization of super fibers was pursued vigorously from the 1970s through to the 1990s, their production was enabled by two technological innovations. The first innovation was the gel spinning method for materials such as Ultra-High Molecular weight PolyEthylene (UHMwPE). The gel spinning method is a process that enables a high degree of orientation by minimizing entanglement of the molecules, using a dilute solution, and drawing the material in a gel state; that is, gel spinning is a method for manufacturing filament by stretching flexible polymers at extremely high drawing ratio. The second innovation is a technology for making fibers from liquid crystal polymers. Liquid crystal spinning, which uses straight, rod-like polymers that have no entanglement, is a method for spinning while using shear stress to give the molecules a high degree of orientation.

Liquid crystal polymers can be divided into two categories: lyotropic liquid crystals that show liquid crystal state within a certain concentration range in solution; and thermotropic liquid crystals that show liquid crystal state within a certain temperature range in solution. Lyotropic liquid crystal polymers include aromatic polyamides and aromatic poly(azomethines), and most of thermotropic liquid crystal polymers are aromatic polyesters. An example of a fiber produced from a lyotropic liquid crystal polymer is aramid fiber, perhaps best represented by Kevlar®, which is manufactured by DuPont-Toray Co., Ltd. This is made of p-phenylene terephthalamide (PPTA), an aromatic polyamide, in liquid crystal state under a sulfuric acid solution, which is then formed to fibers by dry and wet spinning. In contrast to this, Vectran is an example of a fiber produced from a thermotropic liquid crystal polymer, a wholly aromatic polyester (polyarylate) fiber examined in this case study. While a number of thermotropic liquid crystal polymers have been developed and marketed in the past as resins, Vectran is the only product to have been commercialized as a fiber using the technology of Hoechst Celanese. The following section looks briefly at the characteristics of thermotropic liquid crystal polymers while following the Vectran manufacturing sequence.

For the development of super fibers, the fibers themselves must be given greater strength. The basic point in enhancing strength is how to parallel the long molecules (as long as possible) in the direction of the fiber axis. The requisites for giving polymers high strength and high modulus are: (1) strong bonds to form the polymer chain; (2) a small area occupied by the polymer chain; and (3) formation of a molecular structure having little elongation. This is achieved by “designing an aromatic polymer comprised of a highly symmetric, rigid rod-like structure”. The basic structure of this aromatic polyester is formed of self-condensation polyester from p-HydroxyBenzoic Acid (HBA,

see Figure 1) and polyester comprising of Terephthalic Acid (TA) and HydroQuinone (HQ); see Figure 2.



Figure 1. Molecular configuration of self-condensation polyester from HBA.

Source: Reprinted from Nakagawa (1994).

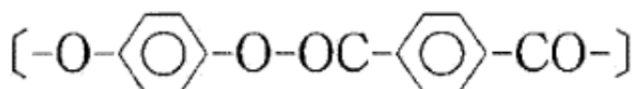


Figure 2. Molecular configuration of polyester formed from TA and HQ.

Source: Reprinted from Nakagawa (1994).

Because the molecules of these polymers are too rigid, their melting points¹⁷ are higher than their decomposition points,¹⁸ making them difficult to process in a liquid crystal state. Consequently, one of following three methods is used to sacrifice either the rigidity or crystallinity of the polymer and bring the melting point below the decomposition point: (1) introduce a flexible alkyl group into the main chain; (2) copolymerize¹⁹ different types of rigid molecules; or (3) introduce a substituent group into the aromatic ring of the main chain. These methods have made it possible to develop thermotropic liquid crystal polymers that can be injection molded or melt spun into fibers as engineering plastics.

Vectran was developed by applying the second methodology. The liquid crystal polymer formed from the molecular structure shown in Figure 3—that is, the thermotropic liquid crystal polymer obtained through the melt polymerization of p-HydroxyBenzoic Acid (HBA) and 2-Hydroxy-6-Naphthoic Acid (HNA)—was turned into fiber by melt spinning. The molecular chain of this liquid crystalline polymer has a high degree of orientation in the direction of the fiber length, which gives it excellent

¹⁷ The temperature at which solids melt and become liquids. For the first polymer, HBA, it is 610°C; for the latter, TA and HQ, it is 600°C.

¹⁸ The temperature at which melting and a decomposition reaction occur. Here, it is 400–450°C.

¹⁹ Polymerization carried out using two or more kinds of monomers.

physical properties.

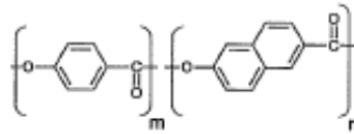


Figure 3. Molecular structure of Vectran's main polymer.

Source: Reprint from Kuraray's Fibers and Industrial Materials Division pamphlet.

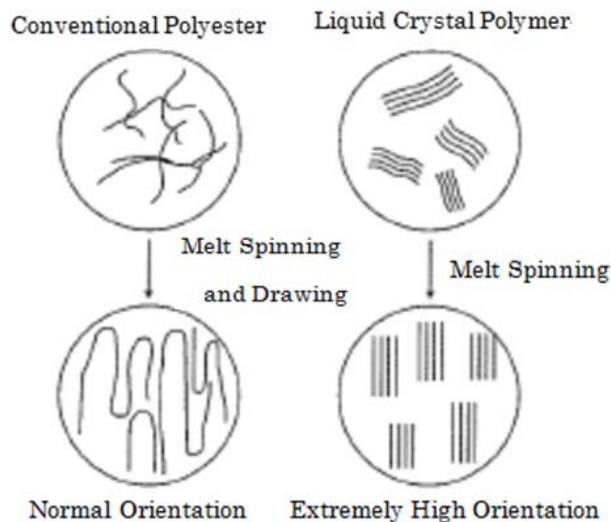


Figure 4. Image diagrams of fiber structures.

Source: Reprint from Kuraray's Fibers and Industrial Materials Division pamphlet.

Description in this figure was translated into English by the authors.

(2) Creating fibers from thermotropic liquid crystal polymers

To turn thermotropic liquid crystal polymers into fibers, pelletized polymer is first dried, then, after being melted in an extruder, it is turned into fibers using the melt spinning method.²⁰ When thermotropic liquid crystal polymer is spun under high shear stress, a high degree of molecular orientation takes place when the material passes

²⁰ A method to melt raw materials by heat and form fibers by extruding them from a device called spinneret, then quench for hardening.

through nozzles; this structure (orientation) is maintained until the fibers are cooled and solidify because of the lengthy relaxation time. If the fiber is ordinary polyester, it must be stretched to improve its strength. On the other hand, because Vectran's molecules are already in a rod-like and aligned state at the spinning phase, there is no need to stretch the spun fibers again at a high draw ratio. The concept for this production of fiber is shown in Figure 5, compared with the one used for the manufacture of flexible polymers such as polyester and nylon.

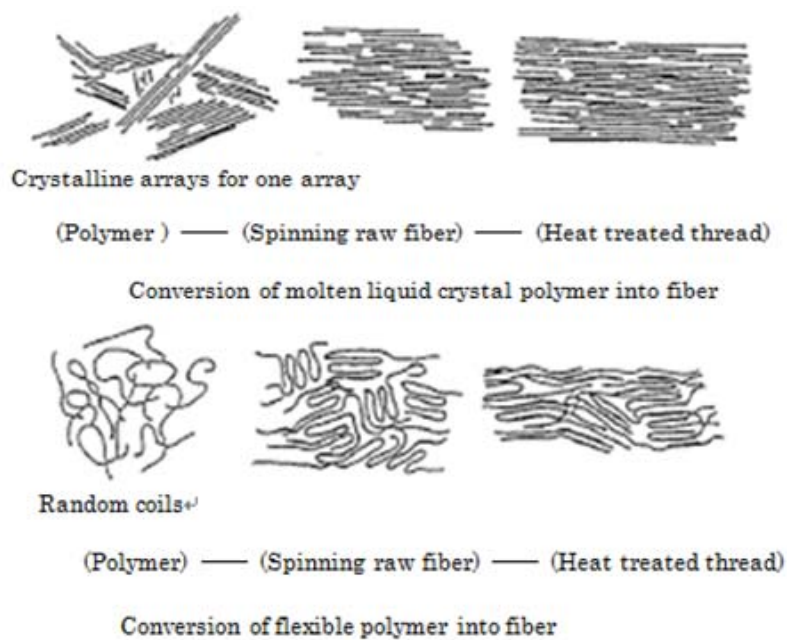


Figure 5. Fiber production concepts.

Source: Reprinted from Nakagawa and Sanefuji (1993).

Description in this figure was translated into English by the authors.

