Study on the PAN carbon-fiber-innovation for modeling a successful R&D management

— An excited-oscillation management model —

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We have investigated the processes of invention of PAN (Polyacrylonitrile) carbon fiber and its technology transfer to private companies. From this investigation and analysis, we have found a new R&D management model, named "excited-oscillation model". This model suggests that both the top-down management and the personal motivation should be in phase and synergetic with each other. In this paper, the results and concept of the above model are described in detail.

Keywords **:** PAN-based carbon fiber, innovation model, technology transfer, management

1 Introduction

"Research" varies by age and by field. Therefore, the results born from the researches may be "results whose relationship with society can be seen in short-term, those that require long-term, and those that are both." Therefore, if they are categorized under one phrase "research useful to society," one may lose sight of the essence. Moreover, there is often a gap between the "useful" perceived by the researcher and the "useful" construed by society.

If this is true, the most useful approach in considering the innovation model (methodology for producing innovation) is to investigate the process of innovation for a case study where the research was actually found to be useful in society, after some time has elapsed. At least, if there are guidelines for actions that can be applied to the present for some technology transfer process, we believe it is useful to study such process to learn the way the research was conducted and how the information was transmitted. Of course, the social background and other conditions may differ, and some elements may not be helpful even if they are reproduced accurately. However, we believe it is possible to extract the essential mechanism of how the research results were transmitted to society and the system in which this transmission occurred effectively, including how the research was conducted, its focal point, and awareness of the supervisor and peers (including companies).

In this paper, we shall focus on the PAN (polyacrylonitrile) carbon fiber, which is an example where the research result of a public institution was recognized widely by society and revolutionized industry. We shall investigate the process of this significant innovation by comparing the activities mainly of the researchers at the Goernment Industrial Research Institute, Osaka (GIRIO) that was part of the Agency of Industrial Science and Technology (AIST), Ministry of International Trade and Industry, and the actual course of events of the PAN carbon fiber research in the following perspectives:

(1) Researchers' mind
(2) Mind of researchers and research management involved in setting the research theme
(3) Transmission and reception of the research results
(4) Human and information network for utilizing the research results

Also, we attempted to derive an innovation model by organizing the process.

Here, we shall not discuss the processes of technological transfer of the manufacturing and assessment methods of PAN carbon fiber to corporation and the following evolution into essential material through the corporate efforts in creating composite material[1]-[3].

Starting from the conclusion, the innovation of PAN carbon fiber occurred because the organic collaboration of the research elements took place in the manner of "excited

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oscillation." Excited oscillation means "'cooperation' where synchronization of the research management and the autonomy was achieved in setting a new research theme that might be useful in society, in the progress of R&D spurred by the researcher's interest," and also includes manifest and latent exchanges and "collaborations" with the companies toward industrial use.

We present the innovation model based on the process of handing over the PAN carbon fiber to industry as the "exited oscillation model," and suggest strengthening the management for future innovation production.

2 Course of technological invention

2.1 Situation of carbon fiber development

(1) Summary of invented carbon fiber

In the 1950s, products made from carbon or graphite (highly crystallized carbon) was used only in molded products that took advantage of the heat resistance and conductivity properties, such as electric equipment brush, electrolysis electrode, graphite for nuclear reactors, or in powder products such as carbon black, activated carbon, and colloid graphite. No carbon material in fiber form was known, and graphite fibers were thought to be extremely difficult to manufacture.

Since graphite does not melt until it is heated to nearly 4000 ºC under high pressure, carbon could not be melted and spun like glass fiber. Like the manufacture of carbon materials in general, fiber could be obtained only by carbonizing organic material, and investigations were done using various fibrous materials such as cellulose and polyvinylidene chloride fibers. As a result, it was found that acrylonitrile fibers, if carbonized under suitable heating conditions, could be made into graphite by releasing the nitrogen and hydrogen in the molecule mainly as ammonia and hydrocyanic acid, providing carbon that maintained the form of the fiber, and by graphitizing this fibrous carbon by high-temperature treatment. The obtained product had metallic luster, and was observed by x-ray measurement to be profoundly graphitized[4]. The PAN carbon fiber was developed in this manner.

(2) Course of development

Originally, carbon fiber was developed in the United States in 1956, using rayon as the raw material (Fig. 1)[1]. In the United States, Union Carbide Corporation (UCC) had some success with the rayon carbon fibers.

In Japan, Dr. Akio Shindo of GIRIO became aware of the events in the United States, and started studying the carbonization of polyacrylonitrile fiber instead of rayon. In September 1959, a patent was filed[5] for the PAN carbon fiber, and a research entitled "Study of graphite fiber (1st report) – Growth of crystallites in heat treatment" was presented at the Annual Meeting of Chemistry-Related Societies held in October 1959[6]. In November 1959, this research result was also published in the *GIRIO News*[7] that was circulated widely among the people of companies in the Kansai region. The details of the research are summarized in the *GIRIO Report* No. 317[8].

Through these activities, it could be imagined that the result of PAN carbon fiber research was strategically announced under the judgment that it was highly innovative and had excellent prospects.

An advice from a U.S. military personnel in 1965 provided a major turning point for Dr. Shindo's R&D[2]. Until then, attempts were made to utilize the PAN carbon fiber as a material characterized for its "flexibility" along with its main properties, heat resistance and conductivity. However, the military specialist mentioned that its superiority was "mechanical strength" and "tensile modulus." The direction of research turned to use as structural material. Since this turning point, the corporate participation in carbon fiber research increased, and the companies' effort toward industrial use accelerated. For these companies, GIRIO was essential because it was producing outstanding results in the PAN carbon fiber research.