(3) Heat-treatment

Although spun fiber already possesses considerable strength and elastic modulus, which means stretching is unnecessary for fiber formation because the molecular orientation has already been achieved (the polymer chain is arranged in a certain direction) in the spun state, heat treatment is performed to enhance further performance. The goal of heat treatment is to increase the strength and elastic modulus, and improve heat resistance.²¹ This is achieved by continuously removing by-product materials in one of the following conditions: (1) reduced-pressure; (2) inert gas

²¹ Nakagawa (2001).

atmosphere; and (3) active gas, including air atmosphere. Fibers are afterwards turned into products by the further application of oiling agents or surface treatments depending on the use.

Super fibers developed before Vectran were made by melting resin in a solvent (lyotropic liquid crystals); because solvents such as sulfuric acid were used, the manufacturing process was complex and costly.²² As Vectran is manufactured by the melt spinning method, this difficulty is eliminated. Moreover, the spun yarns can be produced with thickness ranging from fine to coarse comparatively easily,²³ giving the process the added advantage of being suited to a variety of small-lot orders such as fine multi-filaments and dope-dyed yarns.²⁴

4. Vectran's Development – Background and Issues

(1) Background to development

Liquid crystal polymers, the polymer material for high-performance fibers, first came to the attention of the fiber industry in 1971 when E. I. du Pont de Nemours and Company (hereafter DuPont) discovered that P-Phenylene TerephthalAmide (PPTA), an aromatic polyamide (aramid), forms liquid crystals in solvent, and subsequently used this discovery to begin producing Kevlar®, a high-strength, high-modulus fiber spun from this solution using the dry and wet method.²⁵ Because of Kevlar's superior performance, including high strength and elastic modulus, the demand expanded significantly, and production is believed to have reached 10,000 tons in 1985. In addition, in 1986 Akzo Nobel N.V. in the Netherlands began producing Twaron®, the same kind of para-aramid fiber, followed in 1987 by the start of the commercial manufacture of Technora® by Teijin Limited.²⁶ As stated previously, Kevlar and Twaron are referred to as the first generation of super fibers, and in that sense, Vectran, which entered production in 1990, can be said to belong to the late entrants' group in the super fiber sector.²⁷

At that time, engineers like Junyo Nakagawa, who had played a central role in the

²² Ide (2011b).

²³ Nakagawa (2000).

²⁴ Yorimitsu (2010).

²⁵ Ueda (1988).

²⁶ Teijin Ltd. website, "Para-aramid Fiber Twaron®,"

<http://catalog.teijin.co.jp/template.phtml?id=186&pid=5>; "Para-aramid Fiber Technora®,"

<http://catalog.teijin.co.jp/template.phtml?id=184>, both accessed January 13, 2014.

²⁷ Japan Chemical Fibers Association website, "Kasen Topics,"

<http://www.jcfa.gr.jp/fiber/topics/vol09.html>, accessed December 20, 2013.

development of Vectran, clearly recognized that under such circumstances Kuraray needed to proceed with the development of super fibers in order not to fall behind their competitors.²⁸ The direct opportunity for Nakagawa to be involved in fibers for industrial uses instead of those for textiles was a polymer liquid crystal symposium²⁹ held at Kyoto University in 1983. Numerous researchers from around the world working with liquid crystals attended this symposium, including Stephanie Kwolek, the developer of Kevlar at DuPont, as a prominent participant. Through participation in this symposium, Nakagawa came to feel strongly the need to switch from fibers for apparels to fibers for industrial uses. This was also the period when sales of Kuralon as a replacement for asbestos was expanding in Europe, and Kuraray aimed to advance such industrial applications not only of Kuralon, but also the combination of Kuralon and other fibers. Because its rivals had pushed ahead with sales of super fibers at that point, Kuraray had misgivings that it would end up at a distinct disadvantage in the future if it did not have some super fibers of its own. Nakagawa described the atmosphere within the company at the time in the following words:

The mood at that time, really, was one of, ‘Jeez, isn’t there anything we can do?’
Because all we had was Kuralon.

Moreover, from 1983 to 1985, Kuraray conducted a screening survey of anisotropic thermotropic polyesters (wholly aromatic polyester fibers) at its Central Research Laboratory in Kurashiki. The result gained from this effort was an anisotropic thermotropic polyester fiber formed from HBA and HNA which demonstrated the highest performance. On that occasion, Kuraray received information on a polyarylate resin developed by Hoechst Celanese, and based on the resin’s physical properties, Kuraray believed it must be able to create a highly heat resistant, high-strength fiber comparable with rival Kevlar.³⁰ The reason, it is surmised, why Celanese focused on the development of thermotropic liquid crystal fiber rather than lyotropic liquid crystal fiber like Kevlar is because the company judged the latter to be superior in terms of the fiber’s productivity.³¹ Beginning in the 1970s, Celanese had conducted research into new thermotropic liquid crystal polymers which incorporated monomers, such as the naphthalene monomer into which a 2,6-functionalized substituent had been introduced,

²⁸ The following description is taken from the authors’ interview with Junyo Nakagawa.

²⁹ This symposium was not open to the public. Thus, the number of the participants was limited.

³⁰ Soma (2009).

³¹ Ueda and Kanamaru (1986).

as one of their components. As a result, they found that wholly aromatic polyesters formed from HBA and HNA possess various outstanding characteristics as engineering plastics resins, and in 1984 had proceeded with market deployment under the name Vectra® in collaboration with Polyplastics Co., Ltd.³² Also, Celanese had successfully developed Vectran, a high-function fiber that, like Vectra, is formed from thermotropic liquid crystal polymers of the HNA/HBA group.³³

Given that Celanese had the best among the technologies surveyed by Kuraray, and Kuraray lagged behind other companies at that time in patents for super fibers, Kuraray broached the idea of a joint development with Celanese to turn the product into a fiber.³⁴ Despite its reluctance to enter the fiber business because a giant market for Kevlar already existed,³⁵ Celanese judged that Kuraray's spinning technology would be necessary for it to undertake the application development in the future,³⁶ and thus in 1985 the two firms began joint development based on collaboration.

Meanwhile, because DuPont and other companies in the same industry had already staked out markets to a certain extent, Kuraray felt the need to develop fibers with unique characteristics in order to achieve differentiation. Therefore from the start, Junyo Nakagawa's approach was to develop with the intention of creating a fiber with small thickness which also could be dope-dyed.

Kuraray, which had agreed to proceed with trial sales and the application development of Vectran in cooperation with Celanese, undertook a feasibility study. Kuraray initially adopted a stance of setting up a test plant (annual production 40–50 tons) at its Kurashiki Plant and proceeded with the application development by using polymer supplied by Celanese. Then, as the development progressed steadily with this plan so that steady demand could be anticipated in many sectors in the future, and further spurred by the fact that Celanese started operation of the polymer plant with the capacity of 2,000 tons per year, in 1989 Kuraray decided to construct a full-scale Vectran plant.³⁷

Despite the two firms' joint development work for two years, Celanese ultimately decided to abandon the manufacture of Vectran. Although Celanese had intended from the start of the development to supply Vectran for use in tires, the fact that Vectran

³² Ueda (1988).

³³ Ibid. The developer was a Celanese researcher named G. W. Calundann. According to Junyo Nakagawa, however, Vectran Celanese had developed at this phase corresponded to a pilot version.

³⁴ From the authors' interviews with Junyo Nakagawa.

³⁵ From the authors' interviews with Junyo Nakagawa.

³⁶ *Nikkei Sangyo Shimbun*, May 15, 1986.

³⁷ *The Chemical Daily*, February 3, 1989 and *The Chemical Daily*, February 14, 1990.

proved unsuitable for uses with rubber materials—its bonding to rubber and fatigue resistance were relatively low compared with Kevlar—is assumed to have been a major reason why Celanese abandoned commercialization of the fiber for a second time.³⁸ As a result, Kuraray was left to seek commercialization on its own. In the end Kuraray produced fibers alone, while the sales rights for the Americas and Europe were granted to Celanese and Kuraray retained the rights to sell the product in Japan and throughout Asia.³⁹

(2) Issues during the development and production stages

According to Junyo Nakagawa, the greatest difficulties during development were felt with regard to the heat treatment technology. Normally, heat treatment of thermotropic liquid crystal fiber is performed by continuously removing by-product materials developed in the condition of either reduced-pressure or inert gas atmosphere. Kuraray was confronted with the problem of how to solve removal and recovery on a commercial scale.

Because the basic patent concerning heat-treatment technology in an inert gas (fiber strength is increased by more than 50% in an inert atmosphere) was held by DuPont,⁴⁰ Kuraray approached that company and expressed its willingness to acquire the patent.⁴¹ As DuPont answered that it would respond to Kuraray's request only in the form of a cross-licensing agreement, Kuraray presented several USP patents it held. However, as Kuraray's technology did not meet DuPont's demands, in 1987 Kuraray abandoned the idea to exchange licensing agreement and instead performed the heat processing using its own technology to avoid the violation of the competing patent, which specifically means manufacturing fibers in an activated gas atmosphere including oxygen. However, while the values for abrasion and heat-resistance properties when processing in active gases are superior to those obtained when processing under inert gases atmosphere, the process had the disadvantage of causing an oxidizing reaction that turned the yarns to a yellowish tea color, and also the strength was weaker than in the case of processing in an inert gas environment (19cN/dtex).