In addition to the "collaboration" with industry in research and technical assistance, the research on "standardization," which is mandatory for the development of new materials, started in 1975. The Japan Industrial Standard (JIS) for carbon fibers was established in 1980. These efforts contributed greatly to the increased competitiveness of the Japanese companies in carbon fiber. It was initially used in leisure products for their light weight and strength. Its use expanded to industrial structural materials for architecture and aircrafts that required reliability, and now the world share of carbon fibers by Japanese companies is about 80 %.

2.2 Research environment (research management at GIRIO)

At the time carbon fiber development started, GIRIO declared "promotion of industrial technology through research," and organized the infrastructure and raised people's enthusiasm.

In about 10 years after the World War Ⅱ, there were several products that were put to industrial use from the researches done at GIRIO. The following description is from the *GIRIO Annual Report* for 1959[9]. "Part 1 is the research of inorganic chemical engineering. Research on carbon is one of the traditional researches at GIRIO. In addition to the basic research conducted from the past, research of increasing the density of carbon products, electrode for air cell, carbon material for nuclear reactors, and deboronization of caking additive were conducted, but the greatest achievement for this year was 'the successful manufacturing of graphite fiber and graphite woven fabric with considerable mechanical strength,' and this is expected to become new industrial material in the future." At this point, focus of carbon material shifted to fiber graphite in addition to conventional graphite materials for nuclear reactors, and we could see that this was an organizational effort.

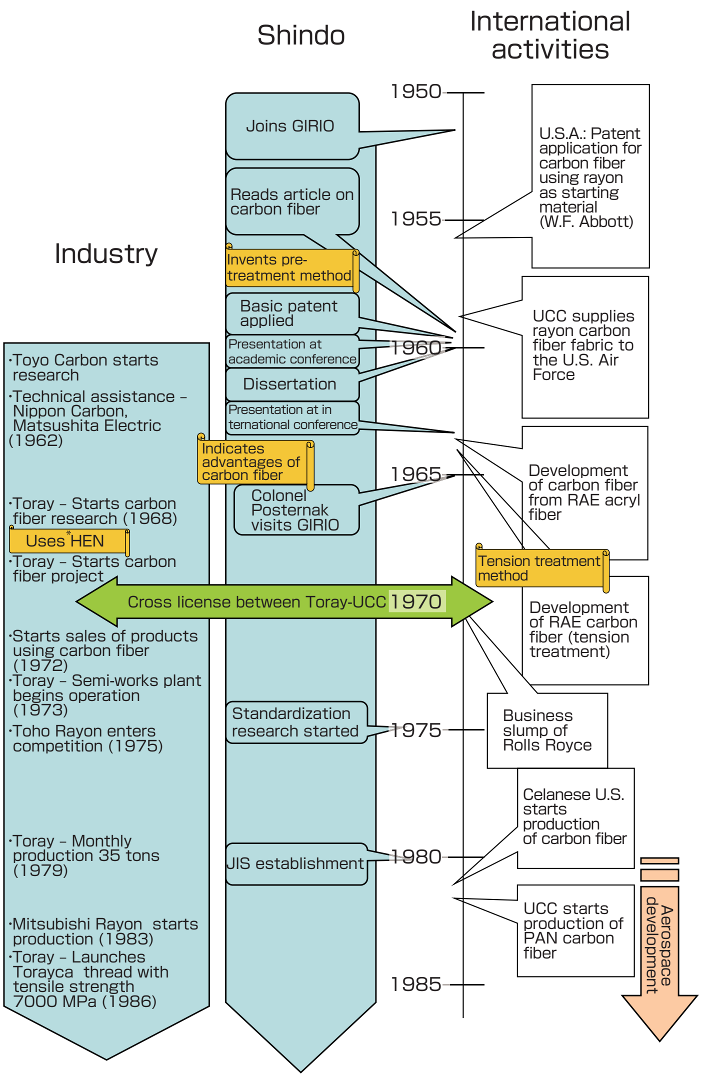
When Tadashi Sengoku became the director general on August 1958, many results were produced at GIRIO and the number of publications and patent applications increased sharply. As will be mentioned later, this was the time when the economic growth was taking off in Japan, and many companies established research laboratories to capture the wave of technological innovations. The companies dispatched their personnel to GIRIO to seek technical assistance. There were several people who left GIRIO at the invitation from the private sectors. The exchange of human resource with industry was promoted.

In 1961, which was two years after filing the basic patent for carbon fiber, the "Technological Consultation Office" was established to process the work of technical assistance and consultation to transfer the research results, many of which were valuable research that remained unused at GIRIO, to the appropriate private companies. The management at that time was highly aware of the collaborations with industry.

2.3 Motivation that lead to the invention

Dr. Shindo, the inventor, joined GIRIO in 1952, and was assigned to work on carbon at the laboratory, yet he did not think that the result would necessarily be put to industrial use. Dr. Shindo sought a novel theme for his engineering technology research with a basic stance of "wanting to be useful to society."

With this mindset, he found an article in a newspaper that he read as part of daily information gathering, that fibrous graphite was manufactured in the United States (Fig. 2)[10].



* HEN: Abbreviation of hydroxyethyl acrylonitrile. By copolymerization, firing time was reduced and great improvement in mechanical property was achieved.

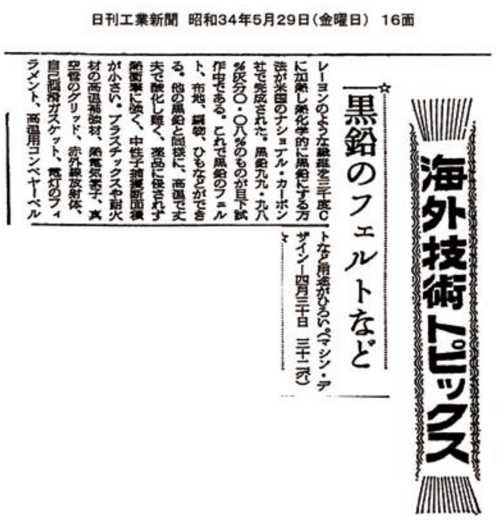
Fig. 1 Flow of carbon fiber development.

Inspired by this article, he started research on the new carbon fiber (one-dimensional carbon material).

In engaging in this research, Dr. Shindo asked himself, "What kind of new uses does the fibrous graphite promise in the future?" and self-answered as follows[7]:

(1) Since it has excellent chemical resistance, it is suitable as filter material for acid and alkali
(2) Since it has very good heat resistance, it can be used for filtering non-oxidized high-temperature gas
(3) Since it has good electric conductivity in addition to heat resistance, it can be used as infrared radiator or vacuum tube filament (Author's note: although transistors were known at this time, vacuum tubes still dominated).
(4) It can be used as filler for synthetic resin
(5) Although there is a problem of black color, it can be useful for preventing static electricity in synthetic resin
(6) String or fabric form product can be used as ribbons for electric devices
(7) It can also be used as fireproofing material.

Since the direction of industrial application of PAN carbon fiber was set on mechanical strength, none of the above was put to practice. What is important here is the idea and basic stance of clarifying the objective of research as something useful in society. Although the research theme was set according to Dr. Shindo's personal interest and enthusiasm, it should be noted that he carefully considered in advance "where in society his own research would be useful."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海外技術トピックス

黒鉛のフェルトなど

レーヨンのような繊維を三千度Cに加熱し熱化学的に黒鉛にする方法が米国のナショナル・カーボン社で完成された。黒鉛九九・九八%灰分〇・〇八%のものが目下試作中である。これで黒鉛のフェルト、布地、編物、ひもなどができる。他の黒鉛と同様に、高温で丈夫で酸化し難く、薬品に侵されず熱衝撃に強く、中性子捕獲断面積が小さい。プラスチックスや耐火材の高温補強材、熱電気素子、真空管のグリッド、赤外線放射体、自己潤滑ガスケット、電灯のフィラメント、高温用コンベヤーベルトなど用途がひろい（マシン・デザイン―四月三十日 三十二頁）

Fig. 2 Newspaper article that provided inspiration for PAN carbon fiber development (used with permission of *Nikkan Kogyo Shimbun*).

Overseas Technology Topics: Graphite Felts, etc.

A method of creating graphite by heat-treating fibers like rayon to 3000 ºC was developed by the National Carbon Company of the United States. The current prototype has 99.98 % graphite and 0.08 % ash. This product can be made into graphite felt, fabrics, textiles, and strings. Like other graphites, it is resistant to high temperature, does not become oxidized, is not corroded by chemicals, resistant to thermal shock, and the thermal neutron capture cross section is small. It can be used widely as high-temperature stiffener of plastic and refractory materials, heat electric element, grid of vacuum tube, infrared radiator, self-lubricating gasket, lighting filament, and for high-temperature conveyor belt. (Machine Design – April 30, p.32)

2.4 Background of technological transfer and researchers' actions

(1) Background

The basic patent for PAN carbon fiber was filed in 1959. This was the year of abolition of the Japanese measuring system (employment of the metric system), start of construction of Tokaido Shinkansen, and start of commercial television stations. In the following 1960s, the primary energy shifted from coal to oil, industrial complexes sprung up along the Pacific coast, and Japan entered the period of rapid economic growth.

The "three holy appliances (black-and-white television, washing machine, and refrigerator)" were becoming common in the households, and people were trying to reach the American and European living standards. However, the industrial products of this age were already realized in the U.S. and Europe, and therefore, if the product had function and price suitable for use in Japan, it could be readily sold in Japan. By the latter half of the 1960s, with the opening of free trade, the necessity of strengthening Japan's industrial technology was felt strongly, and the expectation and interest of industry in the public research institutes rose higher than it was before the World War[11].

In this historical turning point, GIRIO underwent a structural change to promote technological transfer to contribute further to the R&D of industrial technology. In April 1967, the management underwent an organizational change along with five other research institutes under the Agency of Industrial Science and Technology, and the general affairs division and the research planning management were established.

Toray Industries, Inc., which is currently highly successful in the commercialization of PAN carbon fiber, started production of carbon fiber in full force around 1968. This matches the time when GIRIO started technological transfer for carbon fiber to various industries after gaining momentum through this organizational change.

(2) Action of the researchers

While the role of the national research institutes became clear as supporter of development of industry in response to social demand, the researchers started to place importance on actions to carry out their mission, and followed the research management policy of GIRIO. However, their actions were not severely regulated, and Dr. Shindo's research theme was based on the researcher's curiosity and sense of mission (what was expected of the national research institutes) with approval of the supervisor. Unlike the present situation where there is a flood of information, back then it was possible to think thoroughly about one's research while conducting experiments.

On the other hand, the research results were handled appropriately by the research management, by prioritizing patent application rather than the researchers taking initiative to present them at academic conferences. The initial research period of PAN carbon fiber was not only driven by the researchers' interest, but was a result of good judgment and decisions of the research colleagues and managers as well as the industrial policy of the Agency of Industrial Science and Technology.

2.5 Action of industry

(1) GIRIO and local industry

Ever since its inception, GIRIO valued the relationship with local companies. In Osaka, trade developed in modern age, and new businesses were started up using the wealth gained in the trade. In fact, many businesses in pharmaceuticals and home appliances were started in Osaka by individuals, as well as by zaibatsu conglomerates. Because of this environment, people were constantly seeking ideas for business and information about latest developments. GIRIO was a place to obtain information, but GIRIO was not really aware of the underground information exchange outside of its activities as a public organization.