As the DuPont patent for heat treatment was effective until May 1995, Kuraray

³⁸ From the authors' interviews with Junyo Nakagawa.

³⁹ As described below, in 2005 Kuraray would acquire the Vectran fiber business of U.S.-based Celanese Advanced Materials, Inc.

⁴⁰ E. I. du Pont de Nemours and Company. A method to improve the strength of molded products (Japanese Examined Patent Publication No.55-20008). In 1980 the "scope of patented claims" for this technology was revised, and words relating to the processing method were added to what was claimed.

⁴¹ From the authors' interviews with Junyo Nakagawa.

was able to switch to a processing method using inert gas after that. While the greater strength of 24-26cN/dtex was to be obtained as a result, this change led to the need to remove by-product materials (as mentioned earlier)—namely, the acetic acid, phenols, and various oligomers generated during heat treatment. It was necessary to remove these first and foremost for pollution-abatement measures.⁴² Moreover, while fiber strength is enhanced by the solid phase polymerization⁴³ reaction that occurs as a result of performing the heat treatment, to obtain this high strength the heat treatment had to be performed for a lengthy period of time under inert gas or certain gas density conditions. Consequently, the pronounced jump in the cost, as a result of the gas raw material expense, electricity, and other utility charges, became a major obstacle to industrial production.⁴⁴ Finally, because of the large amount of gas required for the heat treatment, Junyo Nakagawa and the development team adopted a method to reduce costs by reusing the gas by circulation. However, the phenols and other by-product materials hindered the polymerization reaction, and adhered to the circulation pipes and blocked the filters during heat recovery, which made it necessary to circulate and re-use the inert gas while continuously removing by-products.

When grappling with these issues, the developers were able to overcome the unwanted by-product elimination problem by installing filters made of nonwoven cloth and by using washing and absorbents to remove the contaminants.⁴⁵ Furthermore, according to Nakagawa, the most difficult challenge was appropriately establishing the various conditions, including the air speed and air volume, when blowing heated gas around the fibers. If these settings are not correct, it results in phenomena such as irregular fiber strength or insufficient strength because of increased density of the by-product materials in the outer layer portion of the fibers wound around the bobbins (cylinders for winding the fibers).⁴⁶ The setting of these optimal values became possible only through repeated trial and error, accounting for the majority of the time expended during the Vectran development period.

A major issue during the production stage was establishment of the spinning technology for mass production.⁴⁷ While the temperature must be raised to about 300°C to melt the raw material, the issue in this case was which molecular arrangement to be

⁴² Ibid.

⁴³ The polymerization progresses to a solid phase state.

⁴⁴ Kuraray Co., Ltd. “Heat-treatment Method for Thermotropic Anisotropic Fibers.” Japanese Unexamined Patent Application Publication No. 03-119110.

⁴⁵ Ibid.

⁴⁶ Ibid.

⁴⁷ The following descriptions concerning the establishment of mass production technology are based on Ide (2011b), Sugishima (1991), and Yamane (2004).

applied to the polymer, and its molecular length. As we have explained, the polymer used for Vectran is obtained through the copolymerization of HBA (p-HydroxyBenzoic Acid) and HNA (6-Hydroxy 2-Naphthoic Acid), but the composition ratio is determined comprehensively by considering the melting point, melt viscosity, spinnability (ability to be spun into fiber), and fiber performance. When the molecule is too long, the viscosity becomes so high that the nozzles will be blocked during spinning, yet fibers cannot be formed if it is too short. Moreover, when the temperature is raised the liquid crystals sometimes break before forming fibers. The optimal molecular structure and temperature combination must therefore be judged from the viscosity when the filaments are extruded from the nozzles as they are spun. The form in which the polymer melts, and the viscosity when melted, can only be understood when the polymer is extruded from the spinneret nozzles; the individuals responsible for the processing technology have established the spinning conditions by taking steps to improve the raw materials and optimize the nozzles, as well as adjusting the spinning conditions of temperature, pressure, and resin extrusion speed. It is assumed that as they did so they put to use the know-how they had cultivated for manufacturing polyester fibers.

5. Application development

(1) Application development during the 1990s

To develop uses for Vectran, Kuraray began shipping samples in 1986. Because of Vectran's high strength, high elastic modulus, and other unique characteristics such as low water permeability and abrasion resistance, the product was adopted as ropes substitute for wire, fishing nets, and tension members. Also, Vectran's high vibration damping and impact resistance characteristics led to its use in goods such as sports equipment.⁴⁸ Although Vectran was still in the R&D phase in 1987,⁴⁹ as progress was made during 1988–1989, the product moved partially into the industrial research phase.⁵⁰ By 1988, samples Kuraray had shipped were being used in products such as ropes to replace crane wires, fishing nets, optical fiber tension members, core wire for electric carpets, reinforcement materials for FRP, speaker cones, FRC (Fiber Reinforced Cement), and ACM (Advanced Composite Materials). For the purpose of ensuring sales volume, Kuraray considered the rope sector to be an especially promising market among

⁴⁸ *The Chemical Daily*, February 3, 1989.

⁴⁹ Kuraray Co., Ltd. Securities Report.

⁵⁰ Kuraray Co., Ltd. Securities Report.

them.⁵¹ In 1990, Kuraray completed its Vectran manufacturing facility (Ehime Prefecture Saijo Plant; annual production: 400 tons), and from February 1990 entered full-scale mass production mode.⁵²

To ensure immediate sales volume, from 1991 the company developed its business by focusing primarily on marine uses and sports composites.⁵³ Before Vectran was introduced, synthetic fibers such as polyester and nylon accounted for the major share of marine uses such as ropes and fishing nets. Vectran's strength and cutting resistance earned the material high marks and thus the sales volume expanded. In addition, when used for various composites Vectran demonstrates energy absorption and high vibration damping properties, and because of its resistance to failure under compression and bending stress, various applications that take advantage of these characteristics were developed, ranging from skis, golf clubs, and tennis rackets to audio speaker materials. At that point, Kuraray had not made a full-fledged foray into the tension member market, where manufacturers of para-aramid fibers including Kevlar had carved out a substantial market share, as para-aramid fibers at the time possessed a superior elastic modulus, the most required characteristic in that field.

In 1992, Kuraray set its sights on further volume expansion and pursued the development of Vectran FRP for use in general industrial applications.⁵⁴ The first industrial use was the frame of brush cutters/trimmers, which made use of Vectran's excellent vibration damping. For this application Vectran was turned into a composite with carbon fiber or glass fiber. Although Kuraray found their earliest FRP uses in sporting goods, as carbon fiber was the leading product in this sector and as it was difficult to link to an expansion of volume because the containing ratio of Vectran was not so high, Kuraray sought to expand industrial applications.

In 1994, Kuraray began working on the development of new uses such as for clothing.⁵⁵ Prior to this, applications had been limited to products such as marine uses because dyeing Vectran was difficult; once the technology for dyeing woven fabrics had been established, Kuraray began making proposals to sporting goods manufacturers to use Vectran for outdoor sports items such as mountaineering wear. In addition, in 1995 a trunk rope for long lines using Vectran was developed, and Kuraray began supplying the yarn in earnest to several rope manufacturers.⁵⁶ This product took advantage of

⁵¹ *The Chemical Daily*, July 14, 1988.

⁵² *The Chemical Daily*, May 7, 1990.

⁵³ *The Chemical Daily*, April 3, 1991.

⁵⁴ *The Chemical Daily*, April 10, 1992.

⁵⁵ *Nikkei Sangyo Shimbun*, September 19, 1994.

⁵⁶ *Nikkan Kogyo Shimbun*, October 20, 1995.

two of Vectran's characteristics: low moisture absorbency, which means that the rope does not become heavier when it is rolled up, and high tensile strength which makes the rope diameter smaller.

In 1997, Kuraray developed a new grade based on Vectran called VECRY™ for precise print screens.⁵⁷ VECRY, a monofilament with a double layer structure that uses Vectran's liquid crystalline polymer raw material as a core,⁵⁸ is characterized by high strength and high elastic modulus despite being an ultrafine fiber at the micron level. Despite being more than three times stronger than the high-strength fibers obtained from general-purpose polymers, and having an elastic modulus more than five times greater, traditional super fibers were difficult to manufacture into high-density woven fabrics or knitted fabrics with detailed stitching because the molecules are highly oriented, making the yarns highly susceptible to fibrillation (fluffiness) when subject to abrasion.⁵⁹ VECRY controlled fibrillation by using the same thermotropic liquid crystal polymer as Vectran in the core constituent of the fiber and a flexible polymer for the sheath constituent, blending the liquid crystal polymer also in the sheath to eliminate the problem of flaking at the core/sheath boundary surface. By forming a robust structure, the rigors of printing can be endured, and in addition to Vectran's characteristics such as high strength, heat resistance, and low water permeability, Kuraray made possible the manufacture of screens whose performance in terms of print dimension accuracy and durability, for example, are superior to those of new stainless steel screens for high-precision printing. These screens were developed jointly by Kuraray and NBC Meshtec Inc., and sold under the name of 'V-Screen'; use of this product gave firms the advantage of not only being able to achieve a cost reduction of roughly 15% during plate-making and printing processes, but also labor savings and lower running costs during printing processes. The development of VECRY had not been undertaken based on requests or proposals from customers, but pursued as a result of Junyo Nakagawa's projection, from the phase when Vectran was developed, that Vectran's uses would expand further if Kuraray were able to compensate for its shortcomings.⁶⁰

Because the Vectran business had achieved profitability in the 1998 financial year, and because repeated demand had emerged in the main market in the marine uses in

⁵⁷ *The Chemical Daily*, November 5, 1997.

⁵⁸ Kuraray Co., Ltd. website, "VECRY,"

http://www.kuraray.co.jp/products/question/medical/polymer_film2.html, accessed July 23, 2013.

⁵⁹ Nakagawa et al. (2004); Nakagawa (2005).

⁶⁰ From the authors' interviews with Junyo Nakagawa.

1999, Kuraray decided to adopt a more proactive strategy for expanding sales that included replacement of other fibers.⁶¹ In addition, in the electronics area the company decided to pursue developments of fabrics for printed circuit boards, where it could take advantage of Vectran's high strength, heat resistance, and low water permeability, and began the development of fine-denier yarns that could meet the need for light woven fabrics arising from the slimming and miniaturization of printed circuit boards.

(2) The 2000s

As noted in the Introduction, in 2004 Vectran was used for the airbags for NASA's unmanned Mars explorer vehicles and received greater coverage from various media. In 2013, the German chemical giant BASF and Samsung Heavy Industries Co., Ltd. of Korea developed blankets that used Basotect®, a melamine resin foam product.⁶² Cubes made of Basotect, covered by Vectran textile cover, and secured to each other with Vectran belts, create a blanket that makes it possible to prevent sloshing inside the containers of liquefied natural gas tankers. As a result, more economical transport of liquefied natural gas is feasible because transport safety is improved and loads can be set freely. As this illustrates, new applications have been developed in addition to conventional uses since the start of the twenty first century as well. The following will look at two examples of the latest trends in the cultivation of markets and developments of applications that deserve special mention.

① *High-performance rope for mooring oil drilling vessels*

In July 2013, together with Tokyo Rope Mfg. Co., Ltd., a leading rope manufacturer, Kuraray made a new proposal via the Japan Industrial Standards Committee (JISC) to the International Organization for Standardization (ISO) concerning the testing methods and performance evaluations of high-performance ropes that use Vectran, which was approved as a new formal proposal.⁶³ If approved as an international standard, the proposal is expected to facilitate and encourage the

⁶¹ *The Chemical Daily*, May 18, 1999.

⁶² *The Chemical Daily*, August 5, 2013; BASF website, "LNG tanka- ni okeru meramin jushi happou hin Basotect® no shin youto" ("New Uses for Basotect® Open-Cell Foam Made from Melamine Resin in LNG Tankers," in Japanese), http://www.japan.basf.com/apex/Japan/ja/upload/new/Press2013/2013_08_01_basotect_LNG, accessed December 23, 2013.

⁶³ Ministry of Economy, Trade and Industry website, "toppu sutanda-do seido ni yoru arata na kokusai hyoujun teian ga shounin sare mashita," ("Approval of New International Standard Proposed by Japan through the Top Standard Scheme," in Japanese), <http://www.meti.go.jp/press/2013/10/20131009001/20131009001.pdf>, accessed January 25, 2014.

development of overseas markets.

This high-performance rope is used as a mooring cable to secure Floating Production, Storage, and Offloading systems (FPSO) when drilling for offshore oil.⁶⁴ In ocean regions where depth exceeds 2,000 meters, the steel cables used in shallower waters have problems from a strength perspective. On the other hand, polyester ropes have substantial elongation, causing vessels to pitch considerably and leading to concerns that pipelines used to draw up oil will be damaged.⁶⁵ Consequently, there is a strong need for mooring rope that possesses the characteristics of light weight resistance to low temperature, low water permeability, and dimensional stability. Several fibers and raw material suppliers are competing for this market.

When promoting products in other countries, Japan Industrial Standards (JIS) alone are often inadequate to persuade buyers.⁶⁶ In addition, it is difficult to show objective numerical values to persuade customers in foreign countries in case there are no international evaluation criteria.⁶⁷ Despite having received an inquiry from Brazil's state-owned oil company for this high-performance rope, it is almost impossible to get the business without international standards, since the delivery terms usually require international standard conformity.⁶⁸

The Top Standard system is a system established in 2012 in Japan to allow the submission of a prompt international standardization proposal to the ISO or the International Electrotechnical Commission (IEC). In the past, proposals for international standards submitted by a single firm or multiple firms would be always reconciled by an industry group that JISC specified. The problem was that given the required time and effort, it was difficult to incorporate state-of-the-art technology into international proposals, and also difficult for small and medium-scale enterprises and venture firms to make proposals.⁶⁹ Enterprise groups are now able to make standardization proposals to an international organization promptly without going through industry reconciliation, by utilizing this Top Standard system. Kuraray and Tokyo Rope submitted a request to use the Top Standard system to the Japan Industrial Standards Committee, which acts as the corresponding organization to the ISO, in May

⁶⁴ This description of FPSO is taken from the Mitsui Ocean Development & Engineering Co., Ltd. website, "FPSO/FSO to wa," (in Japanese), <http://www.modec.com/jp/business/fpso/index.html>, accessed January 25, 2014.

⁶⁵ Ministry of Economy, Trade, and Industry website.

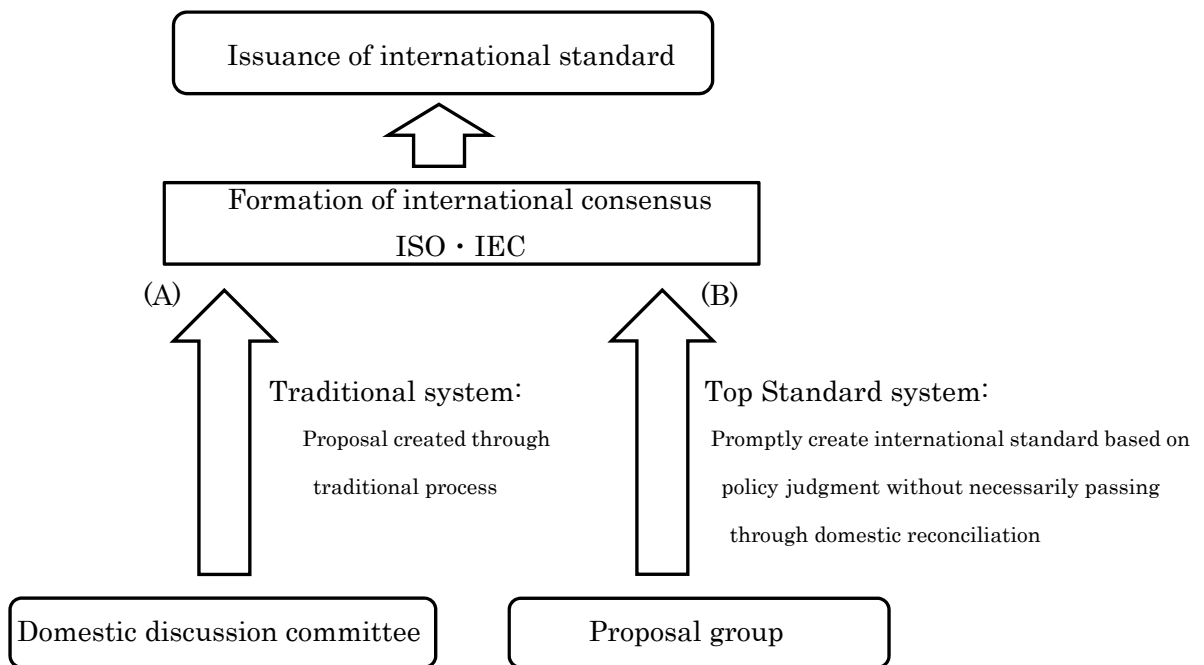
⁶⁶ *Senken Shimbun* July 19, 2013.