In fair-sized companies that engaged in R&D, the supervisors ordered, "If your research gets stuck in a rut, go seek guidance at GIRIO." One of the authors has heard that when a corporate researcher obtained certain results after solving a problem or produced new proposals after getting help by technological information obtained from daily conversations at GIRIO, the researcher went on to company presentation without mentioning that the idea was picked up at GIRIO. Therefore, there are very few official data such as of joint research and patent licensing that show the relationship between GIRIO and a company.

However, there were several cases where technological transfer to companies was done through official technical assistance or joint research, and some companies have expressed gratitude to GIRIO in the "company history." Examples of articles pertaining to PAN carbon fibers include the following:

(1) *Fifty Years History of Nippon Carbon* (Nippon Carbon Co. Ltd., published August 31, 1967)

(2) *Fifty Years History of Toray* (Toray Industries, Inc., published June 1, 1977)

(3) *Progress through Effort: Fifty Years History of SEC Corporation (formerly Showa Electrode Corporation)* (SEC Corporation Ltd., published October 23, 1984)

All mention that joint research and patent licensing from GIRIO for carbon fiber development helped their businesses.

(2) Action of industry in carbon fiber development (Fig. 3)

At the time, there were two groups that engaged in carbon fiber development, the primary group and the second group, and the two groups took different actions. The former worked on the commercialization of carbon composite material CFRP, and conducted high profile R&D. The latter

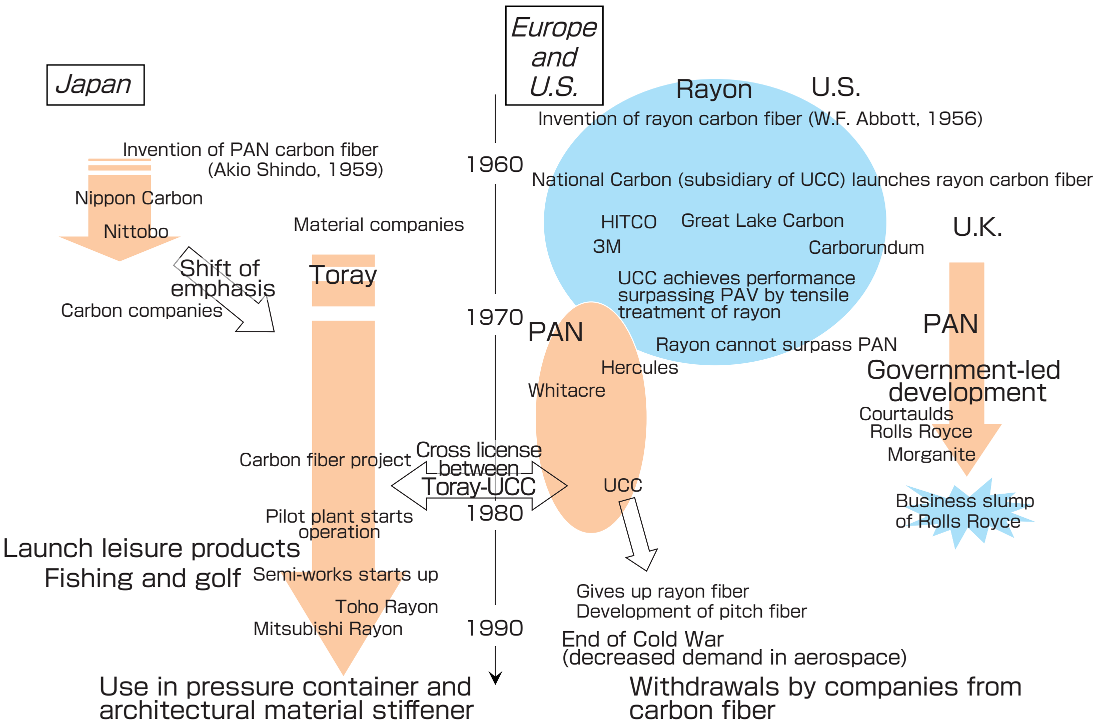

Fig. 3 Efforts by Japanese and overseas industries on carbon fiber

concentrated on lower-cost material as alternative to PAN products and studied cost-reduction manufacturing process, and were not publicized overtly and became "underground" activity. That is, they aimed to obtain actual results through daily but unofficial "conversations" with Dr. Shindo's research group.

Although no product that surpassed the performance of PAN was discovered, GIRIO was able to systematize the effective materials with awareness that the sample and information that the corporate researchers brought to them were to be kept "secret." With the companies' intentions to obtain technological hints and the fine-tuned information compilation of GIRIO, the material development in this area progressed and the international competitiveness increased. The interest of industry ("awareness" and "utilization") and the daily research activities at GIRIO were later proven to be essential for the innovation in a form that did not receive the spotlight.

3 Analysis of the innovation model

3.1 Individual interest and motivation of organizational research (Fig. 4)

(1) Individual interest

In working on carbon fiber, Dr. Shindo started by imagining the social effect of his research and thought, "Perhaps this and that could be accomplished." If one has a specific goal, the goal itself will provide prospect and guidance even when the researcher hits a wall. Also, by changing the goal or by raising or lowering the goal value, an unexpected hint for solving the problem may appear.

The autonomous action driven by personal interest increases the possibility of serendipity. Such serendipity means ability or gift to find something valuable although it may be different from the item one was looking for initially, and is not the "phenomenon" of finding something. As it is an "ability," it can be polished. It is possible to polish such ability by interest and observation, filing (recording), increasing the range of behavior, and by association. It is important to maintain a degree of freedom so personal interest can be nurtured. However, it should not be wild freedom, and it is necessary to instill the mindset of desiring what is wanted by society.