⁶⁷ *Senken Shimbun* May 30, 2013.

⁶⁸ *Nikkan Kogyo Shimbun* October 9, 2013. Takeshi Fukushima also remarked that: "Without this (international standard), we probably won't be selected."

⁶⁹ *The Chemical Daily*. October 23, 2012.

2013; and in July of the same year the JISC submitted an international standard proposal concerning the testing methods and performance evaluations for high-performance rope for mooring oil exploration vessels to the ISO, which was approved as a new proposal.⁷⁰ If a consensus among countries is obtained by the ISO's Technical Committee in the future, the high-performance rope technology using Vectran will be issued as an international standard.⁷¹ Kuraray and Tokyo Rope are the first firms to have used this system for a fiber-related standard; we can view this case as one example of how Kuraray is developing overseas markets through a cooperative effort with the manufacturers that are its customers.



(A): Proposal from existing domestic discussion committee

(B): Proposal group possessing the technology and desire to make a proposal to establish a new technical committee, sub-committee and project committee if the appropriate study venue does not exist

Figure 6. Overview of the Top Standard system.

Source: Prepared based on information from the Ministry of Economy, Trade, and Industry website.

⁷⁰ Ministry of Economy, Trade, and Industry website.

⁷¹ *Senken Shimbun* May 30, 2013.

② *FRP (Fiber Reinforced Plastics)*

The increase in inquiries from customers regarding FRP can be cited as another of Kuraray's new Vectran application developments seen in recent years. Kuraray has analyzed market expansion of composite products made of carbon fiber which are the background of such increase.⁷² The expanding applications include energy-absorbing materials for sports equipment such as golf club shafts and rackets, and Vectran's properties, such as high vibration damping, shock resistance, and energy absorption, have attracted attention to such products.⁷³ Takeshi Fukushima made the following comment on this point:

Vectran can be one of the fibers that might compensate for the shortcomings of carbon as a composite by combining the strength of carbon with Vectran's energy absorption or vibration damping property. In spite of various hurdles, FRP is a sector that looks attractive for us. So the more carbon is used, the more we get inquiries from quite a few fields. People say Vectran looks interesting as a material that could possibly make up for carbon's weaknesses in certain aspects.⁷⁴

Whether or not such application development will advance, particularly when used as a composite, does not depend on the properties of Vectran alone. Although it partly abandoned the development of uses of FRP around 2006, Kuraray has been pursuing such development again since 2012. The reason for this is that obstacles encountered previously can be overcome through technical innovations from use of the product. For example, while holes can be easily and clearly opened in glass and carbon fiber reinforced plastics, holes are difficult to open in plastics reinforced by organic fibers such as Kevlar and Vectran because of fiber toughness. There are indeed cases where application development progresses again after a number of years; as a result of the obstacles encountered when organic fibers are used for FRP being overcome through technical innovations and changes in the cutting tools used to open holes. Yet, this is a parameter that cannot be easily controlled by one firm alone. It can be said to be one factor that makes the development of uses extremely difficult.

⁷² *The Sen-i News* August 20, 2012.

⁷³ From the authors' interviews with Takeshi Fukushima.

⁷⁴ *Ibid.*

6. Management of Application Development

In this section we will look at the characteristics of the management of application development for Vectran while focusing on three points: (1) Kuraray's sales organization; (2) process from development to commercialization; and (3) factors influencing success or failure of application development.

(1) Kuraray's sales organization

① *Domestic sales*

As of 2013, Kuraray introduced an in-house company structure. Fibers and Textiles Company deals fiber businesses. Vectran is handled by Fibers and Industrial Materials Division, one of the divisions in Fibers and Textiles Company. In Industrial Materials Division, Functional Materials Department is responsible for Vectran business, while other sales departments, namely Fibers and Materials Department II, and Functional Textile Department, are also dealing with Vectran as well.

From the time Vectran production was begun in 1990 until now, Vectran sales have not been carried out by a specific department alone, but the departments thought to be the most appropriate based on criteria (axes) such as application, material, and sales region.⁷⁵ While Functional Materials Department (Location: Osaka) is in charge of comprehensive Vectran sales, applications such as ropes, marine uses, and nets are handled by Fibers and Materials Department II Section II (Osaka), and sales to customers in eastern Japan are the responsibility of Fibers and Materials Department II Section II Section I (Tokyo). Functional Textiles Department (Tokyo) deals mainly with government and municipal office-related customers.

Furthermore, application development is currently handled by Industrial Material Research and Development, a department under Fibers and Industrial Materials Division in Okayama, while the development of yarns themselves is mainly undertaken by Fiber Materials Planning and Development Department under the Fibers and Textiles Company's Production and Technology Management Division in Kurashiki. Although Osaka and Tokyo are geographically separated from Okayama and Kurashiki, each sales department is in daily contact with the Industrial Material Development Department and Fiber Materials Planning and Development Department so that it can respond to requests from customers. While the need for such integration between sales and development was specified by (then) Kuraray Chairman Hiroto Matsuo,⁷⁶ this is not limited to the Fibers and Industrial Materials Division, but can be

⁷⁵ From the authors' interviews with Takeshi Fukushima.

⁷⁶ *Nikkei Business*, February 16, 2004.

viewed as a common characteristic within Kuraray as a firm.

Moreover, when we examine past transitions of the Vectran sales organization, Vectran Promoting Department was established within Industrial Materials and Living Goods Division in 1990, directly after the start of Vectran production.⁷⁷ With the goal of increasing sales volume, Vectran Promotion Department was upgraded to the Vectran Sales Department in 1992 and the number of staff including dedicated, full-time sales staff was doubled.⁷⁸ This department was abolished in 1994, however, and its functions were transferred to Fibers and Industrial Materials Department I within the division.⁷⁹ Afterward, in 2007, a cross-operating division Vectran project team was established and the R&D team tasked with application development and quality enhancement (described earlier) was set up at the Okayama Plant, Kurashiki Plant, and Saijo Plant, respectively, in order to strengthen the sales organization in tandem with the increase in Vectran production capacity.⁸⁰ As is evident from these changes, the form of the organizational structure for Vectran sales can be said to have been altered very flexibly in response to the conditions and development phase at each point in time.

② *Overseas sales*

While the departments outlined above are involved in Vectran sales in Japan, four individuals handle sales in the United States as Vectran Division in Kuraray America, Inc. As touched upon in Section 4, the Vectran sales rights in the Americas and Europe had been granted to Celanese, but in 2005 Kuraray acquired all of the Vectran business-related assets owned by Celanese Advanced Materials Inc. (CAMI), for nearly 500 million yen.⁸¹ CAMI's Vectran sales for the fiscal year 2004 amounted to roughly six million dollars, and as a result of the acquisition Kuraray America, Inc., a wholly-owned subsidiary of Kuraray, took over the sales rights for this business in North America, Latin America, and Europe, as well as the warehouses and employees (at that time total seven individuals).

There are two reasons why Kuraray decided to acquire CAMI's Vectran business. First, the objectives of the two firms did not always correspond when production function and sales function were separated.⁸² Kuraray and CAMI were independent firms, so while Kuraray had the production function and tended to focus on sales

⁷⁷ Kuraray Co., Ltd. Securities Report.

⁷⁸ *The Chemical Daily*, July 21, 1992.

⁷⁹ *The Chemical Daily*, June 3, 1994. Currently, the Functional Materials Department has succeeded to this function.

⁸⁰ *Nikkan Kogyo Shimbun*, November 27, 2007.

⁸¹ *The Chemical Daily*, April 8, 2005.

⁸² The following information is taken from interviews with Takeshi Fukushima.

volume, CAMI only had the sales function, was profit-oriented, and tended to avoid anything that would lower its profit ratio. In such cases, there was a real possibility that the actions that were best for Kuraray and the actions that were best for CAMI would not coincide. So behind the decision to acquire Vectran business-related assets was the view that, by eliminating this mismatch through the acquisition, and taking optimal actions as a single organization, earnings could be increased further.

The second reason was to eliminate information asymmetry. Because Kuraray and CAMI were, as stated, separate organizations, and their objectives did not always agree, so-called ‘asymmetric’ information concerning sales arose between the two companies. Being able to exchange customer information and information regarding applications between persons in charge makes it easier to move successfully toward product development and strengthens marketing capabilities as well.⁸³ Junyo Nakagawa had the following to say on this point:

Of course there’s any number of reasons development doesn’t go well; maybe the yarn needs to be improved, for example—there are lots of situations like that. In such cases, provided you understand exactly what’s taking place, it’s possible to respond, but when the situation is not disclosed, you might not respond the way you could; that kind of thing can happen, too.⁸⁴

The organization Kuraray adopted also includes Kuraray Europe GmbH (established 1991), which handles Vectran sales in Europe, as well as the affiliate Kuraray Trading Co., Ltd., which supports sales in Asia, including Japan.

(2) Process from development to commercialization⁸⁵

① *Process until commercialization*

Working closely with customers and developing materials for their specific needs is said to be an ‘ideal’ process in the application development. However, it is not often the case for the development of Kuraray’s Industrial Fiber business. More common process is to develop a unique material based on its own core technology at first and then try to find its suitable applications. This process is generally called ‘product out.’ If a firm takes this strategy, it is important to develop more advanced materials than those of competing firms, which holds true with regard to Vectran. This originated from

⁸³ *Nikkei Sangyo Shimibun*, April 8, 2005; *Nikkei NEEDS Kigyo Senryaku Jouhou (Japan Corporate Watcher)*, May 31, 2005.

⁸⁴ From the authors’ interviews with Junyo Nakagawa.

⁸⁵ The following description is based mainly on interviews with Takeshi Fukushima.

the fact that Kuraray was a late starter in super fiber development, and because of that position it tried to differentiate its product by developing fiber with some unique characteristics. Junyo Nakagawa made the following comment regarding this point:

Well, certainly we were a late starter. Because Kevlar was already ahead in terms of application development, we aimed at things Kevlar can't do, to use them as strong points against Kevlar.⁸⁶

Even if the engineers developed materials based on their technology, they did not necessarily have a clear vision on its application. In Vectran's case, ropes for marine uses, cables, protective clothing, and fishing nets, for example, are sectors in which Vectran's use was envisaged from the initial development. Kuraray approached manufacturers of these applications from their side soon after the development was completed, which consequently resulted in commercialization. On the other hand, in case of applications which were not envisaged in the initial phase of R&D, it was users who found opportunities to utilize the materials for these applications. Therefore, a firm usually makes accessible its newly developed materials to the public by utilizing such methods as websites, trade fairs, and exhibitions, and waits for potential customers' approach. Together with the approaching companies, the firm proceeds to commercialization by customizing the product if necessary. There are some cases where Kuraray leaves nearly everything until commercialization to the customer once it provides product samples. Conversely, there are also cases where Kuraray has requests from customers and repeatedly submits samples and collected data before commercialization over a number of years. Therefore, it can be said that there is no 'typical' pattern in the process before commercialization. In many cases, there are discussions with customers, and through the process of those discussions, products are created. Because the problem of how to use the materials properly remains to be solved on the customer side, the role of the sales department is to provide support in solving that problem. As Takeshi Fukushima noted:

On the way to commercialization, there is a case that customers request some support to us, for example, "Can't you improve the abrasion properties of this a little more?" We are able to realize the business if we succeed to fulfill such request. It is like you play catch with the customer. But even though we have our own basic image or idea to fulfill their request, it's the customer side in the

⁸⁶ From the authors' interviews with Junyo Nakagawa.

end that has to figure out how best to use our yarn to realize the product they want to develop. To put it the other way around, I think from a certain perspective our development work involves supporting customer's request, that is: "We want to use your yarn in this way, but what would be the best way to use it?"; or "We want to use it, so can you change it a little more like this?" It is our job to follow such requests as much as possible for helping our customers to realize what they want to develop.⁸⁷

Wherever a new application is discovered, the people responsible for sales must acquire a high level of knowledge concerning the application and materials because they have to make suggestions about products which match the applications and understand customers' requests. Moreover, because application development for Vectran will progress on a worldwide scale, they must acquire basic linguistic ability to conduct business in English, of course, but also basic knowledge concerning each application in English and the ability to interact with customers based on such knowledge.

② *Period until a product is commercialized*

In the application development of Vectran, the time period until products are brought to market is not constant, yet there can be said to be a correlation between the length of time before a product is commercialized and the length of the product lifecycle. For example, one of Vectran's uses is in high-performance mooring lines for securing undersea oilfield platforms, as noted previously. In such case, it is indispensable to conduct repeatedly simulations and field tests over several years because safety and durability are heavily emphasized. Consequently, a period of at least three to five years will be required prior to commercialization. On the other hand, for sports applications, in particular, commercialization must move forward in less time than the case of rope for platforms because, in addition to functionality, strong fashion parameters come into play. A product such as rope in the former case, however, is a so-called heavy-duty application (i.e. the product must be able to withstand demanding use), so although an extremely lengthy period of time is required prior to commercialization, once the product has been commercialized, it can become a long lifecycle product and other companies are not easily granted entry into the market. In contrast to this situation, in the case of sports and fashion applications, competition can quickly intensify because competitors can enter the market as easily as the market pioneer, and in many instances product lifecycles are shortened by fashion tastes.

⁸⁷ From the interviews with Takeshi Fukushima.

③ *Product customization*

In the case of Vectran, there is little variation in the product customizations made in response to customers' needs. Developing different oiling agents depending on the uses (agents used for yarns' surface treatment to improve the processability) is cited as a typical example. More specifically, an oiling agent compatible with rubber is used to bond the yarn with rubber, an oiling agent compatible with plastics is applied for plastic reinforcement uses, and an agent which provides good abrasion properties and slippage between fibers is used when applying Vectran for ropes.⁸⁸ Development in this manner—various surface treatment agents corresponding to applications—is a typical method of customization. Sales volume is one criterion whether or not to respond to such customization.

(3) Factors influencing the success or failure of application development

According to Takeshi Fukushima, the probability of an application development project becoming successful is 'very low'. In many cases, when Vectran is tested as a substitute for materials used in an existing application such as ropes, cost performance often becomes a problem. In other words, those who test Vectran judge that the performance is not what they initially expected, or the performance is as expected but they conclude Vectran to be unsuitable from a cost perspective because it is too expensive. Moreover, even if Vectran is used for a completely new application that is successfully developed, sales are still not secured by the problem of whether the material or the system that uses Vectran can be accepted in the market. While the LNG tanker anti-sloshing application (described in Section 5) was developed as an entirely new system, what will be watched closely in the future is whether many customers are attracted to the application in the market (i.e., in this case, whether shipping companies will adopt the above-mentioned system).

In addition, Takeshi Fukushima recognizes, from his experiences, that the probability of whether a certain material would be accepted in a specific market is not so much dependent on materials but more on number of inquiries—the more inquiries we receive, the more customers we gain as a result. Furthermore, he thinks that the number of inquiries is determined by three parameters: the extent to which a company has numerous products with characteristics not found in other companies' materials; how broad the scope of these characteristics is; and how the company can present its products and their characteristics to customers.

⁸⁸ Yorimitsu (2010).

Vectran sales are subjected to influence from the first and second parameters because these are problems stemming from the small size of the market for the material. As we have already seen, Kuraray was a late starter in super fiber development, and by the time of the development phase, Kevlar and other competitors' products had already acquired large markets. When it comes to demonstrating a material's unique properties without competing directly with other firms' products, the company tends to aim at a smaller market. In fact, when developing Vectran, Kuraray's aim was to develop the material by taking advantage of its unique characteristics.⁸⁹ Despite the fact that Vectran itself is produced using highly advanced technology, even departments responsible for sales recognize that the product will always be shadowed by the problem of a relatively small market compared with the market for super fibers from other companies.⁹⁰

With regard to the third parameter, namely, how to present products and their characteristics, building and maintaining an established network can be highlighted as the first key issue. More than 70% of the demand for Vectran comes from overseas markets, with the U.S. market accounting for an especially large proportion. Because the existing channels and network constructed so far—NASA as a typical example, which adopted Vectran for the airbags of its Mars explorer vehicles—are recognized as critical for pursuing application development for Vectran, the resources acquired from Celanese in the United States occupy an extremely important position. As Takeshi Fukushima noted:

It is difficult for the Japanese to sell to U.S. companies. Compared with the U.S. it is relatively easier for us to sell to European market. In North America, well, the hurdles to go into the society, including the language difficulty, are just really high. My impression is that, whatever the product, the U.S. is an area where it's best to let Americans handle it.⁹¹

In 2007, Kuraray expanded its Vectran production facility and boosted annual output from 600 to 1,000 tons; the company's decision to accelerate application

⁸⁹ Interview with Junyo Nakagawa.

⁹⁰ As in the case of poval film (used as the base film for polarized film required in the manufacture of liquid crystal displays) for optics. However, even a material with limited uses (within only a very narrow scope) can generate substantial earnings if there is significant demand. Moreover, in the case of golf club shafts, only a tiny amount of Vectran is used per shaft, but the impact from an advertising standpoint can be said to be significant, even though sales volume is low.

⁹¹ From the authors' interviews with Takeshi Fukushima.

development presumably was driven by effects such as much greater clarity of user information, for example, after Kuraray had acquired CAMI's Vectran business as described above.⁹² Former employees of CAMI, who had connections with the existing customer base as well as advanced expertise related to development, are thought to have played a key role in this turn of events.