(2) Motivation of organizational research

GIRIO's policy was management that strongly pushed the industrial use of research results[11]. The ways in which the results were presented to society (patent, papers, reporting sessions, and others) were always planned according to the progress of the research and contact with industry. To propel the results, the scale of the research funding was controlled carefully according to growth. When basic research shifted to Ordinary Research[Term] and many companies participated and the demand for technological development from industry increased, it was shifted to Special Research[Term] where large-scale research funding was granted. The motivation of organizational research starts by capturing the trend of industry. It is necessary to give out a message that if a good result is produced and can be sent out to society, the research driven by the researcher's interest can be supported powerfully.

3.2 Research management

When the research management is investigated carefully, some characteristics can be listed.

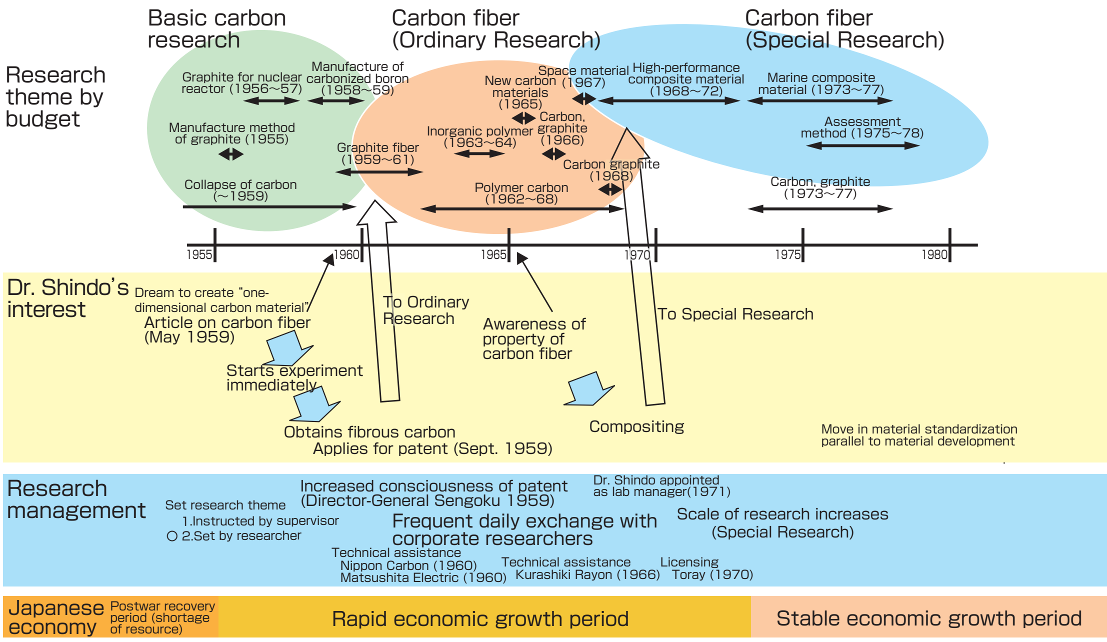

Fig. 4 Personal interest and direction of research theme.

(1) Clear goal
At GIRIO, various efforts for "promoting industrial technology" were conducted. Researches were organized along these policies. Although the research may be driven by personal interest, the researchers are encouraged to consider practical application because the policy of the organization states so. Externally, particularly to the companies, this instilled confidence that the researches would be conducted for application.

(2) Daily exchange with companies
GIRIO became a "reliable place" for local Kansai companies. There was a system where the companies could seek advice casually, and information was exchanged without official procedures. Visits by corporate researchers were frequent, and there were many transfers of human resource from GIRIO to companies, and the ground for "technological transfer through human resource exchange" was laid. Exchange of knowledge would make companies reconfirm their research status and direction of the companies, and this confirmation also induced awareness of the companies. Later in the course, demand for "technological standardization" by the companies was raised, and the standardization research that would be the foundation of industrial use was started.

(3) Research fund allotment in synch with growth of research theme
Since its invention, carbon fiber headed steadily toward industrial use. Until attention was brought to its mechanical properties, corporate participations were mostly done by carbon manufacturers, and there were only little participation by material manufacturers like Toray, which would become greatly successful later. This research was therefore positioned as Ordinary Research, but when the corporate participation increased rapidly and new developments in industrial use were perceived, it became Special Research and large-scale Project Research, and this accelerated the research further.

3.3 Actual state of technological transfer

Through the presentation of Dr. Shindo at the Carbon Conference in the United States in 1963, the British carbon researchers realized the advantage of using PAN fiber and started research of PAN carbon fibers. Also, it was an American military personnel that recognized the value of the invention by Japan that was still a developing nation at the time[2]. This surprised the inventor, Dr. Shindo, himself. "Mechanical strength" was a totally different requirement for a product originally developed for heat resistance, conductivity, and one-dimensional form. The researcher narrowed down the focus, and the focus of research shifted to search something with higher function or whether such product could be synthesized.

At this point, the Japanese carbon product companies and chemical fiber companies started to join. However, they could not reproduce the product with the same strength even when they referred to the publicized patent. What was the condition that determined the property? They sought technical assistance "unofficially" from the inventor group on what should be the center of assessment. The companies that were not fiber manufacturers were eyeing the opportunity to enter this field. This accumulated various data in the inventor group. Since the rule of never disclosing the competitors' information was strictly observed, the world's top data and analysis results were concentrated in the hands of the inventor group.