The use of trade fairs and exhibitions can be listed as another means of sales promotion. Kuraray has been participating in *Techtextil*, the largest trade fair in Europe dedicated to fibers and nonwoven fabrics for industrial applications,⁹³ and utilize such trade fairs as a venue not only for product PR, but also for meeting and exchanging information with its existing customers. Holding meetings at this trade fair venue makes it possible to achieve significant time and cost savings, another major reason to participate in the exhibition.⁹⁴

In all, 1,322 companies from 48 countries and regions exhibited at *Techtextil 2013* (a 10% increase over the event in 2011). Moreover, the number of visitors, including those to the international trade fair for sewing equipment and related technology, which was held during the same period, rose by 15% in comparison with the previous event to approximately 40,000 attendees (from 113 countries and regions).⁹⁵ When Kuraray participated in 2009, it exhibited, in addition to Vectran as the main product, items such as Kuralon, FELIBENDY™ steam-jet nonwoven fabric, VECRUS™ wet-laid nonwoven cloth made from Vectran polymer, and TIRRENINA™ the next-generation man-made leathers. Kuraray also set up a space for rooms within its booth that was as large as its display space, holding meetings with customers in the hall. When it participated in 2011, it also exhibited new materials in addition to setting up a business discussion space, and exhibited an electro-conductive fiber made of Vectran for the first time.⁹⁶

An additional factor affecting the success or failure of application development is the compatibility with the inquired firm. When undertaking application development, there are some firms that 'click' and other firms that 'don't click' in terms of ways of thinking and orientation, which is similar to personal chemistry. Obviously, it is easier

⁹² *The Sen-i News*, January 23, 2007.

⁹³ *The Sen-i News*, June 30, 2009.

⁹⁴ From the authors' interviews with Takeshi Fukushima. In contrast, Kuraray participates in JEC Europe, a trade show for FRP composites, mainly for the purpose of exhibiting its products.

⁹⁵ *The Sen-i News*, June 13, 2013.

⁹⁶ Japan Chemical Fibers Association press release "*Techtextil 2011* no kaisai gaikyou ni tsuite," ("Overview of *Techtextil 2011*," in Japanese), http://www.jcfa.gr.jp/news/press/sonota/110616_techtextil2011.pdf, accessed July 27, 2013; *The Sen-i News* June 9, 2011.

to develop products in collaboration with firms that ‘click.’⁹⁷ Because Kuraray is a technology-oriented firm, the probability of making a successful development would be higher if the counterpart possesses a similar mentality. In particular, developing a product for industrial uses often requires a considerable time investment so that application development through collaboration becomes difficult when firms differ in their approach or thinking regarding time or other factors.

7. Conclusion

In this paper, we have discussed generally the processes and characteristics of R&D and application development for Vectran since its inception. The key element in the R&D and application development for Vectran was discovering applications that take maximum advantage of characteristics not found in products made by other companies, within a very narrow range of applications. This can be said to have been a development effort aimed in a direction completely opposite to commoditization. As Takeshi Fukushima noted:

It is a question of how to find, in any way, points that common products can’t respond to, and build our stronghold there. If we can’t build such stronghold, the material is useless. If we can ensure a stronghold, in a certain respect, in an area with a size sufficient for us to build it up as a business, we are able to live within the field.⁹⁸

This way of thinking also dovetails with top management’s pronouncement:

Products that are highly general in nature are no match for larger competitors when it comes to volume. Aiming at survival is achieved by specializing in particular applications.⁹⁹

This coincides with the remarks made by former development manager Junyo Nakagawa in Section 4. Despite the problems that accompany any small market, Vectran can be described as a fiber that was developed as a result of being faithful to Kuraray’s tradition of “being a big fish in a small pond.”

⁹⁷ From the interviews with Takeshi Fukushima.

⁹⁸ Ibid.

⁹⁹ *Nikkei Sangyo Shimbun* March 12, 1996.

One characteristic deserving special mention is Kuraray's orientation toward technologies and knowledge at a pure research or 'fundamental' level. Even though Kuraray has adopted a new in-house company system and Vectran is administered by the Fibers and Industrial Materials Division under Kuraray's Fibers and Textiles Company, internally, Vectran is understood as "one form of high polymer chemistry technology" rather than 'fiber' business. This was true in the case of Kuralon as well, a synthetic fiber that Kuraray was the first in the world to commercialize. Takeshi Fukushima commented on it as follows:

We have vinyl acetate (VA) as one base technology; Poval (PVA resin) is one of derivatives and one of its forms is fibers. So in that sense, there is a consensus within the company that we have this base technology, VA, and the resins out the technology are our key products. Then, we have films and fibers as their applications. It is the same story for Vectran. Using the same resin, we produce films, nonwovens, and fibers. From that viewpoint, fibers are one converting form of a particular resin.¹⁰⁰

In Section 5, we considered the example of the monofilament VECRY, which was developed as a derivative of Vectran; in this case the base material was a polyarylate liquid crystal polymer. The molecular orientation technology related to this liquid crystal polymer was used not only for the development of fiber but also for that of films. In 2001 Kuraray began marketing VECSTAR™, a highly functional, high-performance film that was the first in the world to be applied successfully to liquid crystal polymer film processing,¹⁰¹ and in 2004 VECRUS, a nonwoven fabric made from the same liquid crystal polymer, for printed circuit boards, was developed.¹⁰² Kuraray's Japanese catchphrase *Mirabakesso* (new materials that transform into the future) can be said to express this company's unique and ideal way of searching for knowledge at a fundamental level.

¹⁰⁰ From the authors' interviews with Takeshi Fukushima.

¹⁰¹ *Nikkei Sangyo Shimbun*, October 31, 2012.

¹⁰² *The Chemical Daily*, June 2, 2004.

References

Fuji-Keizai Group, Osaka Marketing Headquarters Business Dept. No. 2

“2010 nenban koukinou seni kanren gijutsu • shijou no genjou to shourai no tenbou” (2010 Edition Highly Functional Fibers-related Technologies and Markets: Current Status and Outlook) (in Japanese) Fuji-Keizai Group 2010

Fuji-Keizai Management Co., Ltd.

koukinou seni shijou jittai souchousa 2008 (General Survey of Conditions in the High-Performance Fibers Market) (in Japanese) 2008

Hoshino Yusuke

“Korabore—shon wo tsujita koukinou seni no kaihatsu to jigyouka” (Development and Industrialization through Collaboration: Case of Dyneema) (in Japanese) *Hitotsubashi Business Review* 60(2), 72-85, 2012

Ide Junya

“dai 8 kai shouhi kagaku kouza ‘kore nara tsukaeru suupaa seni’ poriarire—to seni <bekutoran> no seinou to youto” “seni seihin shouhi kagaku” (The 8th Lecture on the Science of Textile End-Uses, “Super Textile Fibers Can be Used in These Ways”: Performance and End-use of Polyarylate Fiber, “Vectran”)(in Japanese) *seni seihin shouhi kagaku (Journal of the Japan Research Association for Textile End-Use)* 52(11), 691-695, 2011a

Ide Junya

“koukyouryoku seni <bekutoran> ni tsuite – uchuu materiariu toshite, kongo no kanousei to shite” (High-strength Fiber < Vectran > - Considering its Future Possibilities as a Space Material) (in Japanese) *materiaru sute-ji (Material Stage)* 10(11), 1-3, 2011b

Komasaka Toshiaki

“youyuu ekishou seni – bekutoran (youto kaihatsu ga susumu koubunshi koukyouryokuseni <tokushuu>) (Thermotropic Liquid Crystal Fiber – Vectran (Polymer High-Strength Fiber Sees Ongoing Application Development < Special Feature >) (in Japanese) *Kogyo Zairyo (Engineering Materials)* 40(2), 78-80, 1992

Kuraray Co., Ltd.

soushin: kurare 80 nen no kiseki: 1926-2006 (Innovation: Kuraray's Path over 80 Years: 1926-2006) (in Japanese) 2006

Nakagawa Junyo

“youyuu ekishou poriesuteru seni no seinou to gijutsu no shinpo” (Advances in Thermotropic Liquid Crystal Polyester Fiber Performance and Technology) (in Japanese) *Hyoumen (Surfaces)* 30(6), 444-450, 1992

Nakagawa Junyo

“kouseinou zairyou to shite no koubunshi ekishou seni youyuu ekishou boushi seni no tokuchou to youto” (Properties and Uses of Fiber from Thermotropic Liquid Crystal Polymers) (in Japanese) *Kobunshi (POLIMERS)* 43(10), 726-727, 1994

Nakagawa Junyo

“bekutoran’ no tokuchou to sono youto – youyuu ekishougata seni (supeshariti seni no sekai(5)) (“Vectran” Characteristics and Applications – Thermotropic Liquid Crystal-type Fibers (The World of Specialty Fibers (5)) (in Japanese) *Kasen Geppo (Japan Chemical Fibers Monthly)* 53(7), 36-40, 2000

Nakagawa Junyo

“ekishou boushi” (Liquid Crystal Spinning) (in Japanese) *Nihon Ekisho Gakkaishi (Journal of the Japanese Liquid Crystal Society)* 5(1), 34-41, 2001

Nakagawa Junyo

“poriarire-to seni to youyuu ekisho boushi” (Polyarylate Fibers and Thermotropic Liquid Crystal Spinning) (in Japanese) *Seni Kikai Gakkaishi (Journal of the Textile Machinery Society of Japan)* 56(5), 210-216, 2003

Nakagawa Junyo

“sukuri-nsha you koukyouryoku monofiramento ‘VECRY’” (VECRY High-Strength Monofilament for Printing Screens) (in Japanese) *seni seihin shouhi kagaku (Journal of the Japan Research Association for Textile End-Use)* 46(6), 345-348, 2005

Nakagawa Junyo and Sanefuji Toru, “seni – firumu (shindankai mukaeta ekishou porima- <tokushuu>) (Fiber and Film (Liquid Crystal Polymers Facing a New Stage <Feature>) (in Japanese) *purasuchikkusu (Plastics)* 44(3), 41-45, 1993

Nakagawa Junyo, Hikasa Kazuyuki, Yokomizo Touru and Sano Hiroki

“koukyouryoku monofiramento ‘VECRY’ · seimitsu insatsuyou ‘V-sukuri-n’ no kaihatsu” (Development of High-Performance Hybrid Fiber “VECRY” and “V-Screen”) (in Japanese) *seni gakkaishi (Fiber)* 60(10), 474 -477, 2004

Shiroyama Kazuyuki

“Vectran’ to FRP oyobi haiburiddoka ni tsuite (ACM (senshin fukugouzai) kyouka ni kiken suru saishin oriamu gijutsu to ACM kyouka sozai – koukyoudo kouseinou seni 1 – <tokushuu> (“Vectran”, FRP and Hybridization (Strengthening of ACM (Advanced Compound Materials) Aided by Leading-Edge Weaving Technology and ACM Reinforcing Materials – High-Strength, High-Performance Fibers 1 – < Feature >)) (in Japanese) *seni gakaku (Fiber Science)* 33(7), pp. 58-61, 1991

Soma Isao

“fukugou zairyou monogatari (dai 7 kai) yuukikei suupaa seni (2) kasei ni tonda

‘Vectran’” (The Story of Composite Materials (Part 7) Organic Super Fibers (2) ‘Vectran’ that Rocketed to Mars”) (in Japanese) *porifairu (Polyfile)* 46(7), 62-64, 2009-07

Sugishima Hiroshi

“kyouka seni – X.ekishou seni” (Reinforced Fiber - X. Liquid Crystal Fiber) (in Japanese) *nihon fukugou zairyou gakkaishi (Journal of the Japan Society for Composite Materials)* 17(6), 223-228, 1991

Sugishima Hiroshi

“zenhoukouzoku poriesuteru seni ‘bekutoran’ no kinou to youto kaihatsu” (Properties and Uses of Fully Aromatic Polyester Fiber “Vectran”) (in Japanese) *seni gakkaishi (Fiber)* 54(1), 12-15, 1998

Ueda Keizo

“zenhoukouzoku poriesuteru seni bekutoran (suupaa seni to sono ouyou <tokushuu>” (Vectran Wholly Aromatic Polyester Fiber (Super Fibers and Their Applications)<Feature>) (in Japanese) *seni gakkaishi (Fiber)* 43(4), 135-138, 1987

Ueda Keizo

“zenhoukouzoku poriesuteru seni ‘bekutoran’” (“Vectran” Wholly Aromatic Polyester Fiber) (in Japanese) *Seni Kikai Gakkaishi (Journal of the Textile Machinery Society of Japan)* 41(5), 316-321, 1988

Ueda Keizo and Kanamaru Tasumi

“kouseinou seni ‘bekutoran’ ni tsuite” (“Vectran” High-Performance Fiber) (in Japanese) *kinoushi kenkyuukaishi (Annals of the High Performance Paper Society), Japan* (25), 12-15, 1986

Yamamoto Youichi

“koukyouryoku poriarire-to seni bekutoran no tokusei to youto” (Characteristics and Uses of Vectran High-Strength Polyarylate Fiber) (in Japanese) *seni seihin shouhi kagaku (Journal of the Japan Research Association for Textile End-Use)* 47(9), 520-523, 2006

Yano Research Institute Ltd.

koukinou faiba – shijou no genkyou to shourai tenbou (Current Conditions in the High-Performance Fibers Market and Future Prospects) (in Japanese) 2012

Yorimitsu Shuhei

“poriarire-to seni (sono tokusei to youto)” (The Specific Character and the Use of Polyarylate (sic) Fiber (in Japanese) *seni gakkaishi (Fiber)* 66(3), 86, 2010

Magazines

Matsuo Hiroto

“kaihatsu · eigyou ittaika koso ga ‘dokuji gijutsu’ wo migaku” (Integrating Development and Sales Hones “Proprietary Technology”) (in Japanese) *Nikkei Business* p.1, February 16, 2004 issue.

Yamane Kazuma, Sugiyama Hiroshi and Tadayoshi Koizumi

“metaru kara– no jidai (621) NASA no wakusei tansa wo sasaeta nihon no shinsozai tekunoroji– (1) 24 ko no eabaggu de kasei shinsaki wo supporti oui chakuriku wo seikou saseta kinzoku yori joubu na su–pa– seni ‘bekutoran’ no kaihatsu” (The Age of the Metal Collar (621) New Materials Technologies From Japan that Supported NASA’s Planetary Exploration (1) Development of “Vectran,” the Stronger-than-Metal Super Fiber that Completely Covered the *Mars Explorer* Satellite with 24 Air Bags and Brought it to a Successful Landing) (in Japanese) *shuukan posuto (Weekly Post)* 36(14), 196-199, 2004-03-26

Yamane Kazuma, Sugiyama Hiroshi and Tadayoshi Koizumi

“metaru kara – no jidai (622) NASA no wakusei tansa wo sasaeta nihon no shinsozai tekunoroji – (2) kasei tansaki 2 ki wo buji ni nanchakuriku saseta su-pa- seni “bekutoran” saidai no tokuchou wa ‘mizu wo suwanai’ bunshi hairetsu” (The Age of the Metal Collar (622) New Materials Technologies From Japan that Supported NASA’s Planetary Exploration (2) The Greatest Characteristic of the “Vectran” Super Fiber that Brought the *Mars Explorer 2* to a Trouble-Free Soft Landing is its Non-Moisture-Absorbing Molecular Array) (in Japanese) 『*shuukan posuto (Weekly Post)* 36(15), 196-199, 2004-04-02

Websites

BASF Japan Ltd.

<http://www.japan.basf.com/apex/Japan/ja/>

Kuraray Co., Ltd.

<http://www.kuraray.co.jp/>

The Ministry of Economy, Trade, and Industry

<http://www.meti.go.jp/>

MODEC, Inc.

<http://www.modec.com/jp/>

Japan Chemical Fibers Association

<http://www.jcfa.gr.jp/fiber/index.html>

Teijin Limited

<http://www.teijin.co.jp/>

Interviews

Junyo Nakagawa

Kuraray Co., Ltd. High Performance Materials Division Development Dept.
Development Manager (at that time)

January 31, 2013 At café & gallery Penny Lane (Kurashiki)

Interviewers: Shimizu Hiroshi (Associate Professor, Hitotsubashi University Institute of Innovation Research), Hoshino Yusuke (Lecturer, Faculty of Political Science and Economics, Musashino University), Hori Keisuke (Associate Professor, Department of Economics, Fuji University)

December 20, 2013 At café & gallery Penny Lane (Kurashiki)

Interviewer: Hori Keisuke (Associate Professor, Department of Economics, Fuji University)

Takeshi Fukushima

Kuraray Co., Ltd. Fibers and Textiles Company Fibers and Industrial Materials Division Functional Materials Sales Dept. General Manager

February 26, 2013 At Kuraray Co., Ltd. Osaka headquarters (Osaka)

Interviewers: Shimizu Hiroshi (Associate Professor, Hitotsubashi University Institute of Innovation Research), Hoshino Yusuke (Lecturer, Faculty of Political Science and Economics, Musashino University), Hori Keisuke (Associate Professor, Department of Economics, Fuji University)

December 5, 2013 At Kuraray Co., Ltd. Osaka headquarters (Osaka)

Interviewer: Hori Keisuke (Associate Professor, Department of Economics, Fuji University)