Such spiral can occur even today. In the R&D under market principle, systemization and efficiency cannot be manipulated in this area. Of course, after successfully commercialization through the incessant effort of the primary group, technical assistance to the secondary group may be done systematically without revealing the name of any specific company. In such a case, it is important for both the researchers of the public institution and the companies to be aware that the secondary group does not merely develop the same product as the primary group, but it engages in development to add their own original idea.

This originality is the power that allows the product to grow into something that surpasses the primary product. Various steps exist in the technological revolution including the power to find something that does not exist in the world (inventor group), power to capture the budding research result (primary group), and the power to conduct improvements to enhance the performance of the product that starts to take shape (secondary group). Although the achievement of the inventor group is often praised, it should not be forgotten that the technological innovation through the combination of technologies also strengthens industrial competitiveness.

In the development of PAN carbon fiber, some companies such as manufacturers of carbon products, chemical fiber, and electric appliances became interested and attempted learning the technology, and technological transfers were done 10 years prior to the actual marketing of the product. Since carbon fiber and CFRP that combined resin and carbon fiber were totally new materials, there was a long period of trial and error without evaluation standards to judge whether a product was of the best performance in the R&D phase. Confusion arose in the late-starting companies, and many brought their products to the Shindo lab and asked everything from, "Is this really what you call carbon product?" to "Which property should we set as R&D target?" and "What is the key point in making the same product?" Of course, it would have been lucky if something surpassed the PAN carbon fiber developed at the Shindo lab. However, no such product appeared.

Needless to say, there is no argument against the continued research to improve performance (or check that there is no material that surpasses the current material) by the original researchers and joint researchers. The corporate researcher tries to accumulate peripheral data in R&D considering corporate profit. However, in this case, not all data are publicized. Patent filing for intellectual property is done actively. However, there is a mixture of patents of "the main product" and "everything else." It is necessary to be aware that this is part of the corporate activity. The "everything else" products serve as a smoke screen against competitors, and they may also become barter items when buying and selling the technology.

What is important here is that "technological transfer" is not singular or uniform, but is done by absorbing the background situation. In some cases, the later generations may focus only on the success stories, and the readers must be careful when reading them. What we wish to point out here is the fact that only the best product (in this case PAN) survives with the support of a great quantity of latent research results because there are many competitors and people involved. Researchers of national institutions may be deeply involved in this development.

Lester and Piore propose the "sheltered space" model, because for producing innovation, "if the researchers are given a place where they can engage freely in interpretive effort, the autonomy of the researchers will bring about new development"[12]. On the other hand, the "space" at GIRIO was a gathering of industrial researchers with clear technical demand, but it was of private interactions with the Shindo group rather than a place of exchange among the researchers. However, the space for interaction for improving the international industrial competitiveness around the Shindo group including the Ministry of International Trade and Industry, the Agency for Industrial Science and Technology, and the Japan Carbon Manufacturers Association were open. The authors think that, rather than a "sheltered space" which is a static space, the complex of the interactive space and the Shindo group at GIRIO functioned as a "dynamic space" where the R&D and management mutually interacted in synch.

4 Conclusion

We investigated the process of innovation in detail taking PAN carbon fiber as an example. The development from invention to product realization, though staged in a background that is vastly different from now, is thought provoking for today's researchers.

From the information on carbon fiber development coincidentally learned from the daily information gathering, the researcher considered its industrial use from the beginning, selected themes with clear objectives, searched for the experiment method, and engaged in research. The procedures for timely patent obtainment went smoothly and patent application was accepted. The dramatic progress that followed started with the information that the demand of industry for carbon fiber material was mainly for mechanical strength. The direction of research was shifted, and collaborative and cooperative research was done with industry to optimize the material property, study compositing with plastic, and achieve practical application as CFRP composite material. Even more important was the effort on standardization of measurement of mechanical strength to guarantee the reliability of the product, and this contributed greatly to solidify the foundation of industrial use of carbon fiber. Also, the steady accumulation of research results that might never see the light conducted in the incubation period before the product set out into society including daily information exchange with GIRIO induced new awareness, and this led to joint research. This brought about industrial

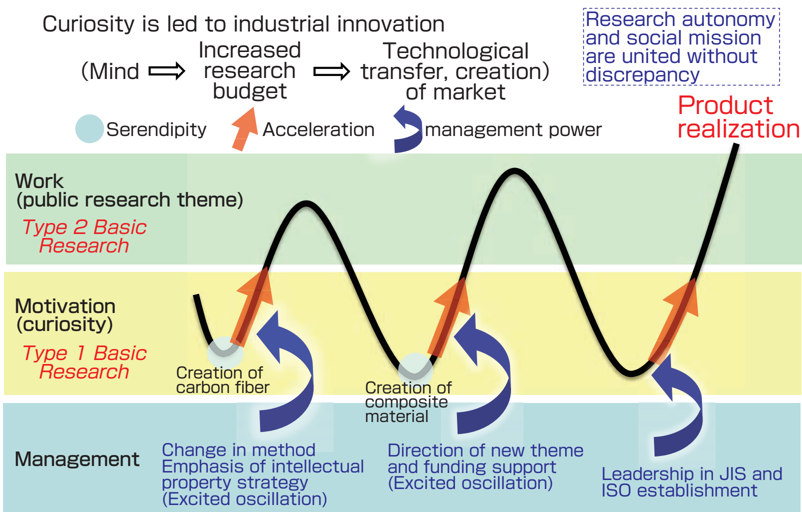

Fig. 5 "Excited oscillation model" of innovation.

change far beyond the original expectation of the inventor.

It was reaffirmed that the following points were important as components of this process:
(1) Serendipity based on clear issue consciousness of the researcher
(2) Matched phase between the researcher's motivation and management
(3) The industry's aggressive desire to develop new business
Today's industrial change would not have resulted or would have remained small, if any of the process was absent.

Moreover, timely cooperation effect of each element is important. This will develop into "excited oscillation" where mutual actions are strengthened, and the progress to industrial use accelerates from a certain point in time. The "excited oscillation model" can be presented as an innovation model to unify the research autonomy and mission in society without discrepancy (Fig. 5).

Again, reconsidering the innovation process of the PAN carbon fiber to check this excited oscillation model, the series of research on PAN carbon fiber was born as a serendipity driven by a researcher's interest in the manufacture method of carbon fiber through graphitization, and the management led it to practical use by encouraging patenting. Also, the unforeseen meeting with a third party offered a chance to shift the focus to mechanical strength, and the R&D for material development and creating composite material (CFRP) was conducted due to this change in policy, the management accelerated the process through funding support by raising its status to a Project, and dramatic progress followed. In addition, research on the standardization of carbon fiber material contributed to guaranteeing the reliability, and pushed the spread of industrial use. All these processes were accomplished under close cooperation of the researcher-management and research-industry.

Positioning the findings obtained through the model and analysis as proposals for the efforts for future creation of innovations, the following will be the key scenario:
(1) Clarification of "mindset" that is the basis of researcher's "autonomy"
(2) Establishment of "management" that synchs the researcher's mind to society
It can be concluded that it is important that the research organization (executer of R&D) and government organization (planner of R&D policy) to understand and to operate appropriately.

Based on this model, the management is required to "motivate the researchers when they are setting the research theme," "review the research theme and system when it is matched against the social values according to the progress of the research," and to "engage in technological transfer and related committee activities to improve or create social values." Organic collaboration, particularly resetting of research theme by the researcher and synchronization by the management as the research progresses, are strongly desired.

This model seems to have similarities with the chain model of Stephan J. Kline[13]. While the Kline model is a phenomenological model, the excited oscillation is a management model for producing innovation. This is a point that we emphasize in this paper, and to produce innovations in the future, the role of management is the most important over everything else, and we believe this model is effective as a model to create a guideline.

Acknowledgement

In preparing this paper, we made full use of an interview with Dr. Akio Shindo, the father of PAN carbon fiber, as an information source for course of events that do not show up in papers and patents. We obtained detailed information about the people's awareness and actual practice in research through interviews with Dr. Yoichiro Nakanishi and Yoshihiro Sawada, who were joint researchers of Dr. Shindo. We learned of the views on Dr. Shindo's interest and curiosity through an interview with Dr. Rokuro Fujii who was a joint researcher in the early stages of carbon fiber research. We learned about the research environment at that time and the daily activities of researchers through interviews with Dr. Kanji Matsuo and Isao Ogino, former senior researchers. This paper was prepared by compiling the information from Dr. Kazuo Ohtani and current AIST employees who were involved.

Terminology

Ordinary Research and Special Research: The researches conducted at the former Agency of Industrial Science and Technology could be roughly grouped into basic "Ordinary Research" and "Special Research" that includes large-scale projects or researches directed by the MITI. Based on the Outline for Research Management of the Agency of Industrial Science and Technology, the theme selection, planning, fund allotment, and management of the results were left to the deliberations of the director general.

Resource Material

Dr. Shindo *et al.* discovered the basic principle of the PAN carbon fiber and its manufacture method, and obtained the patent. Toray received licensing and engaged in long-term R&D as a government-industry collaboration. Many major companies around the world joined the challenge, but the Japanese companies (Toray Industries Ltd., Toho Tenax Co., Ltd., and Mitsubishi Rayon Co., Ltd.) hold 80 % of the world share in the high-performance carbon fiber market. The reasons the Japanese companies conquered the world in this area were:

(1) The American and European companies dropped out in the technological innovation competition

(2) The Japanese companies continued long-term investment in R&D, and

(3) The Japanese government continued to support the R&D.

(Cited from Minoru Yoshinaga (Japan Carbon Manufacturers Association): Innovative materials of the 21st century lead by Japan – carbon fibers that contribute to low-carbon society," Material 4-1 (April 21, 2009) distributed at the 80th Council for Science and Technology Policy.)

References

[1] M. Ishii: *Dokusoteki Na Shohin Kaihatsu O Ninau Kenkyusha Gijutsusha No Kenkyu (Research of Researchers and Engineers Who Engage in Original Product Development)*, National Institute of Science and Technology Policy, Ministry of Education, Culture, Sports, Science and Technology (2005) (in Japanese).

[2] A. Shindo: Tanso sen'i no kenkyu kaihatsu (Research and development of carbon fiber), *Kinki Kagaku Kogyokai*, 611, 5-8 (2004) (in Japanese).

[3] Japan Industrial Technology Association: *Heisei 18 Nendo Kogyo Gijutsuin Homerun Tokkyo No Chosa Bunseki Hyoka Hokoku (Report of Survey and Analysis of Homerun Patents at Agency of Industrial Science and Technology 2006)*, (2007) (in Japanese).

[4] A. Shindo: Tanso sen'i no kenkyu I – netsu shori ni tomonau kesshoshi no seicho (Study of carbon fiber – Growth of crytallite in heat treatment), *Osaka Kogyo Gijutsu Shikenjo Kiho (GIRIO Seasonal Report)*, 12(2), 110-118 (1961) (in Japanese).

[5] A. Shindo, R. Fujii and T. Sengoku: Tokkyo (Patent Application Publication) Sho 37-4405 "Akuriru nitoriru kei gosei kobunshi butsu yori tanso seihin o seizo suru hoho"("Method for manufacturing carbon product from acrylonitrile synthetic macromolecular substance"), (1959) (in Japanese).

[6] A. Shindo, R. Fujii, A. Takahashi and T. Sengoku: Kokuen sen'i no kenkyu (dai 1 po) netsu shori ni tomonau kesshoshi no seicho (Study of graphite fiber (1st report) - Growth of crystallite in heat treatment, *Kagaku Kankeigaku Kyokai Rengo Shuki Happyokai (Annual Meeting of Union of Chemistry-Related Societies)*, (1959) (in Japanese).

[7] "Atarashi tanso zairyo – kokuen sen'i no seizo – ("New carbon material – Manufacture of graphite fiber"), *Daikoshi News (GIRIO News)*, 3(11), (1959) (in Japanese).

[8] A. Shindo: Studies on graphite fibre, *Osaka Kogyo Gijutsu Shikenjo Hokoku (GIRIO Report)* 317 (1961).

[9] GIRIO: *1959 GIRIO Annual Report*, (1959) (in Japanese).

[10] *Nikkan Kogyo Shimbun*, May 29, 1959, Page 16, (1959) (in Japanese).

[11] GIRIO: *Osaka Kogyo Gijutsu Shikenjo Gojunenshi (Fifty Years History of GIRIO)*, (1968) (in Japanese).

[12] R.K. Lester and M.J. Piore: *Innovation - The Missing Dimension*, Harvard University Press (2004). [Japanese translation by N. Yoda: *Innovation*, Seisansei Shuppan (2006).

[13] S.J. Kline: Innovation is not a linear process, *Research Management*, 28(4), 36-45 (1985).

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Withdrew from the doctorate course at the Graduate School of Science, Osaka University in 1973. After some time at the Institute of Scientific and Industrial Research, Osaka University, joined GIRIO in 1974. After 1998, appointed director of Ehime Institute of Industrial Technology, acting director of AIST Kansai, and council member of Evaluation Division. Studied the contribution of research results to society from the aspects of management and evaluation of research organization. In this paper, based on his own experiences at GIRIO and Osaka National Research Institute, and from the interviews to people involved, built the framework of the paper and selected the points of emphasis.

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Discussion with Reviewers

1 R&D scenario

Question and comment (Naoto Kobayashi, AIST Advisor)

The “excited oscillation model” proposed in this paper is new and interesting. I recommend you clarify the scenario for “what should be done to excite innovations in the Japanese industry in the future” (that is, scenario for utilizing the research result). I think the value of this paper will be enhanced by doing so, and therefore I expect you to add descriptions.

Answer (Osamu Nakamura)

As you indicated, the “excited oscillation model” was derived from the analysis of case studies that brought about significant socioeconomic impact among the R&D efforts of AIST. Using the findings gained from this model and the process of analysis as proposals for efforts toward future innovation, the following two points should be particularly emphasized:

- clarification of “mindset” that will be the basis of the researcher’s “autonomy,” and
- establishment of “management” that synchs the researcher’s mind with the society.

We added descriptions that point out that it is important for the research organization (execution of R&D) and government organization (planning of R&D policy) to consider the above points.

2 Components

Question and comment (Naoto Kobayashi)

The pillar of this paper is the statement that the effective correlations and linkages of various components functioned in how the PAN carbon fiber developed by Dr. Shindo was put to practical use. Using the words of the paper, (1) the researcher’s serendipity (product of the researcher’s autonomy), (2) research environment in synch with the researcher’s interest (combination of autonomy and management), and (3) the awareness of the industry (starting point of market creation). You should clarify whether these components are sufficient or that they are merely requirements for building a universal model containing these components. Also, I think you should select words so (1)~(3) will become more universal expressions (they should be understandable when they are cited as “excited oscillation model” in the future). For example, how about (1) free conception and social consciousness of the researcher, (2) appropriate time-space support by the research management, and (3) awareness of the industry and straightforward exchange of opinion, and others. (Also, does the suggestion from the American military personnel belong to (3)?)

Pertaining to (3), do you suggest that the “sheltered space (http://www.arengufond.ee/upload/Editor/industryengines/files/foorum/lester%20slides%20021208.pdf),” as described by Professor R.K. Lester of MIT, existed at GIRIO 40 years ago?

Answer (Osamu Nakamura)

As you indicated, this paper explains the excited oscillation model using the three components. The process leading to innovation was analyzed and summarized into three essential components, and we think they are sufficient as components of this model. However, we shall change the expressions as follows to clarify and to add universal character to the function of each component:

(1) Serendipity based on clear issue consciousness of the researcher
(2) Matched phase between the researcher’s motivation and management
(3) The industry’s aggressive desire to develop new business

For (3), the sheltered space as proposed by Professor Lester did not exist at GIRIO back then. For sheltered space, Professor Lester states, “If the researchers are given a place where they can engage freely in interpretive effort, the autonomy of the researchers will bring about new development.” However, simple provision of a place gives the impression that the model is static. In the “excited oscillation model,” the mutual interaction between the researcher and the management lies at the base, and it is “a dynamic model where the management excavates and exposes the intentions that the researchers themselves may not be aware, and provides action in synch with the phase toward production of innovation.” We analyze that there was a dynamic model at GIRIO from its inception, and in that sense it was different from the sheltered space concept.

In this paper, we explained Professor Lester’s sheltered space and stated the difference from excited oscillation model.

3 Effect of the model

Question and comment (Naoto Kobayashi)

While the proposed “excited oscillation model” is extremely interesting, why have there been just a few results that lead to major innovations in the later Agency of Industrial Technology and Science?

Answer (Osamu Nakamura)

I think there were several cases where results led to major innovations during the time of Agency of Industrial Technology and Science. After reorganization to AIST, there have been more opportunities and efforts than before to send research out into society and to promote innovation, through the “*Full Research*” method. In this paper, we looked at the carbon fiber at GIRIO, but in the future we shall select both old and new cases, study their processes, and help build up the innovation model.